DETRITAL ZIRCON AGES AND GEOCHEMISTRY OF THE METASEDIMENTARY ROCKS ALONG THE SOUTHEASTERN BOUNDARY OF THE CENTRAL FINLAND GRANITOID COMPLEX

by

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The metasedimentary rocks along the southeastern boundary of the Central Finland Granitoid Complex are variably migmatized greywackes, originally deposited as turbidites. They have been classified into several geological units that cannot be distinguished on a geochemical basis. Six samples were collected for detrital zircon study, five from unmigmatized and one from strongly migmatitic rock. In addition, new data are provided here from two previously studied samples. Most studied samples contained a zircon population typical of the paragneisses of central and southern Finland: a bimodal population with Neoarchean (ca. 2700 Ma) and Paleoproterozoic (2100–1920 Ma) peaks. In addition, some samples also recorded a weak metamorphic overprint at 1900 Ma. The one studied migmatitic sample did not contain Archean detrital material and yielded ca. 1885 Ma as the age of anatexis. Based on the results, the majority, if not all, of the paragneisses in the study area were deposited before the onset of volcanism (1895 Ma) in the study area. The combination of the observed zircon age patterns and abrupt changes in the metamorphic degree would have required large vertical movements in the late stages of geological evolution. The results also warrant further discussion on the unit division of the voluminous Svecofennian paragneisses.

Appendix 1 is available at: hhttp://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

Keywords: turbidite, paragneiss, migmatites, metamorphic rocks, Paleoproterozoic, Svecofennian, Finland, zircon, U/Pb, geochronology

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1 INTRODUCTION

Due to a research history over a century long, the overall development of the Svecofennian orogen covering southern and central Finland, as well as adjacent parts of Sweden and Russian, is relatively well constrained. However, interpretations vary and numerous questions regarding the original relationships between different rock units remain open. One of these open questions concerns the unit division of the voluminous paragneisses (Fig. 1). Single-grain studies on detrital zircons, following the early work of Huhma et al. (1991) and Claesson et al. (1993), have refined our understanding of the Svecofennian depositional history. The majority of the metasedimentary rocks were deposited before the onset of younger Svecofennian volcanism (1895 Ma) and magmatism forming the Central Finland Granitoid Complex (hereafter the CFGC; Lahtinen et al. 2002, 2009, 2010, 2017, Kotilainen et al. 2016). A second intracratonic depositional phase occurred following the main collisional phase of the orogeny, i.e. after 1.88 Ga (Korsman et al. 1988, Bergman et al. 2008, Lahtinen & Nironen 2010, Nironen & Mänttäri 2012). Paragneisses and quartzites belonging to this second depositional phase are known from sporadic localities in southern and central Finland.

This study includes both geochemical and detrital zircon data from the southeastern margin of the CFGC from metasedimentary rocks belonging to various geological units. The results are used to evaluate the origin of, and relationships between, the different geological units, which presently occur in close proximity. In addition, the study aimed at clarifying the relationships between the sedimentary and volcanic rock units in the area and evaluating the possible presence of sedimentary rocks belonging to the younger Svecofennian (<1.88 Ga) depositional phase.

2 GEOLOGICAL SETTING

The CFGC is surrounded by metasedimentary rock units, which are often, but not always, migmatized. Along the northern boundary of the CFGC, these metasedimentary rocks belong to the Savo supersuite (Fig. 1). To the south, the CFGC is bounded by the Pirkanmaa migmatite suite of the Western Finland supersuite, whose other suites form the western boundary of the CFGC (Luukas et al. 2017, Nironen 2017). The Häme migmatite suite, belonging to the Southern Finland supersuite, borders the Pirkanmaa migmatite suite to the south and the east. All of the above-mentioned units mainly consist of greywackes, typically containing black schist interbeds of variable thickness (Matisto 1976, Lahtinen 1996, Kilpeläinen 1998). The volcanic interlayers are scarce, mafic to ultramafic in composition and interpreted to represent extensional phases in the evolution of the sedimentary basin(s) (Lahtinen 1996, Korsman et al. 1997, Lahtinen et al. 2017, Kousa et al. 2018b).

In all of these metasedimentary units, the majority of studied samples contain detrital zircon populations that display roughly similar age distributions with two distinctive peaks: Neoarchean ca. 2.7 Ga and Paleoproterozoic 2.05–1.92 Ga (e.g. Huhma et al. 1991, Lahtinen et al. 2002, 2009, 2017, Kotilainen et al. 2016). A similar distribution is found in the Viinijärvi suite (aka Upper Kaleva, Fig. 1) greywackes further east and interpreted as being deposited on the passive margin of the Karelian craton (Lahtinen et al. 2010). The 1895 Ma Pirkanmaa intrusive suite defines the minimum age for the Pirkanmaa migmatite suite (Kallio 1986, Mikkola et al. 2016, Heilimo et al. 2018).

The lowest formation of the classical Tampere group, i.e. the Myllyniemi formation (Kähkönen & Leveinen 1994), consists of well-preserved greywackes that are similar to the paragneisses of the Pirkanmaa migmatite suite in both whole-rock composition and the detrital zircon population (Lahtinen et al. 2009). In addition to the interpreted geological context, the only significant difference between the Myllyniemi formation and the Pirkanmaa migmatitic paragneisses is the higher metamorphic degree of the latter. Karppanen (1970) interpreted that some of the well-preserved greywackes in our study area could be correlated with the sedimentary members of the Tampere group.

All of the units described above have been interpreted as being deposited in a passive margin setting before the onset of subduction and calcalkaline volcanism (1895–1875 Ma) along the southern and western boundary (in current geometry) of the CFGC (Kähkönen 2005, Lahtinen et al. 2009, Kähkönen & Huhma 2012, Mikkola et al. 2018b). Based on similarities in age and geochemistry, Mikkola et al. (2018b) concluded that the mainly volcanic Makkola suite (Fig. 2) in our main study area represents the same phase as the volcanic rocks of the Tampere group, although direct correlation is not possible. One metasedimentary sample from the Pirkanmaa migmatite suite, taken near Tampere, containing zircons that fall into the bracket of the active volcanic phase, was interpreted by Lahtinen et al. (2009) to represent a separate fore-arc unit.

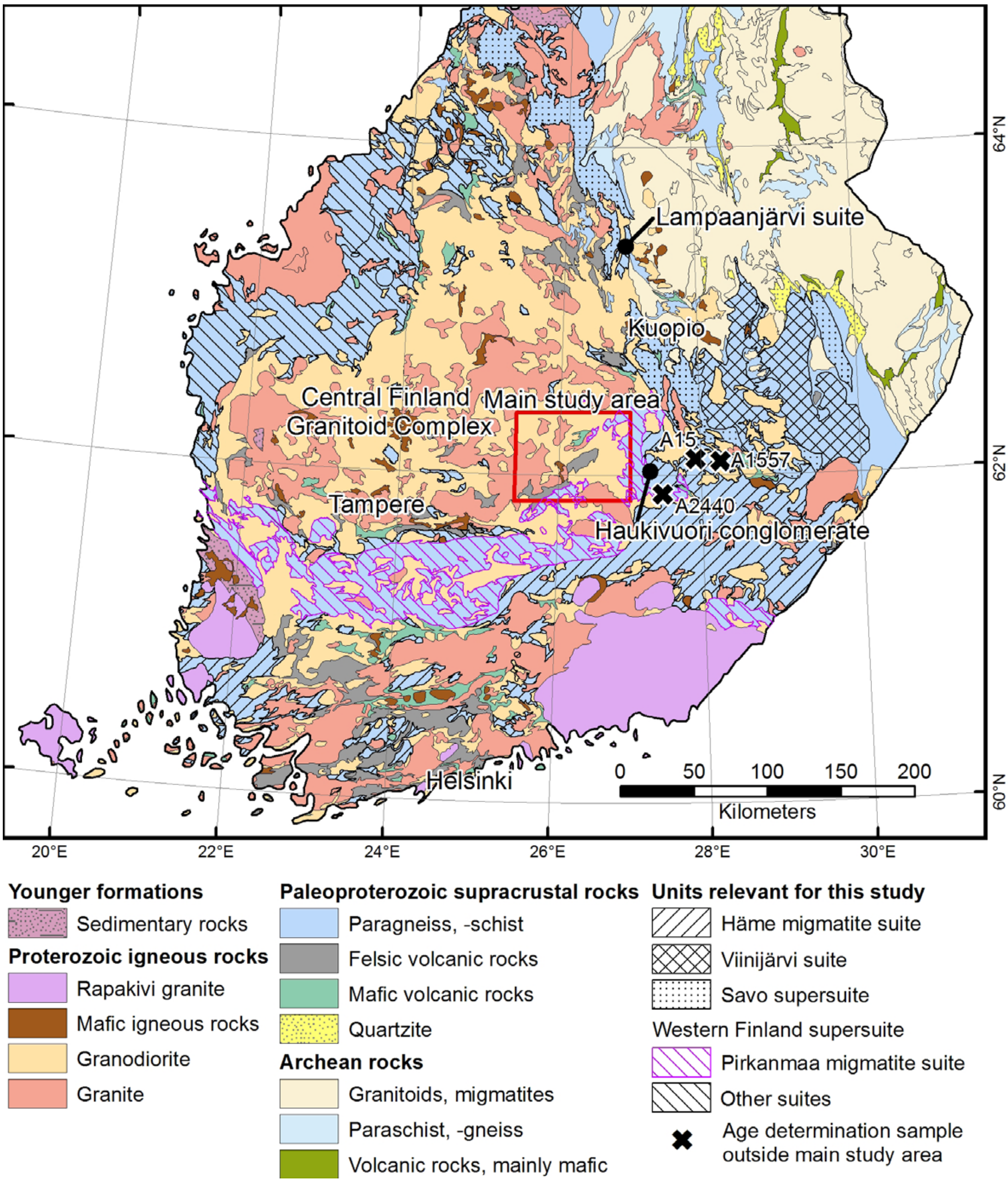

Fig. 1. Bedrock map of southern and central Finland with the geological units relevant for this paper highlighted. Also shown are the locations of the age determination samples outside our main study area. Note that the Myllyniemi formation in the Tampere region cannot be separated on the map due to its small areal extent. Map modified from Nironen et al. (2016) and Bedrock of Finland - DigiKP.

3 METHODS AND MATERIALS

All of the analytical methods are described in Appendix 1. Analytical data from 96 outcrop and drill core samples were used in this study. Five of these originate from Rasilainen et al. (2007) and five have been published by Mikkola et al. (2016). All samples were analysed using XRF for the main and certain trace elements and 49 using ICP-MS for additional trace elements. All of the geochemical data are listed in the Electronic Appendix and representative data are presented in Table 1. The geochemical data were plotted using the Geochemical Data Toolkit (GCDKit) program of Janoušek et al. (2006).

Four age determination samples were taken from selected outcrops and two from drill cores. Single-grain analyses were performed on four of the samples (A2395, A2396, A2397, A2398) using a Cameca IMS 1280 multi-collector ion microprobe at the NORDSIM facility, National Museum of Natural History, Stockholm, Sweden. Two samples (A2440, A2450) were studied in Espoo using a Nu Plasma AttoM single collector ICP-MS. A Nu Plasma HR multicollector ICP-MS was used for additional analyses from two pre-existing age determination samples (A15 & A1557, Lahtinen et al. 2002).

4 RESULTS

4.1 Field observations and petrography

4.1.1 Pirkanmaa migmatite suite

Most of the rocks belonging to the Pirkanmaa migmatite suite have been partially melted, but not all, as two unmigmatized lithodemes were also included in the suite by Mikkola et al. (2016). In addition to metasedimentary rocks, the suite in the study area also includes picritic volcanic rocks (Kousa et al. 2018b).

Undefined migmatitic paragneisses of the Pirkanmaa migmatite suite (hereafter Pirkanmaa paragneisses) form variably sized areas south of the Leivonmäki shear zone (Fig. 2). In addition to larger intact areas, they are typically met as enclaves in the plutonic rocks belonging to the Pirkanmaa intrusive suite (Mikkola et al. 2016). The main minerals of the Pirkanmaa paragneisses are quartz, plagioclase and biotite, and in some samples also K-feldspar and hornblende. Metamorphic index minerals are rarely abundant, the most common ones being garnet and sillimanite, with less common ones being cordierite and orthopyroxene. The leucosome is typically trondhjemitic, although leucogranodiorite variants exist. Locally, the Pirkanmaa paragneisses contain black schist interbeds, represented by two samples in our material.

The Tammijärvi greywacke lithodeme (hereafter Tammijärvi greywackes), belonging to the Pirkanmaa migmatite suite, is located in the southernmost part of the study area (Fig. 2). Their northern contact with the Makkola suite, predominantly consisting of volcanic rocks (Mikkola et al. 2018b), is formed by the Leivonmäki shear zone. The central parts of the lithodeme are intruded by small diorite intrusions. In the south, the greywackes are in contact with variably sized granitoid intrusions. In northern parts, the lithodeme is unmigmatized and does not contain granitoid dykes, while further south the degree of partial melting increases and granitoid dykes related to the intrusives appear, but are not abundant. The contact to the migmatized Pirkanmaa paragneisses is gradual.

