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ORIGINAL PAPER

The temporal variation of Mesoarchaean volcanism in the Suomussalmi greenstone belt, Karelia Province, Eastern Finland

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Abstract This study concentrates in the Kiannanniemi area, situated in the Archaean Suomussalmi greenstone belt, the Karelia Province, Fennoscandian Shield. A zircon U–Pb geochronological study from this area shows that ages of the volcanic rocks are between ca. 2.94 and 2.82 Ga. The results indicate multiphase felsic and intermediate volcanism in three episodes at ca. 2.94, 2.84 and 2.82 Ga, of which the 2.84 Ga event has not been reported earlier from the Suomussalmi greenstone belt. The youngest zircon population in a sedimentary rock sample suggests a depositional age of ≤2.82–2.81 Ga, and the sample contains also ≥2.96 Ga old zircon grains. Based on both new and previously published geochronological data from the volcanic rocks, we propose a chronostratigraphic model for the whole Suomussalmi greenstone belt, dividing it into four units based on their age: Luoma, Tormua, Ahvenlahti, and Mesa-aho. The youngest volcanic rocks in the Suomussalmi greenstone belt are contemporaneous with some of the volcanic rocks recorded from the Kuhmo and Tipasjärvi greenstone belts of the Karelia Province, Finland. The age group ca. 2.94 Ga, however, has not been so far recorded elsewhere. Conversely, in the Suomussalmi greenstone belt, volcanic rocks with an age of ca. 2.80 Ga and sedimentary rocks with depositional ages of <2.75 Ga, frequently found from the Kuhmo and Tipasjärvi greenstone belts, are unknown.

Keywords Absolute age · Archaean · Chronostratigraphy · Karelia Province · Greenstone belt · Suomussalmi · U–Pb

Introduction

Archaean greenstone belts are important pieces of the evolution of the Early Earth. U–Pb ages of originally volcanic and sedimentary rocks from the belts are widely used to constrain the evolution and formation of the earliest crust (e.g., Corfu et al. 1998; Huhma et al. 2012a; Zeh et al. 2013). Single grain analysis methods have proven to be very efficient ways of studying the volcanic rocks of the Archaean greenstone belts, especially for recognising inherited cores and metamorphic overgrowths, which are difficult to observe with bulk analysis methods.

The Karelia Province (hereafter Karelia) of the eastern part of the Fennoscandian Shield (Fig. 1) is characterised by several Meso- to Neoarchaean greenstone belts surrounded by tonalite–trondhjemite–granodiorite (TTG) rocks. The Suomussalmi greenstone belt (hereafter SGB) is the northernmost part of the Archaean Suomussalmi–Kuhmo–Tipasjärvi greenstone complex (hereafter SKT complex; Fig. 1), which is ca. 220 km long and in maximum 15 km wide. The general geochronology of the SKT complex is well-known (Huhma et al. 2012a and references therein); however, a detailed study of felsic and intermediate volcanic rocks of the Kuhmo and Tipasjärvi greenstone belts (Lehtonen et al. 2016; Lehtonen and Käpyaho 2016) shows more variable ages, ca. 2.84,

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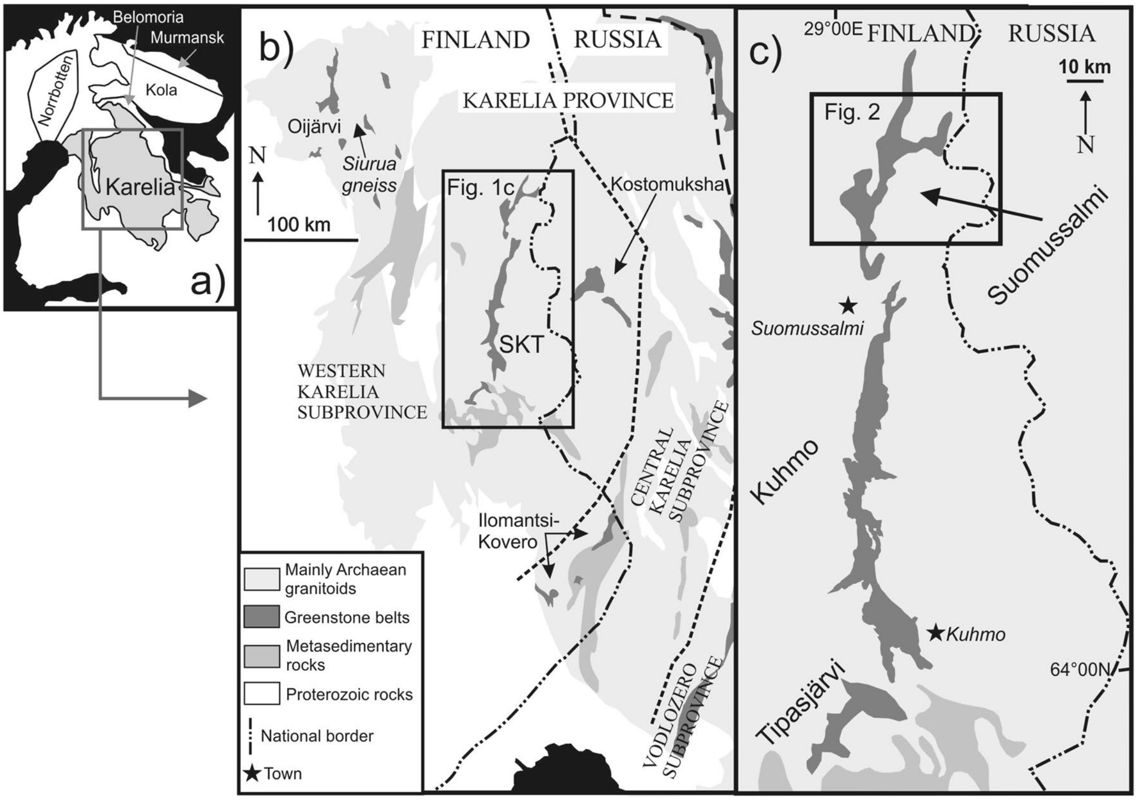


Fig. 1 **a** Geological division of the Fennoscandian Shield. Simplified maps of **b** the Karelian domain in Finland and western Russia and **c** the Suomussalmi–Kuhmo–Tipasjärvi greenstone belt. In Fig. 1b, Oijärvi = the Oijärvi greenstone belt, Ilomantsi–Kovero = the Ilomantsi–Kovero greenstone belt, Kostomuksha = the Kostomuksha greenstone belt, SKT = the Suomussalmi–Kuhmo–Tipasjärvi greenstone belt. The Suomussalmi belt is shown in detail in Fig. 2. Lithologies are simplified after Koistinen et al. (2001)

2.82, and 2.80 Ga. Compared to the Kuhmo and Tipasjärvi greenstone belts (hereafter KGB and TGB), much older volcanic rocks (ca. 2.94 Ga) from the SGB demonstrate clearly an older crustal component present in the area which makes it an interesting object of study (Huhma et al. 2012a; Vaasjoki et al. 1999). The contrasting nature between these belts is also supported by Sm–Nd data, which suggest that the KGB and the TGB consist of largely juvenile material whereas older crust was involved in the genesis of SGB (Huhma et al. 2012b). In addition to the SGB, the Mesoarchaean volcanic rocks with age of ≥2.94 Ga are found mainly only in the Vodlozero subprovince of the Karelia Province (Slabunov et al. 2006; Svetov and Svetova 2011; Arestova et al. 2015; Fig. 1b), and the oldest gneiss is ca. 3.5 Ga with inheritance up to 3.7 Ga (Lauri et al. 2011; Mutanen and Huhma 2003; Arestova et al. 2015). Based on the isotope patterns, the Palaeo- and Mesoarchaean crust of the Karelia Province might represent individual parts of crust evolution, but during Neoarchaean they might have been part of a larger cratonic system (Lauri et al. 2011).

U–Pb geochronological studies of supracrustal rocks from the Archaean greenstone belts are widely used to constrain the evolution of the belts. In this study we have used both secondary ion mass spectrometry (SIMS) and laser ablation multicollector inductively coupled plasma mass spectrometry (LA-MC-ICPMS) to constrain zircon ages of the supracrustal rocks from the SGB. We use both published and new geochronological data to propose a new chronostratigraphic interpretation for the whole SGB, as well as contribute to the discussion of tectonic evolution of the belt. The new data show that the SGB contains more temporal variation in the ages of the volcanic rocks than previously recorded.

Geological setting

Overview of the geology of the Archaean domain of Fennoscandia

The Fennoscandian Shield comprises mainly Archaean and Proterozoic rocks, forming one of the oldest parts of the Europe. The oldest rocks are found in the Archaean domain in the northeastern part of the Shield, which commonly is divided into five provinces: Kola, Belomoria, Karelia, Norrbotten and Murmansk (Gáal and Gorbatchev 1987; Slabunov et al. 2006; Hölttä et al. 2012, 2014; Fig. 1b). Narrow and elongated greenstone belts, surrounded by Archaean TTGs (Luukkonen 1991; Fig. 1) are characteristic for the Karelia, which is further divided into three subprovinces: Western Karelia, Central Karelia and Vodlozero (Slabunov et al. 2006; Hölttä et al. 2012; Fig. 1c). Multiple Archaean and Proterozoic (ca. 2.84–2.81, 2.72–2.60 and 1.9 Ga) metamorphic and deformation events have left overprints in the bedrock (Kontinen et al. 1992; Sorjonen-Ward and Luukkonen 2005; Käpyaho et al. 2007; Mänttäri and Hölttä 2002; Lauri et al. 2011; Mikkola et al. 2011a; Hölttä et al. 2000, 2014).

