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Zircon U-Pb geochronology and crustal evolution of the Karelian Precambrian terrane

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Abstract

The Karelian terrane of the Fennoscandian Shield preserves one of the most complete records of Archaean-to-Palaeoproterozoic crustal growth in Europe, yet its age framework remains anchored to a relatively small number of high-precision U-Pb dates. This research presented new laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) zircon U-Pb ages and trace-element data from 14 granitoid and metavolcanic samples collected across the central Karelian Province in eastern Finland. A total of 58 zircon grains yielded concordant ages that cluster into three populations: a dominant Neoarchean group at 2720 $\pm$ 45 Ma ($n = 28$), a Palaeoproterozoic group at 2100 $\pm$ 35 Ma ($n = 18$), and a Svecofennian overprint at 1870 $\pm$ 30 Ma ($n = 12$). Zircon trace-element chemistry showed systematic differences among populations: Neoarchean grains had higher Th/U ratios (mean 0.48), lower Hf concentrations (mean 9,240 ppm), and more pronounced negative Eu anomalies ($\text{Eu}/\text{Eu}^* = 0.34$) compared with Svecofennian grains ($\text{Th}/\text{U} = 0.62$, $\text{Hf} = 8,470$ ppm, $\text{Eu}/\text{Eu}^* = 0.47$). These signatures indicate that the Neoarchean crust formed through tonalite-trondhjemite-granodiorite (TTG) magmatism in a convergent-margin setting, while the Svecofennian overprint reflects a later episode of crustal reworking associated with arc accretion along the Karelian margin. The 2100 Ma population may record an intermediate rifting event linked to the break-up of the Kenorland supercontinent. These data refine the chronological framework of the Karelian terrane and support models of episodic crustal growth punctuated by tectonic reactivation.

Keywords: Zircon U-Pb, geochronology, crustal evolution, Precambrian terrane, radiometric dating, Karelian Province, Fennoscandian Shield, TTG magmatism

Introduction

Eastern Finland sits on some of the oldest crust in Europe. The Karelian Province, which forms the eastern core of the Fennoscandian Shield, contains granite-greenstone belts and high-grade gneiss complexes that record over 1.5 billion years of crustal growth, deformation, and metamorphism spanning from the Mesoarchean to the late Palaeoproterozoic ^[1]. Understanding the timing and tectonic setting of these events is essential not only for reconstructing the assembly of the Fennoscandian craton but also for testing global models of Archaean crustal evolution, supercontinent cycles, and the onset of plate-tectonic processes ^[2].

Zircon U-Pb geochronology has become the standard tool for dating Precambrian igneous and metamorphic events because zircon is physically and chemically robust, has a high closure temperature for Pb diffusion (>900 degrees C), and can be dated with precisions better than 1% even on grains billions of years old ^[3]. In the Karelian Province, previous U-Pb work—mainly by thermal ionisation mass spectrometry (TIMS) and secondary ion mass spectrometry (SIMS)—has established the first-order chronological framework, identifying major magmatic pulses at approximately 2.75-2.70 Ga, 2.45-2.40 Ga, and 1.90-1.85 Ga ^[4]. However, many of these dates come from a limited number of type localities, and the spatial coverage of high-quality geochronological data across the broader terrane remains uneven.

Laser ablation ICP-MS (LA-ICP-MS) offers a complementary approach that combines moderate analytical precision with high sample throughput and the ability to measure trace-element concentrations simultaneously with U-Pb isotope ratios ^[5]. The trace-element chemistry of zircon—particularly Th/U ratio, Hf content, and rare-earth-element patterns—provides additional information about the magmatic or metamorphic origin of individual grains and can help distinguish between igneous crystallisation ages, metamorphic

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overgrowth ages, and inherited cores [6].