The majority of the rocks are greywackes with variable amounts of mineral clasts (plagioclase and quartz) 1–2 mm in size (Fig. 3B). Lithic fragments are scarce and mainly consist of quartz grain aggregates. The groundmass of the greywackes consists of quartz, biotite, plagioclase and K-feldspar present in various proportions. Interbeds of conglomerate and metapelite are locally abundant in the greywackes. Black schist interbeds are rarely observable at outcrops, but can be recognized as magnetic and conductivity anomalies on aerogeophysical maps.

The Rusalansuo greywacke lithodeme (hereafter Rusalansuo greywackes) is present in two locations: in the vicinity of the Kangasniemi parish and in the Rusalansuo-Pieksämäki area in the northeasternmost corner of the main study area. These greywackes differ from the Tammijärvi greywackes

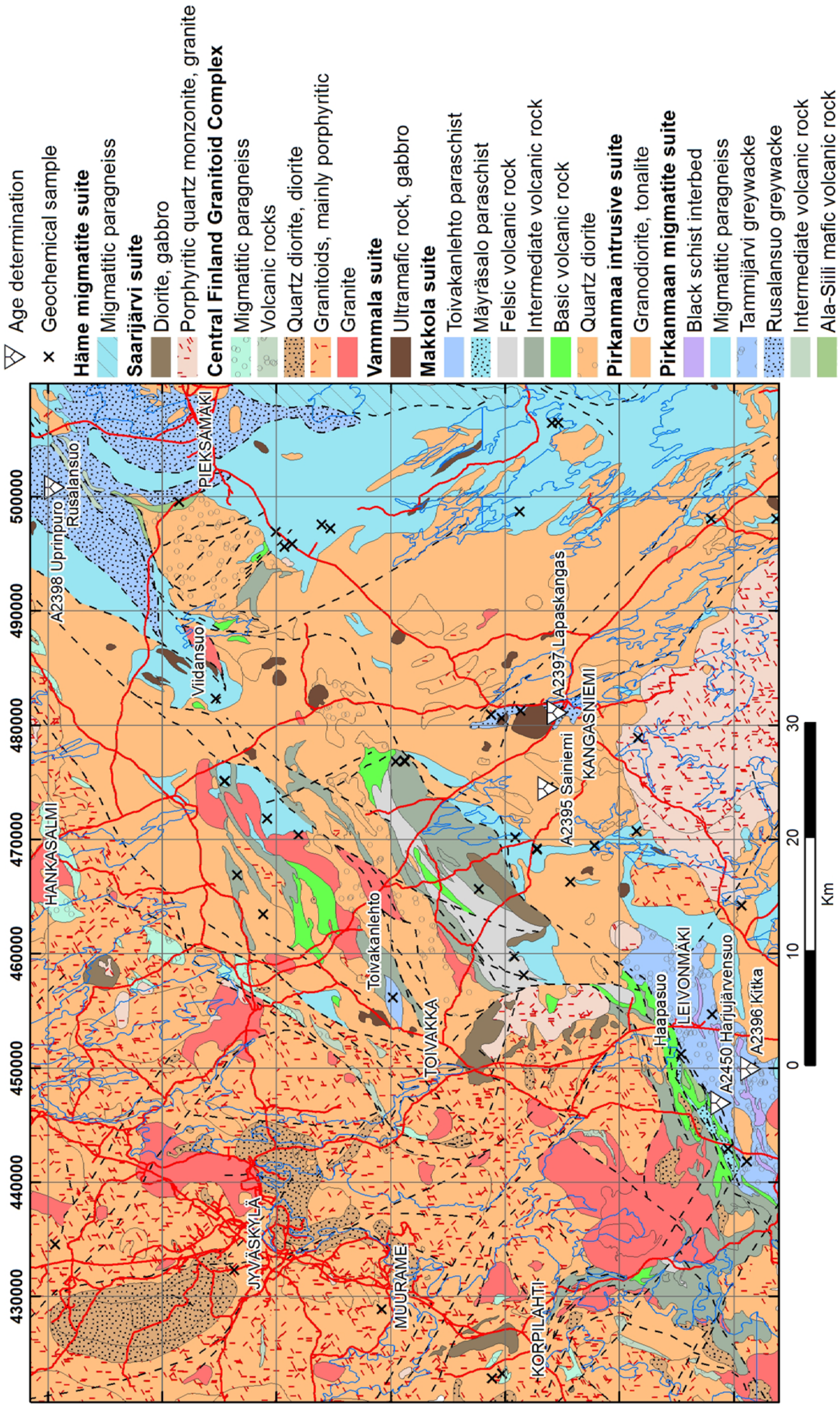

Fig. 2. Bedrock map of the main study area with sample locations. Map modified from Mikkola et al. (2016) and Bedrock of Finland – DigiKP.

by the absence of black schist interbeds. Near Kangasniemi, these relatively homogeneous greywackes lack conglomerate interbeds and are locally weakly migmatized, but significantly less than the Pirkanmaa paragneisses (Fig. 3A vs 3C). This weak anatectic event has been interpreted as contact metamorphism caused by the intrusion of the Salmenkylä gabbro (Mikkola et al. 2016). At Rusalansuo, the greywackes contain quartz pebble conglomerate (Fig. 3D) and intermediate volcanic interbeds. The presence of cordierite in Kangasniemi greywackes indicates either a slightly higher metamorphic grade or higher MgO and Al_2O_3 content in this subarea. Otherwise, Rusalansuo and Kangasniemi greywackes are alike: quartz, biotite, plagioclase and K-feldspar groundmass hosts quartz clasts. In the two areas, the contacts towards the surrounding more intensively metamorphosed rocks are sharp and most likely tectonic.

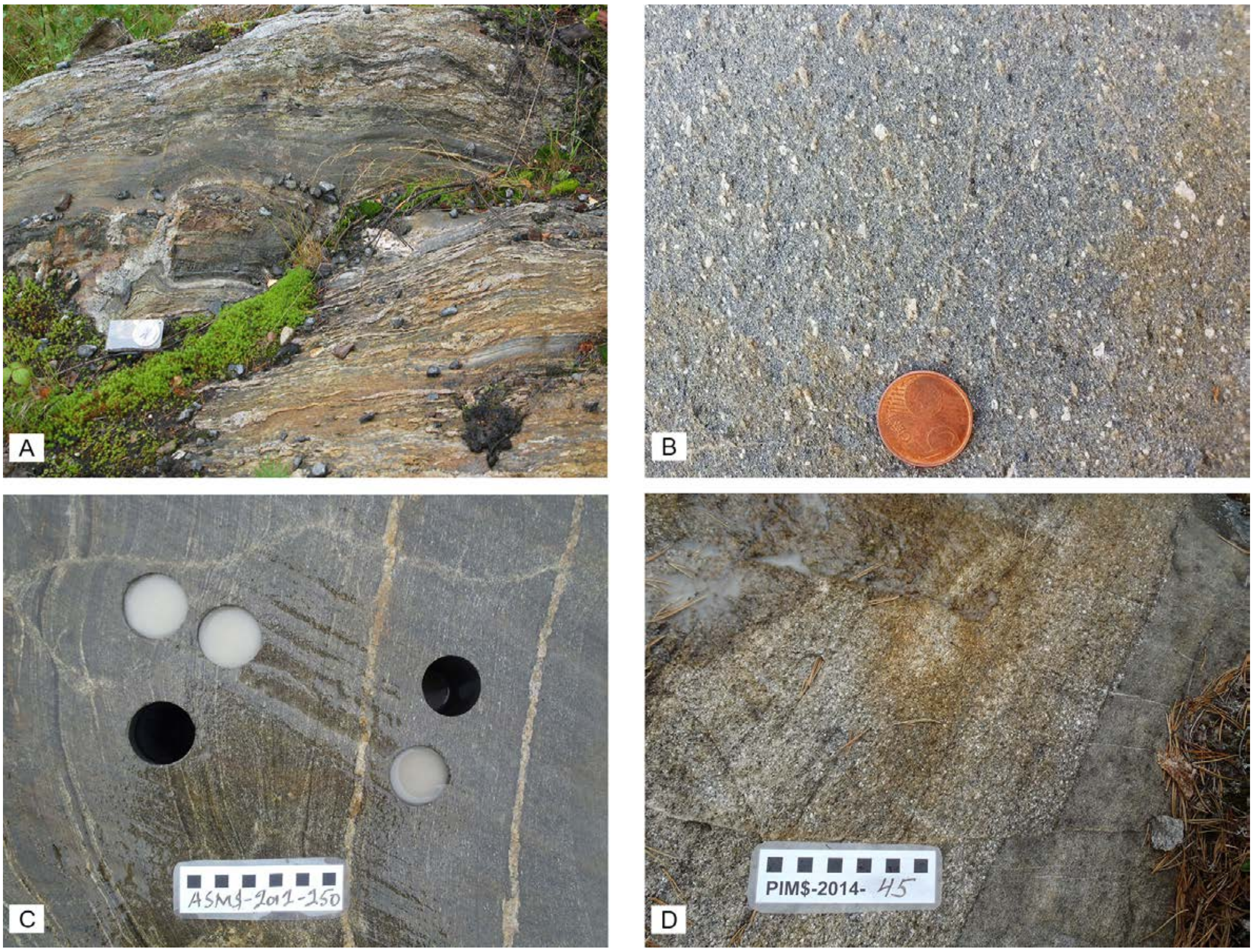

Fig. 3. A) Sample location A2395 Sainiemi, representing the migmatized Pirkanmaa paragneisses occurring in various parts of the study, which occur as large intact areas and variably sized xenoliths in the Pirkanmaa intrusive suite rocks. Length of the compass 12 cm. B) Sample location A2396 Kitka, representing well-preserved Tammijärvi greywackes with mm-scale clasts of plagioclase and quartz. Diameter of the coin 21 mm. C) Weakly migmatized Rusalansuo greywacke from sample location A2397 Lapaskangas. Scale bar with cm division. D) Contact between quartz pebble conglomerate and greywacke from sample location A2398 Rusalansuo. The sample was taken from a greywacke similar in appearance to that on the right in the picture. Scale bar with cm division.

4.1.2 Makkola suite

The Toivakanlehto paraschist lithodeme (hereafter Toivakanlehto paraschists) in the central part of the study area is included in the Makkola suite based on two factors: its location in the vicinity of volcanic units (Fig. 2) and the presence of uralite porphyrite dykes resembling those of the Makkola suite. As the lithodeme name implies, the majority of the rocks are paraschists (Fig. 4A & 4C), and greywackes (Fig. 4B) and calc-silicate rocks are present as interbeds. The fine-grained groundmass of the paraschist consists of variable amounts of quartz, biotite, muscovite and plagioclase. The observed porphyroblasts include K-feldspar and garnet. Muscovite filled pseudomorphs, possibly after andalusite, are also present. The compositional variation of the beds is reflected by the differences in the amount and type of the porphyroblasts.

The Mäyräsalo paraschist lithodeme (hereafter Mäyräsalo paraschists) is present in the southernmost part of the study area, within the Leivonmäki shear zone near the contact of the Tammijärvi greywackes and Makkola suite. The Holla iron formation occurs as an interlayer less than 10 m thick in the Mäyräsalo paraschist. Most of the unit consists of often thinly layered muscovite-biotite paraschist, and coarser grained interbeds are scarce. The observed porphyroblasts are muscovite pseudomorphs, possibly after andalusite, and staurolite.

Black schist beds occurring in the *Teuraanmäki intermediate volcanic rock* lithodeme (hereafter Teuraanmäki black schist) are also included in the material of this study. These black schists occur as relatively thick (<50 m) interbeds in comparatively homogeneous intermediate volcanic rocks.

4.1.3 Central Finland paragneisses

Paragneiss enclaves varying in scale from a few centimetres to a few kilometres are present in the plutonic rocks of the CFGC (Fig. 2). These rocks are hereafter referred to as Central Finland paragneisses. These paragneisses are variably migmatized and do not differ in appearance from Pirkanmaa paragneisses (Fig. 3A vs. 5B).