The volcanic rocks in the greenstone belts of the Karelia are typically younger than 3.0 Ga, but some rocks with an age of ca. 3.05 Ga are found from the Vodlozero subprovince, Russia (e.g., Hyppönen 1983; Luukkonen 1988; Vaasjoki et al. 1999; Svetov and Svetova 2011; Huhma et al. 2012a). In the Western Karelia subprovince, the felsic ca. 2.94 Ga volcanic rocks from the Suomussalmi belt are the oldest recorded supracrustal rocks, and those are contemporaneous with some migmatite palaeosomes around the KGB (Vaasjoki et al. 1999; Käpyaho et al. 2007; Mikkola et al. 2011a; Huhma et al. 2012a). The youngest volcanic rocks, ca. 2.75 Ga, have been dated from the Ilomantsi greenstone belt, part of the Central Karelia subprovince (Huhma et al. 2012a). Coeval volcanic and plutonic rocks are common in Karelia (Vaasjoki et al. 1999; Samsonov et al. 2005; Käpyaho et al. 2006; Mikkola et al. 2011a). Usually, the youngest volcanic rocks are postdated by TTG magmatism (ca. 2.75 Ga) and diverse plutonic magmatism at ca. 2.74–2.69 Ga (Heilimo et al. 2011; Mikkola et al. 2011a, b). Based on the ages from both volcanic and plutonic rocks, 2.80–2.79 Ga is considered to be a major crustal growth period in the Western Karelia subprovince (Hyppönen 1983; Vaasjoki et al. 1999; Bibikova et al. 2005; Lauri et al. 2011; Käpyaho et al. 2006, 2007; Huhma et al. 2012a; Lehtonen and Käpyaho 2016; Lehtonen et al. 2016).

In the Western Karelia subprovince, especially the rocks in the Suomussalmi area contain signs of older >3.0 Ga "protocrust" based on the Pb–Pb data, Sm–Nd model ages and inherited zircons in TTGs (Vaasjoki et al. 1999; Käpyaho et al. 2006; Huhma et al. 2012b; Mikkola et al. 2011a). Such older rocks are exposed only in a few places: the Siurua gneiss has an age of ca. 3.5 Ga (Fig. 1b; Mutanen and Huhma 2003) and a granulite in eastern Finland has a palaeosome with an age of ca. 3.2 Ga (Mänttäri and Hölttä 2002).

Suggestions for tectonic formation environment for the SKT complex have varied from a plume-related rift environment (Luukkonen 1991; Papunen et al. 2009) to a failed rift that was followed by formation of a subduction zone (Piirainen 1988). Maier et al. (2013) proposed that the komatiites in the SGB formed in a continental rift-related environment, whereas the komatiites in the KGB and TGB formed in an oceanic plateau type setting, based on their trace-element geochemistry.

Suomussalmi greenstone belt and adjacent igneous rocks

The volcanic lithologies in the SGB are variable, including felsic–intermediate–mafic–ultramafic volcanic rocks, pyroclastic calc-alkaline rocks, tholeiitic basalts with BIF (banded iron formation) interlayers, komatiites (mainly thin lava flows, but also cumulates), komatiitic basalts, Cr basalts and volcanogenic sedimentary rocks. The SGB is divided into three geographical areas: Kiannanniemi, Tormua and Luoma-Saarikylä (Fig. 2). The peak metamorphic grade in the eastern Luoma-Saarikylä and Tormua area is mainly in upper amphibolite facies and in the western Kiannanniemi area is low and middle amphibolite facies (Papunen et al. 2009).

Initially, the SGB was divided into two groups: the Luoma and the Saarikylä Groups (Piirainen 1988; Luukkonen et al. 2014). Lithostratigraphic and geochronological studies in the Luoma-Saarikylä area suggested that these supracrustal rocks form the oldest parts of the belt and were called the Luoma Formation (ca. 2.94 Ga, Fig. 3; Piirainen 1988; Vaasjoki et al. 1999; Papunen et al. 2009; Huhma et al. 2012a; Luukkonen et al. 2014). The Luoma Formation was suggested to comprise bimodal volcanic rocks and predate the major volcanic phase in the SGB (Papunen et al. 2009). The other volcanic rocks, previously part of the Saarikylä Group (Piirainen 1988), were divided into three Formations: Mesa-aho, Tervonen and Saarikylä (Fig. 3a; Papunen et al. 2009).

In the rock type stratigraphy by Huhma et al. (2012a), some of the previously analysed volcanic rock samples were re-analysed and new geochronological data were presented (Fig. 3b). This study confined the presence of volcanic rocks with ages of ca. 2.82 and 2.94 Ga in the Luoma-Saarikylä area and revealed that the most eastern part of the belt comprises also volcanic rocks with the ages of ca. 2.82 Ga, and a mafic rock with an age of ca. 2.87 Ga (Figs. 2, 3). The last phase in the evolution of the SGB was deposition of sedimentary and volcanogenic sedimentary material after attenuation of the last volcanic phase (Papunen et al. 2009). Age for these rocks was interpreted to be ca. 2.77 Ga (Papunen et al. 2009), but re-analysis of the zircon grains from a felsic volcanic rock (sample A1429) with the LA-MC-ICPMS method yielded an age of ca. 2.82 Ga (Fig. 3; Huhma et al. 2012a). Some sedimentary rocks are significantly younger (depositional age ≤2.75–2.70 Ga) in the Kuhmo and Tipasjärvi greenstone belts than the last volcanic stage (Huhma et al. 2012a;

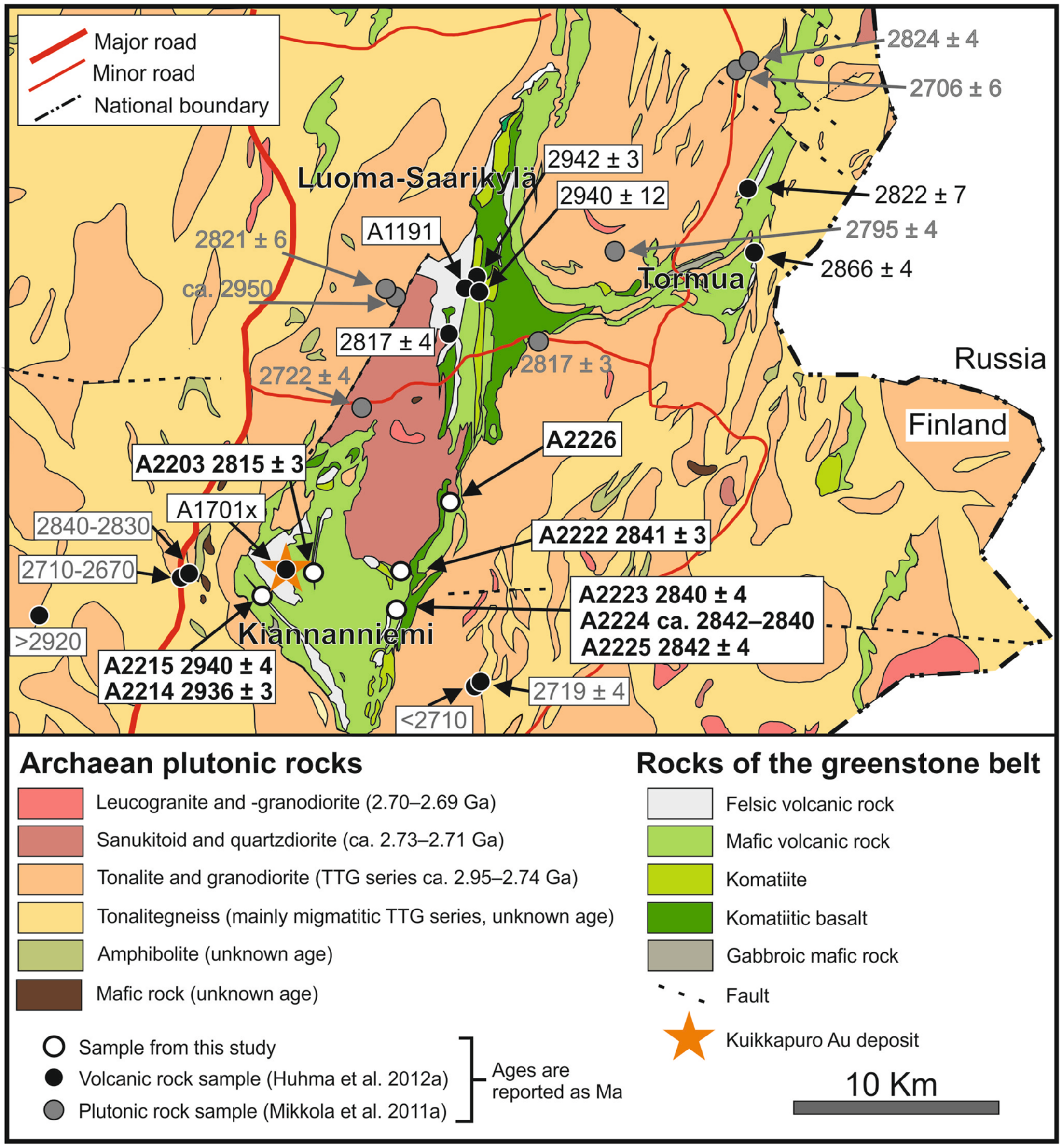
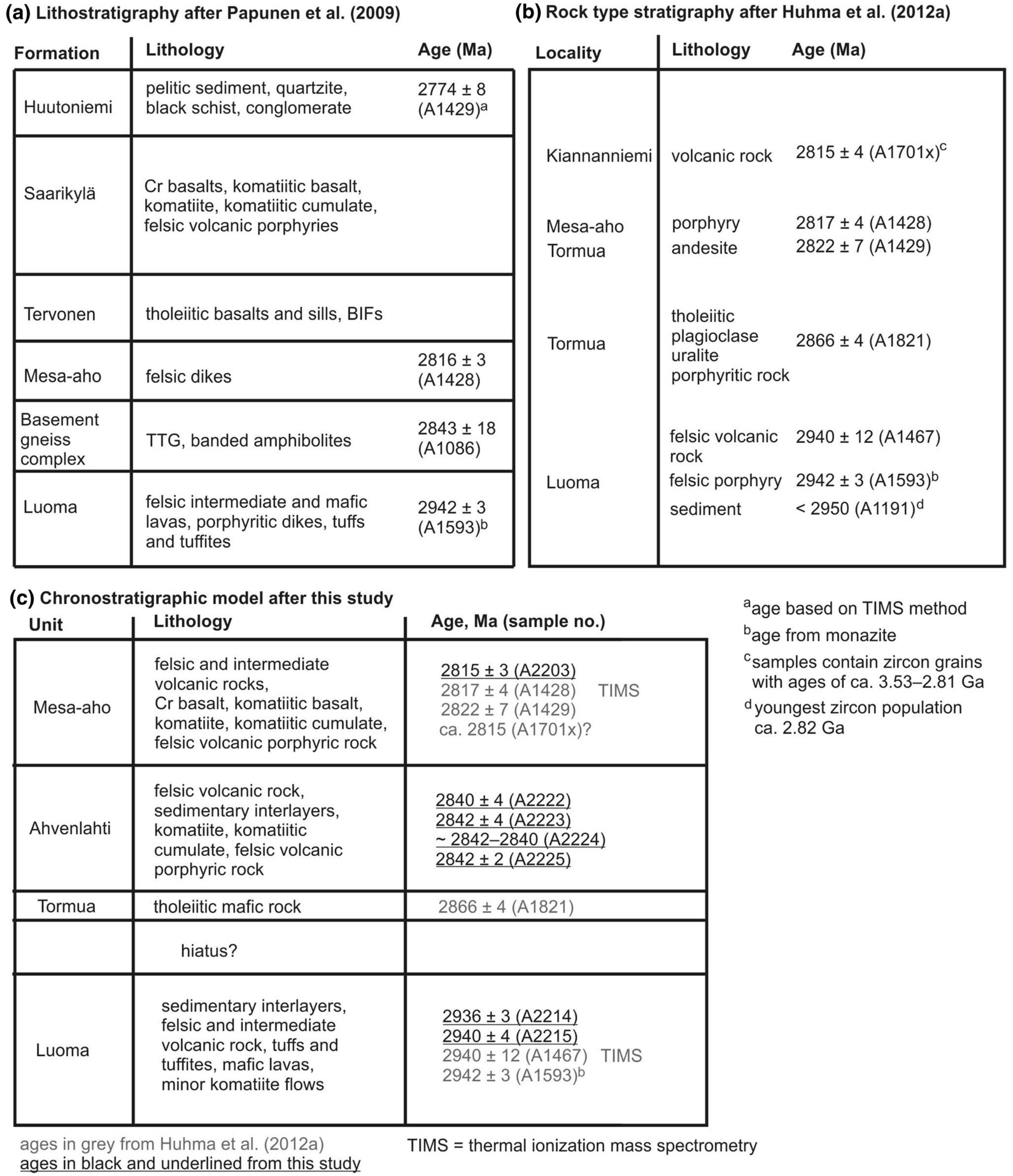


