Development of the Paleoproterozoic Svecofennian orogeny: new constraints from the southeastern boundary of the Central Finland Granitoid Complex
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GEOCHEMISTRY AND AGE OF THE PALEOPROTEROZOIC MAKKOLA SUITE VOLCANIC ROCKS IN CENTRAL FINLAND

by

Perttu Mikkola[1)], Krista Mönkäre[2)], Marjaana Ahven[1)] and Hannu Huhma[3)]

Mikkola, P., Mönkäre, K., Ahven, M. & Huhma, H. 2018. Geochemistry and age of the Paleoproterozoic Makkola suite volcanic rocks in central Finland. *Geological Survey of Finland, Bulletin* 407, 85–105, 8 figures and 2 tables.

The Paleoproterozoic volcanic rocks of the Makkola suite form a discontinuous belt along the southeastern border of the Central Finland Granitoid Complex. Based on single-grain age determinations from four samples, the ages of these volcanic rocks and associated dykes vary from 1895 to 1875 Ma. One volcanogenic-sedimentary sample has a dominant zircon population aged 1885 Ma, the remaining ages varying from 1.98 to 3.09 Ga. The majority of the rocks are intermediate to acid and display enrichment in light rare earth elements and negative Nb, Ti and Zr anomalies on spider diagrams normalized with primitive mantle. Overall, these rocks are typical representatives of calc-alkaline continental arc type magmatism related to subduction during the Svecofennian orogeny. Primary textures are locally well preserved and vary from coarse volcanic breccias to thin layered tuffs and tuffites. Massive tuffs and subvolcanic plagioclase porphyrites are common and differentiation between these two rock types is difficult. Based on similarities in both age and composition, the Makkola suite can be considered as the eastern equivalent of the classical Tampere group volcanic rocks located 100 km to the west.

Appendix 1 is available at: http://tupa.gtk.fi/julkaisu/liiteaineisto/bt_407_appendix_1.pdf

Electronic Appendix is available at: http://tupa.gtk.fi/julkaisu/liiteaineisto/bt_407_electronic_appendix.xlsx

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[1)] Geological Survey of Finland, P.O. Box 1237, FI-70211 Kuopio, Finland
[2)] Department of Geography and Geology, University of Turku, FI-20014 Turku, Finland
[3)] Geological Survey of Finland, P.O. Box 96, FI-02151 Espoo, Finland
E-mail: perttu.mikkola@gtk.fi

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1 INTRODUCTION

The Paleoproterozoic bedrock of southern and central Finland, as well as that in adjacent areas of Sweden and Russia, was formed in accretionary and collisional processes of the collisional Paleoproterozoic Svecofennian orogeny around 1.9 Ga (Lahtinen et al. 2016, 2017, Nironen 2017 and references therein). The majority of the bedrock is formed by granitoids and variably migmatized paragneisses, whereas volcanic rocks are volumetrically less significant and present as narrow elongated belts (Fig. 1). Various models for the overall geological evolution of the Svecofennian orogeny have been proposed (e.g. Rutland et al. 2004, Williams et al. 2008, Lahtinen et al. 2009, 2017), and although they differ in detail, they concur in the main features. As a whole the Svecofennian domain provides an excellent example for studying and understanding the deeply eroded Paleoproterozoic collisional orogeny. Although the overall development of the orogeny is well constrained due to a research history extending back to the 19th century, the amount of data varies significantly from one area to another. For example, the calc-alkaline ~1.89 Ga volcanic succession of the Tampere group along the southern boundary of the Central Finland Granitoid Complex (CFGC, Fig. 1) has been extensively studied (e.g. Seitsaari 1951, Simonen 1953, Kähkönen 1987, 1999, 2005, Nironen 1989) since the early work by Sederholm

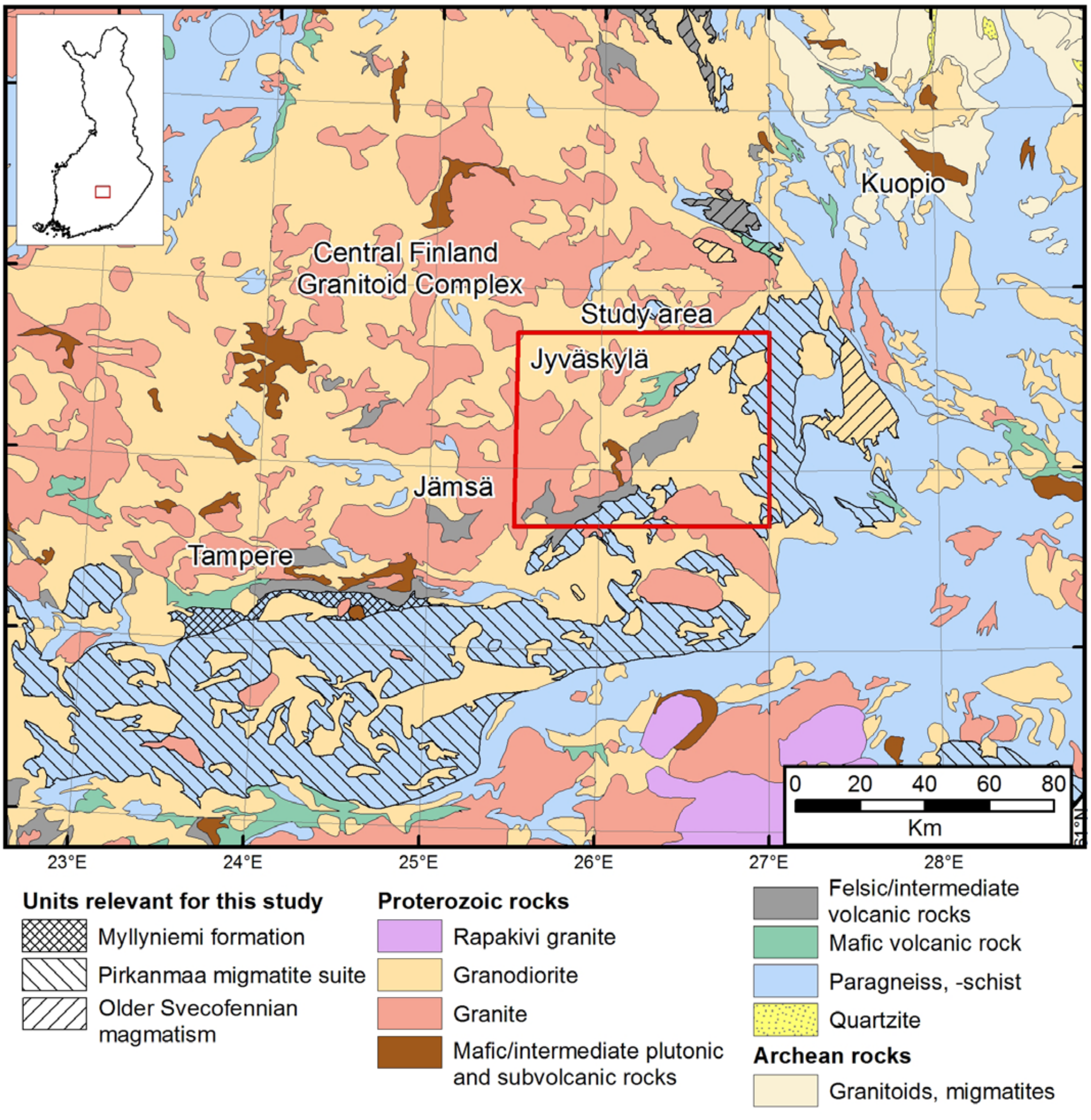

Fig. 1. The location of the study area on an index map and on the geological map of central Finland. Relevant geological units as raster on top of lithological map. Map modified from Nironen et al. (2016) and Bedrock of Finland - DigiKP.

(1897). At the same time, its extensions to the east have been the subject of a limited number of unpublished Master's theses (Karppanen 1970, Ikävalko 1981, Heikura 2017).

This paper describes the field and geochemical characteristics of the volcanic rocks belonging to the previously little studied Makkola suite located along the southeast boundary of CFGC and consisting mainly of intermediate volcanic rocks. Results from single-grain U–Pb zircon age determinations from volcanic units and associated dykes and volcanogenic-sedimentary rock are also presented. The data are used to evaluate the genesis of the Makkola suite, with emphasis on the differences and similarities compared with the classical Tampere group volcanic rocks in order to either confirm or refute the preliminary interpretations of the Makkola suite as a eastern extension of the Tampere group (Karppanen 1970, Ikävalko 1981, Kähkönen 2005).

2 GEOLOGICAL SETTING

The Svecofennian domain in Finland has been divided into Southern and Western Finland Subprovinces (Nironen et al. 2016). Core of the latter is formed by the CFGC, which is surrounded by narrow intermittent volcanic belts and voluminous, often migmatitic paragneisses (Fig.1). In our study area these paragneisses belong to the Pirkanmaa migmatite belt (Luukas et al. 2017).

The oldest Svecofennian magmatic rocks are the 1.93–1.91 Ga volcanic units (Fig. 1) and their plutonic counterparts, which were formed in a primitive arc setting and occur along the boundary of the Archean Karelian Craton (e.g. Vaasjoki et al. 2003, Kousa et al. 2004, 2018a). This older Svecofennian magmatism ended when the arc collided with the Archean continent (e.g. Lahtinen et al. 2014).

