Development of the Paleoproterozoic Svecofennian orogeny: new constraints from the southeastern boundary of the Central Finland Granitoid Complex
Edited by Perttu Mikkola, Pentti Hölttä and Asko Käpyaho
Geological Survey of Finland, Bulletin 407, 5–27, 2018

GEOLOGICAL EVOLUTION AND STRUCTURE ALONG THE SOUTHEASTERN BORDER OF THE CENTRAL FINLAND GRANITOID COMPLEX

by

Perttu Mikkola[1)], Esa Heilimo[1)], Jouni Luukas[1)], Jukka Kousa[1)], Soile Aatos[1)], Hannu Makkonen[1)], Sami Niemi[1)], Maarit Nousiainen[1)], Marjaana Ahven[1)], Ilona Romu[1)] and Janne Hokka[2)]

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, 6 figures and 1 table.

The rock record present along the southeastern border of the Central Finland Granitoid Complex provides evidence for the geological evolution of the Paleoproterozoic Svecofennian orogeny from the magmatism of the Savo arc through paragneisses deposited in a passive margin setting to arc volcanism and the collisional final phases. The older Svecofennian magmatic phase (1.93–1.91 Ga) ended when the Savo arc collided with the Archean Karelia craton. After this collision, the greywacke protoliths of the paragneisses, in most cases having maximum deposition ages close to 1.92 Ga, were deposited. Most of the paragneisses have later been migmatised. The local presence of unmigmatised variants in close proximity to the migmatised ones indicates large vertical movements in the late stages of geological evolution. Mafic and ultramafic volcanic units erupted as interbeds during extensional phases of the depositional basins. Subduction and arc-type plutonic and volcanic activity commenced in the area at 1895 Ga and continued until 1875 Ma. The peak of granitoid magmatism in the area took place at 1885–1880 Ma and includes units with calc-alkaline, alkali-calcic and A-type geochemical characteristics. This bipolarity of granitoid compositions requires simultaneous melting of differing source rocks at varying crustal depths. The A-type granitoids are located in close proximity to large-scale faults that provided pathways for ascending magmas in a transtensional setting. Voluminously, the mafic plutonic rocks are minor compared to the granitoids and represent partial melts from the upper mantle. Their composition has been significantly affected by fractional crystallisation and assimilation processes during ascent through the continental crust. In areas dominated by granitoids, the deformation is characterised by faults and shear zones, whereas the supracrustal units display evidence of deformation linked to compression from the southeast at 1.83 Ga.

Keywords: Fennoscandian Shield, Finland, Svecofennian Orogeny, tectonics, Paleoproterozoic, granitoids, batholiths, volcanic rocks, paragneiss

[1)] *Geological Survey of Finland, P.O. Box 1237, FI-70211 Kuopio, Finland*
[2)] *Geological Survey of Finland, P.O. Box 96, FI-02151 Espoo, Finland*

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https://doi.org/10.30440/bt407.1

Editorial handling by Asko Käpyaho.

Received 5 February 2018; Accepted 9 July 2018

1 INTRODUCTION

The Paleoproterozoic Svecofennian domain, extending from northwestern Russia through Finland to Sweden, is one of the most extensively studied Precambrian accretionary orogens. Due to a research history extending to the 19th century, the overall geological development of the orogeny is well constrained, although discussion of the details continues. Despite extensive research efforts, the basic geological knowledge from certain areas of the Svecofennian domain is outdated. For example, our main study area (Fig. 1) had been systematically studied over a century ago (Frosterus 1903). This is despite the fact that the area represents a junction of several Svecofennian geological units: the Central Finland Granitoid Complex (hereafter CFGC) and voluminous paragneisses of South Finland, as well as older and younger Svecofennian arc magmatism (Fig. 1).

In addition to refining the relationships and boundaries of the different major geological units, the updated data were a prerequisite for being able to reliably estimate the area's true ore potential. Traditionally, the area had been rated as uninteresting with respect to economic geology (e.g. Eilu et al. 2012), and exploration work in the area had mainly comprised target-scale studies. An exception is the more systematic work related to Ni–Cu ores in the southeastern corner of the main study area.

This paper aims at providing a synthesis of the data and conclusions of papers published earlier and in this volume of the Bulletin of the Geological Survey of Finland and provides an updated model for the overall geological development in the area. Additionally, it describes the large-scale structures observed along the southeastern border of the Central Finland Granitoid Complex and sets them in the Svecofennian tectonic framework.

2 GEOLOGICAL UNITS OF THE MAIN STUDY AREA

The following division of the bedrock follows that of Luukas et al. (2017) with respect to the larger scale and that of Mikkola et al. (2016a) at the scale of the study area. The majority of the bedrock in the main study area belongs to the Western Finland Subprovince, and only the areas east of the Mikkeli shear zone (MiSZ) belong to the Southern Finland Subprovince (Fig. 2). The main units of the Western Finland Subprovince in the study area are the CFGC in the north and Pirkanmaa migmatite and intrusive suites, or Pirkanmaa suites collectively, in the south. The boundary between the Pirkanmaa suites and the CFGC is formed by the northeast–southwest-trending sinistral Leivonmäki shear zone (LmSZ, Fig. 2), readily observable in aeromagnetic and gravimetric Bouguer anomaly maps (Fig. 3). The majority of the volcanic rocks in the study area are included in the Makkola suite, forming a discontinuous belt along the LmSZ. In addition to volcanic rocks, the Makkola suite includes a smaller number of sedimentary units and the Lammuste quartz diorite lithodeme, i.e. plutonic rocks directly associated with the volcanic units. Gabbros and ultramafic plutonic rocks intruding into the Pirkanmaa suites belong to the Vammala suite.

The CFGC is dominated by plutonic rocks of the Jyväskylä suite, which comprises Muurame granitoid and Vaajakoski quartz diorite lithodemes. Rocks of the Muurame granitoid lithodeme also intrude into the rocks of Pirkanmaa intrusive suite south of the LmSZ (Fig. 2). The younger bimodal Saarijärvi suite mainly consists of porphyritic granitoids and quartz montzonites, accompanied by less voluminous diorites and gabbros. Intrusions belonging to the Saarijärvi suite are mainly located within the CFGC, although a small number of them are also present south of it. The youngest granitoid suite in the study area is the Oittila granitoid suite, which, like the Saarijärvi suite, is more voluminous within the CFGC, but is also present south of its boundary formed by the LmSZ.

Due to differences in physical properties, the area of the CFGC mainly consisting of felsic plutonic rocks is characterised by faulting. Supracrustal rocks, which are more voluminous south of the LmSZ, and also less competent, more commonly display signs of plastic deformation.

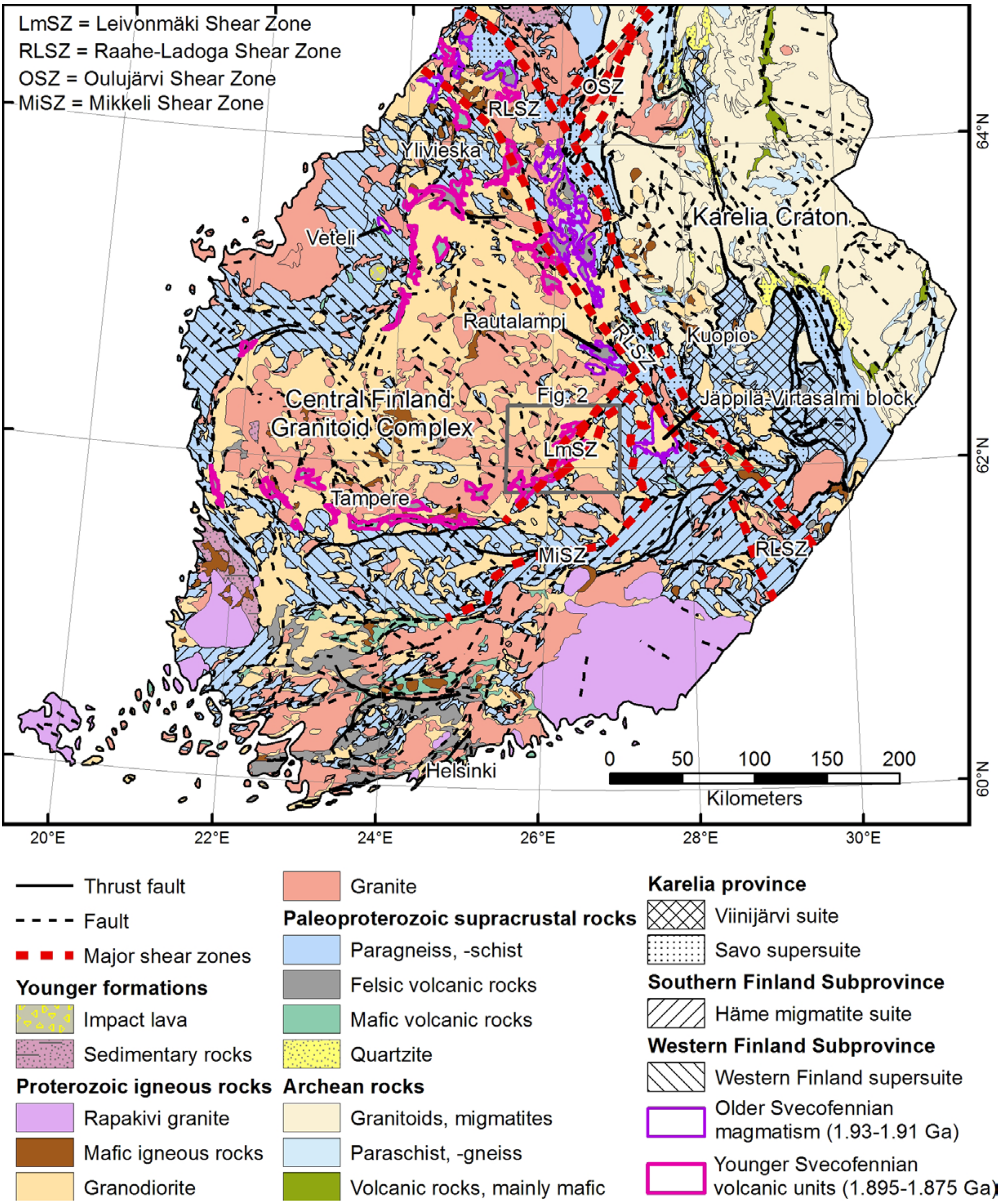


Fig. 1. Geological map of South and Central Finland. Map modified from Nironen et al. (2016) and Bedrock of Finland – DigiKP. Unit division according to Luukas et al. (2017).