Fig. 2 Simplified geological map of the Suomussalmi area modified after Luukkonen and Sorjonen-Ward (1998) and Mikkola (2008). Sampling locations: (1) Hietaharju lapilli tuff (A2203); (2) Kumpula volcanic rocks (A2214 and A2215); (3) Ahvenlahti volcanic rocks (A2223 and A2225) and a volcanogenic sedimentary rock (A2224); (4) Huutoniemi dacite (A2222); (5) Keträvaara sedimentary rock (A2226). Data for samples from previous studies after Huhma et al. (2012a; volcanic rocks) and Mikkola et al. (2011a; plutonic rocks)

Lehtonen et al. 2016; Lehtonen and Käpyaho 2016), but so far these have not been found in the SGB.

Several high grade, but small size Au deposits occur in the Archaean greenstone belts in Finland. In this paper, we highlight the best studied Kuikkapuro Au deposit from the Kiannanniemi area (Fig. 2). The deposit is located in a shear zone between weakly altered mafic volcanic rock and more thoroughly altered garnet-biotite and biotite-rich rocks, and it has been interpreted to represent an orogenic gold deposit (Saarela 2003). Two dates have been defined from these garnet-biotite and biotite rocks under sample number A1701x, and the analyses yielded heterogeneous results (ca. 2.82, 2.85, 2.96, 3.53 Ga; Huhma et al. 2012a). We will return to discuss these samples in "Mesa-aho unit" section.

The SGB is surrounded by granitic and migmatitic rocks, which contain inheritance of >3.0 Ga older crust based on evidence from isotopic studies (Vaasjoki et al. 1999; Mikkola et al. 2011a). The dominant TTG magmatism in the



(a) Lithostratigraphy after Papunen et al. (2009)

Formation	Lithology	Age (Ma)
Huutoniemi	pelitic sediment, quartzite, black schist, conglomerate	2774 ± 8 (A1429)[a]
Saarikylä	Cr basalts, komatiitic basalt, komatiite, komatiitic cumulate, felsic volcanic porphyries	
Tervonen	tholeiitic basalts and sills, BIFs	
Mesa-aho	felsic dikes	2816 ± 3 (A1428)
Basement gneiss complex	TTG, banded amphibolites	2843 ± 18 (A1086)
Luoma	felsic intermediate and mafic lavas, porphyritic dikes, tuffs and tuffites	2942 ± 3 (A1593)[b]

(b) Rock type stratigraphy after Huhma et al. (2012a)

Locality	Lithology	Age (Ma)
Kiannanniemi	volcanic rock	2815 ± 4 (A1701x)[c]
Mesa-aho	porphyry	2817 ± 4 (A1428)
Tormua	andesite	2822 ± 7 (A1429)
Tormua	tholeiitic plagioclase uralite porphyritic rock	2866 ± 4 (A1821)
Luoma	felsic volcanic rock	2940 ± 12 (A1467)
	felsic porphyry	2942 ± 3 (A1593)[b]
	sediment	< 2950 (A1191)[d]

(c) Chronostratigraphic model after this study

Unit	Lithology	Age, Ma (sample no.)
Mesa-aho	felsic and intermediate volcanic rocks, Cr basalt, komatiitic basalt, komatiite, komatiitic cumulate, felsic volcanic porphyric rock	2815 ± 3 (A2203) 2817 ± 4 (A1428) TIMS 2822 ± 7 (A1429) ca. 2815 (A1701x)?
Ahvenlahti	felsic volcanic rock, sedimentary interlayers, komatiite, komatiitic cumulate, felsic volcanic porphyric rock	2840 ± 4 (A2222) 2842 ± 4 (A2223) ~ 2842–2840 (A2224) 2842 ± 2 (A2225)
Tormua	tholeiitic mafic rock	2866 ± 4 (A1821)
	hiatus?	
Luoma	sedimentary interlayers, felsic and intermediate volcanic rock, tuffs and tuffites, mafic lavas, minor komatiite flows	2936 ± 3 (A2214) 2940 ± 4 (A2215) 2940 ± 12 (A1467) TIMS 2942 ± 3 (A1593)[b]

[a] age based on TIMS method

[b] age from monazite

[c] samples contain zircon grains with ages of ca. 3.53–2.81 Ga

[d] youngest zircon population ca. 2.82 Ga

ages in grey from Huhma et al. (2012a)
ages in black and underlined from this study

TIMS = thermal ionization mass spectrometry

Fig. 3 Previous stratigraphic interpretations of the Suomussalmi greenstone belt by **a** Papunen et al. (2009) and **b** Huhma et al. (2012a). Andesite sample A1429 was re-analysed by Huhma et al. (2012a). **c** Suggested chronostratigraphic interpretation of the Suomussalmi greenstone belt by this study. Data from this study and Huhma et al. (2012a)

Suomussalmi area started ca. 2.95 Ga ago and continued more or less continuously to 2.74 Ga, contemporaneously with the volcanism. Negative initial epsilon-Nd values provide evidence that the area contained pre-existing crust at time of the TTG formation (Huhma et al. 2012b). During the Neoarchaean, ca. 2.72–2.70 Ga, the TTG magmatism changed to formation of minor sanukitoid and quartz diorite rocks containing elevated ratios of compatible and incompatible elements (Heilimo et al. 2010; Mikkola et al. 2011a). The last phase of granitoid magmatism was emplacement of heterogeneous leucocratic granodiorites and granites (Mikkola et al. 2011a).

Sampling and analytical methods

Sampling

This study concentrated on the Kiannanniemi area from where only one locality has been previously sampled (Fig. 2; A1701x). Most of the samples were collected from the drill cores due to poor outcrop conditions in the area. Sampling sites were chosen using previous mapping and drill logging information [e.g., unpublished drill core reports by Geological Survey of Finland and Outokumpu Oy, some of them freely available via the Geological Survey of Finland home page (http://hakku.gtk.fi)]. The collected volcanic rock samples are from felsic and intermediate volcanic rocks, in order to maximise the probability of gaining zircon grains for age analyses.

Altogether eight samples were studied of which six were from volcanic rocks, one from a volcanogenic sedimentary rock, and one from another sedimentary rock. The sample details, coordinates, main mineral assemblage, and drill core and field codes are provided in Table 1. The prefix ‘meta-’ is omitted for the sake of clarity, but all the samples have been metamorphosed at least once. The volcanic rock samples consist mainly of feldspars, quartz, biotite and muscovite. Common accessory minerals are opaque minerals, tourmaline and titanite. Most of the samples also contain small amounts of secondary minerals such as carbonate, epidote (clinozoisite), and chlorite. The fine-grained and layered Ahvenlahti volcanogenic sedimentary rock (A2224) was collected between two volcanic units (A2223, A2225). Sample A2224 was studied in order to resolve whether older material compared to adjacent volcanic rocks was available while the detritus was deposited. The Keträvaara sedimentary rock sample (A2226) is very fine-grained and layered rock.

The samples were sawn, washed, crushed and milled. The rock powders for the whole-rock geochemical analysis were ground with a carbon steel mill. The zircon grains were separated from the rock powders with a standard heavy liquid separation (methylene iodide 3.3 g/cm^3, Clerici® solution). The heavy fractions of the samples were run through a Franz Magnetic Separator between methylene iodide and Clerici® solutions. The individual zircon grains were hand-picked, mounted in epoxy resin and then polished to reveal the grain interiors. Analytical spot selection was done after backscattered electron (BSE) images of the zircon grains.