Protoliths of the Pirkanmaa migmatite suite (Fig. 1) were deposited as greywackes immediately after, or partly coevally with the first collisional stage, as their maximum depositional ages are typically close to 1.92 Ga (Lahtinen et al. 2009, 2017, Mikkola et al. 2018b). Ultramafic and mafic volcanic rocks belonging to the Pirkanmaa migmatite suite have been interpreted to represent 1.91–1.90 Ga extensional phases of the depositional basin(s) (e.g. Lahtinen 1996, Lahtinen et al. 2017, Kousa et al. 2018b). A small number of more intermediate volcanic rocks from small areas or narrow interbeds have also been included in the Pirkanmaa migmatite suite. These are located in southern and eastern parts of our study area. In all locations, these rocks are intensively deformed and do not display clear primary structures. Their classification as volcanic rocks is mainly based on their small grain size and mineralogy. Most of the paragneisses of the Pirkanmaa migmatite suite are, as the name implies, variably migmatitic, but are locally of a lower metamorphic grade, and well-preserved primary structures are observable, for example, in the Tammijärvi area (Fig. 2, Mikkola et al. 2018b).

The ca. 1895 Ma plutonic rocks of the Pirkanmaa intrusive suite intrude into the Pirkanmaa migmatite suite and mainly consist of granodiorites, with smaller areas of tonalites and diorites (Kallio 1986, Heilimo et al. 2018). The plutonic rocks of the CFGC forming the majority of the bedrock north of the Makkola suite rocks are typically porphyritic granodiorites and granites, yielding zircon ages between 1885 and 1875 Ma (Rämö et al. 2001, Lahtinen et al. 2016, Nikkilä et al. 2016, Heilimo unpublished data). The small areas of volcanic rocks north of the Leivonmäki shear zone in our study area have been classified as belonging to the CFGC (Fig. 2, Mikkola et al. 2016). These rocks have not been correlated with the units of the Makkola suite due to their scattered nature, although they do not display significant differences from them in the field. Due to later deformation, primary textures are only locally observable in these rocks, varying mineralogically from amphibolites to hornblende-biotite–quartz–feldspar gneisses. The volcanic and subvolcanic areas within the central parts of the CFGC are aged between 1890 and 1886 Ma (Nikkilä et al. 2016). Calc-alkaline magmatic rocks of Tampere group, its equivalents and the majority of the CFGC have been interpreted as originating in a subduction setting (e.g. Kähkönen 2005, Lahtinen et al. 2017) or alternatively as a result of partial melting of island arc crust thickened in the 1.91 Ga collision of the Archean craton and the older Svecofennian arc (Nikkilä et al. 2016). All of the above-mentioned rock units in the study area are cross-cut by granite intrusions and veins belonging to the Oittila suite, with an age of ca. 1875 (Heilimo unpublished data), which also defines the minimum age of the Makkola suite.

The rocks of the here-studied Makkola suite are located in the border zone between the CFGC and Pirkanmaa migmatite and intrusive suites, where they occur as several elongated belts separated by both faulting and intrusive units (Fig. 2). The largest intact segment is 25 by 9 km in size, whereas the smallest fragments are inclusions less than 50 cm across in the surrounding plutonic rocks. The same general structure of scattered volcanic belts between the often migmatitic paragneisses and the CFGC is evident along the whole length of the CFGC border (Fig. 1).

3 MAKKOLA SUITE

Based on geological setting and field observations the volcanic rocks of the Makkola suite have been tentatively considered as an eastern continuation of the Tampere group (Karppanen 1970, Ikävalko 1981, Kähkönen 2005). The lowermost unit of the Tampere group, the Haveri formation, with its EMORB affinity, has been interpreted to represent early extensional phases (Kähkönen 2005) followed by the deposition of greywackes of the Myllyniemi Formation, having maximum depositional ages close to 1.91 Ga (Huhma et al. 1991, Claesson et al. 1993, Lahtinen et al. 2009). The volcanic units in the Tampere area display zircon ages between 1895 and 1880 Ma and calc-alkaline arc type geochemistry (Kähkönen 2005 and references therein, Kähkönen & Huhma 2012). Heikura (2017) concluded that the volcanic rocks in the Jämsä area (Fig. 1) are similar in composition to those of the Tampere group, but the material did not include age determinations.

Due to the combination of often poor exposure and intensive deformation, no attempt at a stratigraphic approach has been made and the Makkola suite has been divided into lithodemes (Mikkola et al. 2016). A brief description of these lithodemes is given in Table 1 and below. More detailed descriptions can be found from Mikkola et al. (2016). In addition to more specifically described lithodemes, the suite also contains "undefined volcanic rock" lithodemes, which include rocks from certain areally small segments that cannot be correlated with a specific lithodeme.

The preservation of primary textures in the Makkola suite is highly variable, and in most parts these have been destroyed by deformation. However, especially the central parts of the Makkola area display well-preserved depositional structures (Fig. 3A). The main deformation in the area is related to the sinistral Leivonmäki shear zone trending from northeast to southwest (Mikkola et al. 2018a, Fig. 2). Rocks of the Makkola suite have been metamorphosed in low amphibolite facies (Hölttä & Heilimo 2018). The majority of the volcanic rocks, especially in the Makkola area and in smaller segments north of it, are relatively felsic tuffs (Teuraanmäki and Mesiänmäki lithodemes) and tuffites (Myllypelto and Keijupelto lithodemes). In some places, these rocks show thin bedding or pyroclastic features, but more commonly they are massive and lack clear primary features (Fig. 3B). In Korospohja, large areas consist of homogeneous, weakly oriented, intermediate uralite-plagioclase porphyrites and plagioclase porphyrites (Töppöspohja and Kieroselkä lithodemes). Based on locally observable cross-cutting relationships, these rocks can be interpreted as subvolcanic (Fig. 3C). Both tuffs and subvolcanic intrusives have a common texture where uralite and plagioclase phenocrysts few millimetres in size are hosted by a finer grained, typically plagioclase-rich ground mass.

Paraschist units interpreted to belong to the Makkola suite are known from two locations (Toivakanlehto and Mäyräsalo lithodemes). This interpretation is based on the close spatial association these rocks display with the volcanic units. Another feature distinguishing between the well-preserved lithodemes of Pirkanmaa migmatite suite (Mikkola et al. 2018b) and the sedimentary units of the Makkola suite is the smaller proportion or lack of greywackes of the latter. Closely related to the Mäyräsalo lithodeme is an iron formation (Holla lithodeme), which is also present as enclaves in the adjacent granitoids.

Mafic units (Oralanmäki, Orala and Kivisuo lithodemes) are less voluminous and occur as both larger areas and interbeds or dykes in the more felsic units. The uralite and plagioclase porphyritic dykes are usually concordant or nearly concordant with the bedding, thus their separation from lava interbeds in poorly exposed areas is difficult. Texturally similar dykes cross-cut the surrounding plutonic rocks (Fig. 3D), especially in the area between Makkola and Halttula (Fig. 2).

Table 1. Summary table of the lithodemes forming the Makkola suite.

Lithodeme	Areal extent	Lithology	Geochemistry
Toivakanlehto paraschist, Mikkola et al. 2017a	In the Halttula area, extent poorly constrained, thickness at least 800 metres.	Paraschist with greywacke and calc-silicate rock interbeds.	----
Keijupelto felsic volcanogenic sedimentary rock	Two small areas in the Korospohja area.	Small grained quartz rich rock, no preserved primary structures, locally weak signs of anatexis	SiO_2=63–65%, Trachydacite, dacite
Myllypelto tuffite	Small segments in the Makkola and Halttula area. Sporadic observations also from Korospohja area. Not shown in Figure 2.	Laminar felsic rock, with graded bedding, cross-bedding also often visible.	SiO_2=61–71%, Andesite, dacite
Orala mafic volcanic rock	200–400 m wide and 3–7 km long sections. Most common in Makkola area, but present in all subareas.	Fine grained tuff, often with pyroclastic fragments alternating with laminary layers.	SiO_2=47–51%, Basalt, basaltic andesite
Mesiänmäki felsic volcanic rock	20 km long and 1–5 km wide section in the Makkola area. Lacking from other parts.	Relatively massive, ejected fragments locally observable.	SiO_2=58–74%, Rhyolite, dacite
Teuraanmäki intermediate volcanic rock	Most voluminous lithodeme of the suite. Present in all subareas.	Variably preserved tuffs, variation from massive type to crystal tuffs displaying layering. Larger ejecta fragments scarce.	SiO_2=50–72%, Basaltic andesite to trachyte
Oralanmäki uralite porphyrite	Separated areas less than 4 km in length from Korospohja to Makkola	Massive rocks with porphyritic structure caused by clinopyroxene phenocrysts completely altered to amphibole.	SiO_2=47–56%, Basalt, basaltic andesite
Kieroselkä plagioclase porphyrite	Dykes/sills in Makkola area intruding both the volcanic segment and surrounding plutonic rocks.	Massive rocks with variable amounts of porphyritic plagioclase crystals.	SiO_2=54–67%, Basaltic andesite to dacite
Töppöspohja intermediate subvolcanic rock	Dominant rock type in the Korospohja area. Smaller segements also in Halttula area.	Homogeneous in outcrop scale, in larger scale variable amounts of plagioclase phenocrysts and/or amphibole-biotite agglomerates 2–4 across.	SiO_2=56–65%, Trachyandesite, trachyte
Holla iron formation, Mikkola et al. 2016	As less than 10 m thick interbed in Mäyräsalo parachist, also as enclaves in granitoids	Laminar silicate facies iron formation.	Fe_2O_3=22–47%, Al_2O_3=1–12%
Mäyräsalo paraschist, Mikkola et al. 2017a	In the proximity of Kivisuo mafic volcanic rock in the contact zone between Makkola suite and Pirkanmaa migmatite suite in the Leivonmäki area	Paraschist, often displaying laminar bedding.	----
Kivisuo mafic volcanic rock	Dominant rock type in the contact zone between Makkola suite and Pirkanmaa migmatite suite.	Lava structures typical, only locally tuff and pyroclastic interbeds. Calc-silicate interbeds common.	SiO_2=43–54%, Basalt, basaltic andesite