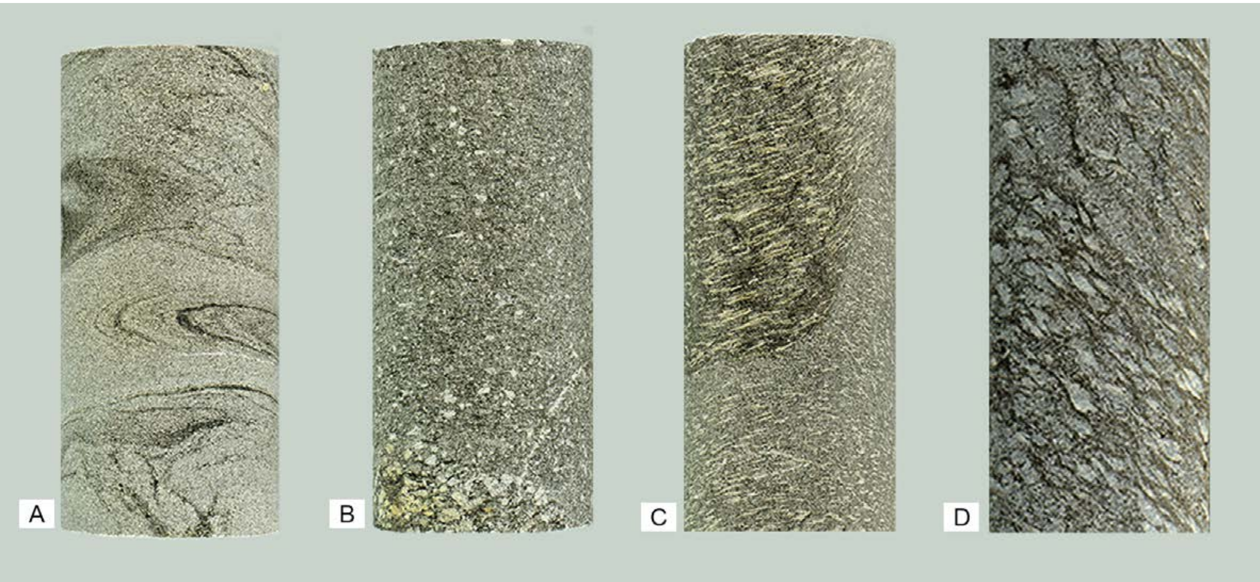

Fig. 4. A) Folded paraschist, B) greywacke and C) paraschist with abundant muscovite filled pseudomorphs from Toivakanlehto. D) Sillimanite-biotite paragneiss from Loukee (A2440). Diameter of drill cores 42 mm.

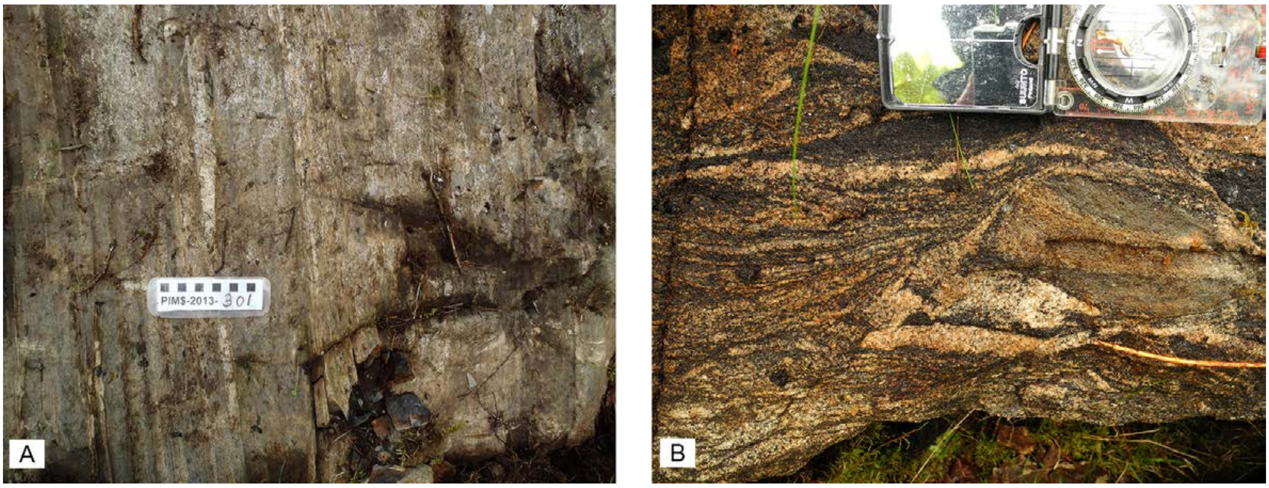

Fig. 5. A) An outcrop of Mäyräsalo paraschist, with variation in grain size and mineralogy of the beds. Scale bar with cm division. B) Migmatitic Central Finland paragneiss. Length of the compass 15 cm.

4.2 Geochemistry

In the sediment type classification diagram, the analysed samples mainly plot in the greywacke field, with a limited number of samples in lithic arenite and arkose fields (Fig. 6A). The compositional variation of the samples is large, as SiO_2 ranges from 46 to 77%. When all of the samples are viewed together, a correlation between SiO_2 and certain elements is observable in the more felsic compositions (e.g. MgO and Al_2O_3), but with respect to most elements, no correlations exist (e.g. Sr and CaO, Fig. 6). When taking the division into lithological units into consideration, the correlations become somewhat stronger, but not significantly in all of the units. Especially the samples representing the Pirkanmaa migmatite suite paragneisses and Mäyräsalo paraschists display significant scatter with respect to practically all elements. In case of the Pirkanmaa paragneisses, the compositionally differing types (e.g. samples with high Sr) do not represent unique subareas. On the other hand, samples deviating from the general trend towards higher MgO contents of the Mäyräsalo paraschist come from the Haapasuo area, but even so, not all samples from this area have high MgO. The samples with high Sr and belonging to the Tammijärvi greywackes come from the Harjujärvensuo area. The Tammijärvi greywackes and Toivakanlehto paraschists partially overlap with the compositional spectrum of the Myllyniemi greywackes, whereas the Mäyräsalo paraschist plots outside the spectrum.

The chondrite-normalized REE patterns of all of the studied units (shown as median values of the samples) display a similar trend, with moderate enrichment in LREE respective to HREE and a weak or missing Eu anomaly (Fig. 7A). Primitive mantle-normalized trace element compositions of the units also display distinctly similar patterns, i.e. negative Nb, P and Ti anomalies. Additionally, the black schists display a positive U anomaly.

Table 1. Representative chemical analyses.

Sample	EPHE-2013-386.1	N4312014R1 22.00-22.95	N4342013R2 46.00-47.00	HEKI-2013-166.1	ASM$-2012-250.2
Rock type	Paragneiss	Paraschist	Black schist	Biotite paragneiss	Greywacke
Suite / complex	Central Finland Granitoid Complex	Makkola suite	Makkola suite	Makkola suite	Pirkanmaa migmatite suite
Lithodeme	undefined migma-titic paragneiss	Mäyräsalo paraschist	Teuraanmäki black schist	Toivakanlehto paraschist	Rusalansuo greywacke
Age sample	---	---	---	---	A2397
SiO_2 %	64.1	61.3	53.2	70.7	67.0
TiO_2	0.79	0.61	0.63	0.48	0.61
Al_2O_3	17.30	17.70	15.50	14.50	13.90
Fe_2O_3t	6.82	7.50	9.10	3.76	5.59
MnO	0.08	0.08	0.03	0.04	0.15
MgO	2.61	3.66	3.30	1.59	2.08
CaO	2.26	2.19	1.74	1.82	7.14
Na_2O	2.40	2.67	2.06	3.20	1.65
K_2O	2.85	3.32	5.43	3.38	1.13
P_2O_5	0.19	0.28	0.12	0.14	0.20
C ppm	<500	<500	51900	1110	1180
Ba	581	856	954	716	n.a.
Cl	186	112	<60	<60	78
Co	n.a.	17.5	23.0	8.9	18.1
Cr	132	355	128	43	181
Ga	24	26	20	21	<20
Hf	n.a.	4.92	3.36	6.67	6.46
Nb	7.0	12.0	11.2	8.4	12.8
Ni	52.0	60	253	31	46
Pb	34	23	48	35	<20
Rb	138.0	102.0	219.0	100.0	54.3
S	310	164	31500	102	1813
Sc	<20	17.4	16.4	8.5	24.5
Sn	<20	20	<20	20	26
Sr	182	250	335	321	402
Ta	n.a.	0.51	0.41	0.61	1.04
Th	31.0	9.3	12.3	10.7	13.3
U	<10	2.56	12.50	2.02	3.43
V	123.0	96.3	669.0	54.7	132.0
Y	35.0	25.7	31.7	15.4	30.6
Zn	117	108	1170	112	70
Zr	165	193	140	171	317
La	<30	43.4	42.1	23.4	43.5
Ce	81.0	88.1	64.2	47.3	88.8
Pr	n.a.	37.1	32.4	17.0	37.8
Nd	n.a.	9.48	8.50	4.71	10.3
Sm	n.a.	6.53	6.08	3.21	6.86
Eu	n.a.	1.23	1.32	0.93	1.34
Gd	n.a.	5.80	5.87	2.92	6.17
Tb	n.a.	0.82	0.84	0.45	0.88
Dy	n.a.	4.85	n.a.	2.80	4.99
Ho	n.a.	0.93	1.08	0.56	0.96
Er	n.a.	2.7	3.4	1.7	2.77
Tm	n.a.	0.39	0.48	0.25	0.41
Yb	n.a.	2.59	3.64	1.71	2.64
Lu	n.a.	0.39	0.53	0.24	0.39

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

Table 1. Cont.

Sample	PIM$-2014-45.1	PIM$-2013-274.1	N4332013R6 29.40-30.60	ASM$-2012-115.1	N4342015R24 8.75-9.25
Rock type	Greywacke	Greywacke	Black schist	Biotite paragneiss	Paragneiss
Suite / complex	Pirkanmaa migmatite suite	Pirkanmaa migmatite suite	Pirkanmaa migmatite suite	Pirkanmaa migmatite suite	Pirkanmaa migmatite suite
Lithodeme	Rusalansuo greywacke	Tammijärvi greywacke	undefined black schist	undefined migmatitic paragneiss	undefined migmatitic paragneiss
Age sample	A2398	A2396	---	A2395	---
SiO_2 %	76.7	71.4	49.2	62.6	57.9
TiO_2	0.36	0.52	0.57	0.78	0.69
Al_2O_3	11.50	13.90	13.90	17.80	15.90
Fe_2O_3t	3.45	4.23	10.70	7.23	8.74
MnO	0.05	0.05	0.06	0.04	0.11
MgO	0.87	1.62	5.79	3.14	3.51
CaO	1.15	1.86	2.16	1.11	6.39
Na_2O	2.24	3.09	2.49	2.28	3.27
K_2O	3.26	2.88	2.86	4.17	1.77
P_2O_5	0.11	0.14	0.14	0.06	0.26
C ppm	<500	667	70100	3820	707
Ba	739	547	459	643	603
Cl	83	83	65	306	205
Co	5.6	<5	27.6	15.5	n.a.
Cr	43	67	130	138	43
Ga	<20	<20	<20	28	<20
Hf	4.05	5.38	3.02	3.89	n.a.
Nb	6.0	7.1	8.5	10.8	<7
Ni	<20	<20	325	69	<20
Pb	<20	<20	22	<20	<20
Rb	88.0	91.7	141.0	154.0	58.0
S	103	468	41600	2443	21650
Sc	7.4	11.4	15.5	19.8	<20
Sn	<20	<20	26	<20	20
Sr	222	212	174	141	534
Ta	0.56	0.52	0.46	0.50	n.a.
Th	18.0	14.2	11.4	12.3	<30
U	2.63	2.92	15.90	2.61	<10
V	49.9	73.7	765.0	137.0	199.0
Y	19.1	18.0	33.4	22.3	n.a.
Zn	35	55	1760	137	90
Zr	169	233	129	158	114
La	55.9	16.0	34.5	38.7	<30
Ce	116.0	29.1	54.1	77.8	70.0
Pr	41.7	9.9	28.4	33.9	n.a.
Nd	12.10	3.04	7.24	9.38	n.a.
Sm	6.69	2.12	5.81	6.27	n.a.
Eu	1.19	0.95	1.23	1.41	n.a.
Gd	5.40	2.45	5.78	5.35	n.a.
Tb	0.70	0.48	0.89	0.74	n.a.
Dy	4.00	3.32	n.a.	4.41	n.a.
Ho	0.77	0.70	1.19	0.86	n.a.
Er	2.3	2.2	3.8	2.5	n.a.
Tm	0.32	0.30	0.55	0.34	n.a.
Yb	2.19	2.12	4.28	2.38	n.a.
Lu	0.32	0.31	0.61	0.35	n.a.