Analysis methods and data reduction

Laser ablation multicollector inductively coupled plasma mass spectrometry (LA-MC-ICPMS) and secondary ion mass spectrometry (SIMS) were used for U–Pb analyses, and the analysis method used is indicated with results. The results of age analyses are presented in Figs. 2, 5, Table 1, and Appendix 1 in Electronic supplementary material. For a comparison, the concordant data from samples A2223, A2224 and A2225, which represent same succession, are shown in Fig. 4. Volcanic rock samples A2223 and A2225 were analysed with SIMS and a volcanogenic sedimentary rock sample A2224 with LA-MC-ICPMS. The results of these two methods are comparable, although LA-MC-ICPMS error ellipses and error in ^{207}Pb/^{206}Pb age are mainly larger compared to most of the SIMS ellipses and ^{207}Pb/^{206}Pb age errors.

The Nu Plasma MC ICP-MS is located at the Geological Survey of Finland in Espoo. The applied technique is similar to that described in Rosa et al. (2009), except a Photon Machine Analyte G2 laser microprobe was used. Static ablation mode was used and the ablation gas in a HelEx ablation cell was He (gas flows = 0.4 and 0.11 l/min; Müller et al. 2009). Ar was mixed with gas flow (gas flow = 0.81 l/min) before passing the He aerosol into the plasma. Conditions for ablation were: beam diameter 20 µm, pulse frequency 5 Hz, and beam energy density 0.55 J/cm^2. At the beginning, end and regular intervals of each analytical session, calibration standards were run twice. Raw data were corrected using practices from Andersen et al. (2004) and Jackson et al. (2004). In-house standards A382 (1877 ± 2 Ma, Patchett and Kouvo 1986; Huhma et al. 2012a) and A1772 (2712 ± 1 Ma, Huhma et al. 2012a) and GJ-01 zircon grains (609 ± 1 Ma; Belousova et al. 2006) were used as calibration standards. The LA-MC-ICPMS analyses with central discordance <±10 are taken into consideration in this study, and at 2σ level these data points are concordant in concordia diagrams.

The Cameca IMS1280 ion microprobe is located at the Swedish Museum of Natural History, Stockholm (Nordsim facility). Detailed technical information is described in Whitehouse et al. (1999) and Whitehouse and Kamber (2005). The analyses were done using an O$_2$-primary beam with a spot size of ca. 20 µm, and secondary ions were

Table 1 Sample information

Sample	Rock type	Major minerals	Accessory minerals	Characteristics	Age (Ma)	Analyse Method	Latitude	Longitude	Drill core/ field code	Sample depth (m)	Comment
A2203 Hietaharju	Lapilli tuff	bt, plg, qtz, mus	*cb*, *ep*, *chl*	Schistosed, lineated fragments composed of biotite or plagioclase and quartz; muscovite porphyroblasts; fine-grained matrix	2815 ± 3	SIMS	65°8′54.461″	29°4′54.89″	ESL-12-002		
A2214 Kumpula 1	Dacite	qtz, plg, bt, mus	*ep*, *clz*, *cb*	Schistosed; fine-grained; banded based on the mineral composition a few euhedral garnet porphyroblasts (Ø = 0.5–1 mm)	2936 ± 3	LA-MC-ICPMS	65°8′23.245″	29°1′40.897″	M52.2/ 4511/95/304	55.56–57.40	
A2215 Kumpula 2	Dacite	bt, mus, qtz	*chl*, *ep*, tit, op	Schistosed; fine-grained; banded based on the mineral composition; a few subhedral garnet porphyroblasts	2940 ± 4	LA-MC-ICPMS	65°8′23.245″	29°1′40.897″	M52.2/ 4511/95/304	13.20–14.20	Duplicate sample for sample the age of the Kumpula volcanic unit
A2222 Huutoniemi	Dacite	plg, qtz	op, tit, *cb*, *ep*, *chl*	Grey; plagioclase and quartz porphyroclasts; very fine-grained felsic matrix	2841 ± 3	SIMS	65°8′57.671″	29°10′42.777″	M52.2/ 4513/95/R459	139.50–140.90	Upper contact with the volcanic rock is gradual
A2223 Ahvenlahti 1	Trachydacite	plg, kfs, qtz, bt	tor, op, *chl*	Grey; feldspar porphyroclasts; fine-grained matrix; opaque minerals are present as euhedral/subhedral grains and as a network surrounding other minerals	2840 ± 4	SIMS	65°7′56.537″	29°10′32.778″	M52.2/4513/96/ R480	69.35–71.30	Lower contact with the unit from where sample A2224 was collected is sharp, upper contact with a mafic volcanic rock is gradual
A2224 Ahvenlahti 3	Volcanogenic sedimentary rock	plg, kfs, qtz	tor, op	Grey; layered; graded bedding; very fine-grained; some of the layers are similar to the mineral assemblage of sample A2225	ca. 2842–2840	LA-MC-ICPMS	65°7′56.537″	29°10′ 32.778″	M52.2/4513/96/ R480	100.53–102.05	

Table 1 continued

Sample	Rock type	Major minerals	Accessory minerals	Characteristics	Age (Ma)	Analyse Method	Latitude	Longitude	Drill core/field code	Sample depth (m)	Comment
A2225 Ahvenlahti 2	Dacite	plg, kfs, qtz	mus, op, tor, tit, *cb*	Schistosed; fine-grained matrix; feldspar and quartz porphyroclasts	2842 ± 2	SIMS	65°7′56.537″	29°10′ 32.778″	M52.2/4513/96/R480	107.35–109.35	
A2226 Keträvaara	Sedimentary rock	qtz, bt, mus	op, tit, *chl*, *ep*	Schistosed; very fine-grained; muscovite filled pseudomorphs that might have been feldspar; cracks filled with epidote, biotite and quartz	<2810	LA-MC-ICPMS	65°10′53.351″	29°14′ 4.914″	M19/52/4513/-00/R719	16.35–18.80	

Coordinates are in the ETRS89 system

bt biotite, *cb* carbonate, *chl* chlorite, *clz* clinozoisite, *ep* epidote, *kfs* k-feldspar, *mus* muscovite, *op* opaque minerals, *plg* plagioclase, *qtz* quartz, *tit* titanite, *tor* tourmaline; italics denote secondary minerals

separated at a mass resolution ($M/\Delta M$) of 5400, which is sufficient to resolve Pb from molecular interferences, and measured in a low-noise ion-counting electron multiplier. For the Pb/U calibration, the Geostandards 91,500 zircon was used, assuming an age of 1065.5 ± 0.3 Ma at 1σ level (Wiedenbeck et al. 1995). A heterogeneity of ca. 15 % for the concentration of U has been reported, and this affects the calibrated elemental concentrations of the unknown but not inter-element ratios (Garbe-Schönberg and Arpe 1997). The data reduction was done using NordAge, which is a Nordsim-developed suite of software (M.J. Whitehouse, unpublished). Isoplot version 4.15 was used to plot the U–Pb isotopic data and calculate the ages (Ludwig 2012). The ages are given with 2σ or 95 % uncertainties in the text, tables, appendixes and figures, unless otherwise stated.

Whole-rock geochemistry of the samples was analysed by Labtium Oy (Labtium 2013). Major elements as well as some minor elements were analysed with a wavelength-dispersive X-ray fluorescence spectrometer (XRF) from powder pellets (method code 175X), and trace elements were analysed by ICP-MS from a solution (method code 307M). Precisions for both analysis methods are <5 % (Labtium 2013). The whole-rock geochemical data with detection limits are provided in Table 2 and were plotted on diagrams using GCDKit 3.00 (Janoušek et al. 2006).

Results

Sample descriptions and U–Pb results

Hietaharju intermediate lapilli tuff (A2203)

The Hietaharju intermediate lapilli tuff sample (A2203) contains zircon grains with length/width (l/w) ratio varying between 1.5 and 4.5, and length of 100–200 µm. Most of the grains show oscillatory zoning and some have metamict parts (Fig. 6a). A total of 15 zircon grains was analysed with SIMS, of which 12 are concordant at 2σ level yielding a calculated concordia age of 2815 ± 3 Ma (MSWD with concordance and equivalence = 1.18, probability = 0.25; Fig. 5a), which we conclude to be the best estimate for the magmatic age of sample A2203.

Kumpula dacite 1 (A2214)

The Kumpula dacite 1 sample (A2214) yielded a small amount of zircon grains that are euhedral, prismatic grains with l/w ratio of 1.7–5.5, and length varying from 100 to 200 µm. Most of the grains show weak magmatic oscillatory zoning (Fig. 6b). A total of 20 zircon domains from 18 zircon grains were analysed with LA-MC-ICPMS. From these 19 are concordant at

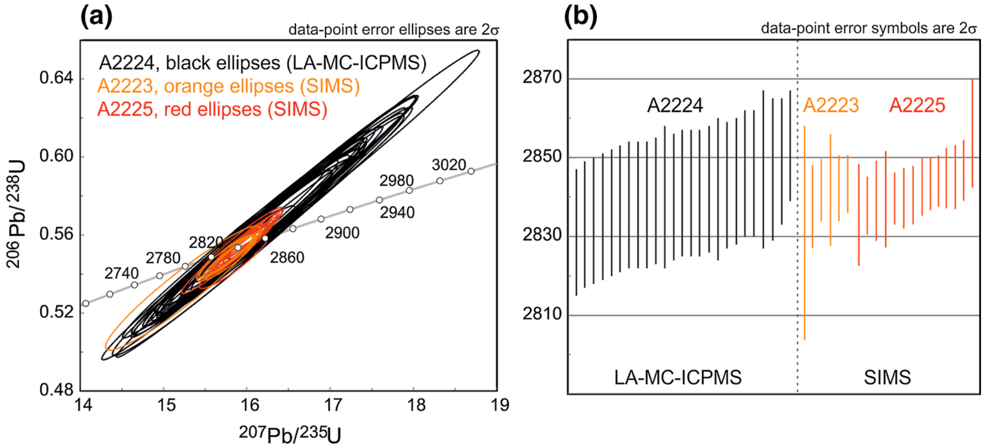


Fig. 4 Comparison of data from SIMS and LA-ICP-MS methods

2σ level and a concordia age of 2936 ± 3 Ma (MSWD with concordance and equivalence = 0.77, probability = 0.84; Fig. 5b) can be calculated. From two grains, both inner and outer domains of the grains were analysed, but no age differences were recorded. We interpret 2936 ± 3 Ma to represent the extrusion age of the volcanic rock.