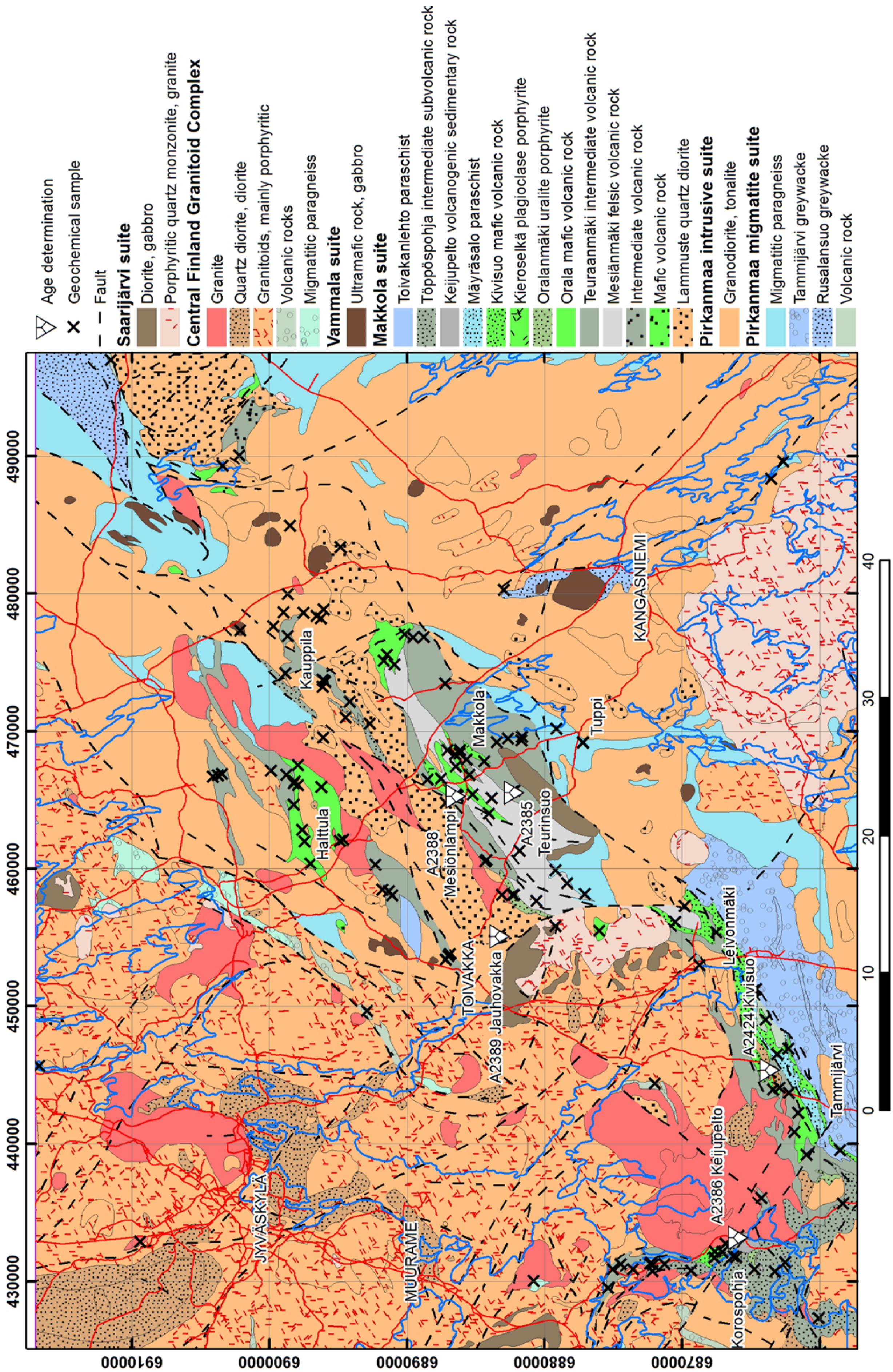

Fig. 2. Sample locations on the geological map modified from Mikkola et al. (2016). The location of the study area is indicated in Figure 1.

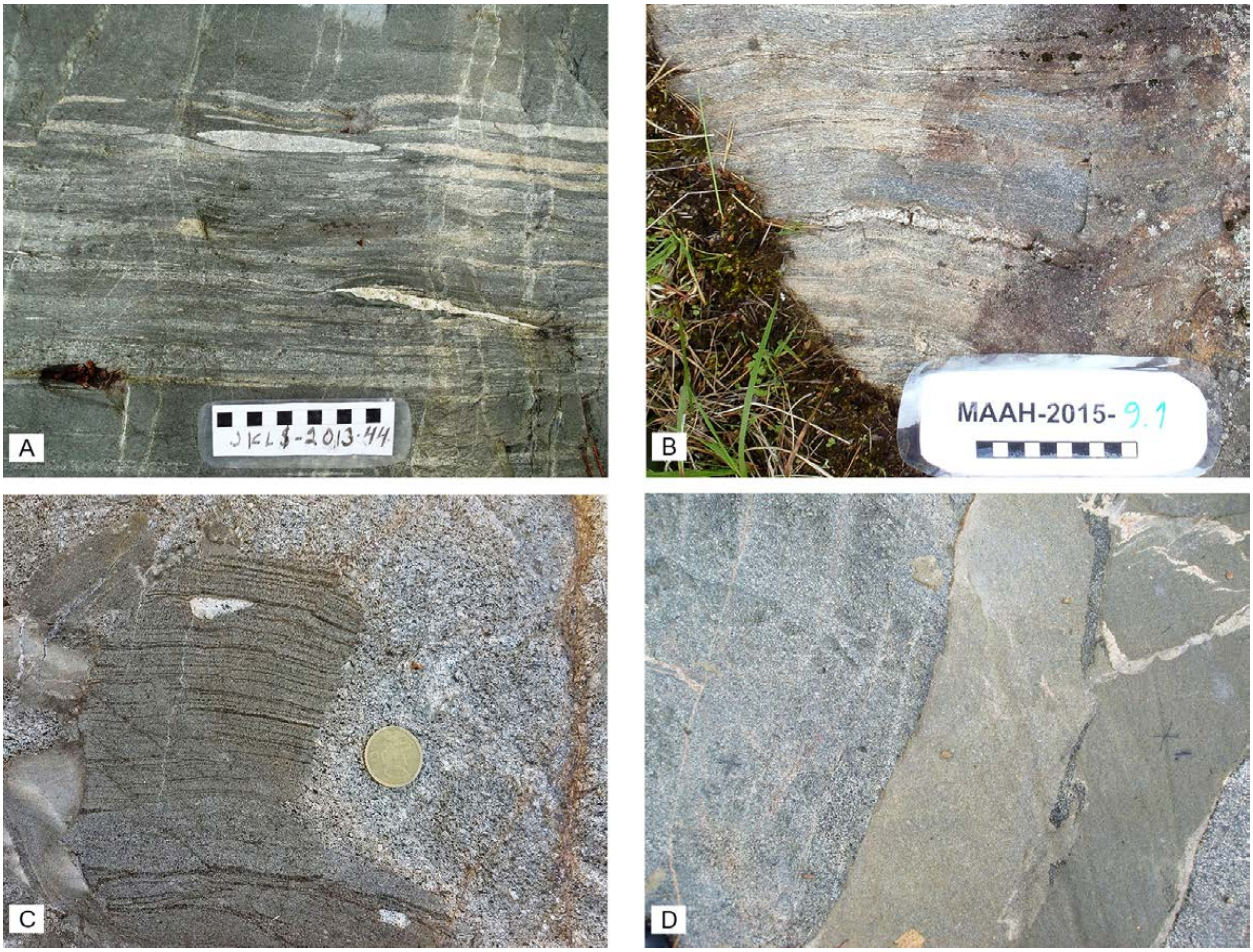

Fig. 3. A) Volcanic breccia, with felsic volcanic rock fragments and more mafic groundmass. Scale bar with cm scale. B) Felsic volcanic rock displaying secondary banding and lacking clear primary features. Scale bar with cm scale. C) Subvolcanic plagioclase porphyrite hosting fragments of sedimentary rocks. Diameter of the coin 24 mm. D) Two parallel weakly plagioclase porphyrite dykes cross-cutting diorite. The width of the dykes is ca. 30 cm.

4 ANALYTICAL METHODS AND SAMPLE MATERIAL

Altogether, 213 analyses from outcrops and drill cores were selected for analysis. In addition to new samples, five previously published analyses from Rasilainen et al. (2007) were included in the material, making the total number of used samples 218. In this study, the compositions of the samples are classified based on their interpreted lithodeme and the locations are not taken into account, as Mönkäre (2016) demonstrated that compositional differences between the different volcanic segments making up the Makkola suite are insignificant. Out of the 218 samples, 187 represent volcanic or subvolcanic units of the Makkola suite, 17 are porphyrite dykes cross-cutting the surrounding plutonic rocks. Six samples represent the volcanic units of the Pirkanmaa migmatite suite and seven samples from volcanic units of the CFGC are also included for comparison. All analytical results are listed in the Electronic Appendix and representative ones are presented in Table 2. All of the new samples were analysed by Labtium Oy using XRF (Labtium code 175X) for major elements and certain trace elements. Additional trace elements were analysed from 167 samples using ICP-MS (Labtium code 308 PM). A description of the analytical methods and list of elements is provided in Appendix 1. The geochemical data were plotted using the Geochemical Data Toolkit (GCDKit) program of Janoušek et al. (2006).

For age determinations, five samples (5 to 10 kg each) representing different lithodemes and subareas were taken from selected outcrops or drill holes. Four of the samples were dated using a Nu

Plasma HR multicollector ICP-MS and one using a Nu Plasma AttoM single collector ICP-MS. The analytical methods are described in Appendix 1 and data are listed in the Electronic Appendix.