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

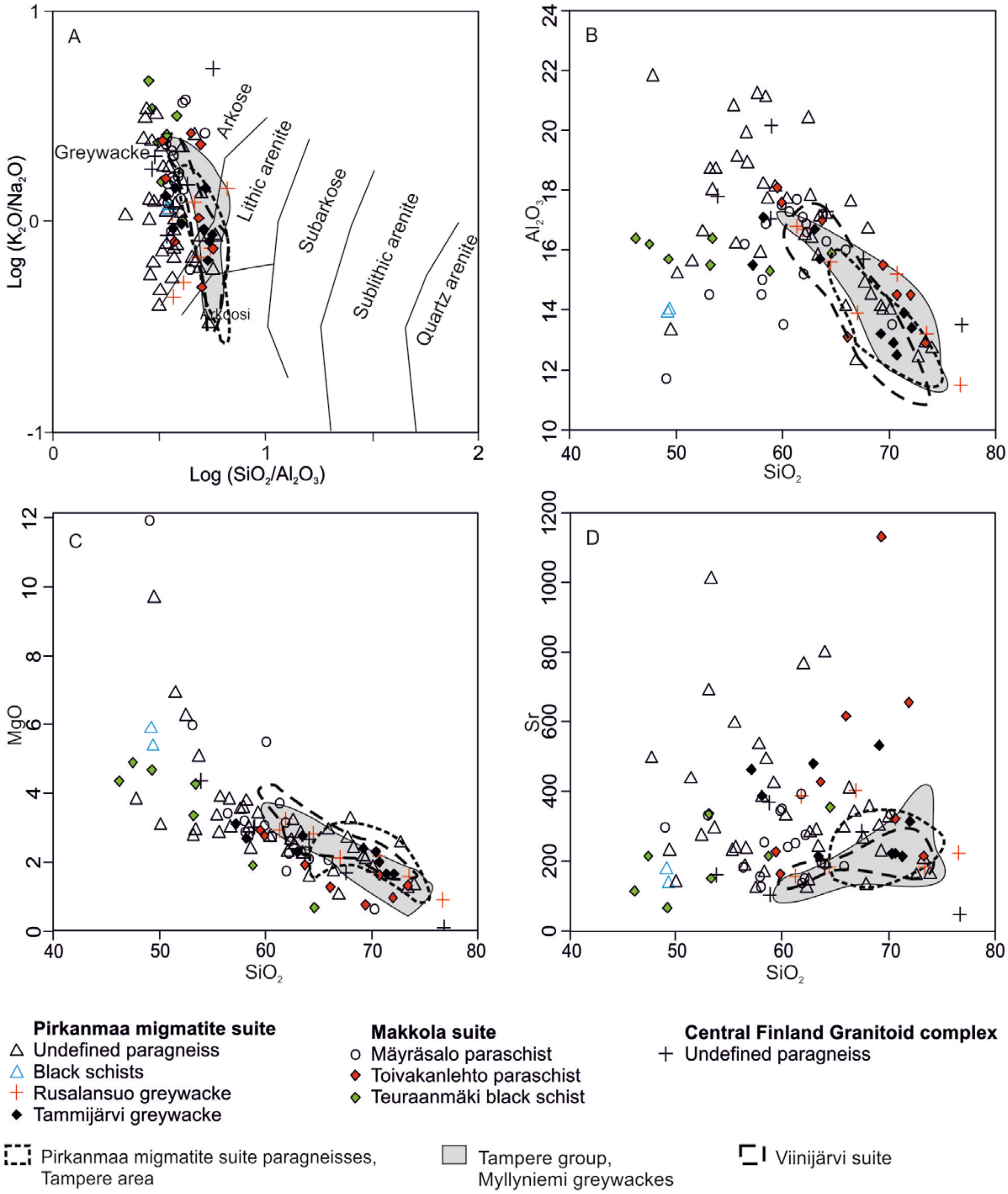

Fig. 6. The studied samples plotted on a sediment type classification diagram (A; Pettijohn et al. 1972, with boundaries modified by Herron 1988) and Harker diagrams (B–D). Reference data (Viinijärvi suite, Myllyniemi formation, Pirkanmaa paragneisses from the Tampere area) from Lahtinen et al. (2009, 2010).

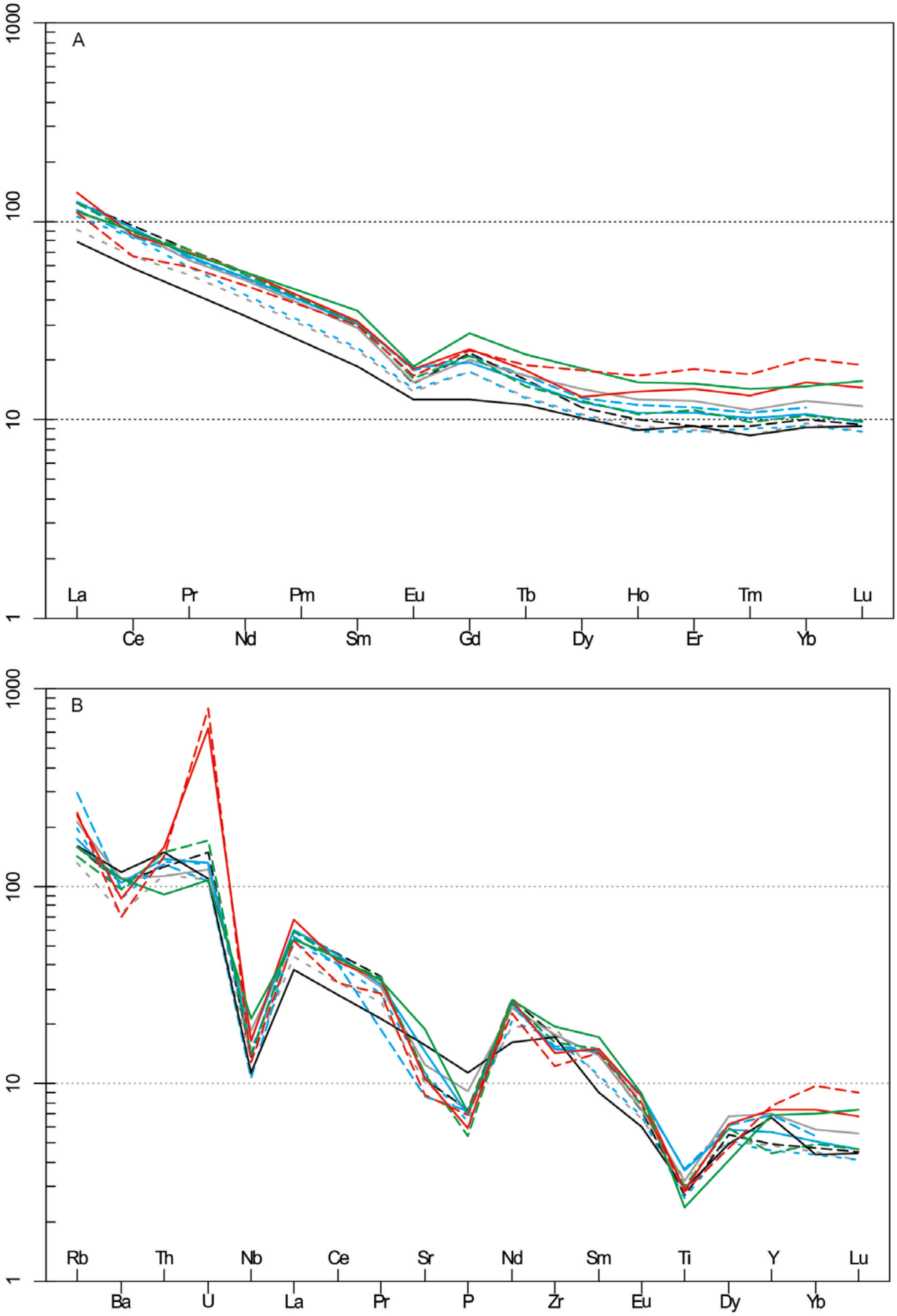

Fig. 7. A) Chondrite-normalized REE values of the studied units. B) Primitive mantle-normalized trace element compositions of the units. The displayed value is the median of each suite. Chondrite values from Boynton (1984) and primitive mantle values from McDonough & Sun (1995). Reference data from Lahtinen et al. (2009, 2010).

4.3 Zircon ages

4.3.1 A2395 Sainiemi

Sample A2395 (Sainiemi) represents the migmatic paragneiss of the study area hosted as variably sized (from cm to km scale) enclaves in the plutonic units of the area (Fig. 2). On the outcrop, the rock is characterized by narrow neosome veining (Fig. 3A). As the veining is so small scaled, no attempt to separate the paleosome from the neosome was made, and a bulk sample was instead taken. Mineralogically, the neosome is trondhjemitic and the paleosome is biotite-rich paragneiss. The zircon population is characterized by two types: homogeneous unzoned grains and grains displaying oscillatory zoned cores with unzoned dark overgrowths (Fig. 8). Altogether, 43 spots were analysed (Electronic Appendix), and out of these, 3 were discarded due to a high level of discordance. All of the spots yield Paleoproterozoic ages ($^{207}Pb/^{206}Pb$ = 1876–2190 Ma, Fig. 9). Dark unzoned grains and overgrowths yield ages younger than 1900 Ma, whereas zoned cores and one light-coloured rim yield $^{207}Pb/^{206}Pb$ ages between 1885 and 2190 Ma, with maxima close to 1900 Ma. We interpret that the dark unzoned grains and rims indicate the migmatization event at 1885 Ma, as discordia calculated using all of these points yields an upper intercept at 1887 ± 6 Ma. Alternatively, a concordia age of 1883 ± 2 Ma using only the concordant analyses (n = 13) can be calculated. In our interpretation, the zoned cores are inherited grains and the nonexisting gap between the metamorphic and youngest inherited ages (1885 Ma) indicates rapid erosion and burial into anatectic conditions. However, the lack of an age gap can partially be an artefact of the lead loss of older crystals during intensive metamorphism.

4.3.2 A2396 Kitka

Sample A2396 (Kitka) represents the well-preserved Tammijärvi greywackes typical of the Leivonmäki area (Fig. 2). On the outcrop scale, the sample is relatively homogeneous and massive with ca. 1 mm clasts (Fig. 3B) in a finer grained groundmass. The majority of the clasts are quartz grains or grain aggregates and a minority are plagioclase grains, whereas lithic fragments are lacking. The zircon population is characterized by rounded grains with strong oscillatory zoning, often displaying homogeneous overgrowths, most of them too narrow for analysis. In cathodoluminescence pictures, the overgrowths form two groups: one is light and the other dark coloured (Fig. 8). The darkness of the cores also varies, but to a lesser extent. The majority of the 35 spots analysed (Electronic Appendix) from 23 different grains are concordant.

Out of the analysed spots, 31 are Paleoproterozoic with $^{207}Pb/^{206}Pb$ ages varying from 1905 to 2090 Ma, and the remaining 4 spots are Neoarchean ($^{207}Pb/^{206}Pb$ =2684–2743 Ma, Fig. 9). All of the Neoarchean cores (n = 3) are relatively dark and show weaker than average zoning, while the one Neoarchean rim is light coloured. The Paleoproterozoic spots do not show any significant correlation between morphology and age. The analysed rims (n = 10), for example, do not define a single metamorphic event; instead, they indicate that they were derived from terrain(s) displaying a range of metamorphic ages. Interpretation of the meaning of the youngest concordant analysis (n5441-23b, 1905 ± 12 Ma) is not self-evident, as the spot is from a weakly zoned rim on an older core (n5441-23a, 2009 ± 12 Ma). If the age of the rim is taken as inherited, it marks the maximum age of deposition, and if taken as metamorphic, it gives the minimum age of deposition for this sample. As the analysis has a low Th/U ratio (0.02) typical for metamorphic zircons (Williams et al. 1996), we prefer the latter interpretation and regard ca. 1.92 Ga as the maximum depositional age of this sample.