Kumpula dacite 2 (A2215)

The sample separation of the Kumpula dacite 2 sample (A2215) yielded also only a small amount of zircon grains. The grains are euhedral prismatic with l/w ratio varying between 1.6 and 4.7, or occasionally roundish. Length of the grains varies from 50 µm to 200 µm. Most of the grains show weak oscillatory zoning and have metamict outer parts (Fig. 6c). From 23 zircon grains, a total of 26 zircon domains were analysed with LA-MC-ICPMS, and the data are concordant at 2σ level (Fig. 5c). Saved for 6 analyses, data are concordant at ca. 2940 Ma, and a concordia age of 2940 ± 4 Ma could be calculated from concordant data (MSWD with concordance and equivalence = 1.18, probability = 0.002; Fig. 5c). The zircon grains that yielded deviating Archaean ages (ca. 2.96 and 2.72 Ga) are small, roundish and do not show oscillatory zoning. Proterozoic ages (ca. 1.76 and 1.88 Ga) are from one euhedral prismatic grain, with no oscillatory zoning. We interpret the two younger Archaean ages to represent younger metamorphism and the Proterozoic ages might be due to Proterozoic overprint during Svecofennian orogeny at 1.9–1.8 Ga or to contamination during sample preparation. Therefore, we excluded these deviating ages from interpretation and conclude that based on the data 2940 ± 4 Ma is the best estimate for the magmatic age for the volcanic rock.

Huutoniemi dacite (A2222)

The Huutoniemi dacite sample (A2222) contains zircon grains that are mostly euhedral and prismatic, with l/w ratio of 1.9–4, length varying from 50 to 200 µm, mostly being ~100 µm, and showing oscillatory zoning (Fig. 6d). A total of 14 zircon grains was analysed with SIMS, of which nine are concordant at 2σ level. A concordia age of 2841 ± 3 Ma (MSWD with concordance and equivalence = 0.97, probability = 0.49; Fig. 5d). We conclude that the age of 2841 ± 3 Ma represents the age of the Huutoniemi dacite (A2222).

Ahvenlahti trachydacite (A2223)

The Ahvenlahti trachydacite sample (A2223) contains euhedral and prismatic zircon grains with l/w ratio varying from 1.6 to 3, and subhedral and roundish grains. Length of the grains varies from 50 µm to 150 µm, and the grains show oscillatory magmatic zoning (Fig. 6e). A total of 15 zircon grains was analysed with SIMS, of which 6 are concordant at 2σ level (Fig. 5e). A calculated concordia age is 2840 ± 4 Ma (MSWD with concordance and equivalence = 0.84, probability = 0.60), which we interpret to be a best estimate for the magmatic age of the volcanic rock.

Ahvenlahti dacite (A2225)

Most of the zircon grains of the Ahvenlahti dacite sample (A2225) are euhedral prismatic, 50–170 µm long, with l/w ratio of 1.6–3.6, and showing oscillatory zoning (Fig. 6f). The total of 15 zircon grains was dated with LA-MC-ICPMS, of which 14 are concordant. Using the concordant analyses, a concordia age of 2842 ± 2 Ma (MSWD with concordance and equivalence = 0.69, probability = 0.88;

Table 2 Whole-rock elemental analyses of the studied samples

	Volcanic rock, ca. 2.82	Volcanic rocks, ca. 2.84			Volcanic rocks, ca. 2.94 Ga		Volcanogenic sedimentary rock	Sedimentary rock
	A2203	A2222	A2223	A2224	A2214	A2215	A2224	A2226
wt%								
SiO_2	65.9	64.6	65.2	65.1	68.6	68.6	65.9	58.1
TiO_2	0.8	0.5	0.5	0.5	0.4	0.4	0.5	0.8
Al_2O_3	16.3	17.4	17.5	17.7	15.8	17.4	17.6	19.3
$Fe_2O_3^{tot}$	5.8	7.2	4.7	5.0	4.2	3.3	6.0	7.8
MnO	0.06	0.02	0.05	0.07	0.06	0.10	0.07	0.16
MgO	1.75	2.16	2.90	2.74	1.36	1.45	2.23	2.69
CaO	2.2	1.8	1.1	2.3	3.2	3.7	1.7	5.5
Na_2O	4.5	4.5	7.3	5.4	3.8	2.9	2.9	2.9
K_2O	2.2	1.4	0.5	0.8	2.2	1.9	2.5	1.7
P_2O_5	0.25	0.11	0.10	0.11	0.17	0.14	0.10	0.08
SUM (oxides)	99.7	99.7	99.8	99.6	99.9	99.9	99.5	99.0
Mg#	37.4	37.1	55.1	52.3	39.0	46.9	42.5	40.5
ppm								
La	46	13	10	20	30	16	12	12
Ce	77	25	20	38	57	33	24	26
Pr	9.2	2.9	2.4	4.4	6.3	3.7	2.7	3.1
Nd	31	12	10	16	24	13	10	12
Sm	5.0	2.2	2.2	3.0	4.4	2.7	1.9	2.7
Eu	1.43	0.48	0.85	0.97	1.3	1.08	0.73	0.95
Gd	4.9	2.0	2.1	2.7	4.6	2.8	2.0	3.2
Tb	0.67	0.24	0.29	0.33	0.63	0.42	0.28	0.48
Dy	3.54	1.17	1.47	1.54	3.03	2.08	1.48	2.80
Ho	0.72	0.23	0.30	0.29	0.62	0.41	0.30	0.58
Er	2.23	0.67	0.86	0.83	1.79	1.21	0.86	1.72
Tm	0.31	0.09	0.11	0.11	0.24	0.17	0.12	0.23
Lu	0.33	0.09	0.10	0.11	0.24	0.16	0.11	0.23
Y	19.3	5.5	7.4	6.9	16.6	10.6	7.5	14.0
Rb	76	30	16	23	104	60	52	56
Ba	1240	258	253	432	565	669	738	622
Zr	225	90	95	109	168	195	113	117
Th	13.6	3.3	3.0	4.2	8.4	6.0	5.2	5.2
U	2.7	1.4	1.3	1.6	2.1	1.5	1.8	1.9
Cu	15	1190	190	142	28	16	84	112
Co	16	23	21	25	16	16	36	59
Ni	22	22	27	37	26	27	71	247
Sc	8.6	5.5	5.5	7.7	8.8	6.1	9.6	32.4
V	107	83	81	96	69	57	99	242
Cr	*<15*	56	49	76	53	37	123	642
Li	23	29	27	34	72	37	31	44
Ti	5110	3060	3130	3670	3980	3070	3080	5750
Zn	60	162	94	171	112	114	186	208
$(La/Lu)_N$	14.5	15.1	10.3	18.5	13.0	10.3	11.3	5.5
Eu/Eu*	0.9	0.7	1.2	1.1	0.9	1.2	1.1	1.0

Italic font denotes the values of detection limit

Detection limits (wt%): SiO_2 (0.02), TiO_2 (0.005), Al_2O_3 (0.02), Fe_2O_3 (0.01), MnO (0.006), MgO (0.03), CaO (0.003), Na_2O (0.07), K_2O (0.004), P_2O_5 (0.006), S (0.006)

Detection limits (ppm): La (0.3), Ce (0.5), Pr (0.05), Nd (0.3), Sm (0.05), Eu (0.02), Gd (0.05), Tb (0.01), Dy (0.05), Y (0.05), Ho (0.01), Er (0.05), Tm (0.001), Lu (0.01), Rb (1), Ba (20), Zr (10), Th (0.1), U (0.05), Cu (5), Co (5), Ni (5), Sc (1), V (5), Cr (15), Li (10), Ti (50), Zn (50)

$(La/Lu)_N$ and Eu/Eu* calculated using normalising values from Taylor and McLennan (1985)

Fig. 5 Concordia and $^{207}Pb/^{206}Pb$ mean age diagrams of the samples: **a** A2203, **b** A2214, **c** A2215, **d** A2222, **e** A2223, **f** A2225, **g** A2224, **h**, **i** A2226. In the concordia diagrams, *grey ellipses* indicate discordant data or data omitted from the concordant age calculation, except for sample A2226 *grey ellipses* are rim ages with central discordance <±10 %. In relatively probability plot for A2226, all data was plotted and core-rim pars indicated with *grey bar*. MSWD and probability are reported with concordance and equivalence (c + e)