5 RESULTS

5.1 Geochemistry

5.1.1 Makkola suite

Compositionally, the Makkola suite forms a continuum from basic to acid compositions, the majority of the samples being intermediate to acid (Fig. 4). CaO and Fe_2O_3 display a good correlation with SiO_2, whereas the other major elements are scattered. In the case of P_2O_5, Al_2O_3, MgO and TiO_2, the scatter concentrates in the compositions with low SiO_2 and is likely to be caused by fractional crystallization processes. The Kivisuo and Orala mafic volcanic rocks especially display this type of scatter.

With respect to alkalies, the scatter is present regardless of the SiO_2 concentrations and is likely to be caused by variable alteration of the original compositions. Thus, the TAS diagram in Figure 5A, in which the samples mainly plot in the subalkaline/tholeiitic field, should be treated as only tentative. However, in the plot of Ishikawa's alteration index (Ishikawa et al. 1976) against the chlorite-carbonate-pyrite index, samples mainly plot within the box of least altered composition of Large et al. (2001) (Fig. 5B). On diagrams based on less mobile elements, the scatter is significantly less than on those involving alkalies. In the Nb/Y vs. Zr/Ti plot, the samples are mainly subalkaline and only the most evolved samples transect the field of alkaline compositions. In Th vs. Co classification diagram of Hastie et al. (2007), the samples plot on both sides of the boundary between calc-alkaline and high-K calc-alkaline fields (Fig. 5D). Most of the samples form a tight group in the volcanic arc array on Pearce's (2008) classification diagram (Fig. 5E).

On chondrite-normalized REE diagrams (Fig. 6), all units display similar trends and the variation in absolute values is mainly related to the main element compositions of the samples. The mafic units have lower LREE concentrations and thus weaker REE fractionation than the more felsic units, as the HREE levels do not vary significantly. Eu anomalies of the units vary from non-existent to weakly negative.

On spider diagrams (Fig. 6), the differences in LILE concentrations are one order of magnitude, and like the LREE concentrations, they correlate with the SiO_2 concentrations, as the more mafic units display lower concentrations. All units display negative Nb, Ti and Zr anomalies, the exception being the Myllypelto lithodeme, which lacks a Zr anomaly. In most of the units, Sr and Nd form positive anomalies.

Most of the porphyrite dykes cross-cutting the plutonic rocks are intermediate in composition, although SiO_2 concentrations vary from 46.8 to 71.4 wt%. With respect to the main elements, they are compositionally similar to the volcanic units. At the basic end of the compositional spectrum, they also display a similar compositional scatter with respect to Al_2O_3, MgO, P_2O_5 and TiO_2 as the volcanic units (Fig. 4). On the classification diagrams, the samples also plot in the same fields as the volcanic rock samples (Fig. 5). Furthermore, they also display similar trends in REE and spider diagrams (Fig. 6), with the same negative Nb, Zr and Ti anomalies along positive ones in Sr and Nd.

5.1.2 Volcanic rocks of the Central Finland Granitoid Complex

The seven samples representing the variably sized volcanic xenoliths within the granitoids of the CFGC vary from basic to acid in composition (SiO_2 = 45.0–65.5%) and display similar compositional characteristics to the samples from the Makkola suite with respect to both main (Fig. 4) and trace elements (Fig. 6).

Table 2. Representative analyses from the studied volcanic units.

Sample	PIM$-2013-24.1	KK4$-2012-900.1	HEKI-2012-271.2	KK4$-2012-802.1	N4342013R1 32.00-32.80	PIM$-2013-300.1	N4342014R13 177.05-177.75
Rock type	Felsic volcanic rock	Felsic tuffite	Uralite porphyrite	Felsic volcanic rock	Intermediate volcanic rock	Plagioclase porphyrite	Uralite porphyrite
Suite / complex	Makkola suite	Makkola suite	Makkola suite	Makkola suite	Makkola suite	Makkola suite	Makkola suite
Lithodeme	Keijupelto volcanogenic sedimentary rock	Myllypelto tuffite	Orala mafic volcanic rock	Mesiänmäki felsic volcanic rock	Teuraanmäki intermediate volcanic rock	Teuraanmäki intermediate volcanic rock	Oralanmäki uralite porphyrite
Occurrence type	Main rock	Main rock	Main rock	Main rock	Main rock	Main rock	Main rock
Age sample	A2386	----	----	A2388	A2385	A2424	----
SiO_2 wt. %	65.20	68.30	50.80	69.10	59.50	61.23	50.10
TiO_2	0.27	0.67	0.82	0.31	0.62	0.74	0.50
Al_2O_3	17.90	15.60	14.00	15.80	18.80	17.95	14.50
Fe_2O_3t	3.02	4.57	11.60	3.84	6.61	6.51	9.58
MnO	0.06	0.07	0.19	0.07	0.13	0.08	0.15
MgO	1.13	1.35	7.27	0.93	1.65	2.31	7.12
CaO	2.35	2.99	8.57	3.06	3.71	3.77	10.81
Na_2O	4.93	3.66	2.63	4.18	5.44	2.87	1.91
K_2O	4.06	2.16	2.17	2.19	2.82	3.11	1.29
P_2O_5	0.15	0.20	0.25	0.11	0.23	0.28	0.23
C ppm	n.a.	<500	<500	1240	1610	<500	760
Ba	1530	641	864	1011	1490	1110	395
Cl	0	<60	<60	90	167	300	233
Co	6.6	10.8	31.4	4.3	10.8	12.8	39.7
Cr	13	118	289	<20	5	140	444
Ga	<20	27	<20	22	24	<30	<20
Hf	2.2	10.6	1.6	4.4	3.5	5.1	1.0
Nb	5.1	11.0	4.7	10.3	11.8	12.4	5.2
Pb	32	<20	<20	<20	<20	40	<20
Rb	107.0	90.3	41.9	38.1	60.5	110.0	38.7
S	120	<60	<60	61	944	700	127
Sc	4.4	11.7	31.8	5.7	12.9	13.4	37.7
Ta	<0.2	1.78	0.33	0.45	0.40	0.50	<0.2
Th	5.2	19.7	2.9	7.2	4.1	7.7	2.2
U	1.7	3.9	1.1	2.0	1.7	3.9	0.8
V	36.9	69.7	n.a.	24.9	68.8	91.4	197.0
Y	9.3	26.1	13.5	16.9	19.4	19.8	12.8
Zn	87	60	106	50	190	90	107
Zr	103.0	336.0	60.4	164.0	174.0	183.0	50.3
La	24.0	41.0	14.2	43.6	38.9	31.0	15.6
Ce	37.2	87.2	29.4	85.0	69.5	61.5	25.1
Pr	13.6	36.0	14.7	34.8	34.3	27.5	11.3
Nd	3.79	9.54	3.65	9.33	8.44	7.20	3.13
Sm	1.77	6.76	3.12	5.71	6.22	5.10	2.46
Eu	0.34	1.44	0.88	1.41	1.93	1.40	0.78
Gd	1.52	5.90	3.24	4.55	5.36	4.60	2.51
Tb	<0.1	0.87	0.45	0.58	0.68	0.70	0.39
Dy	1.13	5.09	2.60	3.33	n.a.	n.a.	2.29
Ho	<0.1	1.00	0.50	0.63	0.73	0.80	0.46
Er	0.56	3.00	1.40	1.90	2.09	2.30	1.35
Tm	<0.1	0.46	0.20	0.28	0.29	0.30	0.21
Yb	0.72	3.12	1.35	1.90	2.11	2.20	1.36
Lu	<0.1	0.50	0.19	0.31	0.29	0.30	0.19

n.a. = not analysed
<30 = below detection limit and the approriate limit

Table 2. Cont.

Sample	**ASM$-2013-259.1**	**HEKI-2012-26.1**	**KOROS-POHJA-SK-007 39.00-40.00**	**ASM$-2012-360.1**	**MAAH-2012-177.2**	**PIM$-2014-266.1**	**N4332013R2 70.40-70.55**
Rock type	Plagioclase porphyrite	Plagioclase porphyrite	Plagioclase porphyrite	Mafic volcanic rock	Intermediate volcanic rock	Plagioclase porphyrite	Garnet amphibolite
Suite / complex	Makkola suite	Makkola suite	Makkola suite	Makkola suite	Makkola suite	Central Finland Granitoid Complex	Pirkanmaa migmatite suite
Lithodeme	Kieroselkä plagioclase porphyrite	Kieroselkä plagioclase porphyrite	Töppöspohja intermediate subvolcanic rock	Kivisuo mafic volcanic rock	undefined volcanic rock	undefined volcanic rock	undefined volcanic rock
Occurrence type	Porphyrite dyke in plutonic rock	Porphyrite dyke in plutonic rock	Main rock	Main rock	Enclave in plutonic rock	Main rock	Interbed / Dyke
Age sample	A2389	----	----	----	----	----	----
SiO_2 wt. %	71.40	57.80	58.20	50.30	53.10	52.20	55.20
TiO_2	0.22	0.77	0.57	2.86	0.91	1.29	1.10
Al_2O_3	15.10	15.30	17.40	16.30	18.90	17.50	18.20
Fe_2O_3t	2.54	7.57	6.18	8.67	8.49	8.98	10.50
MnO	0.05	0.09	0.18	0.10	0.12	0.12	0.14
MgO	0.49	4.68	3.15	4.15	3.74	5.02	3.30
CaO	2.63	6.39	4.58	6.00	6.55	8.83	5.97
Na_2O	3.63	3.42	2.93	3.10	4.33	3.04	1.65
K_2O	3.37	2.14	4.37	4.40	1.64	1.90	2.96
P_2O_5	0.05	0.23	0.32	1.36	0.41	0.58	0.35
C ppm	<500	<500	608	821	587	614	1000
Ba	2254	1412	1160	n.a.	890	772	813
Cl	156	205	307	350	215	432	332
Co	2.9	18.6	15.6	28.1	17.8	35.3	27.4
Cr	<20	103	60	55	71	128	18
Ga	<20	25	22	30	<20	22	26
Hf	3.1	2.3	3.2	6.0	1.4	3.4	4.9
Nb	6.3	7.7	8.9	31.0	8.2	11.0	11.0
Pb	<20	<20	66	22	<20	<20	22
Rb	58.9	43.2	178.0	129.0	42.0	58.0	116.0
S	245	<60	1890	1517	219	213	748
Sc	1.9	18.2	17.1	22.9	17.1	24.1	15.8
Ta	0.46	0.47	<0.2	1.64	0.41	0.58	1.42
Th	10.2	2.6	6.5	2.5	0.6	3.1	6.9
U	3.3	1.4	3.2	1.2	0.5	1.0	2.4
V	14.9	174.0	94.5	208.0	n.a.	170.0	140.0
Y	6.7	10.8	14.4	19.9	13.2	19.5	24.4
Zn	39	71	219	137	102	102	182
Zr	128.0	74.1	133.0	341.0	59.4	116.0	148.0
La	35.5	14.9	32.4	68.3	20.9	24.5	42.9
Ce	57.9	31.4	54.6	148.0	41.5	57.7	67.5
Pr	18.3	15.6	24.3	68.6	19.8	29.8	32.7
Nd	5.73	3.76	6.37	18.50	4.99	7.52	8.13
Sm	2.26	3.00	4.22	10.20	3.52	5.74	6.11
Eu	0.95	0.92	1.09	2.91	1.42	1.58	1.68
Gd	1.68	2.85	3.56	7.49	3.57	5.02	5.81
Tb	0.21	0.40	0.51	0.90	0.48	0.65	0.79
Dy	1.11	2.22	2.87	4.06	2.62	3.75	n.a.
Ho	0.22	0.42	0.57	0.65	0.49	0.78	0.85
Er	0.76	1.18	1.70	1.62	1.32	2.10	2.44
Tm	0.12	0.17	0.23	0.21	0.18	0.32	0.33
Yb	0.95	1.08	1.68	1.31	1.23	1.87	2.50
Lu	0.15	0.17	0.23	0.19	0.17	0.27	0.33