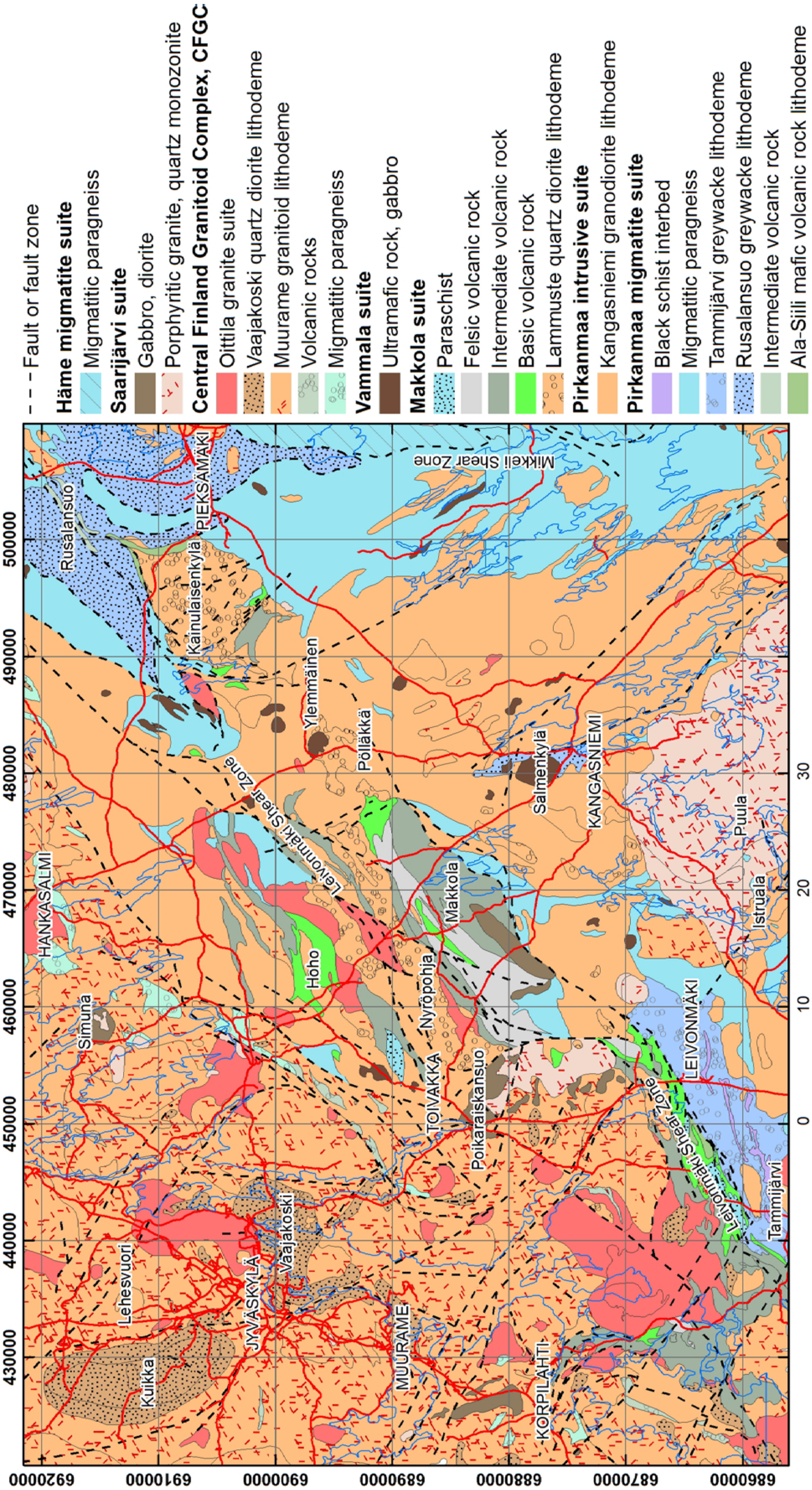


Fig. 2. Geological map of the main study area. Map modified from Mikkola et al. (2016a) and Bedrock of Finland – DigiKP.

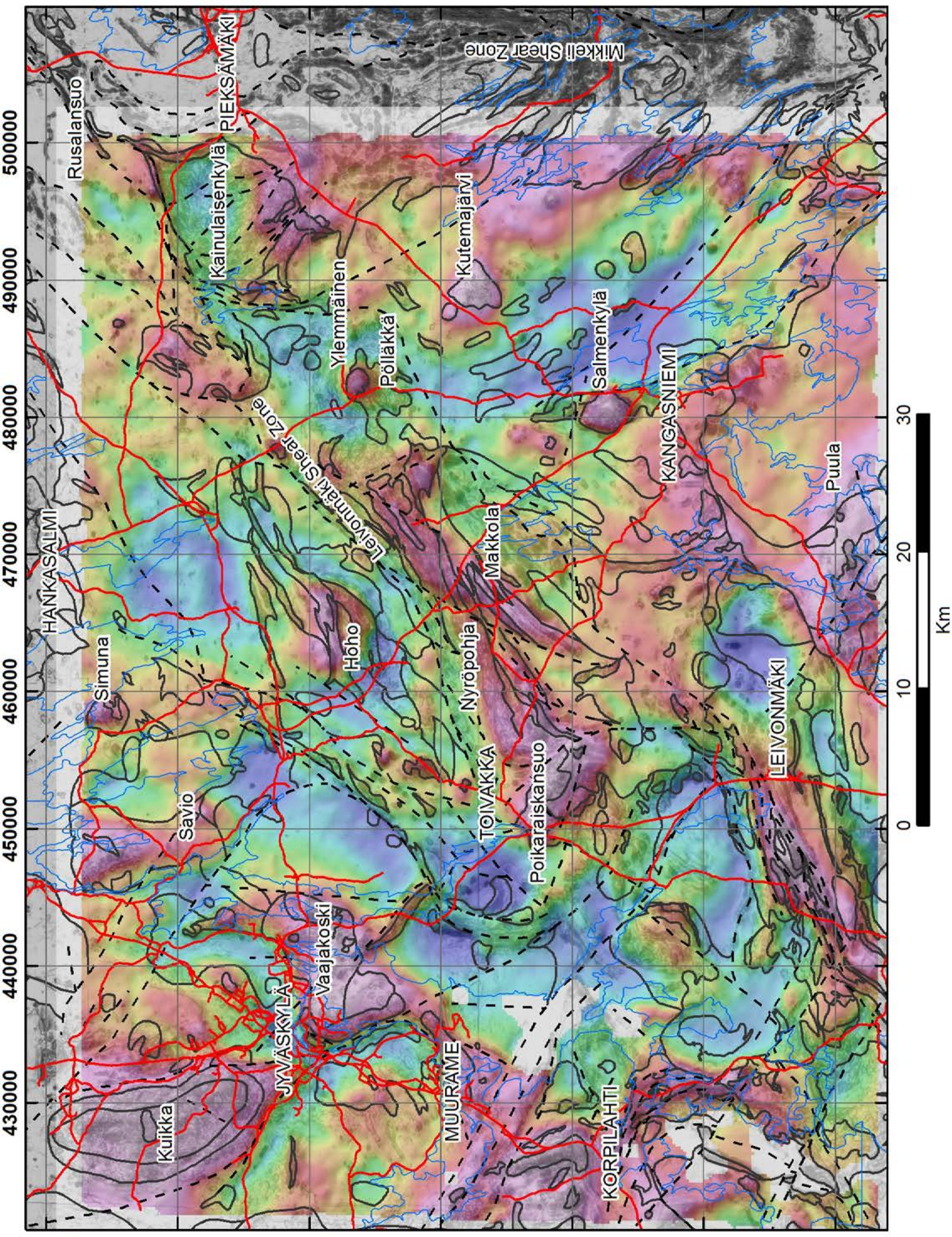


Fig. 3. Combination of aeromagnetic (grey shade: light colour = low values, dark colour = high values) and residual Bouguer anomaly (colour ramp: blue = low values, red = high values) maps of the study area.

3 GRAVITY DATA

The western part of the study area (~2400 km^2) was covered by a regional gravimetric survey in 2012–2016, whereas the eastern part was already measured in the 1980s. On average, there were 4 points per 1 km^2. The majority of the residual gravity anomalies visible in Figure 3 can be explained by the observed surface rocks. The strong, often round positive anomalies, 2–5 km across, are caused by mafic intrusions belonging to either the Vammala suite (e.g. Salmenkylä, Ylemmäinen) or the Saarijärvi suite (e.g. Simuna, Poikaraiskansuo). The rocks of the Vaajakoski lithodeme (mainly diorites and quartz diorites) also cause clear positive anomalies, often larger in area (e.g. Kuikka, Vaajakoski). In some cases, the areal extent of the gravity anomaly is distinctly larger than the observed surface area of the intrusion and/or the magnetic anomaly associated with the intrusion. This suggests that these intrusions broaden below the current erosion surface. For example, the surface width of the Kuikka intrusion, based on both field observations and aeromagnetic data, is six kilometres, but the gravity anomaly associated with it is nine kilometres wide.