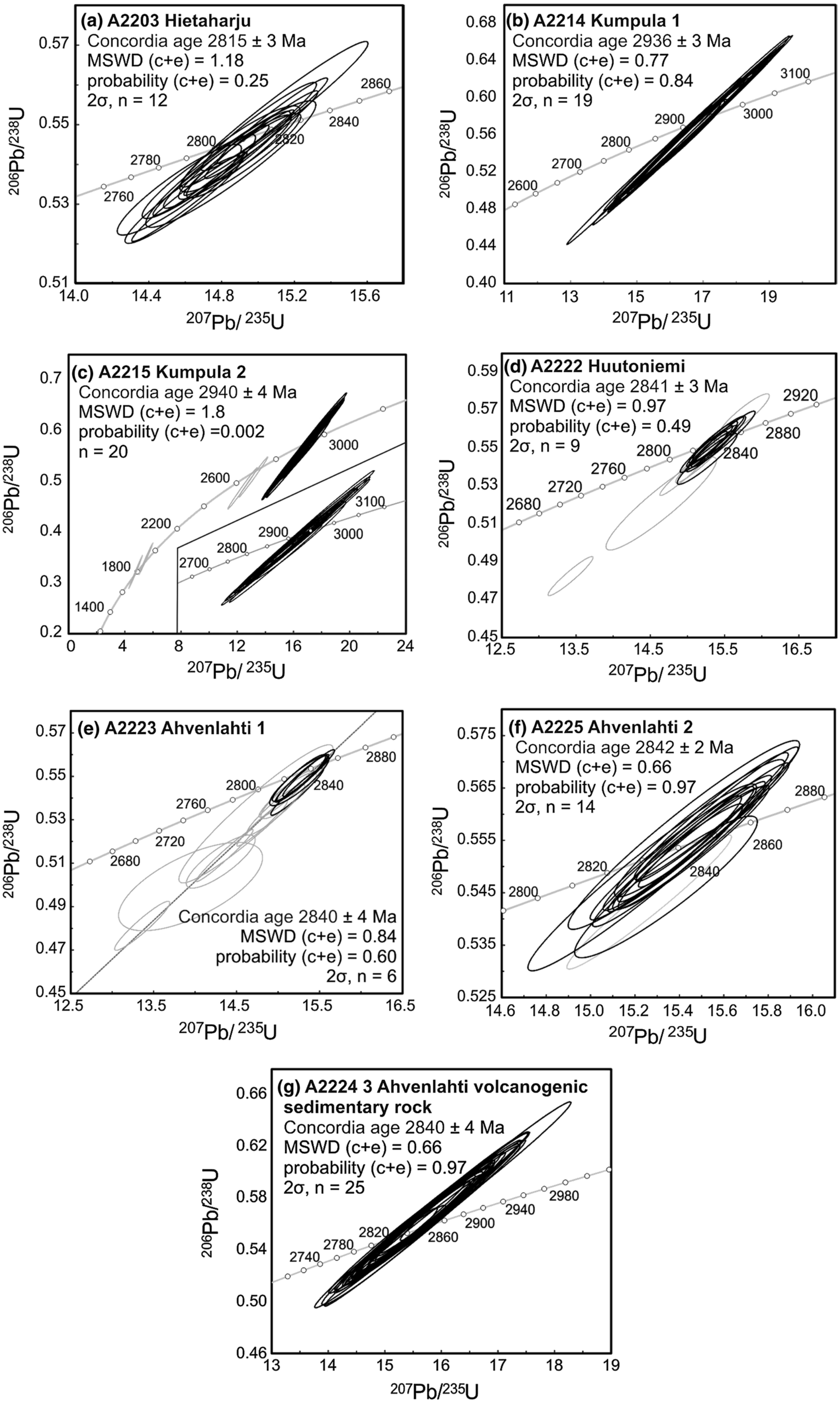


Fig. 5 continued

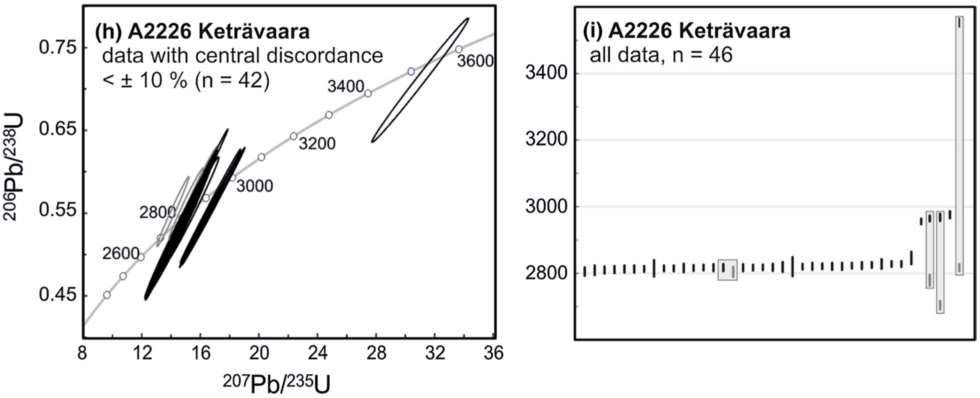


Fig. 6 BSE images from selected analysed zircon grains, ages shown as Ma

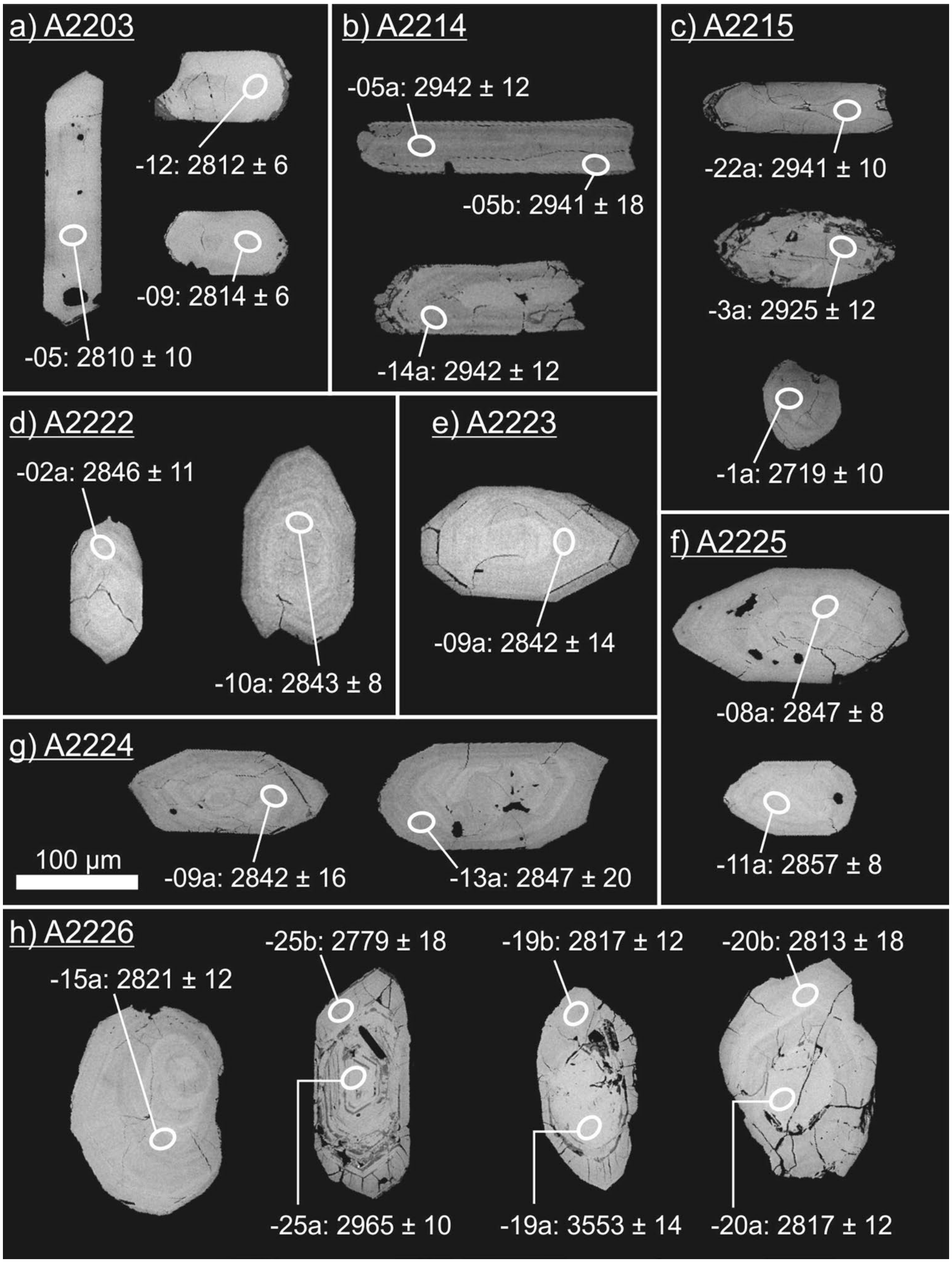


Fig. 5f) can be calculated, from we conclude that the age of 2842 ± 2 Ma is the age of the volcanic rock.

Ahvenlahti volcanogenic sedimentary rock (A2224)

The Ahvenlahti volcanogenic sedimentary rock (A2224) yielded a large amount of zircon grains. The zircon population is homogeneous based on the morphology. The zircons are mainly euhedral and prismatic with l/w ratios of 1.7–3.1, length varying from 50 to 180 µm, and showing oscillatory zoning (Fig. 6g). A total of 25 zircon grains was analysed with LA-MC-ICPMS, all being concordant at 2σ level (Fig. 5g). A concordia age of 2841 ± 3 Ma (MSWD with concordance and equivalence = 0.66, probability = 0.97). Based on comparison of the SIMS ages from samples A2223 (2842 ± 4 Ma) and A2225 (2842 ± 2 Ma) from the same drill core, we interpret that detritus of the volcanogenic sedimentary rock was deposited ca. 2.84 Ga between the two volcanic formations and do not contain detrital zircons from exotic sources.

Keträvaara sedimentary rock (A2226)

The Keträvaara sedimentary rock sample (A2226) yielded a large amount of zircon grains. Based on the BSE images the zircon population is heterogeneous and can be divided into (1) euhedral to subhedral grains with visible core and rim texture, (2) euhedral prismatic grains and roundish grains with weak oscillatory zoning, and (3) euhedral prismatic and subhedral roundish grains with cores showing no zonation with metamict rims (Fig. 6h). A total of 46 grain domains from 41 individual zircon grains were analysed with LA-MC-ICPMS, of which 42 analyses are concordant at 2σ level. From these analyses, 38 represent core or inner domains of the grains. The ages from the core/inner domains of the grains settles mainly into two groups: ca. 2.97 and ca. 2.84–2.81 Ga (Fig. 5h, i). The core of one grain yielded an age of 3553 ± 14 Ma. From two zircon grains with core ages of ca. 2.97 Ga, also rims were dated, yielding ages of 2704 ± 14 and 2779 ± 18 Ma. Based on the data, the maximum deposition age of the sediment is $\leq$2.82–2.81 Ga and the younger ages from grain rims might record later metamorphism after lithification of detritus, although precise minimum depositional age for this material is unknown.