n.a. = not analysed
<30 = below detection limit and the approriate limit

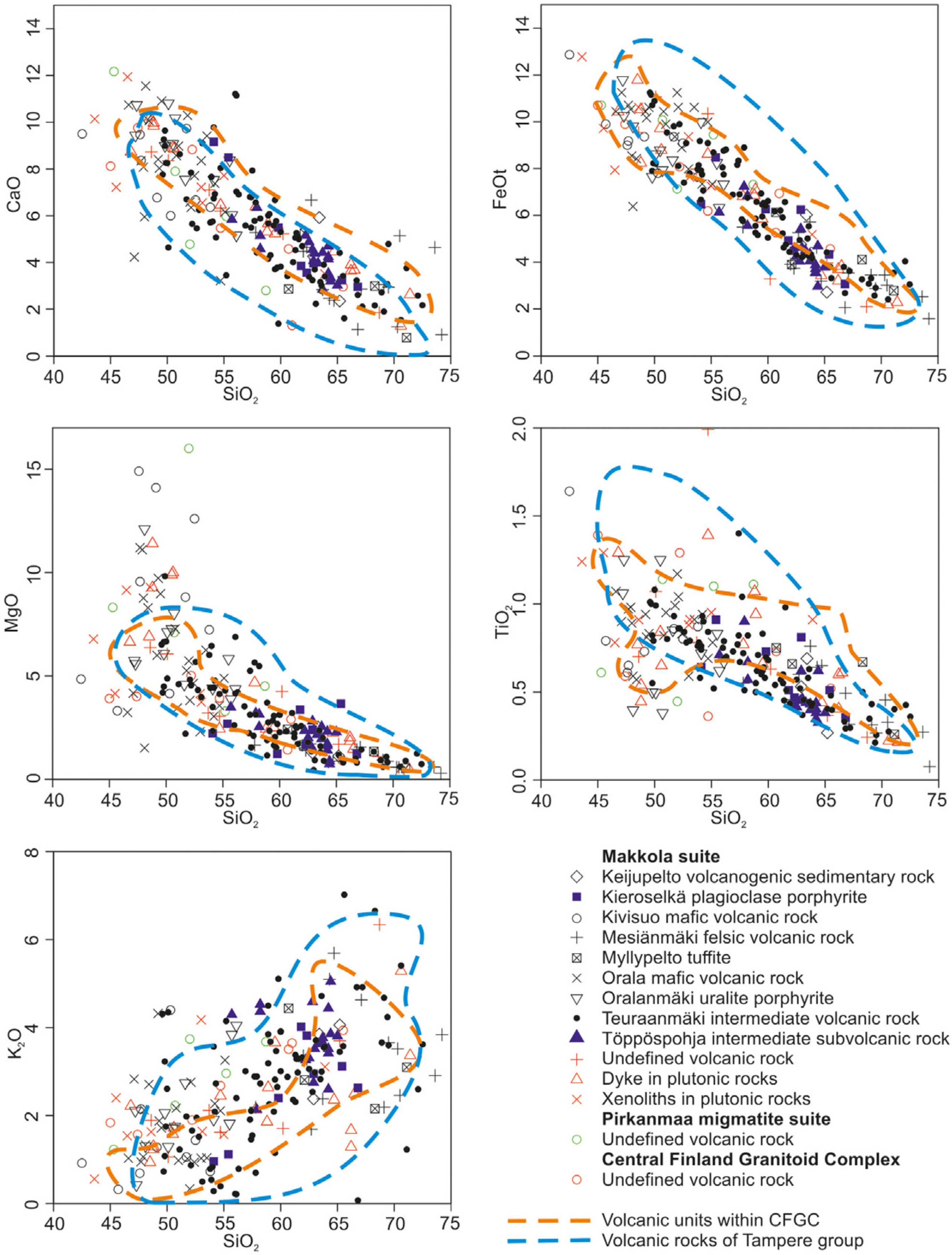

Fig. 4. The studied samples plotted on Harker diagrams. Data for the Tampere group (Kähkönen 1989, unpublished material) and volcanic rocks from central parts of the Central Finland Granitoid Complex (CFGC, Nikkilä et al. 2016) are shown for reference.

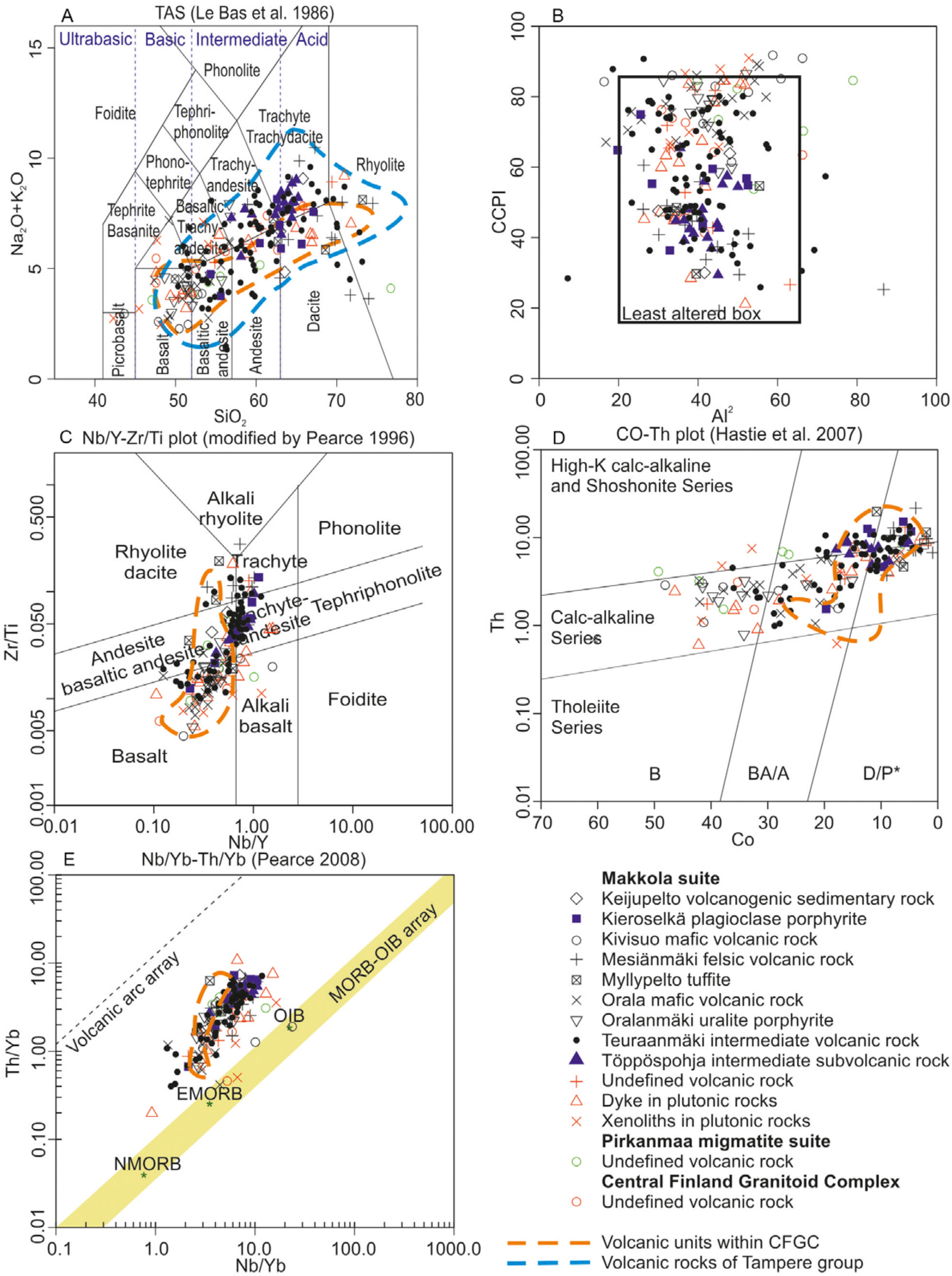

Fig. 5. The studied samples plotted on A) a TAS diagram (Le Bas et al. 1986), B) Ishikawa's alteration index (AI = 100*(K_2O+MgO)/(K_2O+MgO+Na2O+CaO), (Ishikawa et al. 1976) plotted against the chlorite-carbonate-pyrite index (CCPI = 100(MgO+FeO)/(MgO+FeO+Na_2O+K_2O), least altered box according to Large et al. (2001), C) Nb/Y vs Zr/Ti diagram (Pearce 1996), D) Co vs. Th (Hastie et al. 2007) and E) Nb/Yb vs. Th/Yb diagram (Pearce 2008). Data for the Tampere group (in A, Kähkönen 1989, unpublished material) and volcanic rocks from central parts of the Central Finland Granitoid Complex (CFGC, in A, C, D, E. Nikkilä et al. 2016) are shown for reference.