In certain areas, the observed gravity anomalies do not correlate with the observed surface geology. For example, north of Savio (Fig. 3), an elongated north–south-trending anomaly can be observed in an area that based on outcrop observations mainly consists of granitoids belonging to the CFGC, in addition to small diorite intrusions belonging to both the Istruala and Vaajakoski lithodemes. The anomaly indicates that the granodiorite is a relatively thin layer covering a larger diorite body. In the Hoho area (Fig. 3), a round-shaped positive gravity anomaly is present in an area where the bedrock, based on both aeromagnetic data and outcrop observations, consists of NE–SW-trending volcanic segments surrounded by granitoids. Based on gravity modelling, the anomaly in this area could be caused by volcanic units dipping to the north and hidden underneath the granitoid cover.

The connection between intrusions belonging to the Lammuste suite and gravity data is not self-evident. The Nyröpohja intrusion flanking the volcanic Makkola segment to the north shows up as a positive anomaly in the gravity data (Fig. 3), while the Pölläkkä intrusion is mainly located in a gravity low. Especially interesting is the Kainulaisenkylä intrusion, which is divided so that the southern half coincides with a positive anomaly and the northern half with a negative anomaly. Based on petrophysical measurements and field observations, this could partly be due to the lower average density of the rocks in the northern half, but it is also possible that the depth extent of the quartz diorite diminishes from south to north.

The large positive anomaly along the eastern edge of the study area is partly caused by paragneisses belonging to the Pirkanmaa migmatite suite and displaying a higher metamorphic degree. However, areas that, based on field observations, mainly consist of granitoids belonging to the Pirkanmaa intrusive suite also fall within this positive anomaly. Thus, it is possible that in addition to the observed small gabbro and diorite areas, there is a larger mafic body hidden below the surface.

The positive Bouguer anomalies along the western contact of the Puula quartz monzonite–granite intrusion are caused by diorite–gabbro intrusions of the Istruala lithodeme. These mafic intrusives, coeval with the granitoid intrusion, are small at the present erosion level, but significantly more voluminous at depth, based on gravity data. Thus, the crustal structure resembles that associated with the classic rapakivi granites in South Finland (Luosto et al. 1990, Elo & Korja 1993).

4 GEOLOGICAL EVOLUTION AND ITS CONNECTION TO THE ROCK UNITS

4.1 Older Svecofennian magmatism

Rocks formed as part of the older Svecofennian magmatism (1.93–1.91 Ga) are mainly present within the Raahe–Ladoga shear zone (RLSZ) between the CFGC and the Archean Karelia craton (Fig. 1, e.g. Ekdahl 1993, Vaasjoki et al. 2003, Kousa et al. 2013). In the current unit classification, these calc-alkaline rocks with arc-type affinity are grouped into the Northern Ostrobothnia supergroup and Venetpalo plutonic suite (Luukas et al. 2017). Earlier, these rocks were interpreted to have a purely linear spatial distribution in the vicinity of the RLSZ. This view changed when Lahtinen et al. (2016) included the Veteli intrusion (Fig. 1) in this group. The results of Kousa et al. (2018a) broaden the known areal extent of the older Svecofennian units by 65 km to the southeast, as the volcanic and plutonic rocks from the Jäppilä–Virtasalmi block (Viholanniemi volcanic suite, Maavesi Suite, Kousa et al. 2017) are shown to be part of this older succession. The current gap in rocks of these older magmatic units between the Jäppilä–Virtasalmi and Rautalampi areas (Fig. 1) is likely to be an artefact of inconsistent studies. We base this on the field characteristics of tonalites and associated volcanic rocks adjacent to the RLSZ in this area (Mikkola et al. 2016b), from which neither age nor up-to-date geochemical data are available.

In several models, older Svecofennian magmatism, forming the Savo arc, or belt, is linked to subduction towards the southwest and it ends with the collision of the arc with the Karelian craton in the Lapland–Savo orogen at 1.92–1.91 Ga (e.g. Lahtinen et al. 2005, 2009b, Nironen 2017). In certain models, the Savo arc developed at the edge of a small crustal block referred to as Keitele microcontinent (ibid.). The areal extent of this crustal block approximately equalled that of the current CFGC. The existence of this crustal fragment, aged ca. 2.0 Ga, has been interpreted based on Sm–Nd model ages and detrital/inherited zircons (Lahtinen & Huhma 1997, Rämö et al. 2001), as rocks with ages close to 2.0 Ga have not been reported from the area of the CFGC. Alternatively, the Sm–Nd model ages could be a result of mixing between Archean and juvenile sources, but this has been and can be regarded as an unlikely explanation, because reflection seismic data indicate that the Karelia craton ends abruptly at the RLSZ (Kontinen & Paavola 2006, Lahtinen et al. 2009b). The complete reworking of the Keitele microcontinent to what is now the CFGC has been attributed to extensive partial melting and crustal reworking in the culmination stages of the Svecofennian orogeny at 1.88 Ga (e.g. Nikkilä et al. 2016).

In this text, the term 'Savo arc', in addition to the older Svecofennian magmatic rocks, also includes the whole area of the CFGC referred to as the Keitele microcontinent in the publications cited above. In our opinion, the separation of the Savo arc and Keitele microcontinent is problematic and most importantly it unnecessarily complicates the tectonic models. The observed isotopic signatures do not require a separate microcontinent; instead, they can be readily explained by variation in the age of the rocks included in the Savo arc itself. For example, the basement of the modern Japanese arc includes voluminous Jurassic rocks representing older phases of the same arc system (e.g. Taira 2001). The collision of such an arc with a continent and nearly complete reworking of it during later stages would result in a situation similar to that in Central Finland, where these older segments are only observable in the isotopic fingerprint of the younger rocks. The preservation of the 1.93–1.91 Ga rocks along the boundary of the Karelia craton, with the exception of the Veteli intrusion (Fig. 1), is a result of later tectonic phases. The dismissal of the Keitele microcontinent becomes especially tempting, as we agree with the terrain wreck model of Lahtinen et al. (2014), in which the originally linear Savo arc (Keitele microcontinent in the reference) transformed into the rounded CFGC close to ~1.87 Ga. The width of the CFGC in its current geometry is ca. 300 km. Thus, its width must have originally been closer to 100–150 km, roughly the same as any modern island arc.

4.2 Paragneisses

The voluminous paragneisses surrounding the CFGC are divided between the Karelia Province and Western Finland supersuite (Fig. 1). In our main study area the latter is represented by the Pirkanmaa migmatite suite (Fig. 2). Paragneisses of the Karelia Province along the northern boundary of the CFGC belong to the Savo supersuite, and further east to the Viinijärvi suite (Fig. 1, Luukas et al. 2017), also known as the Upper Kaleva greywackes (e.g. Lahtinen et al. 2010). Paragneisses east of the main study area belong to the Häme migmatite suite of the Southern Finland Subprovince (Luukas et al. 2017).

Volcanic interlayers in paragneisses of the Pirkanmaa and Häme migmatite suites are mafic to ultramafic in composition and clearly differ from the calc-alkaline arc-type volcanic rocks within, and flanking the CFGC (Kähkönen 2005, Lehtonen et al. 2005, Lahtinen et al. 2017, Kousa et al. 2018b, Mikkola et al. 2018b). On a compositional basis, these mafic to ultramafic (picrites) volcanic rocks can be classified as partial melts of the mantle and probably represent extensional phase(s) of the basin(s) the paragneisses were deposited in (ibid.). The Enriched Mid-Ocean Ridge Basalt (EMORB)-like lavas of the Haveri formation, the lowermost unit of the Tampere group, have been interpreted in the same way (Kähkönen & Nironen 1994, Kähkönen 2005). In our study area, the majority of the volcanic interlayers (Ala-Siili lithodeme) within the Pirkanmaa intrusive suite are picrites with certain compositional characteristics often associated with rocks formed in volcanic arcs, e.g. Light Rare Earth Element (LREE) enrichment and negative Nb and Ti anomalies (Kousa et al. 2018b). On the other hand, the mafic to ultramafic interbeds (Pahakkala suite) hosted by the Häme migmatite suite display normal MORB affinities, with the exception of samples from one location displaying features similar to the Ala-Siili lithodeme (ibid.). There are most probably multiple causes behind these differences, including variation in the melting depth and temperature, as well as in contamination during ascent. Mikkola et al. (2018b) included a small number of calc-alkaline volcanic rocks in the Pirkanmaa migmatite suite, but as these samples are from highly deformed and poorly exposed areas, this was mainly done on a geographical basis, and further studies could show that these rocks are part of the Makkola suite.

Paragneisses of both the Southern Finland and Western Finland supersuites, as well as the Karelia Province, most often display maximum depositional ages close to 1.92 Ga, and their detrital zircon populations have bimodal distribution patterns with peaks at 2.7 Ga and 2.05–1.92 Ga (Huhma et al. 1991, Lahtinen et al. 2002, 2009a, 2015, Kotilainen et al. 2016, Mikkola et al. 2018a). Despite unit level similarities, there is variation between samples representing the same geological unit, e.g. the proportion of Archean zircons and their age. A classical question with respect to the paragneisses and schists of Central and South Finland is the source of the ~2.0 Ga zircons. One possibility is the Lapland–Kola orogen, culminating close to 1.95 Ga (Daly et al. 2006). Rocks with such ages have also been reported from the vicinity of Moscow, 1000 km to the southeast, hidden below the platform covers (Samsonov et al. 2016). The proposed sources also include the above-discussed Savo arc, with respect to which an interesting phenomenon is the small proportion of zircon grains with ages falling between 1.93 and 1.91 Ga (e.g. Lahtinen et al. 2002, Mikkola et al. 2018a). This is interesting, as the newly formed Lapland–Savo orogen would appear to be a bountiful source for sedimentary input. A possible explanation for the small number of detrital zircons with ages between 1.93 and 1.91 Ga could be a paleogeographic setting that favoured transport from areas other than that hosting the rocks belonging to the older Svecofennian magmatism, or burial of these during the collisional phase. Because most of the paragneiss samples from areas surrounding the CFGC do not contain detrital zircons with 1.90–1.88 Ga ages typical for volcanic rocks within, and surrounding the CFGC (e.g. Kähkönen & Huhma 2012, Nikkilä et al. 2016, Mikkola et al. 2018b), they must have been deposited prior to the onset of active volcanism in the area that later became the CFGC.