Geochemistry

The whole-rock major and trace-element data for the studied 8 volcanic rock samples, volcanogenic sedimentary and sedimentary rock samples are presented in Table 2, and summary geochemical diagrams are presented in Fig. 7. All the samples represent thermally overprinted metamorphic rocks, and it is noted that mobility of some elements might have occurred.

All samples are compositionally relatively homogenous. The volcanic rocks are intermediate and acid (SiO2 = 58.1–68.6 wt%), showing mainly dacitic composition in TAS diagram, but one sample (A2223) displays trachydacite composition (Fig. 7a). The Mg# (Mg# = 100 × (MgO/40.31)/[(MgO/40.31) + (FeO^{tot}/79.85)] varies from 37 to 52. Analysed samples are compositionally calc-alkaline in the AFM diagram (Fig. 7b). The chondrite-normalised REE patterns (Fig. 7c–e) of the volcanic rocks are fractionated ($[La/Yb]_N$ = 10.2–18.5) with very weak positive or negative Eu anomaly (Eu/Eu* = 0.9–1.2). The REE patterns shapes are alike between different age groups.

Comparison of 2.84 Ga felsic and intermediate volcanic rocks of the SGB with the contemporaneous volcanic rocks from the KGB and TGB shows that LREE patterns are similar, apart from Eu, but HREEs of the 2.84 Ga SGB volcanic rocks are slightly lower compared to the KGB and TGB (Fig. 7d). Sample A2203 was compared with the 2.82 and 2.80 Ga volcanic rocks of the TGB. REE pattern of ca. 2.82 Ga rhyolitic rock from the TGB have different elemental compositions, but 2.80 Ga felsic and intermediate volcanic rocks of the TGB have similar compared to sample A2203 (Fig. 7e). The limited amount of geochemical data from the felsic and intermediate volcanic rocks do not give opportunity for more detailed comparison between different greenstone belts.

The volcanogenic sedimentary rock sample (A2224) and the sedimentary rock sample (A2226) have intermediate content of SiO_2 that is 58.1 and 65.9 wt% as well as alike Mg# (40 and 42). The samples have MgO content from 2.23 to 2.69 wt%, as well as LREE enrichment, with the (La/Lu)N ratio varying from 5.5 to 11.3. No significant Eu anomaly is seen (Fig. 7f). The REEs in the sedimentary samples are similar to the typical Archaean sedimentary REE patterns combined by McLennan and Taylor (1984; Fig. 7f), but sample A2224 shows slightly lower values for Dy–Tm. The HREE pattern of sample A2224 is similar with volcanic samples A2223 and A2225.

Discussion

Chronostratigraphic interpretation

Our study from the Kiannanniemi area supplements the previous observations from the SGB (Vaasjoki et al. 1999; Huhma et al. 2012a) and provides also new data about the age of the volcanism along the belt. Combined new and previously published geochronological data, as well as observations from the field and drill cores, allow us to suggest a chronostratigraphic interpretation for the whole

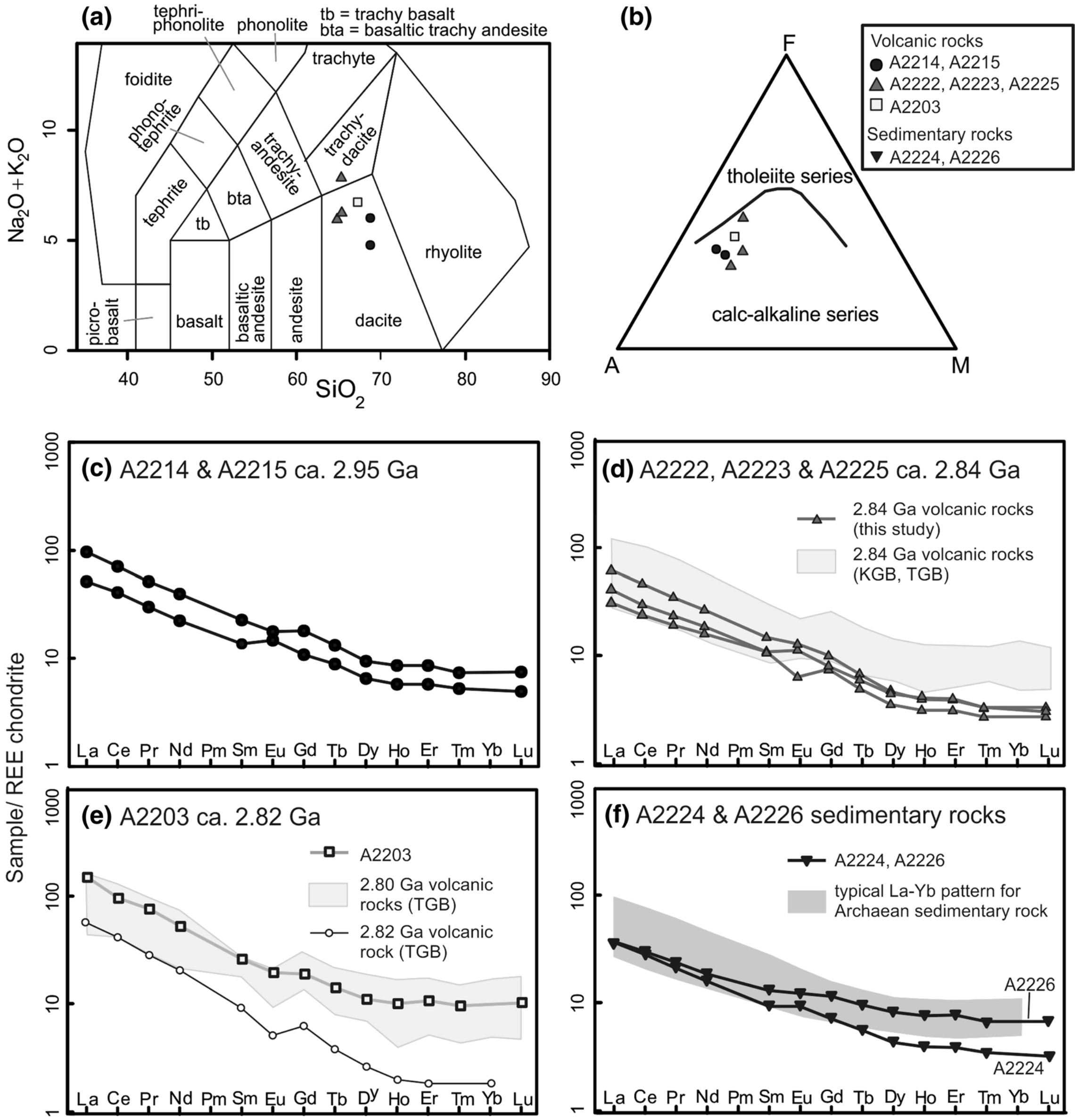


Fig. 7 **a** Chemical compositions of the studied rocks in $Na_2O + K_2O$ versus SiO_2 TAS diagram (Le Bas et al. 1986; Middlemost 1994); **b** in AFM diagram (Irvine and Baragar 1971); **c**–**f** chondrite-normalised REE patterns of all the studied volcanic and sedimentary rocks (after Boynton 1984; normalising values from McDonough and Sun 1995). For comparison **d** geochemistry of 2.84 Ga felsic and intermediate volcanic rocks from the Kuhmo and Tipasjärvi greenstone belts are shown, data from Lehtonen et al. (2016) and Lehtonen and Käpyaho (2016); **e** geochemistry of 2.82 and 2.80 Ga felsic and intermediate volcanic rocks from the Tipasjärvi greenstone belt are shown, data from Pietikäinen et al. (2008) and Lehtonen and Käpyaho (2016); **f** most typical Archaean sedimentary REE patterns with a source of calc-alkaline composition or mixture of felsic and mafic sources, data from McLennan and Taylor (1984)

SGB (Fig. 3c). In this study, we use term “unit” to group the volcanic rocks with the same age together. We use informal nomenclature to classify the different age groups because type sections cannot be defined based on the scarce amount of outcrops and available isotopic and geochemical data. Based on lithostratigraphy (Papunen et al. 2009), the supracrustal rocks have been divided into five formations (Fig. 3a), of which two comprise mainly felsic and intermediate volcanic rocks (the Luoma and Mesa-Aho Formations); tholeiitic basalt rocks with BIF interlayers were called as the Tervonen Formation; ultramafic volcanic rocks and komatiitic basalt formed the Saarikylä Formation, and the Huutoniemi Formation was used to group the youngest sedimentary and volcaniclastic sedimentary rocks together. As can be seen from Fig. 3c, the suggested chronostratigraphic interpretation lacks the Huutoniemi, Tervonen and Saarikylä Formations. Based on the U–Pb age determinations from the felsic and intermediate volcanic rocks combined with field relationships of the volcanic rocks, we interpret that the mafic and ultramafic volcanic rocks were formed in several stages (Fig. 3c). We have also used the name "Ahvenlahti" to group the new age group of ca. 2.84 Ga together. The two previously analysed samples representing the Kuikkapuro Au deposit both yielded somewhat heterogeneous age populations of zircon ages (Huhma et al. 2012a). In the rock type stratigraphy by Huhma et al. (2012a), these samples were not included to be part of any Formation or Group (Fig. 3b). In the chronostratigraphic interpretation samples, A1701x are tentatively placed into the Mesa-aho unit (Fig. 3c), this interpretation is discussed further in "Mesa-aho unit" section.