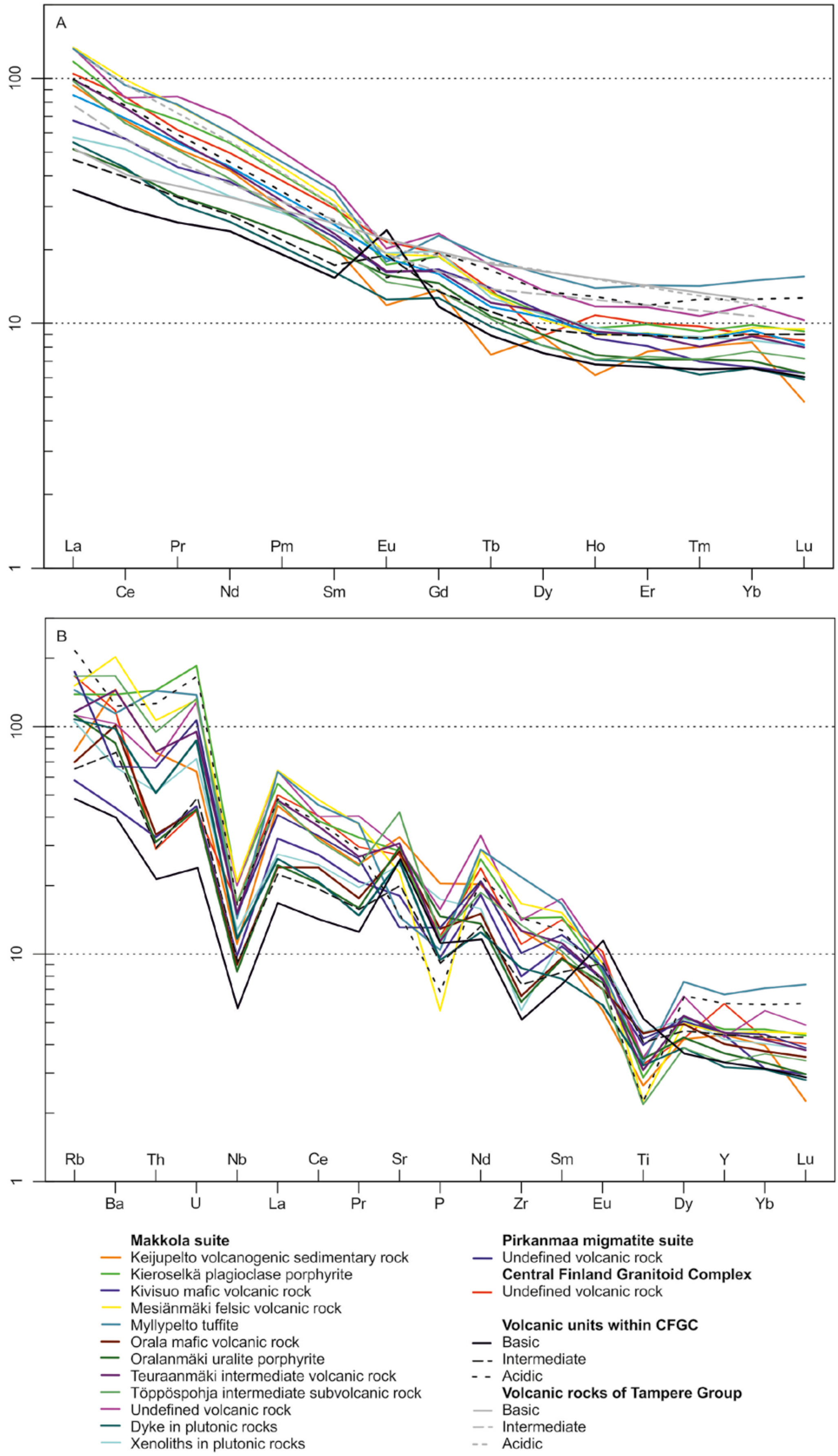

Fig. 6. Median values of each volcanic unit plotted on a chondrite-normalized REE diagram (A) and spider diagram normalized with primitive mantle (B). Chondrite values from Boynton (1984) and primitive mantle values from McDonough & Sun (1995).

5.1.3 Volcanic rocks of the Pirkanmaa migmatite suite

The volcanic samples interpreted as representing the Pirkanmaa migmatite suite are on average more basic than those from the Makkola suite, as SiO_2 varies from 45.3 to 58.7%, excluding an altered sample with 76.4% SiO_2. In other respects, the samples of the Pirkanmaa migmatite suite do not deviate from the samples of the Makkola suite, but the reader should note that the picritic Ala-Siili mafic volcanic rock lithodeme is dealt with in a separate paper (Kousa et al. 2018).

5.2 Age results

5.2.1 Teurinsuo intermediate volcanic rock, sample A2385

The Teurinsuo sample is an intermediate, homogeneous, grey and weakly bedded tuff from the best-preserved part of the Makkola suite. The zircons are mostly subhedral to euhedral (prismatic 100–150 µm long) and lack visible zoning or inherited cores. They contain numerous inclusions, although metamictisation is minor. All 14 analysed spots constitute a concordia age of 1894 ± 4 Ma (Fig. 7). The homogeneity of the zircons supports a volcanic origin for the Teurinsuo intermediate tuff, distinguishing it from the intermediate volcanogenic sediments.

5.2.2 Mesiänlampi acid tuff, sample A2388

The Mesiänlampi acid tuff sample is foliated, displays primary bedding and contains small ellipsoid shapes of quartz and calcite, interpreted as filled pore spaces or amygdales. The zircons from the Mesiänlampi acid tuff are small (<100 µm), euhedral, rounded, inclusion rich and display magmatic oscillatory zoning. Some grains have strongly metamict inner domains and some weakly developed zoning, or no zoning at all. Altogether, 14 spots were analysed from the intact cores and rims, and a concordia age of 1891 ± 4 Ma (Fig. 7) can be calculated for them. The homogeneity of the zircons confirms the origin of the Mesiänlampi tuff as volcanic, although it occurs on the same outcrop group as laminar, clearly sedimentary rocks.

5.2.3 Jauhovakka dyke, sample A2389

The Jauhovakka dacitic plagioclase porphyrite dyke cross-cuts a diorite 3 km northwest of the Makkola volcanic belt. The plagioclase porphyrite is similar to the porphyries in the Korospohja area, as well as to the porphyries in the northeast Kauppila area. Zircons from the porphyrite display weak oscillatory zoning and are rounded, but euhedral, with minor metamictization on the rims. Inclusions are a typical feature. The length of the grains is ≤150 µm. Altogether, 12 spot analyses were executed. The analysed inner domains and rims of the same zircon (n = 2) are of the same age within error limits. All data point error ellipses are concordant and define a concordant age of 1894 ± 4 Ma (Fig. 7). The obtained age shows that the dyke is coeval with the Makkola volcanic suite magmatism.

5.2.4 Keijupelto acid volcanogenic sedimentary rock, sample A2386

The Keijupelto sample is a strongly recrystallized sedimentary quartz-rich rock. The zircons are eroded (rounded and fragmented) and display mostly well-developed magmatic oscillatory zoning. A small number of crystals have metamict cores. The size of the grains is ≥100 µm, which is larger than in most of the studied samples. Altogether, 21 spots from 16 zircons were analysed, and of these, 9 define a concordia age of 1888 ± 5 Ma (MSWD = 4.7, probability of concordance 0.030, Fig. 8). Out of the remaining spots, seven yield $^{207}Pb/^{206}Pb$ ages between 2095–1979 Ma, three are Archean (3092–2700 Ma) and one plots near the Archean–Proterozoic transition (2488 Ma). The rim on one of the zircons yields a slightly younger $^{207}Pb/^{206}Pb$ age (1863 Ma), possibly reflecting metamorphic effects. Otherwise, the morphology of the zircon grains does not show any age-dependent differences. We interpret that the concordia age of 1888 ± 5 Ma represents the maximum age of deposition of this volcano-sedimentary unit. The presence of detrital zircons, with both Archean and ~2000 Ma ages, is typical for the sedimentary units surrounding the CFGC (Lahtinen et al. 2009, 2017, Mikkola et al. 2018b), although the occurrence of ca. 2000 Ma rocks is not known from the vicinity.