Differentiation between the Pirkanmaa and Häme migmatite suites (Fig. 1) has partly been based on the presence of black schist interbeds in the former and their absence from the latter (Luukas et al. 2017). However, especially in the vicinity of our study area, this is not the case, as the Häme migmatite suite also contains abundant black schist interbeds (Bedrock of Finland - DigiKP). In our study area, the boundary between the Pirkanmaa and Häme migmatite suites (Fig. 2) is in the current interpretation formed by the MiSZ. This zone also represents a major change in metamorphic degree from granulite facies of the Pirkanmaa migmatite suite to lower amphibolite facies of the Häme migmatite suite (Korsman et al. 1988). Based on the above and the similarities of the detrital zircon populations displaying peaks at 2.7 and 2.0 Ga (Mikkola et al. 2018a), we agree with Lahtinen et al. (2017), who noted that the two suites might represent protoliths deposited in different parts of the same basin, and the current unit division reflects post-depositional effects.

The question with respect to the unit divisions is also topical in relation to the Tammijärvi greywacke lithodeme in our study area (Fig. 2) and the lowermost unit of the Tampere group, i.e. greywackes of the Myllyniemi formation. Both of these units consist of chemically similar greywackes with conglomerate and metapelite interbeds, as well as mafic to ultramafic volcanic rocks (Kähkönen & Nironen 1994, Kousa et al. 2018b, Mikkola et al. 2018a) interpreted to represent extensional phases in the development of the depositional basins. Both units have detrital zircon populations similar to each other and to the Pirkanmaa migmatite suite (Huhma et al. 1991, Lahtinen et al. 2009a, Mikkola et al. 2018a), and occur in the vicinity of calc-alkaline magmatism aged 1895–1875 Ma. The only significant difference between the Tammijärvi lithodeme and Myllyniemi formation is the lack of black schist interbeds in the latter (Kähkönen 2005). Despite significant similarities, the Tammijärvi greywackes are included in the Pirkanmaa migmatite suite and the Myllyniemi formation in the Tampere group. This difference in interpretations is partly due to the nature of the contacts. The Tammijärvi greywackes have gradual contacts towards the migmatised members of the Pirkanmaa migmatite suite, whereas the Myllyniemi formation is separated from the Pirkanmaa migmatite suite by a more abrupt change in metamorphic grade, not unlike the Mikkeli shear zone in our study area between the Häme and Pirkanmaa migmatite suites.

The most significant difference between the Savo supersuite and the Häme, Pirkanmaa and Viinijärvi suites is the uniformly unmigmatised character of

Table 1. Timeline of the main geological units and events of the study area.

Time (Ma)	
1920–1910	Magmatism belonging to the older Svecofennian phase in the Jäppilä-Virtasalmi block
	Granitoids and volcanic rocks that can be correlated with those in the Vihanti–Pyhäsalmi area
>1900	Deposition of rocks of the Pirkanmaa migmatite suite and Häme migmatite suite
	Greywackes deposited by turbidites. Most, but not all, were migmatized in later stages. Observed differences in metamorphic degree due to late vertical movements.
	Mafic/ultramafic volcanic rocks erupted on the sediments during extensional phases
~1900	Onset of subduction in the area
1895	Pirkanmaa intrusive suite
	Calc-alkaline granodiorites and tonalites intruding into rocks of the Pirkanmaa migmatite suite.
1895–1875	Makkola suite
	Mainly felsic to intermediate calc-alkaline volcanic rocks, small amounts of associated plutonic rocks and sedimentary rocks. Dykes related to the suite cross-cut the Pirkanmaa intrusive suite.
1885	Vammala suite
	Gabbros and ultramafic plutonic rocks as small intrusions and dykes intruding the Pirkanmaa migmatite and intrusive suites.
1885–1880	Jyväskylä suite
	Porphyritic calc-alkaline granitoids (Muurame lithodeme), smaller amounts of dioritoids (Vaajakoski lithodeme). The majority of the rocks of the Cental Finland Granitoid Complex. Also intrude into Pirkanmaa intrusive and migmatite suites. Partial melts of SOME crust.
~1880	End of subduction in the area
1880–1875	Saarijärvi suite
	Bimodal suite consisting of diorites, granitoids and quartz monzonites. Chemically A-type, felsic members are typically K-feldspar porphyritic.
1875	Oittila suite
	Granitoid dykes and intrusions less than 10 km across, often leucocratic, low degree partial melts of pre-existing crust or last remaining melt fractions from intrsuions below current erosion level.
1830	Thrusting of Pirkanmaa migmatite and intrusive suites from south on top of the Central Finland Granitoid Complex
	Major activity along the Leivonmäki shear zone
	Activity along the southeast-northwest-trending faults within Central Finland Granitoid Complex
1830–1790	Late Svecofennian granites
	Rutalahti peridotites
	Small ultramafic intrusions representing mantle derived melts. Ascent and emplacement controlled by large scale faults. Precise age unknown.
1670–1620	Kuisaari suite
	Subophitic gabbros and diorites, belonging to the Häme dyke swarm of the Southern Finland rapakivi supersuite.

the paragneisses of the last suite. Protoliths of all of these units were deposited as greywackes and all host mafic to ultramafic volcanic interlayers. In the Viinijärvi suite, these are the ophiolites of the Outokumpu assemblage and in the Häme and Pirkanmaa migmatite suites the picrites and MORB affinity rocks (Peltonen 2005a, Lahtinen et al. 2017, Kousa et al. 2018a). Lahtinen et al. (2009a) proposed, based on similar compositions and detrital zircon populations, that the Viinijärvi suite greywackes represent a major source area of the Western Finland supersuite. However, the gradual differences in Ba, Sr, Th/Sc and Ti/Al displayed by rocks of the Pirkanmaa migmatite and Viinijärvi suites, and used by Lahtinen et al. (2009a) for their model, could also result from variation in the mixing ratio from the same source areas. Based on tectonic interpretation and detrital zircon populations, Lahtinen et al. (2015) concluded that the paragneisses of the Savo supersuite northwest of Kuopio (Fig. 1) are part of the Karelia Province and equivalents of the Viinijärvi suite. However, no age data are available from paragneisses of the Savo supersuite southeast of Kuopio and the tectonic setting of the unit is also less well defined. Based on the above, the unit division in areas surrounding the Jäppilä–Virtasalmi block are more or less tentative, as also noted by Luukas et al. (2017). The necessary revision cannot be carried out based on the current material, but would not be an overwhelming task, either.

4.3 Into the active subduction phase, 1895 Ma

Volcanic rocks aged 1895–1875 Ma form a discontinuous belt along the boundary between the CFGC and the paragneisses surrounding it. These volcanic segments have been incorporated in the Central Ostrobothian supergroup (Luukas et al. 2017), which includes, among others, the Tampere group (Fig. 1, Kähkönen 2005) and Ylivieska group (Kousa & Lundqvist 2000). The less extensively studied units are grouped into a number of suites within the Western Finland supersuite. Based on material in Mikkola et al. (2018b), the Makkola suite volcanic rocks correlate with respect to age and composition with the Central Ostrobothnia supergroup and represent the eastern end of the discontinuous volcanic belts of this age. Volcanic and subvolcanic units within the CFGC mainly yield ages close to 1885 Ma (Rämö et al. 2001, Nironen 2003, Nikkilä et al. 2016), although ages close to 1895 Ma are also known (Tiainen & Kähkönen 1994). The genesis of these volcanic rocks has been linked to active subduction along the southern and western edge (current geometry) of the CFGC (Kähkönen 2005, Lahtinen et al. 2009b, Nironen 2017) or alternatively considered to be a result of post-accretional partial melting of crust thickened during the collision of the Savo arc with the Karelia craton (Nikkilä et al 2016). The oldest ages (~1895 Ma) from the volcanic rocks belonging to the Makkola suite (Mikkola et al. 2018b) and Tampere group (Kähkönen & Huhma 2012) are similar to that of the Pirkanmaa intrusive suite (Kallio 1986, authors' unpublished data). As the Pirkanmaa intrusive and Makkola suites display significant compositional similarities in addition to age (Mikkola et al. 2018b, Heilimo et al. 2018), the latter can be regarded as the plutonic equivalent of the volcanic rocks of the former. As rocks belonging to the Pirkanmaa intrusive suite intrude the rocks of the Pirkanmaa migmatite suite, the 1895 Ma age of the former marks the minimum age of the latter. Overall, the observations from our study area support the interpretation of Lahtinen et al. (2009b) and Nironen (2017) concerning the onset of subduction and magmatism related to it in Central Finland close to 1.90 Ga. Weak indications of 1.90 Ga metamorphism given by zircon studies on greywackes (Lahtinen et al. 2009a, Mikkola et al. 2018a) could be linked to this onset of subduction, resulting in the creation of an accretionary prism. The presence of both Archean and Paleoproterozoic detrital zircons in a volcano-sedimentary sample belonging to the Makkola suite (Mikkola et al. 2018b) requires that the volcanism must have taken place in a continental arc setting, as zircons significantly older than the active volcanism are not commonly known from island arcs. Also, the highly evolved chemical characteristics of the volcanic rocks support a continental arc origin for the Makkola suite (Mikkola et al. 2018b).