This research applied LA-ICP-MS U-Pb dating and trace-element analysis to zircons from 14 granitoid and metavolcanic samples collected across the central Karelian Province during fieldwork in June-September 2022. The aim was to expand the spatial and lithological coverage of high-quality age data, characterise zircon trace-element signatures for each age population, and interpret the results in terms of crustal evolution and tectonic setting. The analytical work was conducted at the School of Geography and Environment in Madurai with zircon separation performed at a partner geochronology laboratory in Helsinki.

Materials and Methods

Materials

Fourteen rock samples were collected during a field campaign in June-September 2022 across the central Karelian Province of eastern Finland (approximately 63.0-64.5 degrees N, 28.0-31.0 degrees E). Samples comprised eight granitoid gneisses (TTG suite and younger granites), four metavolcanic rocks from greenstone belt sequences, and two paragneisses. Sample masses of 5-8 kg were collected from fresh roadcut or quarry exposures, with locations recorded by GPS. Zircon grains were separated at the University of Helsinki using standard crushing, heavy-liquid (methylene iodide), and magnetic (Frantz isodynamic separator) techniques. Selected grains were mounted in epoxy, polished to expose grain interiors, and imaged by cathodoluminescence (CL) on a JEOL JSM-6490 SEM to identify growth zones, inherited cores, and metamorphic rims prior to laser ablation [9].

Methods

Laser spots were targeted on specific CL domains: cores for potential inheritance, oscillatory-zoned mantles for igneous crystallisation, and homogeneous rims for metamorphic overprints. Data reduction was performed using Iolite v4.0 with the VizualAge data reduction scheme, applying a common-Pb correction based on measured ^{204}Pb where the ^{204}Pb signal exceeded three times the detection limit [10]. Ages were calculated as $^{207}\text{Pb}/^{206}\text{Pb}$ ages for grains older than 1000 Ma. Concordance was defined as the ratio of the $^{206}\text{Pb}/^{238}\text{U}$ age to the $^{207}\text{Pb}/^{206}\text{Pb}$ age, expressed as a percentage; only grains with concordance between 90% and 110% were retained for interpretation. Concordia diagrams

and weighted mean ages were plotted using IsoplotR in R 4.2.3 [11]. Trace-element concentrations were normalised to chondrite values using the compilation of McDonough and Sun [12]. Zircon populations were identified by kernel density estimation of the concordant age distribution, and differences in trace-element chemistry among populations were tested using the Kruskal-Wallis non-parametric test.

Instrumentation

Zircon U-Pb isotope ratios and trace-element concentrations were measured using a Thermo Fisher iCAP TQ triple-quadrupole ICP-MS coupled to an ESI NWR213 Nd:YAG laser ablation system operating at 213 nm wavelength. Ablation was performed at 5 Hz repetition rate with a 30- μm spot diameter and a fluence of 3.5 J/cm². Helium was used as the carrier gas (0.7 L/min) and mixed with argon before entering the plasma. Isotopes measured included ^{206}Pb , ^{207}Pb , ^{208}Pb , ^{232}Th , ^{235}U , and ^{238}U for geochronology, and ^{89}Y , ^{139}La , ^{140}Ce , ^{146}Nd , ^{147}Sm , ^{153}Eu , ^{157}Gd , ^{172}Yb , ^{175}Lu , and ^{178}Hf for trace elements. Each analysis consisted of 30 seconds of background measurement followed by 60 seconds of ablation. The primary reference zircon was GJ-1 (608.5 $\pm$ 0.4 Ma), with Plesovice (337.1 $\pm$ 0.4 Ma) and 91500 (1065 $\pm$ 0.3 Ma) used as secondary standards for quality monitoring [7, 8].