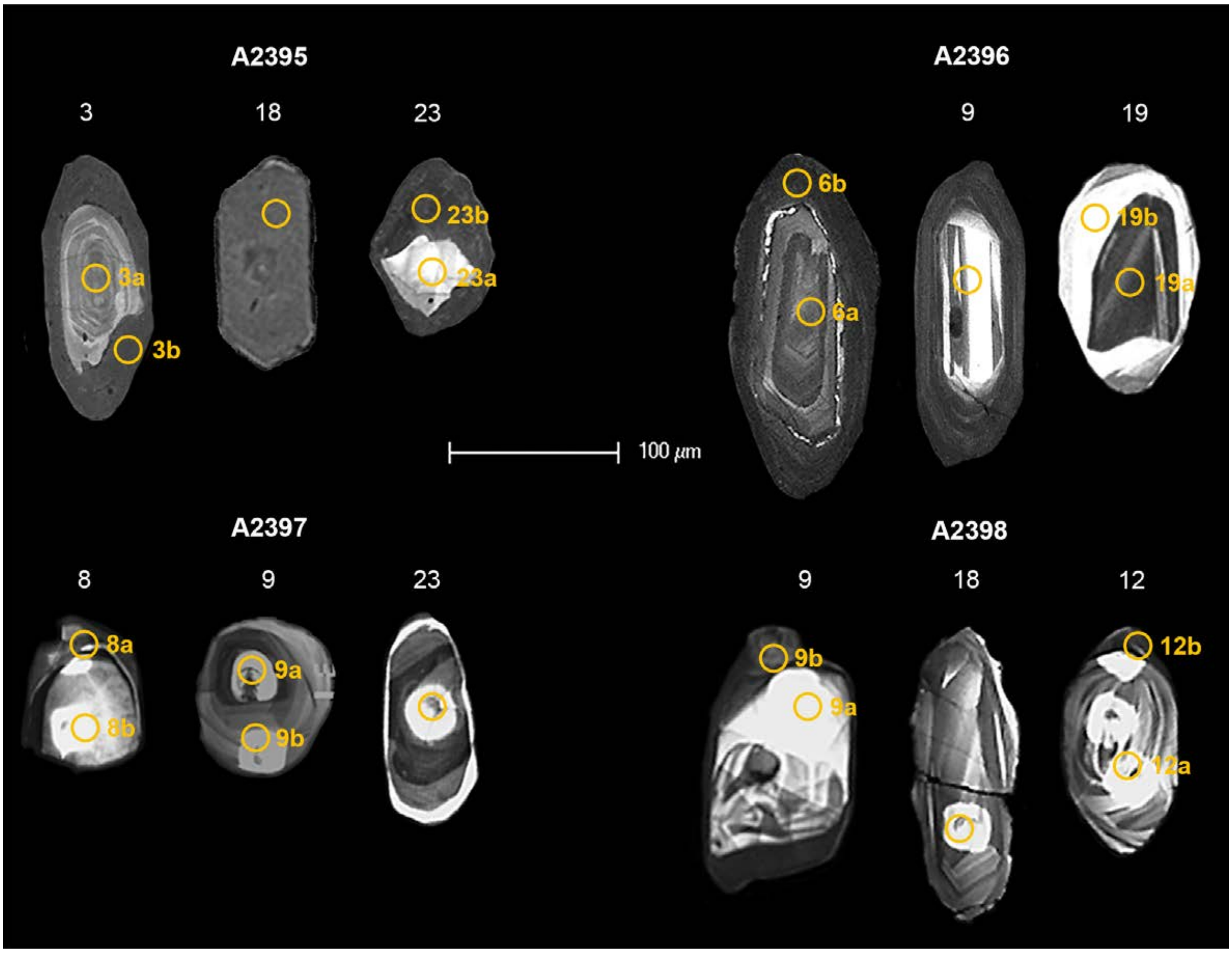

Fig. 8. Representative zircons of the studied samples with analysed spots shown. Note that samples A2397 and A2398 were imaged after the analyses; thus, the rastered area is visible as a light-coloured spot.

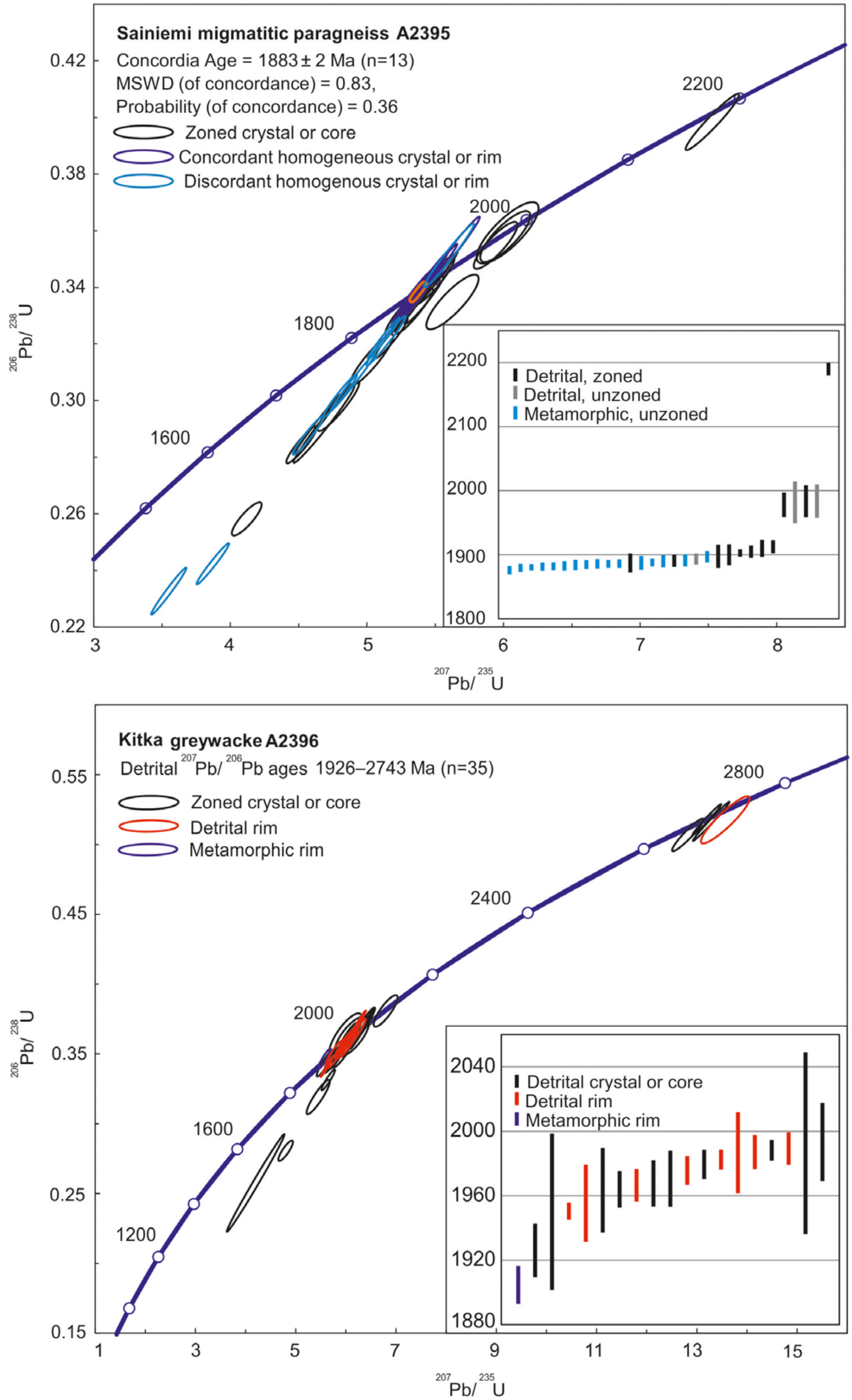

Fig. 9. Concordia diagrams for samples A2395 and A2396. In the insets, the distribution of $^{207}Pb/^{206}Pb$ ages of spots with a discordance of <5%. In A2395 concordia age calculated on basis of spots interpreted as metamorphic shown as orange ellipse. In A2396, only spots with $^{207}Pb/^{206}Pb$ ages younger than 2000 Ma are shown. All data are plotted at the 2σ confidence level.

4.3.3 A2450 Harjujärvensuo

Sample A2450 is from a conglomerate interbed in Tammijärvi greywackes. It was taken from a drilling profile intersecting the Harjujärvensuo Au mineralization (Fig. 2, Mikkola et al. 2018c). The sample represents a conglomerate type referred to as heterogeneous by Mikkola et al. (2018c). It is characterised by variably rounded pebbles up to 5 cm in size. The coarser pebbles are schist fragments and smaller ones are quartz grains or quartz aggregates. This type differs from the typical conglomerate interbeds of the Tammijärvi greywackes, in which the pebbles have on average a more felsic composition and uniform size distribution.

The zircon grains are variably rounded, most display magmatic zoning and some have homogeneous overgrowths. Out of the 51 analyses (Electronic Appendix), from an equal number of grains, most are concordant (Fig. 10). The spread of $^{207}Pb/^{206}Pb$ ages extends from 1905 to 3394 Ma and the population is strongly bimodal with peaks close to 2000 and 2700 Ma. The definition of the maximum depositional age for this sample also depends on the interpretation of the youngest obtained age (1905 ± 14 Ma). As this analysis has a high U concentration (893 ppm), we consider it as being affected by lead loss during metamorphism and regard 1.92 Ga defined by the remaining analysis (Fig. 10) as the best estimation for the maximum depositional age of this sample.

4.3.4 A2397 Lapaskangas

Sample A2397 (Lapaskangas) represents the weakly migmatized greywackes (Fig. 3C) found from a small area near Kangasniemi village (Fig. 2). The outcrop has abundant calc-silicate concretions. The migmatization of this greywacke type clearly differs from the intensive veining displayed by the more common paragneiss type in the area represented in this study by sample A2395 (Fig. 3A). In the case

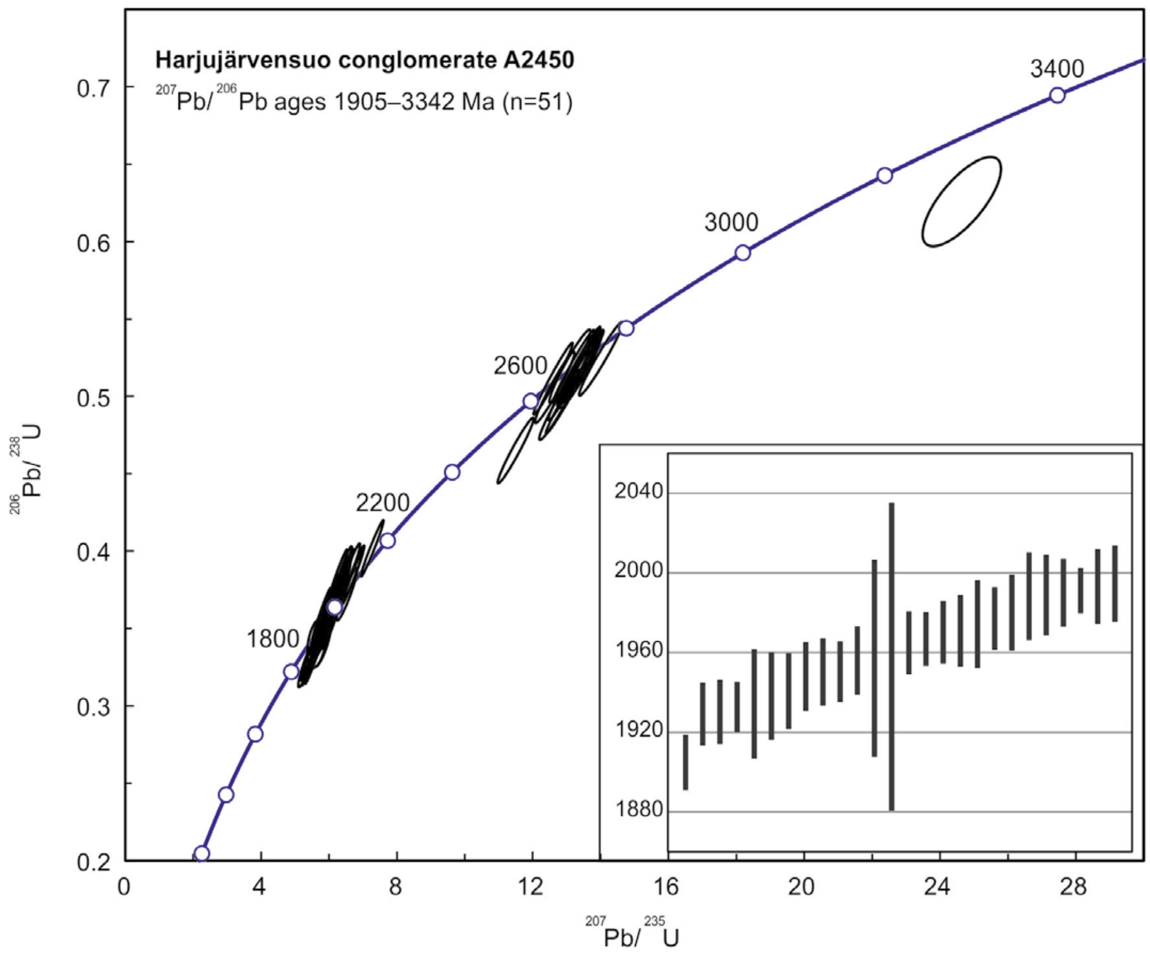

Fig. 10. Concordia diagram of sample A2450. In the inset, the distribution of $^{207}Pb/^{206}Pb$ ages of spots younger than 2000 Ma and with a discordance of <5%. All data are plotted at the 2σ confidence level.

of sample A2397, the migmatization is most likely caused by contact metamorphism related to a large gabbro intrusion in the vicinity of the sample site. Nearly all of the zircons show oscillatory zoning. Two types of rims exist: wider darker coloured and narrower bright ones (Fig. 8). The latter are always too narrow for analysis, as also are most of the former.