4.4 Vammala suite

The Svecofennian gabbro and ultramafic intrusions have been intensively studied due to their Ni potential. In our study area, these intrusions are emplaced in the Pirkanmaa suites and thus grouped into the

Vammala suite (Luukas et al. 2017). The mafic to ultramafic interbeds occurring in paragneisses of the Häme migmatite suite belong to the Pahakkala suite (Luukas et al. 2017), although Makkonen and Huhma (2007), for example, concluded that the gabbro and ultramafic intrusions of the Vammala suite are the plutonic equivalents of these volcanic interlayers. However, new data (Lahtinen et al. 2017, Kousa et al. 2018b, Mikkola et al. 2018a) confirm the interpretation of Peltonen (1995) that the mafic to ultramafic volcanic rocks are not co-magmatic with these so-called Ni gabbros. Instead, the volcanic units erupted at 1.91–1.90 Ga on the protoliths of Pirkanmaa and Häme migmatite belts, whereas the ages of the Ni gabbros are 1.89–1.88 Ga (Peltonen 2005b and references therein). In the study area, the minimum age of intrusions is 1875 Ma, defined by the cross-cutting Oittila suite granitoids (Mikkola et al. 2016a, authors' unpublished data). Thus, based on the available age constraints, the youngest Vammala suite intrusions are coeval with the peak of the granitoid magmatism within the CFGC and the oldest ones are roughly of the same age as the oldest volcanism forming the Makkola suite.

Based on the above-described time constraints, the physical location and the overall tectonic setting, we interpret that the Vammala suite intruded during active subduction into tensional structures of the accretionary wedge consisting of the Pirkanmaa suites. This interpretation is in line with that of, for example, Peltonen (1995, 2005b) and Nironen (1997). Due to their syntectonic character, the Ni gabbros were intensively deformed, boudinaged and contaminated by surrounding rocks and fluids over their whole distribution area (Peltonen 2005b, Mikkola et al. 2016a). It should be noted that the Ni gabbros of the coeval Kotalahti suite intruding the Savo supersuite (Fig. 1) were emplaced in a different structural environment, i.e. the transtensional RLSZ between the Savo arc and the Archean craton (Peltonen 2005b).

4.5 Formation of the CFGC at 1885–1875 Ma

The majority of the granitoids forming the CFGC crystallised at 1885–1875 Ma (e.g. Rämö et al. 2001, Nironen 2003, Nikkilä et al. 2016, Kallio et al. 2018). These rocks have earlier been subdivided in variable ways based on either interpreted relationships with kinematics or compositional bases. Nironen (2003) divided these rocks into synkinematic and postkinematic groups and Nikkilä et al. (2016) into three different groups mainly based on their compositional characteristics, interpreted as signs of variation in depth and the degree of melting, as well as in the emplacement depth. The Jyväskylä suite, consisting of porphyritic granitoids accompanied by smaller volumes of dioritoids (Mikkola et al. 2016a, Heilimo et al. 2018), equals the synkinematic group of Nironen (2003) and group 2 of Nikkilä at al. (2016). The bimodal Saarijärvi suite (Luukas et al. 2017, Virtanen & Heilimo 2018) corresponds to the post-kinematic group of Nironen (2003) and group 3 of Nikkilä et al. (2016).

4.5.1 Jyväskylä suite

Based on its chemical characteristics, the Jyväskylä suite represents typical calc-alkaline arc type magmatism. Compositions span from basic to felsic, the majority being relatively felsic porphyritic granodiorites (e.g. Nironen 2003, Nikkilä et al. 2016, Heilimo et al. 2018). Despite compositional similarities with modern arc rocks, Nikkilä et al. (2016) explained the genesis of the Jyväskylä suite granitoids with a model that did not involve active subduction. Instead, these rocks would have been formed due to partial melting of crust thickened in the collision of the Savo arc with the Karelia craton at 1.91 Ga. This model was based on material from the central parts of the CFGC lacking the mafic members of the suite (diorites, quartz diorites), which seem to increase in abundance when moving south from the central parts of the CFGC (Bedrock of Finland - DigiKP). This could possibly be an indication of crustal thickness at the time of emplacement. Diorites originating from the mantle (Heilimo et al. 2018) would have experienced less fractionation and crustal assimilation in areas of thinner crust, i.e. closer to the subduction zone.

4.5.2 Saarijärvi suite

Rocks of the bimodal Saarijärvi suite have been referred to as postkinematic (e.g. Nironen et al. 2000, Nironen 2003), because they are relatively undeformed compared to the rocks of the Jyväskylä suite (ibid. synkinematic). This observation is valid, and the cross-cutting relationships are also clear; the Saarijärvi suite is younger than the Jyväskylä suite (Nironen et al. 2000, Mikkola et al. 2016a, Virtanen & Heilimo 2018). However, the age determinations of both of these suites yield ages close to 1880 Ma and overlap within error. In the model of Nikkilä et al. (2016), the Saarijärvi suite represents partial melts of the lower crust that were emplaced in an extensional setting, which allowed magmas generated in the lower crust to rise efficiently. Due to the overlap in absolute ages of the Jyväskylä and Saarijärvi suites, this would have meant an extremely rapid transition from a compressional setting to an extensional one. Saarijärvi suite rocks typically occur in, or in the proximity of, large-scale faults, both in our study area (Mikkola et al. 2016a, Virtanen & Heilimo 2018) and in other parts of the CFGC and in its vicinity (Nironen 2003, Kousa & Luukas 2007, Nikkilä et al. 2016). For example, in our study area, the largest intrusions of this suite (Fig. 2, Puula–Viiniperä–Riitalampi–Poikaraiskansuo) form a condensation on a roughly southeast–northwest-trending line, coinciding with the major fault direction within the CFGC. Based on this, it seems that these faults were already active 1880 Ma ago, which is in agreement with the model of Nironen (2017). The transtensional crustal scale faults would have provided pathways for ascending magma created in the lower crust.

Support for the coeval existence of two geochemically differing granitoid melts at 1880 Ma in our study area is given by the observations of Virtanen & Heilimo (2018). They demonstrated that certain samples representing the Saarijärvi suite deviate from an A-type composition due to contamination by arc-type granite melts or rocks (i.e. Jyväskylä suite). Samples representing the Jyväskylä suite also display signs of interaction with the Saarijärvi suite (Heilimo et al. 2018). However, clear observations of magma mixing and mingling have only been reported between the mafic and felsic members of the Saarijärvi suite (e.g. Nironen et al. 2000, Virtanen & Heilimo 2018).

4.5.3 Oittila suite

The Oittila suite, present as intrusions and abundant dykes, represents the youngest granitoid magmatism in the area (~1875 Ma, authors' unpublished data). Often, these granitoids are more leucocratic than those of the Jyväskylä suite and can be distinguished both in the field from cross-cutting relationships and by using geochemistry (Heilimo et al. 2018). However, overlap between these two suites exists and their differentiation is sometimes challenging. The observed compositions of rocks of the Oittila suite can be interpreted in two differing ways: they are either the last remaining melt fractions or result from a low degree of partial melting. As the Oittila suite granitoids display sharp contacts with the rocks they intrude into, and migmatites are rare in our study area outside the Pirkanmaa migmatite suite, the partial melting would have occurred below the current erosion level. However, on a compositional basis, Heilimo et al. (2018) suggested that the Oittila suite represents more evolved intrusions of magma compositionally similar to those of the Jyväskylä suite.

4.5.4 Connection between volcanism and plutonism, building a batholith

The older volcanic activity (~1895 Ma) of both the Makkola suite (Mikkola et al. 2018b) and the Tampere group (Kähkönen & Huhma 2012) is coeval with the Pirkanmaa intrusive suite, whereas younger activity (1885–1875 Ma) is coeval with the Jyväskylä suite plutonic rocks. None of these suites display significant compositional differences (Heilimo et al. 2018, Mikkola et al. 2018b), and they also display similar trace element characteristics, namely those typical for arc-type magmatism. This similarity is demonstrated by the fact that an individual sample from the Pirkanmaa intrusive suite cannot be reliably differentiated from one representing the Jyväskylä suite of the CFGC, and neither can a single sample representing the Makkola suite be separated from a volcanic sample within the CFGC. This should be taken as evidence that the aforementioned suites were all generated in the same processes from roughly similar sources in an arc environment (Heilimo et al. 2018, Mikkola et al. 2018b). It should also be noted that the close spatial association between the CFGC and the Pirkanmaa intrusive suite is not purely a product of later tectonic movements. This is evidenced by the observation that rocks belonging to the CFGC locally intrude in the slightly older Pirkanmaa intrusive suite in a triangle formed by Kangasniemi, Hankasalmi and Leivonmäki (Fig. 2).

Despite strong similarities, there is an overall trend from the tonalite–granodiorite compositions of the Pirkanmaa intrusive suite towards the granodiorite compositions of the Jyväskylä suite and further to the granite compositions of the Oittila suite (Heilimo et al. 2018). Certain trace element ratios also indicate subtle differences between central parts of the CFGC and its "outer rim". For example, volcanic samples from central parts of the CFGC and Jyväskylä suite granitoids display enrichment in Zr and Th over those of the Makkola and Pirkanmaa intrusive suite, which causes them to plot on differing trends in the classification diagrams of Pearce (1996, 2008, Fig. 4). Such subtle differences are what would be expected during the maturation of the arc. The ca. 5–10 Ma age difference between the Oittila and Jyväskylä suites would equal 5–10 km of crust removed between the emplacement of the two suites if assuming an erosion rate of 1 mm/year, which is typical in the modern-day Alps (Wittmann et al. 2007). Assuming such rates for a Paleoproterozoic orogen in an environment without vegetation and a more acid atmosphere is likely to lead to an underestimate rather than an overestimate. In response to uplift and erosion, the pooling level of granitoid magmas would respectively shift lower in the crust, resulting in more evolved magmas reaching the currently exposed level. This would fit the interpretation of Heilimo et al. (2018), i.e. the Oittila suite represents a more evolved version of Jyväskylä suite magmas. Such a model based solely on the depth of the intrusions would in many ways be the simplest one; it would explain the compositional continuum of the Jyväskylä and Oittila suites without the need for differing melt sources in a geologically brief time period.