Luoma and Tormua units

The volcanic rocks belonging to the Luoma unit/Formation have been described to contain felsic-intermediate-mafic tuff and tuffitic rocks, banded amphibolite, and quartz porphyry dykes (Papunen et al. 2009). This group was considered as the oldest by Piirainen (1988) who named it as the Luoma Formation. Engel and Diez (1989) suggested that the rocks of the Luoma Formation were deposited on, or in close proximity to the sialic basement in shallow-water based on e.g., presence of sedimentary interlayers and the lack of pillow structures in basaltic lavas. They suggested that the Luoma Formation was separated from the other supracrustal rocks by an unconformity. Sorjonen-Ward and Luukkonen (2005) suggested, however, that a mylonitic zone with intense alteration separates the Luoma Formation from the younger volcanic rocks. Geochronological study by Huhma et al. (2012a) reported that the felsic volcanic rocks interpreted to belong to the Luoma Formation in the Luoma area had ages of ca. 2.94 Ga (Fig. 2). Our study verified that volcanic rocks with age of ca. 2.94 Ga are also found from the Kiannanniemi area situated at the most western margin of the SGB (Fig. 2). Based on the new U–Pb results combined with the field and drill core observations, the Luoma unit contains also mafic lavas and minor komatiite flows (Fig. 3c). In previous study, volcanogenic sedimentary rock sample A1191 was included in the Luoma Formation (Fig. 2; Huhma et al. 2012a). The main age population of zircon grains in sample A1191 was ca. 2.95 Ga, but the sample contained also two oscillatory zoned zircon grains with concordant ages of ca. 2.82 Ga, and it was interpreted that the material was deposited much later than 2.95 Ga. Based on the age determinations from the volcanic rocks (Huhma et al. 2012a, this study), it is evident that the SGB contains also a volcanic phase with the age of ca. 2.82 Ga and therefore raises the question could sample A1191 belong to the younger volcanic phase? The minimum age for this sedimentary rock sample is unknown and therefore we have excluded this sample from the chronostratigraphic interpretation. Volcanic rocks with ages of ca. 2.94 Ga have not been found from the KGB and the TGB. This age group represents also the oldest volcanic rocks recorded from Finland (Huhma et al. 2012a, this study).

Previously from the eastern branch of the belt, a tholeiitic plagioclase uralite porphyritic rock was dated, yielding an age of ca. 2.87 Ga (Fig. 2; Huhma et al. 2012a). We included this rock as a part of the chronostratigraphic interpretation under name of the Tormua unit (Fig. 3c). However, other volcanic rocks of this age have not been found in the other parts of the SKT complex.

Ahvenlahti unit

Based on the new U–Pb age results, it is evident that the SGB contains volcanic rocks with the age of ca. 2.84 Ga (Fig. 3c). This age phase has not been previously recorded from the SGB, but volcanic rocks have yielded contemporaneous ages from the KGB and the TGB (Huhma et al. 2012a; Lehtonen et al. 2016; Lehtonen and Käpyaho 2016). Based on the field and drill core observations, the felsic and intermediate volcanic rocks of the Ahvenlahti unit occur near the komatiitic rocks and komatiitic cumulates previously included in the Saarikylä Formation (e.g., Papunen et al. 2009), and this allows us tentatively to suggest that ultramafic volcanic rocks were formed also during ca. 2.84 Ga (Fig. 3c). The two volcanic rock units (A2223 and A2225), which gave the age of ca. 2.84 Ga, had the sedimentary rock (A2224) as an interlayer from which all analysed zircon grains have the same age. This might imply to a homogeneous source and/or short time and length for the deposition of the detritus. Based on the age data and layered graded bedding visible in the part of the drill core from which sample A2224 was collected, it most likely represents re-deposited volcanic material.

Mesa-aho unit

The Mesa-aho unit comprises of felsic-intermediate volcanic rocks with an age of ca. 2.82 Ga (Huhma et al. 2012a; this study; Fig. 3c). Volcanic rocks of this age are recorded dispersed along the SGB and their presence in the Kiannanniemi area was verified by our study (Fig. 2). The felsic and intermediate volcanic rocks with ages of ca. 2.82 occur in close proximity to komatiitic basalts, Cr basalts, komatiites and komatiitic cumulates that have been previously interpreted to form the Saarikylä Formation (see discussion in e.g., Papunen et al. 2009; Konnunaho et al. 2016). The 2.82 Ga Hietaharju intermediate lapilli tuff sample (A2203) was collected <2 km to east from the Kuikkapuro Au-prospect. From there, previously two samples have been analysed from the strongly altered rocks and they were interpreted to represent volcanic rocks with magmatic ages of ca. 2.82 Ga (Figs. 2 and 3; A1701x; Huhma et al. 2012a). Both samples contained also older zircon grains (3.53–2.85 Ga), which were interpreted to represent inherited grains. Based on the field observations, sample A2203 is likely of volcanic origin with the magmatic age of 2816 ± 3 Ma and does not contain evidence of inheritance. According to our interpretation, the heterogeneous zircon ages from samples A1701x (Huhma et al. 2012a) might imply that these samples represent sedimentary material from various sources. The detritus might have deposited coevally with the volcanism or with short time difference, as the strongly altered rock units are located between mafic volcanic rock units. If samples A1701x represent sedimentary material deposited coevally with the volcanic rocks of the Mesa-aho unit, this suggests that older crustal material (>2.85 Ga) was present during the deposition and volcanism. However, this subject remains open for future research.

The age group of 2.82 Ga has also been recorded from the felsic and intermediate volcanic rocks of the TGB (Huhma et al. 2012a; Lehtonen and Käpyaho 2016). Age determinations from felsic supracrustal rock samples and a gabbro in the KGBt contain zircon grains with ages of ca. 2.82 Ga. Some of the felsic rock samples contained heterogeneous zircon population and yielded also older ages as in the case of samples A1701x (Huhma et al. 2012a), but based on the zircon age distribution these might represent sedimentary material.

Keträvaara sedimentary rock

In this study, the Keträvaara sedimentary rock sample (A2226) was collected in order to study its zircon population. Sample A2226 contained heterogeneous population of zircons with morphology and age. The recorded ages vary from 3.55 Ga (core age from the grain with the rim age of ca. 2.82 Ga; Figs. 5o, p) to 2.70 Ga, majority ($n = 39$) being ca. 2.85–2.80 Ga. The youngest recorded ages (ca. 2.70 and 2.78 Ga) are ages from rims on grains with older cores (ca. 2.97 Ga), and therefore we cannot rule out the possibility that they represent younger metamorphic event. The most reliable maximum depositional age for sample A2226 is ≤2.82–2.81 Ga, which represents the youngest age population obtained from the zircon cores. The core age of ca 3.55 Ga is almost same to oldest known rock from the Karelia, trondhjemite gneiss ca. 3.5 Ga with inheritance up to 3.7 Ga (Mutanen and Huhma 2003). We do not include sample A2226 in the chronostratigraphic interpretation due to its unknown minimum depositional age. Based on the similar geochemistry with volcanic rocks of the Mesa-aho unit and the youngest zircon population, sample A2226 could either be part of the Mesa-aho unit, or represent detritus deposited after the end of the youngest volcanic phase. Sedimentary rocks containing much younger crustal material (<2.75 Ga) compared to the volcanic rocks are commonly found from the KGB and TGB (Huhma et al. 2012a; Lehtonen et al. 2016; Lehtonen and Käpyaho 2016), but have not been recorded from the SGB.

Meaning of the hiatus between 2.93 and 2.85 Ga in the Suomussalmi greenstone belt?

On the grounds of the available geochronological data from the felsic and intermediate volcanic rocks, the SGB contain two clearly different aged Mesoarchaean volcanic groups: ca. 2.94 and 2.84–2.82 Ga. The minor magmatic activity during the time period between 2.93 and 2.85 Ga in the Western Karelia subprovince has been noted also from the age data from the TTG association rocks (Käpyaho et al. 2006; Mikkola et al. 2011a). Similar evidence can be drawn from sedimentary rock sample A2226 that lacks zircon grains with ages 2.93–2.85 Ga, but contains significantly older grains than the volcanic rocks in the SGB. The detrital zircon record in the Western Karelia subprovince, however, contains minor amounts of material that have ages between 2.93–2.85 Ga (Kontinen et al. 2007; Huhma et al. 2012a; Lehtonen and Käpyaho 2016; Lehtonen et al. 2016). The origin for these grains is unknown, but ages of ca. 2.90–2.85 Ga have been reported from the mafic rock of the SGB (Huhma et al. 2012a), from the felsic volcanic rocks of the Central Karelia subprovince as well as from the volcanic rocks of the Vodlozero subprovince (Slabunov et al. 2006; Svetov and Svetova 2011; Huhma et al. 2012a).

The presence of an unconformity and division of the SGB into two separate assemblages has been suggested already by Engel and Diez (1989) and supported by isotope studies (Vaasjoki et al. 1999; Huhma et al. 2012a). Also the sulphur isotope compositions from komatiite-hosted sulphide deposits from different parts of the SGB carry differing signatures, which lends additional evidence to variable emplacement history of the komatiitic rocks and/or different parental magma composition (Konnunaho et al. 2016). This evidence and the scarcity of volcanic rocks with ages 2.93–2.85 Ga solidify the suggestion that the SGB is comprised of individual crustal bodies with different tectonic evolution (see e.g., Papunen et al. 2009). However, based on the new age results, the evolution of the belt is more complex than previously suggested.

Conclusions

Based on the results of this study and discussion, we draw following conclusions:

1. The Suomussalmi greenstone belt was formed between 2.94 and 2.82 Ga. The oldest volcanic rocks, 2.94 Ga, locate on the western margins of the Kiannanniemi and the Luoma-Saarikylä areas.
2. With the previously published and new U–Pb data combined, we suggest a chronostratigraphic interpretation of the Suomussalmi greenstone belt, containing four units: Luoma (ca. 2.94 Ga), Tormua (ca. 2.87 Ga), Ahvenlahti (2.84 Ga), and Mesa-aho (2.82 Ga). Based on the close proximity of the ultramafic and mafic volcanic rocks, we have tentatively suggested that ultramafic and mafic volcanic rocks were formed in several stages even though the absolute ages of these rocks is unknown.
3. Based on the geochronological studies from both the volcanic and plutonic rocks, the magmatic activity in the Western Karelia subprovince was significantly less during the time period of 2.93–2.85 Ga.
4. The Keträvaara sedimentary rock was deposited after/around ca. 2.82–2.81 Ga. It contains also zircon population with ages of ca. 2.96 Ga, and age of ca. 3.55 Ga was obtained from the core of one grain.

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