Out of the 28 analysed spots from 25 zircons (Electronic Appendix), 22 yielded Paleoproterozoic ages ($^{207}Pb/^{206}Pb$ = 1900–2215 Ma, Fig. 11). The remaining six spots are Archean with $^{207}Pb/^{206}Pb$ ages from 2550 to 2807 Ma. Most of the analyses are concordant. The analysed dark wider rims are interpreted to indicate predepositional metamorphic events, as one yields a $^{207}Pb/^{206}Pb$ age of 2083 Ma and the other one 2807 Ma. The narrow bright rims are interpreted as metamorphic. The youngest age (n5442-13; 1900 ± 22 Ma) is from a morphologically atypical crystal with a low Th/U ratio of 0.03 typical for metamorphic zircons (Williams et al. 1996). Based on these two characteristics, its age is interpreted as metamorphic, therefore marking the minimum age of deposition for this sample. Thus, the maximum depositional age of this sample is ca. 1.92 Ga.

4.3.5 A2398 Uprinpuro

Sample A2398 (Uprinpuro) is an unmigmatized and weakly deformed greywacke from an outcrop with conglomerate interbeds (Fig. 3D). The <1 mm clasts are quartz crystals and aggregates. The zircon population of the sample mostly consists of oscillatory zoned grains (Fig. 8), some of which have dark coloured rims.

Out of the 38 analyses from 34 crystals (Electronic Appendix), two were discarded due to high common lead. Most of the spots are concordant and 23 yield Paleoproterozoic ages ($^{207}Pb/^{206}Pb$ =1903–2083 Ma, Fig. 11). The remaining 13 spots are mainly Neoarchean, but one grain (n5443-12) is Paleoarchean with a $^{207}Pb/^{206}Pb$ age close to 3600 Ma (Fig. 8). This grain also has an unzoned rim that yields a $^{207}Pb/^{206}Pb$ age of 3065 Ma (Fig. 10B). Two out of three spots yielding the youngest ages are from dark unzoned overgrowths and all three have low Th/U ratios typical for metamorphic zircons. Therefore, the ca. 1900 Ma ages given by these three analyses are interpreted as the metamorphic age and the minimum age of deposition for this sample. Based on the above, the best estimation for the maximum depositional age of this sample is ca. 1.91 Ga.

4.3.6 A2440 Loukee

Sample A2440 (Loukee) is outside our main study area (see Figure 1 for sample location). This sillimanite-biotite paragneiss sample (Fig. 4D) represents the Häme migmatite suite flanking the Pirkanmaa migmatite suite to the south and east (Fig. 1). The zircon population of the sample consists of crystals displaying oscillatory zoning, and core-rim structures are observable, but rims are too narrow for dating. Altogether, 25 spots from 19 grains were analysed (Electronic Appendix), and 22 of the spots are concordant (Fig. 12) and display $^{207}Pb/^{206}Pb$ ages from 3382 to 1880 Ma. Five of the grains yield Archean ages (2745–3382 Ma) and the rest are Paleoproterozoic (1880–2166 Ma). No correlation was observed between zircon size, morphology or the U/Th ratio and age. Although the nominal ages of three of the analysed spots are younger than 1900 Ma, their true ages might be over 1900 Ma when errors are taken into account at the 2σ level. Thus, we interpret ca. 1.90 Ga as the maximum depositional age of this sample.

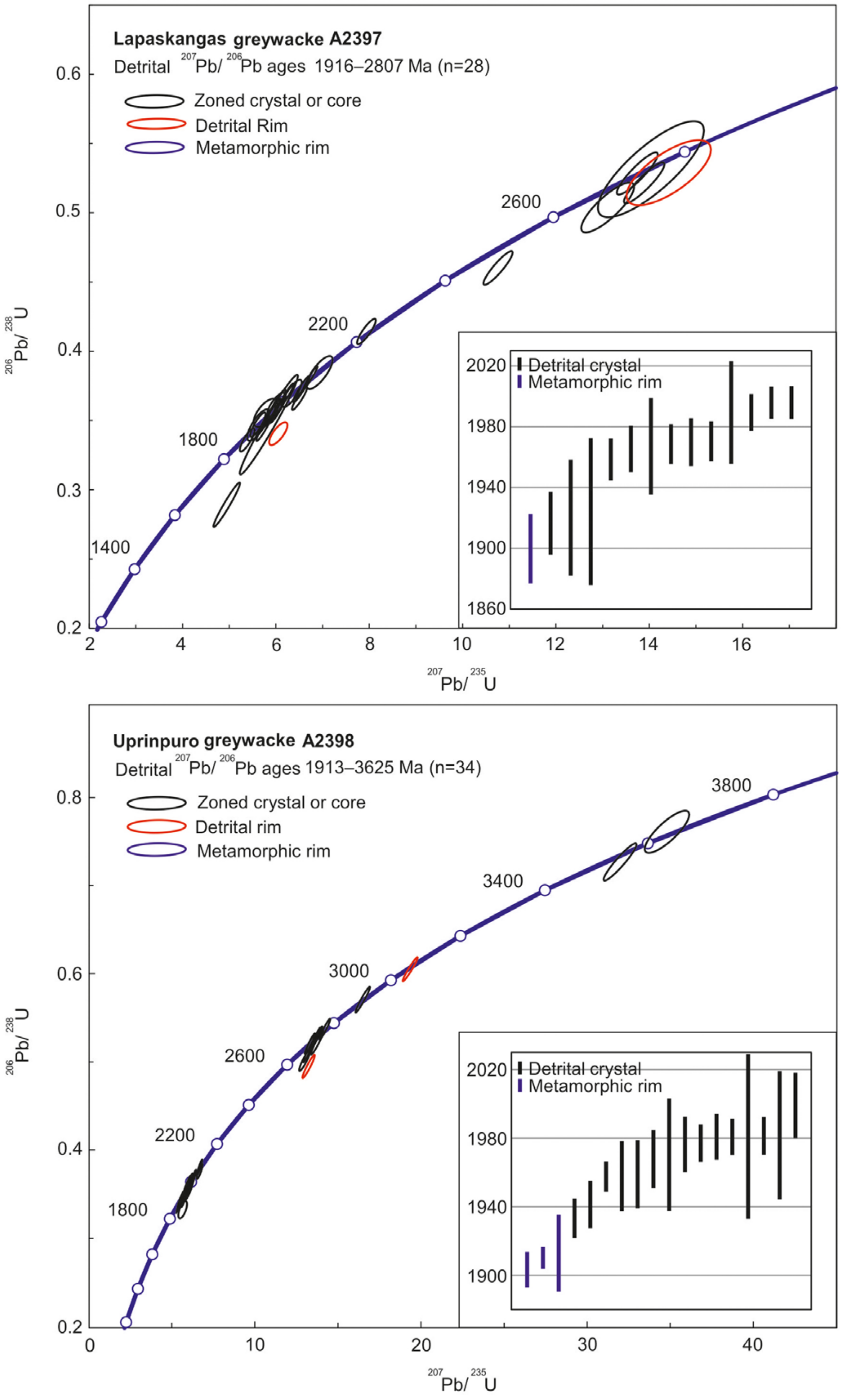

Fig. 11. Concordia diagrams of samples A2397 and A2398. In the insets, the distribution of $^{207}Pb/^{206}Pb$ ages of spots younger than 2000 Ma and with a discordance of <5%. All data are plotted at the 2σ confidence level.

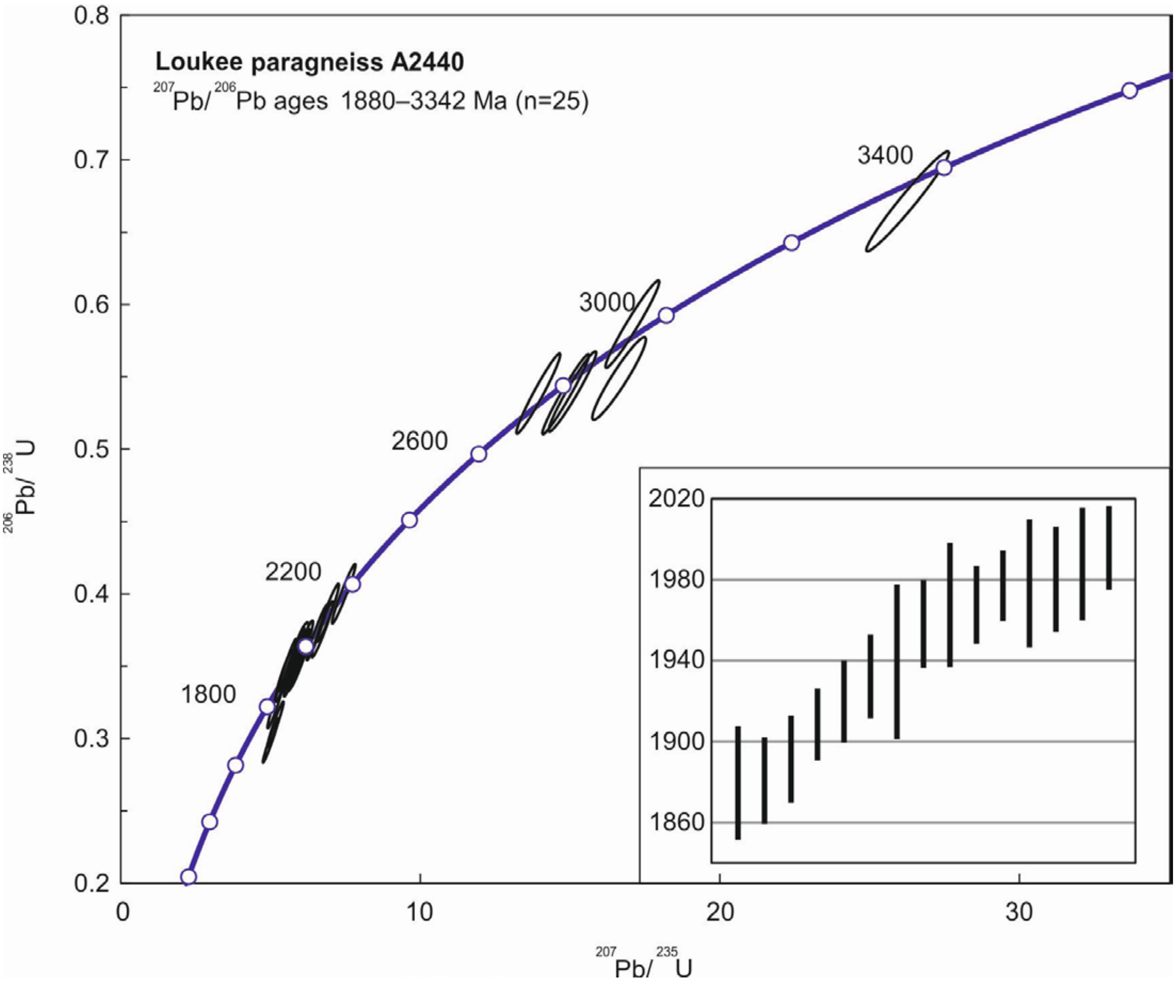

Fig. 12. Concordia diagram of sample A2440. In the insets, the distribution of $^{207}Pb/^{206}Pb$ ages of spots younger than 2000 Ma and with a discordance of <5%. All data are plotted at the 2σ confidence level.

4.3.7 A15 Vuotsinsuo

Metagreywacke sample A15 (Vuotsinsuo), belonging to the Häme migmatite suite, was described by Lahtinen et al. (2002), who published single-grain SIMS analyses of 19 spots representing 18 zircon grains. Out of these analyses, we discarded four based on high common lead and/or a high degree of discordancy. The new data published here consist of 47 analyses from 40 individual zircon grains (Electronic Appendix). Seven of the analyses are discarded due to high common lead. The remaining new analyses are concordant within error. The combined data set includes 12 Archean zircon grains with $^{207}Pb/^{206}Pb$ ages from 2662 to 2741 Ma. Out of the 45 Paleoproterozoic analyses from 38 crystals, 43 yield $^{207}Pb/^{206}Pb$ ages between 1917 and 2085 Ma and the remaining two analyses have $^{207}Pb/^{206}Pb$ ages of 2428 and 1889 Ma. Another analysis from the same morphological domain (Fig. 5 in Lahtinen et al. 2002) as the latter result yielded a $^{207}Pb/^{206}Pb$ age of 1917 Ma. Thus, the significance of this youngest observed age is not self-evident. We consider that the new data confirm the interpretation of Lahtinen et al. (2002), i.e. the phenomenon has either a natural (e.g. small inclusion, lead loss) or analytical cause, and the maximum depositional age of this sample is determined by the bulk of the analyses as ca. 1.92 Ga (Fig. 13).