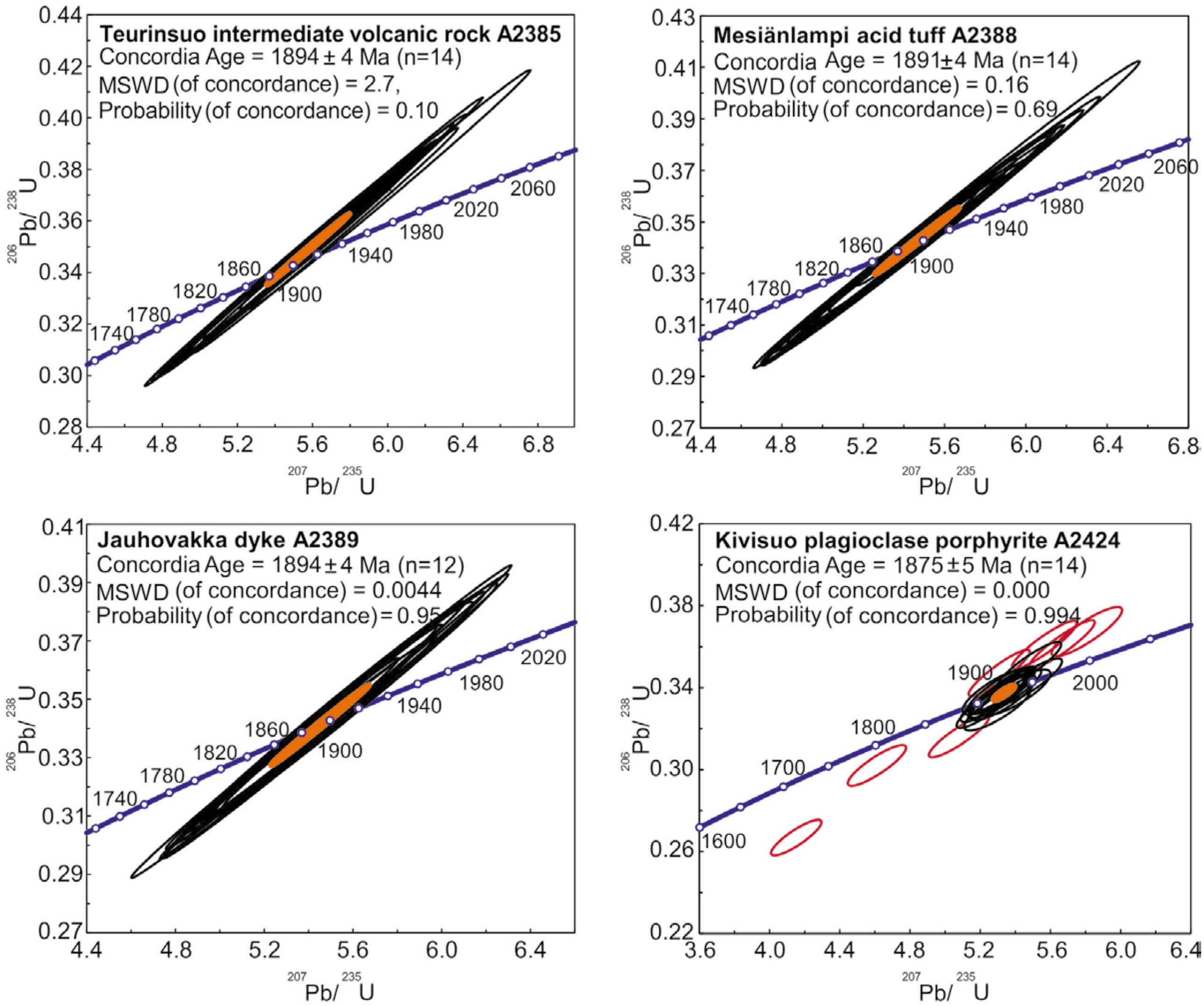

Fig. 7. Concordia diagrams of samples A2388, A2385, A2389 and A2424. All data plotted at the 2σ confidence level.

5.2.5 Kivisuo plagioclase porphyrite A2424

The Kivisuo plagioclase porphyrite sample consists of plagioclase porphyritic ground mass hosting ca. 5% of paraschist fragments up to 20 cm in size. Based on locally observable weak layering, most likely original bedding, the plagioclase porphyrite has been interpreted as a massive tuff or tuffite containing older sediment fragments. The bulk sample was crushed, because the sedimentary fragments could not be reliably removed due to their small size. Most of the zircons are elongated and euhedral, metamict domains are common and magmatic zoning is commonly visible. Out of the 21 analysed spots, 3 were discarded due to high common lead or high uranium contents. The remaining 18 spots are scattered and yield $^{207}Pb/^{206}Pb$ ages between 1852 and 1902 Ma (Fig. 7). Two of the spots are reversely discordant and two are normally discordant. The 14 concordant spots define a concordia age of 1875 ± 5 Ma, which is interpreted as best estimation for the age of this sample. Despite the scatter, it is evident that the sedimentary fragments do not contain significantly older zircons than the plagioclase porphyrite hosting them.

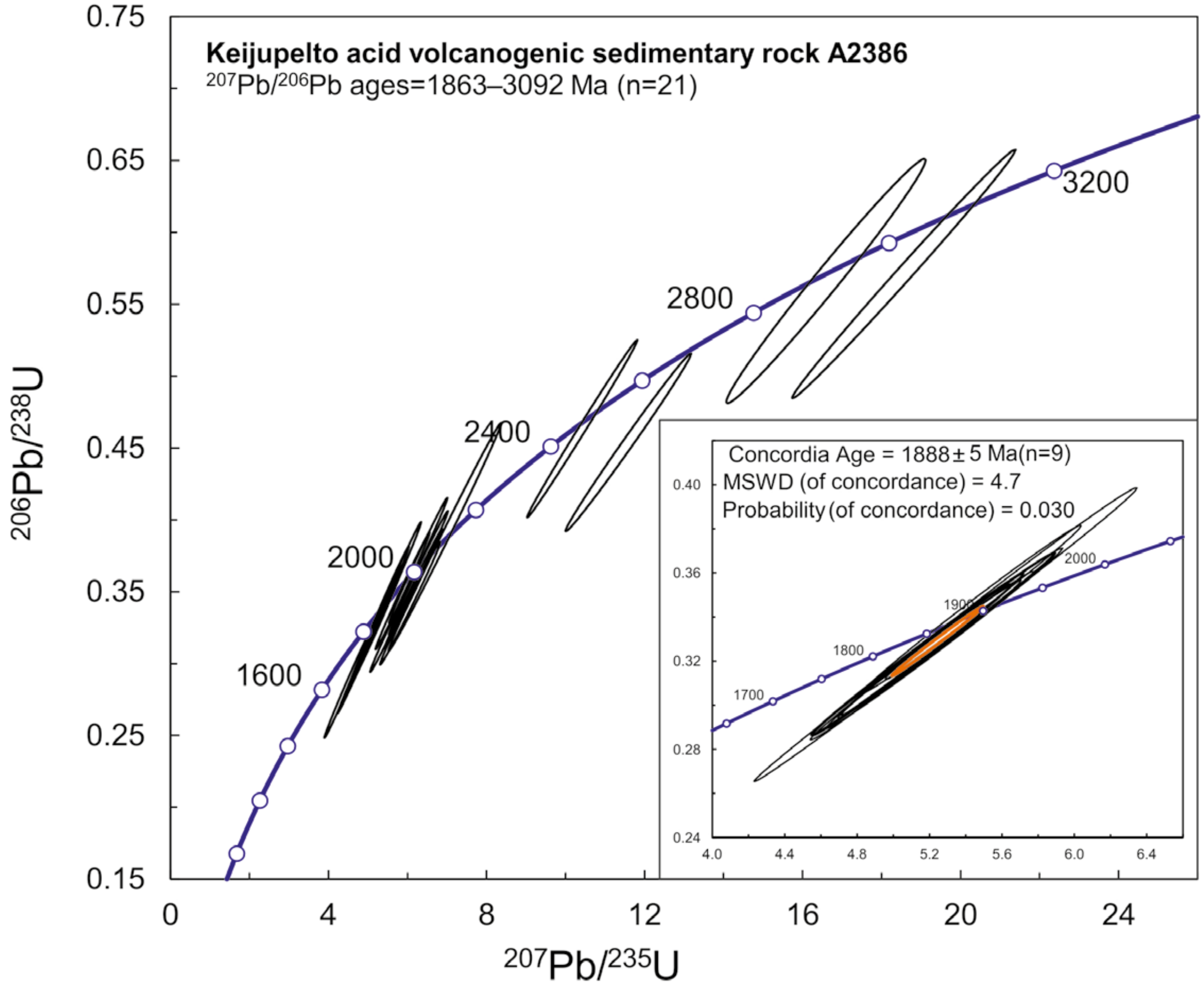

Fig. 8. Concordia diagram of sample A2386. In the inset, a close-up of the analyses with $^{207}Pb/^{206}Pb$ ages between 1875 and 1895 Ma and the concordia age calculated based on them. All data plotted at the 2σ confidence level.

6 DISCUSSION

6.1 Makkola suite

The volcanic rocks of the Makkola suite form continuous trends on Harker diagrams, excluding a certain amount of scatter, e.g. MgO and TiO_2, in basic compositions. The latter is likely to be due to fractional processes operating more efficiently in less viscous magmas. As the patterns on both REE and spider diagrams also display similar shapes, the suite can be interpreted as comagmatic. Geochemistry of the volcanic rocks suggest that they were formed in arc type setting. Distinct negative Ti and Nb anomalies, as well as enrichment of large-ion lithophile elements over high-field strength elements can be interpreted as signs of a subduction source (e.g. Turner et al. 1996, Wang et al. 2006). The observed Ta/Yb ratios between 0.10 and 1.00 suggest continental arc-type affinity (Pearce 1983). The relatively high Al_2O_3 concentrations of the Makkola suite are also a typical feature for volcanic rocks formed in a mature continental arc setting (e.g. Condie 1997), as is the dominance of intermediate and acid compositions. The observed elevated K_2O concentrations are also characteristic for continental arcs, but in the case of the Makkola suite, this can be partially caused by alteration, as the values display a large amount of scatter. Based on the above, we conclude that the Makkola suite originated in an active continental margin setting.

Based on the similarities of the age and composition, the hypabyssal porphyrite dykes cross-cutting the plutonic rocks in the study area are interpreted to be part of the Makkola suite. This indicates that the volcanic segments and the plutonic rocks surrounding them originated in close proximity and do not represent significantly differing erosion levels. This has implications for the ore potential of the study area, as it supports the possibility for porphyry-type deposits in the area, for which the mineralisation condensation of the Hiekkapohja area (Halonen 2015) gives additional evidence.