Based on the discussion above, we agree with Nironen (2003, 2017), for example, and regard the CFGC as a batholith formed in an active continental arc. The relatively abundant preservation of the volcanic units along the borders of the CFGC is likely to be the result of bulging of the complex during later tectonic movements, resulting in a deeper crustal section being exposed in its central parts. In these areas, volcanic and subvolcanic units have only locally been preserved in areas of down-warped blocks. The current erosion level in the central CFGC coincides with the emplacement level of the main granitoid magmatism. This explains the lack of rocks older than 1.90 Ga that formed the Savo arc. It should also be borne in mind that the inner parts of the CFGC are poorly studied and rocks with such ages could be found in future studies. Rocks of the Pirkanmaa migmatite suite resided at this stage in the accretionary prism, as proposed by Lahtinen et al. (2009a), among others. Fore-arc deposits of this period have been eroded in later stages, and preservation has only locally been possible in

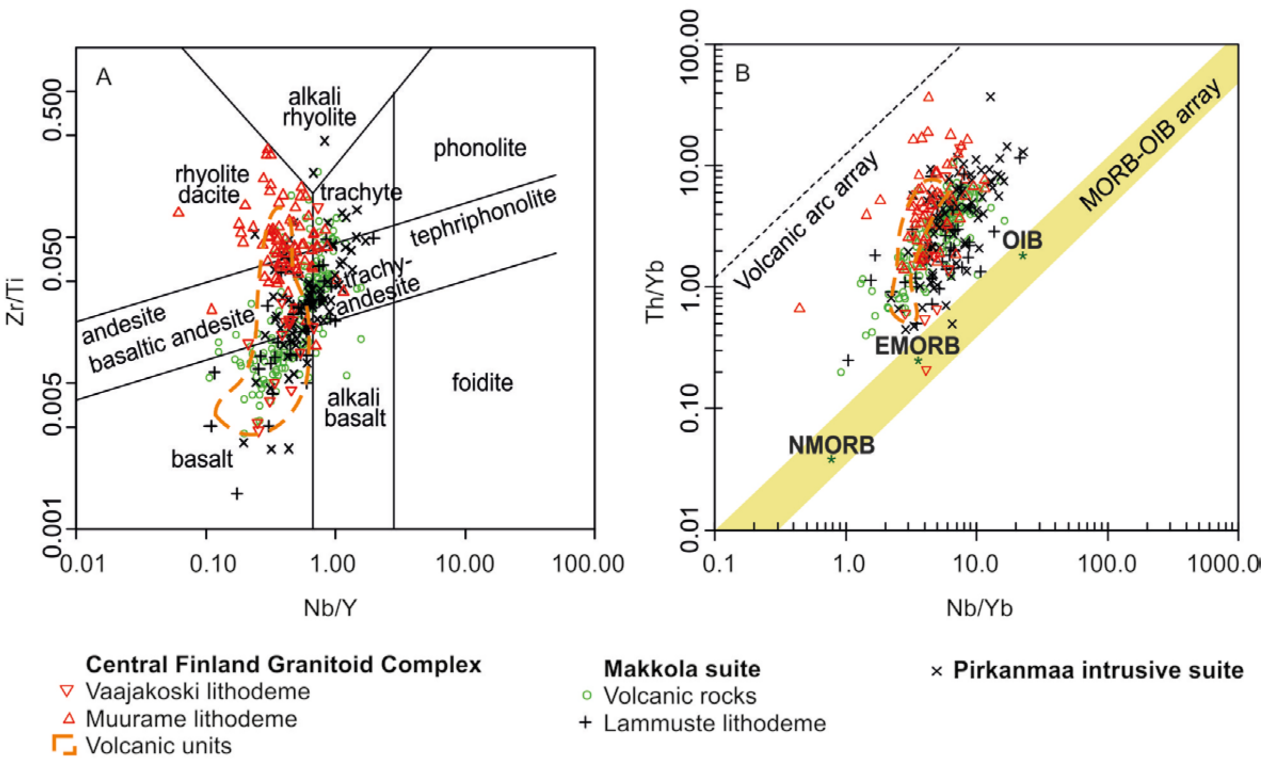


Fig. 4. Comparison between different rock units of the Central Finland Granitoid Complex, Makkola suite and Pirkanmaa intrusive suite. A) Nb/Y vs. Zr/Ti plot of Pearce (1996) and B) Nb/Yb vs. Th/Yb plot of Pearce (2008). Data from Nikkilä et al. (2016), Heilimo et al. (2018) and Mikkola et al. (2018a). Despite overlap, rocks from the CFGC form a trend differing from that defined by samples belonging to the Makkola suite and Pirkanmaa intrusive suite. See the text for further discussion.

structurally favourable locations (e.g. Korsman et al. 1988, Nironen & Mänttäri 2012).

An alternative solution to the active subduction model would be to regard the CFGC as a result of partial melting triggered by thermal relaxation of crust thickened during the accretion of the Savo arc with the Karelia craton close to 1.91 Ga (Nikkilä et al. 2016). The rounded, rather than elongated, shape of the CFGC (Fig. 1), and rock units surrounding it, would seem to favour this post-accretionary partial melting model for its genesis. This is because 180° bends in modern active subduction systems are not at the scale of hundreds, but thousands of kilometres. A solution to this geometrical challenge was proposed by Lahtinen et al. (2014), who argued that the current shape of the CFGC is a result of crustal-scale buckling that bent the originally linear complex, as well as the surrounding units, into their current shape. This would have occurred at 1.88–1.86 Ga, during major activity along the RLSZ, and would have been linked to the dextral rotation of the CFGC (Pajunen et al. 2008) in connection with the collision of the Bergslagen microcontinent from the south (e.g. Lahtinen et al. 2009a, Nironen 2017).

4.5.5 Metamorphism

Most of the age samples from the study area do not provide constraints on the timing of metamorphism, an exception being the relatively precise 1885 Ma age for the anatexis of the Pirkanmaa suite migmatites (Mikkola et al. 2018a). As this age coincides with the main phase of the plutonic activity in the whole study area, it can be assumed that it marks the peak of areal metamorphism in the area, although further to the east, in the vicinity of the Sulkava thermal dome, the metamorphism appears to be somewhat younger, i.e. 1840–1810 Ma (Vaasjoki & Sakko 1988, Kousa et al. 2018b). As the chaotic diatexites rarely show constant deformational structures, correlation with the migmatisation-related deformational phase was not carried out. Based on P-T calculations from migmatitic paragneisses in the study area, the metamorphism of the Pirkanmaa migmatite suite east of Leivonmäki was of the high-T, medium-P type (700–800 °C, 5–6 kbar), suggesting that it was caused by heat transferred to the present erosion level by voluminous magmatism (Romu unpublished data).

4.6 Younger sedimentary phase

A limited number of paragneiss samples from the Pirkanmaa migmatite suite contain detrital zircons that could be coeval with the ca. 1895 Ma active volcanism along the southern boundary of the CFGC (Lahtinen et al. 2009a, Mikkola et al. 2018a). These rocks were named as "fore-arc sediments" by Lahtinen et al. (2009a), who separated them from older greywackes mainly based on Sr contents. Paragneisses with elevated Sr contents were also encountered from the study area, but based on currently available data, they cannot be separated into a different unit (Mikkola et al. 2018a). Furthermore, the possible effects of ancient lead loss must be borne in mind when making interpretations from a limited number of detrital zircons on highly metamorphosed rocks. It is possible that some of the ages now interpreted as detrital in fact result from metamorphic resetting.

Regardless of the above, the Haukivuori conglomerate with granitoid clasts aged 1885 ± 6 Ma (Korsman et al. 1988) represents a later depositional phase in the presently studied area and equals the "fore-arc sediments" of the Pirkanmaa migmatite suite. Its preservation is probably caused by the structural location on a downthrown block, as suggested by the abrupt change in metamorphic grade (ibid.) related to the Mikkeli shear zone. The change in metamorphic grade also correlates with a change on the Bouguer anomaly map.

4.7 Thrusting and folding before the main activity of the LmSZ

Volcanic rocks of the Makkola suite record only one clear folding event prior to the development of the LmSZ (Fig. 5A, B). As rocks belonging to the Pirkanmaa migmatite suite mainly occur as scattered areas between igneous rocks of the Pirkanmaa intrusive suite, their structural history is more difficult to constrain, but their general structural trends are identical to those of the volcanic segments. Thus, it is likely that they have experienced the same compressional deformation as rocks of the Makkola suite. This compression from the southeast resulted in southwest–northeast-trending folding along the edge of the CFGC and later faulting and thrusting of the Pirkanmaa suites and Makkola suite on top of the CFGC. Major horizontal movements are likely to be associated with this folding and thrusting phase. This is evidenced by the juxtaposition of well-preserved greywackes (Mikkola et al. 2018a) on top of intensively migmatised paragneisses or igneous rocks in several locations. The maximum age of 1885 Ma for these vertical movements is given by paragneisses in the vicinity of Kangasniemi, where the well-preserved greywackes show no signs of the intensive migmatisation of this age characterising their surroundings (Mikkola et al. 2018a). Later activity along the LmSZ has largely obscured the structures related to this phase.

The directions of the fold planes related to this compressional stage are similar to those observed further southeast in the Mikkeli and Sulkava areas and could indicate that the folding is associated with the final stages of Svecofennian development in South Finland (e.g. Pajunen et al. 2008, Nironen 2017). Based on reflection seismic data from the NW parts of the CFGC, Sorjonen-Ward (2006) identified several reflectors dipping at a low angle towards the SE and interpreted them as thrust faults that could be linked to the same event at ~1.83 Ga as the deformation in our study area. However, the timing of the activity along these thrust faults is challenging, and they could also be related to compressional deformation already occurring at 1.88–1.87 Ga (Pajunen et al. 2008, Sorjonen-Ward 2006).