4.3.8 A1557 Jyrkkäaho

Metapsammite sample A1557 (Jyrkkäaho), belonging to the Häme migmatite suite, was described by Lahtinen et al. (2002). Their dataset included 22 analyses from 20 individual zircon crystals, out of which seven were discarded based on high common lead and/or a high degree of discordancy. We analysed an additional 44 spots from 40 zircon grains (Electronic Appendix), all analyses are concordant

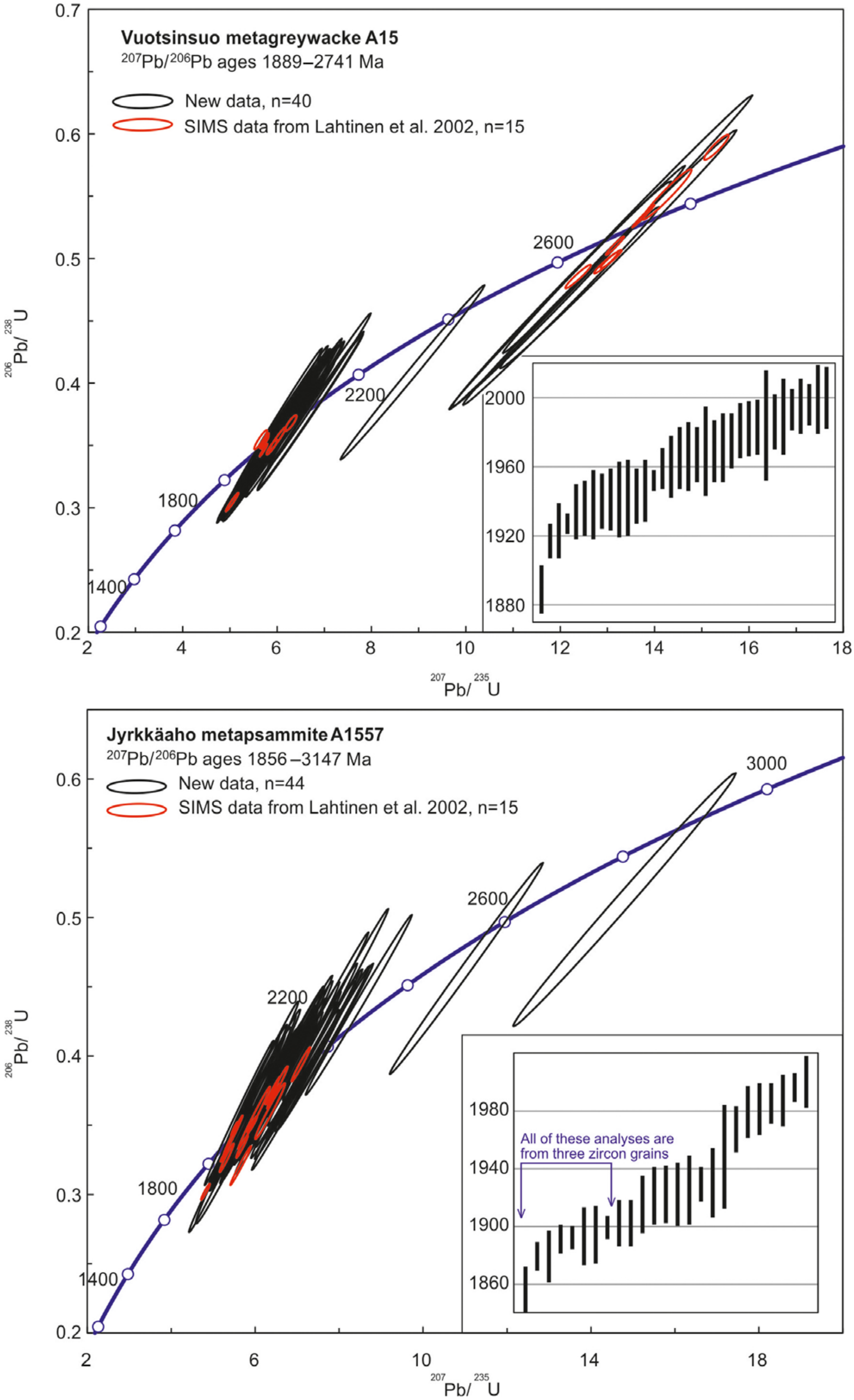

Fig. 13. Concordia diagrams for samples A15 and A1557. In the insets, the distribution of $^{207}Pb/^{206}Pb$ ages of spots younger than 2000 Ma and with a discordance of <5%. Note that the analysis from A1557 yielding a $^{207}Pb/^{206}Pb$ age of 3147 ± 10 Ma plots outside the diagram.

within error. As some of our analyses were carried out on the same zircon grains as the SIMS analyses of Lahtinen et al (2002), the 59 spots represent 43 different crystals. The data set includes only three Archean zircon crystals with $^{207}Pb/^{206}Pb$ ages of 3.15 Ga, 2.90 Ga and 2.58 Ga. The 40 Paleoproterozoic zircons yielded $^{207}Pb/^{206}Pb$ ages from 1856 to 2234 Ma, the majority being in the range 1915–2150 Ma (Fig. 13). Common lead ratios of the two youngest zircon grains are similar to the others and all of them have relatively high U concentrations (>350 ppm in LAMS data), although similar U levels are also present in a small number of analyses yielding older ages. Nevertheless, it is possible that the zircons with higher than average U concentrations have been more prone to post-crystallisation lead loss, resulting in ages younger than the original crystallisation. However definitive conclusions cannot be made, but based on the larger dataset we regard ca. 1.90 Ga as the best estimation for the maximum depositional age of this sample is, i.e. slightly older than the 1.89 Ga proposed earlier by Lahtinen et al. (2002).

5 DISCUSSION

5.1 Composition

All of the analysed samples represent relatively immature metasedimentary rocks, which can be compositionally classified as greywackes and lithic arenites. Based on the preserved graded bedding structures, unsorted textures and conglomerate interbeds, they originated as turbidites (Fig. 3B, D). In this sense, they do not differ from the typical paragneisses of southern and central Finland (e.g. Lahtinen et al. 2002, 2009, 2017, Kotilainen 2016). The different units present in the study area cannot be separated from each other on a compositional basis, and the current division is thus based on their spatial distribution and certain differences in associated rock types and primary structures between the subareas. Further refinement of the units would require detailed isotope studies. The observed LREE enrichment indicates derivation from a relatively felsic source, but does not allow discrimination between, for example, the felsic to intermediate volcanic rocks and granitoids.

The large compositional scatter in our samples from the Pirkanmaa migmatites compared to those of Lahtinen et al. (2009) has several possible explanations. These include the type of the study areas; the samples of this study originate from several small subareas scattered between plutonic rocks, whereas the samples of Lahtinen et al. (2009) represent a single, relatively connected geological domain. However, as even closely spaced samples from our area display significant mutual differences, this is not the sole reason behind the differences. Variation in the degree of migmatization and also the sampling methodology has effects; our samples are on average more strongly migmatized than those of Lahtinen et al. (2009), and as a consequence of this, our samples inevitably contain neosome in varying proportions. The on average lower SiO_2 contents of our samples could partly be an artefact of the segregation of silica-rich melt during anatexis, which would lower the SiO_2 contents of the residue. Overall, the large scatter cannot be explained by sampling alone; it seems to reflect the heterogeneity of the material in the original sedimentary basin(s).

Lahtinen et al. (2009) recognized from the Tampere area a separate fore-arc sedimentary unit that deviated from the other Pirkanmaa paragneisses in both geochemistry (high Sr) and the detrital zircon population. The samples most enriched in Sr from our study area all come from four subareas, but material from one of these areas, Viidansuo, includes only Sr-enriched samples. As no age data are available from the Viidansuo location and it does not differ significantly in texture or structure from other samples of the Pirkanmaa paragneisses, we do not interpret it to represent a separate geological unit.

Out of the described units, the Mäyräsalo paraschists show deviation to lower Al_2O_3 associated with higher MgO and CaO concentrations. This probably reflects proximity to active basic volcanism at the time of deposition, resulting in compositional variation in the sediments deposited during the active eruption phase and between such phases. A number of Pirkanmaa paragneiss samples also show similar compositional deviation to the Mäyräsalo paraschists and possibly reflect proximity to active volcanism during deposition. The Toivakanlehto paraschist, the other sedimentary unit associated with the Makkola suite, differs in this sense from the Mäyräsalo paraschists, as all samples plot on the same trend with respect to Al_2O_3 and MgO. Instead, some of the samples are enriched in Sr (<1135 ppm, Fig. 6A) and CaO (<11.8%), most likely due to the simultaneous deposition of calc and siliciclastic material.

5.2 Geological unit divisions

5.2.1 Pirkanmaa migmatite suite

At the beginning of this study, the hypothesis was that the three age samples representing the well-preserved Tammijärvi and Rusalansuo greywackes would display maximum depositional ages similar to, or younger than, the active volcanic phase of the Makkola suite (i.e. 1895–1875 Ma, Mikkola et al. 2018b). This would have correlated them with the same phase as the Haukivuori conglomerate or the Lampaanjärvi suite further north (Fig. 1), both of which have maximum depositional ages of ca. 1885 Ma (Korsman et al. 1988, Lahtinen et al. 2015). This would have been in line with the early interpretation of Karppanen (1970), who regarded the Tammijärvi greywackes as an eastern extension of the upper sediments of the Tampere group. This hypothesis was made even more attractive, as it has been confirmed, based on age and geochemistry, that the Makkola suite represents the same magmatic phase as the volcanic rocks of the Tampere group (Mikkola et al. 2018b).

However, contrary to our hypothesis, unmigmatized samples A2396 and A2450 from Tammijärvi displayed similar detrital zircon patterns to the variably migmatized paragneisses surrounding the CFGC (Huhma et al. 1991, Lahtinen et al. 2009, Kotilainen et al. 2016), with a maximum depositional age of ca. 1.92 Ga and a bimodal distribution with peaks at 2.0 and 2.7 Ga. The Myllyniemi formation, the lowermost unit of the Tampere group, also has a similar zircon population and maximum depositional age. Based on these characteristics, the Tammijärvi lithodeme could be correlated with the Myllyniemi formation. However, mainly based on the following two points, we regard the Tammijärvi lithodeme to be part of the Pirkanmaa migmatite suite. The contact between the Makkola suite and the Tammijärvi lithodeme is formed by the Leivonmäki shear zone (Mikkola et al. 2018a), and is not sedimentary, as in Tampere (Kähkönen 2005). The contact between the migmatized members of the Pirkanmaa migmatite suite and the Tammijärvi lithodeme is gradual and interpreted to be a result of a differing metamorphic grade.

The samples (A2397, A2398) from the Rusalansuo lithodeme also have maximum depositional ages close to 1.92 Ga and display bimodal detrital zircon populations, closely resembling that of the sample A2396 from Tammijärvi (Fig. 14). A curiosity worth pointing out is the ca. 3.6 Ga zircon core from sample A2398, which is the oldest zircon dated so far from the Svecofennian domain, the second oldest being a 3.5 Ga grain from the Bothnian Belt (Kotilainen et al. 2016). The contact between the Rusalansuo lithodeme and its surrounding units has been interpreted as tectonic based on an abrupt change in metamorphic degree. In their type area, Rusalansuo greywackes host interlayers of intermediate volcanic rocks of unknown age, which based on the zircon population of the greywackes cannot belong to the Makkola suite. In samples representing Tammijärvi and Rusalansuo greywackes, the timing of the metamorphic event is not self-evident, but all show weak indications of metamorphism and thus a minimum age of deposition of ca. 1.90 Ga. Similar hints of ~1.90 Ga metamorphism were also

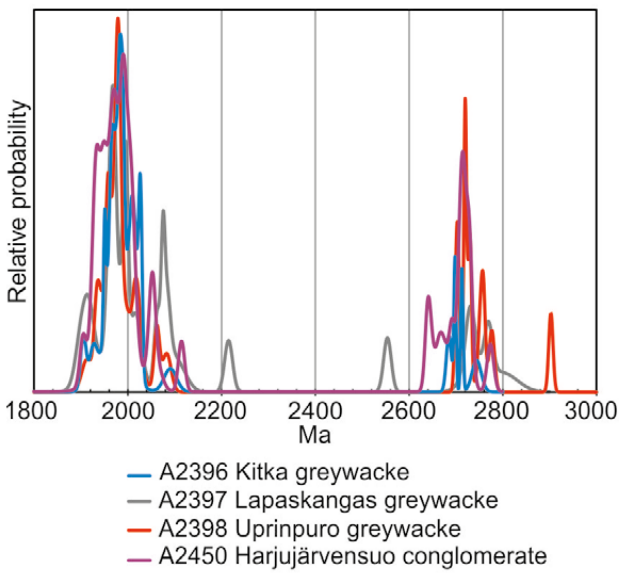

Fig. 14. Probability density plot of $^{207}Pb/^{206}Pb$ ages of spots with a discordance of <5% and interpreted as detrital from samples representing the Tammijärvi and Rusalansuo lithodemes. Note that analyses older than 3000 Ma from sample A2398 and A2450 are not shown.

recognized by Lahtinen et al. (2009) in their samples from near Tampere. The definitive minimum depositional age of these lithodemes is ca. 1885 Ma, as they are intruded by plutonic rocks of this age. Due to the similarities between the Tammijärvi and Rusalansuo lithodemes, we also regard the latter as part of the Pirkanmaa migmatite suite.