Excluding the zircons younger than 1900 Ma, the zircon population of the volcano-sedimentary Keijupelto sample is similar to that of the Svecofennian metasedimentary units surrounding the CFGC (Lahtinen et al. 2009. 2017, Kotilainen et al. 2016, Mikkola et al. 2018b). The Keijupelto sample, containing zircons with Archean ages, and active volcanism in the area is one constrain in respect to the overall tectonic scenario. The depositional environment was most likely a continental arc, as the transportation of Archean detrital zircons into a juvenile island arc environment seems unlikely. The Keijupelto sample also contains a zircon population aged ca. 2000 Ma. The well-recognized but unresolved problem with the 2000 Ma zircons is their source; felsic rocks of this age are scarce in the Fennoscandian Shield, but zircons are abundant (e.g. Lahtinen et al. 2009, 2010). Possible explanations for their source include the hypothetical Keitele microcontinent, which would have been completely destroyed at least at the current erosion level during the culmination of the Svecofennian orogeny, or transportation from the Lapland–Kola orogeny (Lahtinen et al. 2009). An additional possible source could be the Central Russian fold belt near Moscow, containing ca. 2000 Ma juvenile volcanic and sedimentary units (Samsonov et al. 2016).

Based on the age determinations from our study area, it seems that the volcanic rocks from the Makkola area are older than those further to the southwest; 1895–1890 Ma vs. 1885–1875 Ma. Verification of this difference would require a number of additional age determinations, as the subareas of the Makkola suite cannot be differentiated on a geochemical (Mönkäre 2016, this study) or petrographical basis. The older ages are clearly similar to those of the Pirkanmaa igneous suite, whereas the latter are more akin in age to the main phase of plutonic activity of the CFGC (e.g. Nikkilä et al. 2016). It should be noted that the youngest volcanic activity is within error margins coeval with three of the four granitoid suites in the area: Oittila, Saarijärvi and Muurame (1885–1875 Ma, Heilimo et al. 2018). The close proximity of rock suites with differing geochemical characteristics but overlapping ages further emphasizes the rapid geological evolution of the area.

6.2 Relationship of the Pirkanmaa migmatite and Makkola suites

The majority of the samples from the metasedimentary units of the Pirkanmaa migmatite suite bounding the volcanic units to the south, both in the current study area (Mikkola et al. 2018b) and further west (Lahtinen et al. 2009, 2017), do not contain detrital zircons with ages similar to those of the here-studied volcanic units. Therefore, they were most likely deposited prior to the active volcanic phase. The age distribution of the detrital zircons, and thus the maximum age of the well-preserved greywackes within the Pirkanmaa suite (Tammijärvi and Rusalansuo lithodemes, Fig. 2) in the study area, is approximately similar to that of the lowest sedimentary members of the Tampere group (Myllyniemi formation, Huhma et al. 1991, Claesson et al. 1993, Mikkola et al. 2018b). However, the well-preserved greywackes of the Tammijärvi lithodeme have not been interpreted as equivalent to the Myllyniemi formation and the depositional basement of the Makkola suite. The main reason is that the contact between the Makkola suite and the Tammijärvi lithodeme is formed by the large-scale southwest-trending Leivonmäki shear zone (Mikkola et al. 2018a).

Typical volcanic rocks in the Pirkanmaa migmatite suite show MORB or picritic compositions in the study area, as well as further west (e.g. Peltonen 1995, Kähkönen 2005, Kousa et al 2018b, Lahtinen et al. 2017). However, six samples interpreted as volcanic in origin from three different locations and included in the Pirkanmaa migmatite suite do not show significantly differing chemical compositions from those of the Makkola suite. Due to limited exposure in these areas, this observation has to be treated with prudence; for example, half of these samples originate from drill cores from Tuppi (Fig. 2), and they were taken from narrow sections interpreted as volcanic interbeds in migmatitic paragneisses. Nevertheless, it is not inconceivable that they could be narrow veins similar to those sampled cross-cutting the plutonic rocks in the vicinity of Makkola. These samples also originate from the same area as a paragneiss sample with detrital zircon population differing from that typical for the Pirkanmaa migmatite suite (Mikkola et al. 2018b), i.e. it lacks Archean zircons and contains detrital grains that could be coeval with the magmatic activity of the Makkola suite. Therefore, it is not unfeasible that some of the paragneisses included in Pirkanmaa migmatite suite could belong to the Makkola suite, but further evaluation of this would require additional age determination samples, both from these small volcanic units and the paragneisses in their vicinity.

6.3 Comparison with the Tampere group and volcanic units within the CFGC

Geochemically, the volcanic rocks of the Tampere group are similar to those of the Makkola suite (Figs. 4, 5). The rock types present in the two units also show strong similarities; plagioclase and uralite porphyrites are typical, although sedimentary rocks are more abundant in Tampere group than in the Makkola suite. Despite strong similarities, a direct correlation of the various subunits cannot be achieved due to the scattered nature of the volcanic belts, extending over 200 km along strike, and the often poor exposure of the units. The age results from the Makkola suite are similar to those reported from the Tampere group, the oldest samples from both locations yielding ages from 1895 to 1890 Ma (Kähkönen et al. 1989, Kähkönen 2005, Kähkönen & Huhma 2012), and our younger Kivisuo sample (1875 ± 5 Ma) coincides in error limits with the younger ca. 1880 Ma activity in Tampere (ibid). Based on the above, the Makkola suite can be regarded as the eastern equivalent of the Tampere group. The main difference between Makkola suite and the Tampere group is the Haveri and Myllyniemi formations of the latter, which have no analogue in the former. The Haveri formation, with its EMORB affinity, has been interpreted to represent the initial rifting stages, followed by deposition of the greywackes of the Myllyniemi formation, and later transition to arc-type volcanism (Kähkönen 2005). In our study area, the analogues for the Haveri and Myllyniemi formations are the mafic volcanic rocks of the Ala-Siili lithodeme and greywackes of the Tammijärvi lithodeme, which are interpreted as belonging to the Pirkanmaa migmatite suite (Kousa et al. 2018b, Mikkola et al. 2018b).

The volcanic samples of this study interpreted as belonging to volcanic units within the CFGC do not show any geochemical differences from the Makkola suite. This could, however, be a result of the limited number of samples, as when the compositions of the Makkola suite are compared with the larger data set from the central part of the CFGC (Nikkilä et al. 2016), certain small differences are apparent, such as the lower TiO_2 concentrations of the Makkola suite at the acidic end of the compositional spectrum and the lower trend of the samples from the central CFGC on the TAS diagram (Fig. 5). On the Nb/Y versus Zr/Ti plot, intermediate and acid volcanic rocks in the two groups also deviate, as the samples from the central CFGC, due to slightly higher Y concentrations (Fig. 6B) display lower Nb/Y ratios at higher Zr/Ti ratios. On the Nb/Yb versus Th/Yb plot, the two groups also show different patterns, as the samples of the Makkola suite form a trend towards a lower angle with respect to the volcanic and subvolcanic samples from the central CFGC. This is caused by the higher variation in Th concentrations of the latter group (Fig. 6), as the Yb concentrations and their variation are similar. The same difference in the Nb/Yb versus Th/Yb plot is also observable between the Pirkanmaa intrusive suite and granitoids of the CFGC (Mikkola et al. 2018a). Both the basic and intermediate volcanic rocks from the CFGC display a positive Eu anomaly, which is not found in any of the lithodemes making up the Makkola suite (or in individual samples). This could indicate melting in higher pressure, i.e. outside the stability field of plagioclase, in central parts of the CFGC. On the spider diagram, the basic samples from the central CFGC lack the negative Ti anomaly that is present in all of the other groups (Fig. 6).

The subtle compositional differences shown by the volcanic rocks within CFGC and those flanking it to the south indicate certain differences in magma genesis. Nikkilä et al. (2016) suggested that the main plutonic activity between 1890 and 1880 Ma forming the CFGC (ibid, Rämö et al. 2001, authors' unpublished data) is not directly related to subduction, as the plutonic rocks have crustal affinity. They interpreted that the magma genesis was mainly a consequence of partial melting due to heating caused by radioactive decay in a thickened crust during and after terrain accretion with the Karelian craton. However, the onset of the plutonic main phase after 1890 Ma within the CFGC coincides with continuing active volcanism along the southern boundary of it. This volcanism, forming younger parts of both the Tampere group and Makkola suite, has been interpreted as being related to active subduction (Lahtinen et al. 2009, Kähkönen & Huhma 2012, this study). Taking into account the overlap in ages, compositional similarities and the geologically small areal extent of the CFGC, it is reasonable to presume that volcanism within, and south of, the CFGC was a result of the same process(es). The last point is especially true if the orocline model of Lahtinen et al. (2014) is taken into account, and the now rounded shape of CFGC is a result of the deformation of an originally narrower linear belt. The small compositional differences most likely reflect a variable distance from the trench and in crustal thickness. The overall geological evolution of the study area is further discussed in Mikkola et al. (2018a) in this volume.

7 CONCLUSIONS

The age span of volcanism of the Makkola suite extends from 1895 to 1875 Ma.

Compositionally, the volcanic rocks forming the Makkola suite represent typical calc-alkaline arc-type magmas.

As subvolcanic dykes locally cutting the plutonic rocks are compositionally akin to the Makkola suite volcanic rocks and coeval with them, they can be regarded as part of the same suite.

Based on the resemblance of the volcanic rocks of the Tampere group and the Makkola suite in both age and composition, the latter can be regarded as representing the same phase of arc magmatism. However, a direct correlation of the geological sub-units is not possible due to deformation, locally poor exposure and the strike length of the volcanic belt extending over 200 km.

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