4.8 Leivonmäki shear zone (LmSZ)

The LmSZ is a NE–SW-trending sinistral shear system that differs from the large-scale southeast–northwest-trending fold and fault structures characterising the Raahe–Ladoga shear zone. These fault zones probably developed as a conjugate shear system. The system formed about 1830–1800 Ma ago, probably as a continuation of the previous thrusting and folding phase. The Oulujärvi Shear Zone further north (Fig. 1) represents a similar conjugate of the RLSZ, and the age of the post-orogenic granites (1790 Ma, Kontinen et al. 2013) it deforms can also be tentatively taken as the maximum age of the last major activity along the LmSZ.

The width of the LmSZ in the central part of the main study area is up to 25 km and the total displacement it causes is thus difficult to estimate, but it is in order of tens of kilometres. In the Leivonmäki area, the LmSZ narrows to four kilometres and the shear is distributed in several fault surfaces, forming dextral fault duplexis (Figs 2, 5C). Folding associated with the shearing is the dominant structure of the metasedimentary units in this area (Mikkola & Niemi 2015). The contacts between the Pirkanmaa migmatite suite and the Makkola suite coincide in two places with faults of the LmSZ: south of the Makkola segment, where the Synsiö fault separates the migmatitic paragneisses from the volcanic units, and in Leivonmäki area, where the unmigmatised Tammijärvi greywackes are present south of the shear zone. In both of these locations, the fault also presents a significant change in metamorphic degree.

Due to its large scale and variable outcrop conditions in the study area, the LmSZ can most readily be observed when it affects geological units with varying magnetic properties. For example, the 10 by 10 km Kainulaisenkylä quartz diorite intrusion in the northeastern corner of the study area was rotated, forming a “mega-augen” structure (Fig. 3). Another place where the displacement caused by the LmSZ is easily observable is the volcanic segment at Makkola. Here, one fault transects the volcanic units, displacing them by ca. 2 km, and the western end of the belt is truncated by a fault displacing the western continuum of the suite in the Leivonmäki area by 7 km (Figs 2, 3).

The gold potential in our study area is mainly related to activity along the LmSZ (Luukkonen 1994, Mikkola et al. 2018c). The observed differences between the mineralisations also provide indications of prolonged activity along the LmSZ, which is additionally evidenced by locally intensive signs of brittle activity, in addition to the main plastic deformation phase (Fig. 5D). Observations of the brittle deformation are mainly from drill cores (Fig. 5E, Mikkola & Niemi 2016), as such fault breccias are covered by Quaternary deposits.

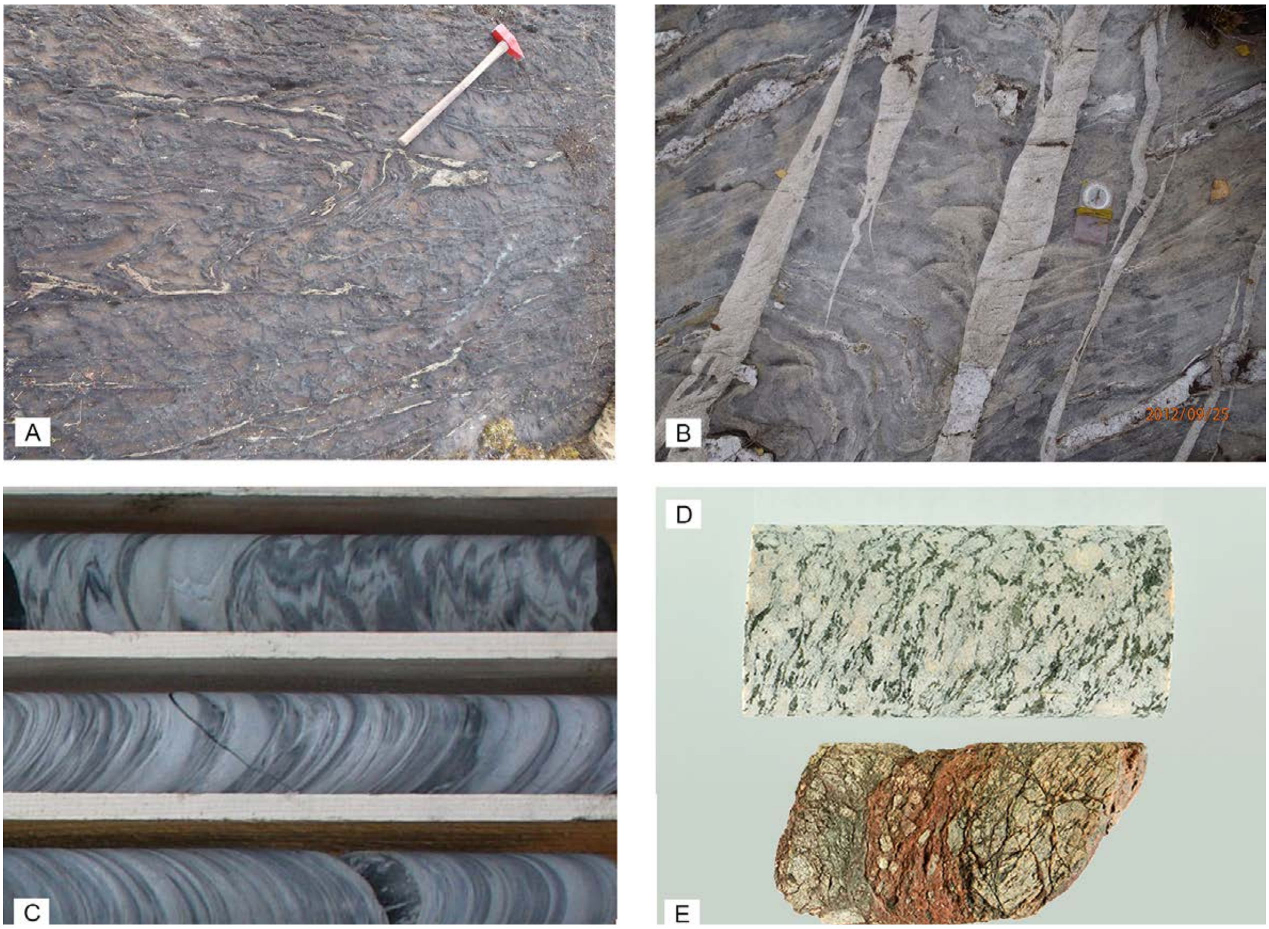


Fig. 5. A) Folded volcanic breccia from central parts of the Makkola segment. The handle of the hammer points to north. Length of the hammer 60 cm. B) Intermediate volcanic rock with folded bedding from the eastern part of the Makkola segment. Length of compass 12 cm. C) Thinly bedded paraschist from the Tammijärvi area displaying locally intensive small-scale left-handed fault duplexing formed during plastic phase of the Leivonmäki shear zone. D) Mylonitised Jyväskylä suite granite from the Leivonmäki shear zone. Drill core from the vicinity of Toivakka. E) Plagioclase porphyrite belonging to the Makkola suite from the vicinity of Toivakka affected by brittle movements along the Leivonmäki shear zone. Diameter of the drill core in all photos 42 mm.

4.9 Later events

Kallio et al. (2018) interpreted that the Suolikko Pb–Zn mineralisation near Muurame is related to hydrothermal alteration caused by magmatism at 1785 Ma. If so, it is evidence for the existence of postorogenic magmatism within the CFGC, in addition to areas surrounding it (e.g. Eklund et al. 1998, Kontinen et al. 2013). Observations from Suolikko also provide ways to estimate the age of the activity along the numerous NW–SE-trending faults. The major ductile phase must have taken place before 1785 Ma, as the mineralisation is controlled by the ductile shear zone, but only affected by the late brittle activity along it.

No absolute age is available for the Rutalahti peridotites, but based on field relationships and magnetic anomaly patterns, they represent relatively young mantle-derived magmatism (Heilimo et al. 2018). They are spatially associated with large SE–NW-trending faults characterising the CFGC, and thus a plausible explanation would be that these faults provided pathways for ascending magmas. What is more difficult to explain is the follow-up question: what triggered the partial melting of the mantle generating these low volume ultramafic intrusions known from various parts of the CFGC (e.g. Salli 1967, Pipping 1972, Pääjärvi 1991)? A possible trigger for the partial melting could be the delamination of the crust thickened during the collisional stages of the Svecofennian orogeny.

Diabase dykes of the Kuisaari suite (Luukas et al. 2017) are likely to be part of the 1670–1620 Ma rapakivi magmatism in Southeast Finland (Rämö &

Haapala 2005). These dykes have the same structural trend as the northwest–southeast faults characterising the CFGC in the study area. This does not imply significant tectonic activity at this stage, but instead it is more probable that the diabase magma intruded into existing crustal weaknesses.

5 SUMMARY

Our interpretation of the geological evolution of CFGC and areas surrounding it during the Svecofennian orogen is summarised in Figure 6. The older Svecofennian magmatism aged 1.93–1.91 Ga and represented by the Savo arc ended with the collision of the arc with the Karelia craton. We interpret the Sm–Nd model ages reported earlier from the CFGC to simply represent the roots of the Savo arc and regard a separate "microcontinent" as an overinterpretation.

After the collision of the Savo arc, the protoliths of the voluminous Svecofennian paragneisses were deposited in a passive margin setting. Locally preserved mafic to ultramafic volcanic rocks represent extensional phases of the depositional basin(s). Subduction below the Savo arc and calc-alkaline magmatism commenced close to 1895 Ma, as witnessed by the oldest volcanic units and the Pirkanmaa intrusive suite. Vammala suite gabbro and ultramafic intrusions represent mantle-derived melts mainly intruding into the accretionary prism. Mantle-derived melts intruding the CFGC further evolved due to the larger crustal thickness, resulting in crustal contamination and fractional crystallisation being more significant. Calc-alkaline magmatism continued until 1875 Ma, peaking in the current erosion level close to 1885–1880 Ma, when the Jyväskylä suite was formed. The chemically A-type Saarijärvi suite was placed in proximity to crustal-scale transtensional faults at ~1880 Ma. Erosion and uplift shifted the pooling level of granitoid magmas to a lower level, resulting in more evolved granitoid magmas reaching the current erosion level at 1875 Ma. This explains the significant compositional similarities displayed by the Jyväskylä and Oittila suites.