The migmatitic sample (A2395) differs from the unmigmatized samples with respect to the zircon population in two ways: the population does not include Archean zircons and youngest detrital zircons are ca. 1885 Ma in age, and thus 30–40 Ma younger than in the unmigmatized samples. The first difference is relatively undisputable, but the significance of the latter can be questioned. The ~1885 Ma ages obtained from zircons displaying magmatic zoning and inferred as detrital could be due to the high degree of metamorphism at that time, resulting in lead loss, resetting the U–Pb system to a younger age. This possibility seems likely, as the granitoids hosting the paragneiss sample are 1895 Ma in age (Kallio 1986, authors' unpublished data). However, if the ages are taken to represent the primary crystallization ages of the zircons, they indicate extremely fast burial to depths and temperatures required for anatexis. In the data of Lahtinen et al. (2009) from the Pirkanmaa migmatite suite further west, one sample contains zircons aged 1900–1890 Ma and was interpreted as representing a younger fore-arc sequence within the Pirkanmaa migmatite suite. The metamorphic age, ~1885 Ma, of sample A2395 is in line with metamorphic zircon ages (1885–1875 Ma, Lahtinen et al. 2009) reported earlier for the Pirkanmaa migmatite suite further west.

5.2.2 Häme migmatite suite

The three samples interpreted as part of the Häme migmatite suite (A15, A1557, A2440) and used in this study display differing detrital zircon populations. The maximum depositional age of sample A15 is the one that is best defined, 1.92 Ga. The other two could have marginally younger maximum depositional ages, i.e. 1.90 Ga, although this heavily depends on the significance that is given to the few youngest zircons. An interesting point is the lack of the peak of 2.7 Ga zircons in samples A1557 and A2440 (Fig. 15), shown by sample A15 and data from previously studied samples (Claesson et al. 1993, Lahtinen et al. 2002, Nironen & Mänttäri 2012). Nevertheless, both of these samples contain

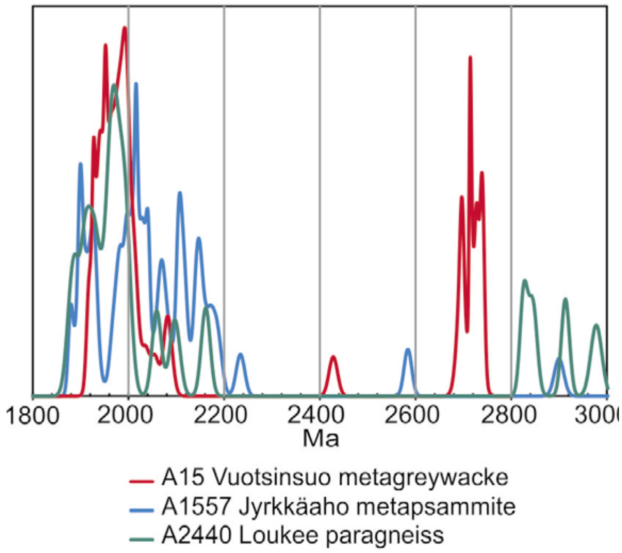

Fig. 15. Probability density plot of the $^{207}Pb/^{206}Pb$ ages of spots with a discordance of <5% and interpreted as detrital from samples representing the Häme migmatite suite. Note that analyses older than 3000 Ma from samples A1557 and A2440 are not shown. For grains with multiple analyses, only the median value was used for constructing the plot.

Archean zircons, but of differing ages and in smaller quantities. However, it should be noted that the amount of data from sample A2440 is too limited to draw definitive conclusions on its detrital zircon population. All three samples from the Häme migmatite suite display a peak in the zircon population close to 2.00 Ga, but some differences in the location of the peak can also be identified; A15 displays a sharp peak between 1.92 and 2.00 Ga, whereas A1557 has a broader distribution from 1.9 to 2.2 Ga (Fig.15).

5.2.3 Demarcation between the various suites

Despite differences between individual samples, all the metasedimentary units within our study area and its vicinity display similar detrital zircon patterns when examined at the unit level (Fig. 16), i.e. all of them contain Archean zircons peaking at ~2.7 Ga in addition to Paleoproterozoic ones peaking at ~2.0 Ga and spanning from 2.2 to 1.9 Ga. The nearly complete lack of grains with ages 2.5–2.2 Ga is also characteristic of all of the units, as noted in earlier studies (e.g. Huhma et al. 1991, Lahtinen et al. 2009, 2010, Kotilainen et al. 2016). The observed Neoarchean (~2.7 Ga) peak coincides with the late magmatic phase of the Karelia Province consisting of granitoids of differing compositions (e.g. Heilimo et al. 2011, Mikkola et al. 2011). The sources proposed so far for the detrital zircons with ages from 2.05 Ga to 1.95 Ga include the Lapland–Kola orogeny (Lahtinen et al. 2010) and the Keitele microcontinent (Lahtinen et al. 2009), which would have amalgamated with the Karelia Craton at 1.92 Ga. Another possibility could be the Central Russian Fold Belt in the east, which has also been proposed to contain rocks of this age (Samsonov et al. 2016).

The variation shown by individual samples representing the same suite (Figs. 14, 15) and on the other hand the close resemblance of the populations on the suite level (Fig. 16) warrants discussion of the existing geological division of the metasedimentary units in southern and central Finland. Lahtinen et al. (2017) suggested that the protoliths of the Häme and Pirkanmaa migmatite suites could have been deposited in the same basin. Based on our material from the northeastern parts of these units, this model also seems plausible; the age distribution of both suites is nearly identical. The differences individual samples display in the proportion of Archean and Paleoproterozoic zircon grains indicate that variation in the age spectrum of the source area(s) existed either spatially or over time. Lahtinen et al. (2017) additionally pointed out the close resemblance of the Myllyniemi formation of the Tampere group and the two migmatite suites. In our main study area, the Tammijärvi lithodeme is, with respect to the rock types present (Kähkönen 2005) and the zircon population (Fig. 15), identical to the Myllyniemi formation. However, it is interpreted as belonging to the Pirkanmaa migmatite suite instead of the Makkola suite, which is the equivalent of the volcanic formations of the Tampere group (Mikkola et al. 2018b). Thus, it seems that the current unit division in this respect reflects the late tectonic movements and differences in metamorphic degree and not differences in protoliths. Resolving these contradicting interpretations requires additional data from the little studied area between our study area and Tampere.

A likely source for the zircon grains with ages 1.93–1.91 Ga in the studied samples would be the older Svecofennian plutonic and volcanic rocks along the southwestern border of the Karelian Craton (e.g. Lahtinen & Huhma 1997, Vaasjoki et al. 2003, Kousa et al. 2018a), as proposed earlier, for example, by Lahtinen et al. (2002, 2009). An interesting phenomenon with respect to these 1.93–1.91 Ga zircons is their small proportion in the Pirkanmaa and Häme migmatite suites (Fig. 16). These suites, according to the proposed models (e.g. Lahtinen et al. 2017, Nironen 2017), were deposited after the collision of the older Svecofennian arc with the Archean Craton. Such a newly formed orogeny would seem like a bountiful source of detrital material, but the number of zircon crystals of this age is limited. Possible explanations for their unexpectedly small proportion could be paleotransportation in other directions or burial beneath older rocks during collision.

The Viinijärvi suite (Fig. 1), which was deposited before and deformed during the ~1.92 Ga collision (Lahtinen et al. 2010), shares several characteristics with both Pirkanmaa and Häme migmatite suites. All three were deposited as turbidites and host black schist interbeds, albeit in differing proportions. All three have similar zircon populations (Fig. 16) and all three host mafic to ultramafic volcanic sequences related to extensional phases: the Outokumpu ophiolite assemblage in the Viinijärvi suite (Peltonen 2005) and the volcanic rocks with EMORB and picrite affinity in the migmatite suites (Lahtinen et al. 2017, Kousa et al. 2018b). Lahtinen et al. (2009) explained the similarities in geochemistry and detrital zircon populations shown by the Pirkanmaa migmatite suite and the Viinijärvi suite by suggesting that the latter formed a major source area for the former. This interpretation could be correct, but makes reliable separation of these units lacking distinctive characteristics in an intensively deformed area, like the one from where samples A15 and A1557 were taken, difficult, if not impossible. Thus, it is in our opinion possible that the current demarcation between Viinijärvi and the Pirkanmaa and Häme migmatite suites could reflect late deformation phases instead of differences in the time and place of deposition. However, further evaluation of this idea would require additional work, including detrital zircon samples from the paragneisses of the Savo supersuite. This unit extends as a narrow band along the southwestern boundary of the Viinijärvi suite in the current interpretations (Fig. 1), but all available age data from it are north of Kuopio. This lack of data from areas relevant to this study is the reason why we have excluded this unit from discussion.

The lack of detrital zircons with ages similar to the ages of the volcanic rocks of the Makkola suite and the Tampere group (1895–1875 Ma; Kähkönen & Huhma 2012, Mikkola et al. 2018b) either requires that the studied metasedimentary units were deposited before the volcanic activity in the area, or that in such a location these volcanic rocks were not in their source area. The latter explanation would require late tectonic transportation to their current position, which would mean the complete dismissal of the models previously proposed (e.g. Lahtinen et al. 2017, Nironen 2017 and references therein). Smaller scale tectonic movements are the most likely explanation for the subareas with a lower metamorphic degree but sharing a common origin. The well-preserved rocks of the Tammijärvi and Rusalansuo lithodemes were juxtaposed by vertical movements in the late stages of the Svecofennian evolution with their counterparts that had been metamorphosed to a higher degree.

Evidence for rocks belonging to the younger Svecofennian sedimentation phase (1.88–1.83 Ga; Korsman et al. 1988, Bergman et al. 2008, Nironen & Mänttäri 2012, Lahtinen et al. 2015) known from a number of locations in southern and central Finland was not found from our main study area. Their existence cannot be completely ruled out due to locally extensive Quaternary coverage, but their presence seems unlikely.

The significance of the presented data for the overall geological development and structure of the study area and its surroundings is further discussed in the article of Mikkola et al. (2018a).

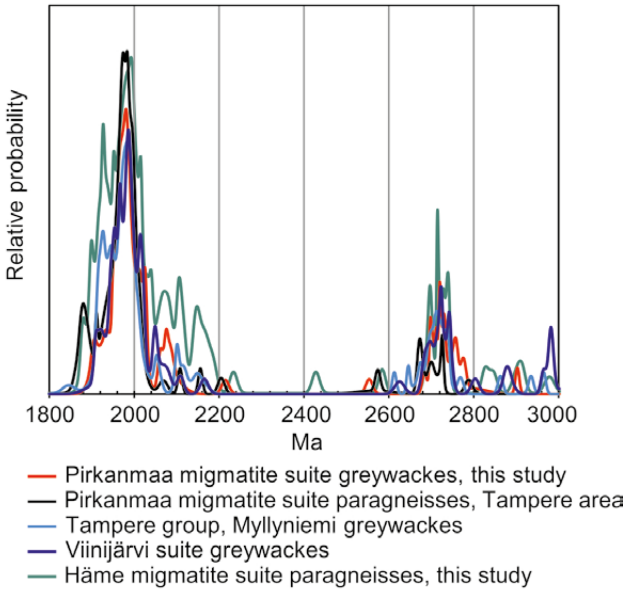

Fig. 16. Comparison of detrital zircon populations from the unmigmatized greywackes of the study area, samples representing the eastern end of the Häme migmatite suite, the Pirkanmaa migmatite suite in the Tampere area, Myllyniemi greywackes of the Tampere group and Viinijärvi suite greywackes. Data for the last three are from Lahtinen et al. (2009, 2010).

6 CONCLUSIONS

Metasedimentary units on the southeastern flank of Central Finland Granitoid Complex were deposited as turbidites before the onset of the main phase of volcanic activity in the area.

The maximum depositional ages of the studied metasedimentary samples vary between 1.92 and 1.90 Ga. In the majority of the samples, detrital zircon populations display age distribution patterns with Neoarchean (~2.7 Ga) and Paleoproterozoic (2.00–1.92 Ga) peaks. Thus, the populations are similar to the majority of the paragneiss samples from central and southern Finland.

Our data support the earlier presented idea that the Häme migmatite suite and Pirkanmaa migmatite suite were deposited in the same sedimentary basin. The material in the basin was heterogeneous, which is reflected in the large scatter in chemical composition of the analysed samples. The different stratigraphic units could not be distinguished on a geochemical basis.

The present unit division in southern and central Finland reflects the original differences in the depositional environment, but the boundaries result from tectonic movements. Thus, the current unit division should be re-evaluated on a tectonostratigraphic basis.

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