After formation, the bedrock of the study area was subjected to deformation in connection with the further development of the Svecofennian orogeny further south. The Leivonmäki shear zone developed as a conjugate system to the Raahe–Ladoga system.

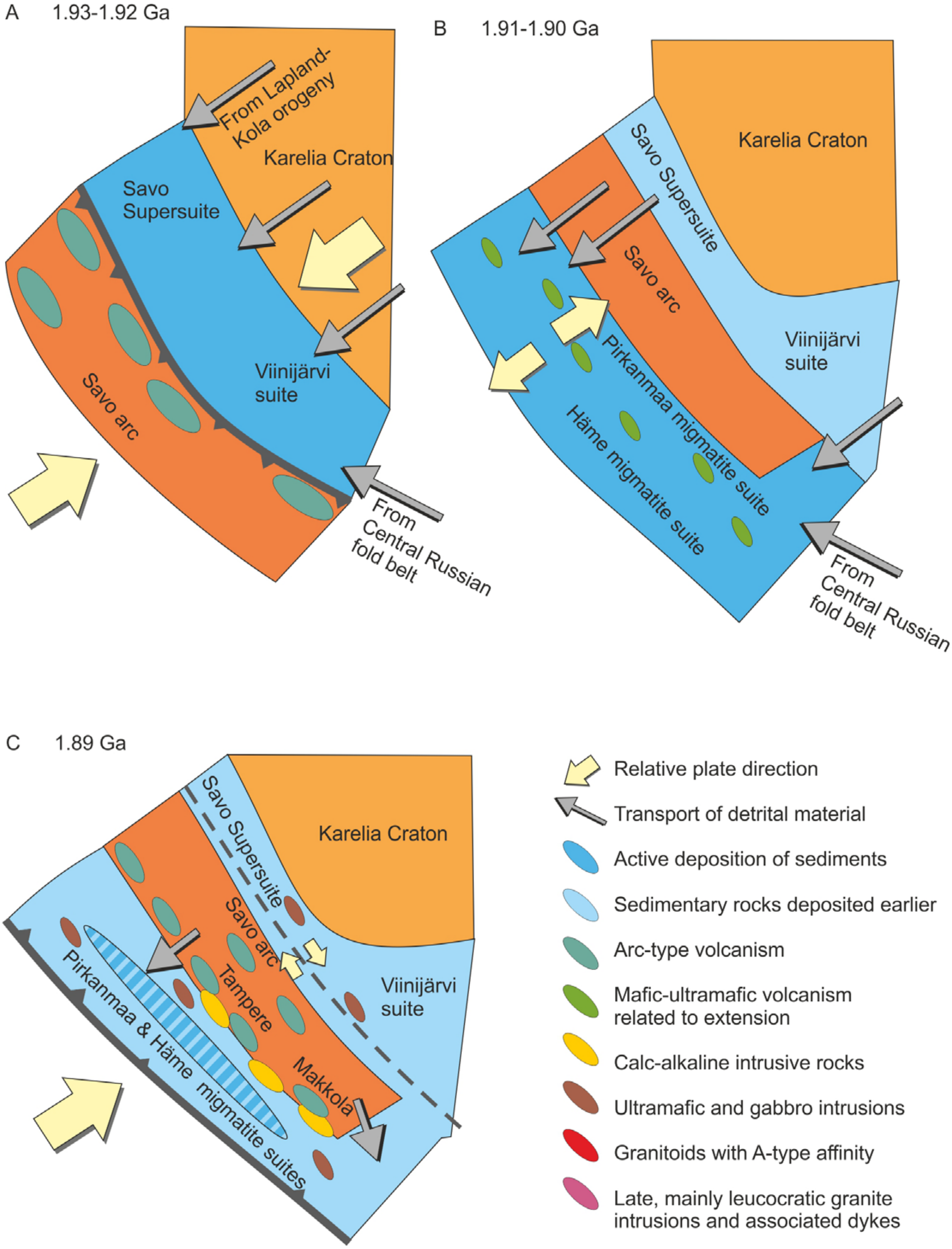
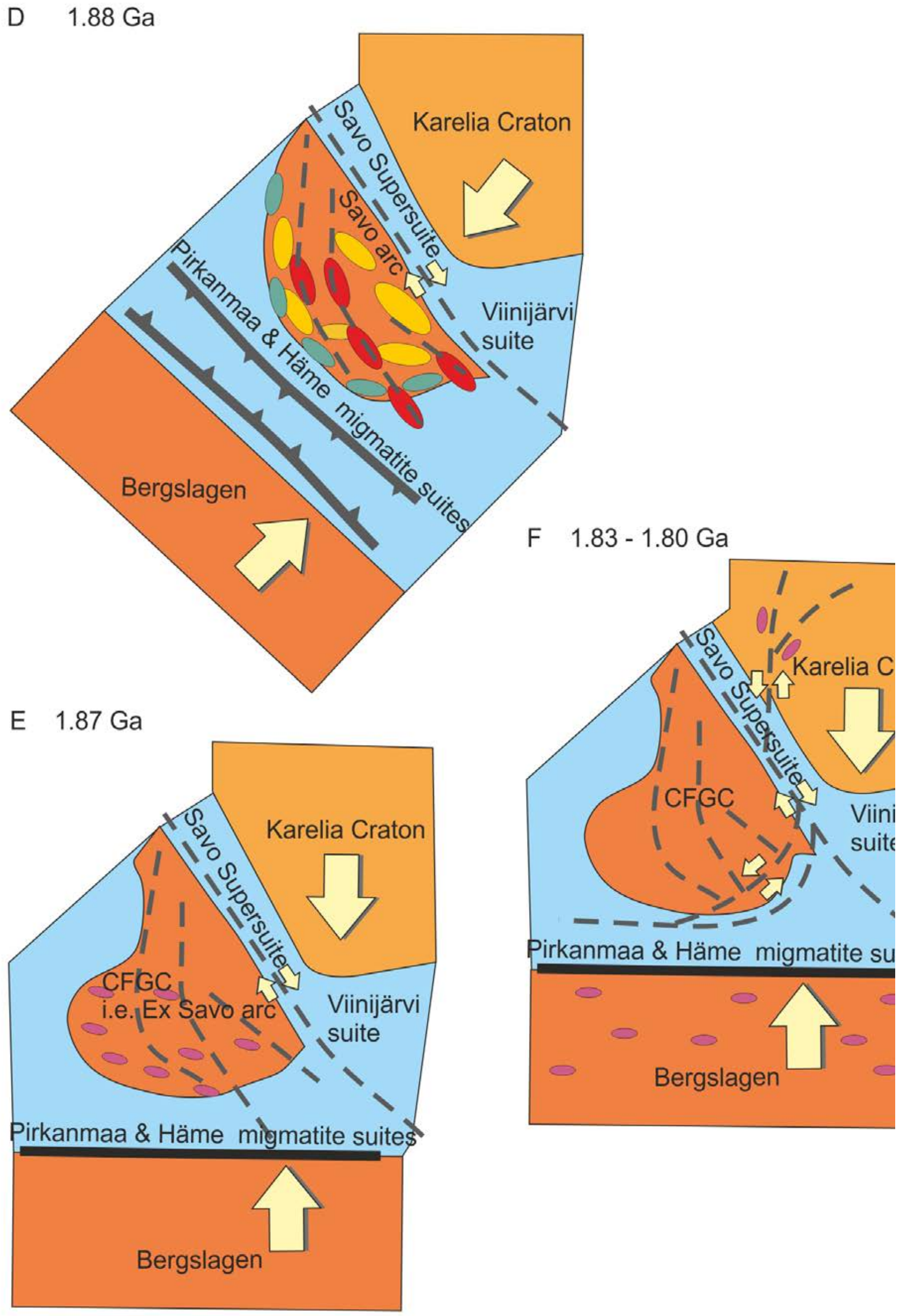


Fig. 6. Revised model for the development of the Svecofennian orogeny in Finland. A) At 1.93–1.91 Ga, the Savo arc is on top of a southwest-directed subduction zone. Paragneisses of the Karelia Province (Viinijärvi and Savo suites) are deposited along the passive margin of the Karelia craton. B) At 1.91 Ga, arc magmatism ends with the collision of the Savo arc and Karelia craton. Following this, the majority of the Svecofennian paragneisses (Häme and Pirkanmaa migmatite suites) are deposited as greywackes by turbidite currents. Local mafic to ultramafic volcanic interbeds represent extensional phases of the depositional basins. C) Close to 1.895 Ga, a subduction zone



is formed west of the Savo arc and calc-alkaline magmatism commences. Paragneisses deposited before 1.90 Ga form the accretionary prism that is intruded by plutonic equivalents (Pirkanmaa intrusive suite, Vammala suite) of the volcanic units and overlain by fore-arc deposits. D) Plutonic activity forming the CFGC peaks (Jyväskylä suite), while volcanic activity continues. The linear Savo arc starts to round due to the beginning of collision with the Bergslagen block. Transtensional faults are formed within the CFGC, providing pathways for geochemically A-type magmas (Saarijärvi suite) ascending from the lower crust. E) Rounding of the CFGC continues. Uplift and erosion shift the pooling depth of calc-alkaline granitoid magmas below the current erosion level. Therefore, only more evolved melt fractions reach the current erosion level as small intrusions and dykes (Oittila suite). See the text for further discussion. F) Compression from the south–southeast continues and the sinistral Leivonmäki shear zone develops along the southeastern boundary of the CFGC as a conjugate of the Raahe–Ladoga shear zone. A similar conjugate is the Oulujärvi shear zone transecting the Karelia craton.

ACKNOWLEDGEMENTS

Reviews by Drs Matti Kurhila and Alexander Slabunov helped in improving the original manuscript.

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