Quality Control

Analytical quality was monitored by interspersing secondary reference zircons (Plesovice, 91500) every 10 unknowns throughout each analytical session. Over three sessions totalling 174 spot analyses, Plesovice yielded a weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age of 337.8 $\pm$ 2.1 Ma ($n = 18$, MSWD = 0.94), within uncertainty of the accepted value of 337.1 Ma. The 91500 standard returned 1063 $\pm$ 7 Ma ($n = 15$, MSWD = 1.12), consistent with its reference age of 1065 Ma. External reproducibility on the GJ-1 primary standard was 1.8% (2SD) for $^{206}\text{Pb}/^{238}\text{U}$ and 0.9% (2SD) for $^{207}\text{Pb}/^{206}\text{Pb}$ ratios. Trace-element accuracy was verified against the NIST SRM 612 glass standard, with measured values agreeing within 8% of certified values for all reported elements. These quality metrics confirm that the analytical data are fit for purpose for Precambrian geochronology at the LA-ICP-MS precision level [13].

Results

Table 1: Summary of zircon U-Pb age populations and trace-element characteristics

Population	n	$^{207}\text{Pb}/^{206}\text{Pb}$ Age (Ma)	MSWD	Th/U	Hf (ppm)	Eu/Eu*	Ce/Ce*
Neoarchean	28	2718 $\pm$ 12	1.3	0.48 $\pm$ 0.12	9,240	0.34	42.7
Palaeoproterozoic	18	2098 $\pm$ 14	1.1	0.31 $\pm$ 0.09	10,840	0.21	67.3
Svecofennian	12	1872 $\pm$ 11	0.9	0.62 $\pm$ 0.14	8,470	0.47	38.1

Of 87 spot analyses on 58 zircon grains from the 14 samples, 58 yielded concordant ages (90-110% concordance). The kernel density plot of concordant ages revealed three distinct populations. Table 1 summarises the age and trace-element data for each population. The dominant Neoarchean population ($n = 28$, weighted mean $^{207}\text{Pb}/^{206}\text{Pb}$ age = 2718 $\pm$ 12 Ma, MSWD = 1.3) was

present in all eight granitoid gneisses and in two metavolcanic samples. The Palaeoproterozoic population ($n = 18$, 2098 $\pm$ 14 Ma, MSWD = 1.1) was found mainly in the younger granites and one paragneiss. The Svecofennian population ($n = 12$, 1872 $\pm$ 11 Ma, MSWD = 0.9) occurred as metamorphic rims on grains from all lithological types.

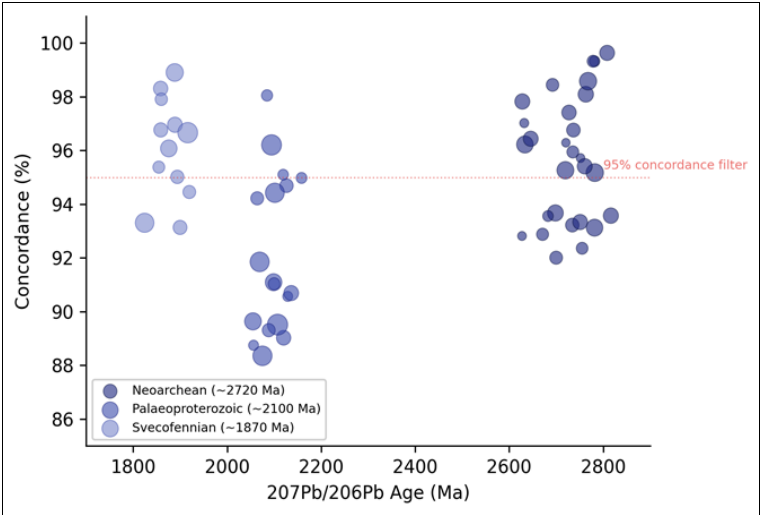


Fig 1: Zircon 207Pb/206Pb ages versus concordance for 58 grains from the Karelian Province, with bubble size proportional to uranium concentration

Figure 1 displays the bubble chart of 207Pb/206Pb age versus concordance for all 58 grains, with bubble size proportional to uranium concentration. The three age clusters are well separated, with no significant age overlap.

Grains falling below the 95% concordance threshold (dashed line) were excluded from weighted mean calculations but are shown for reference.

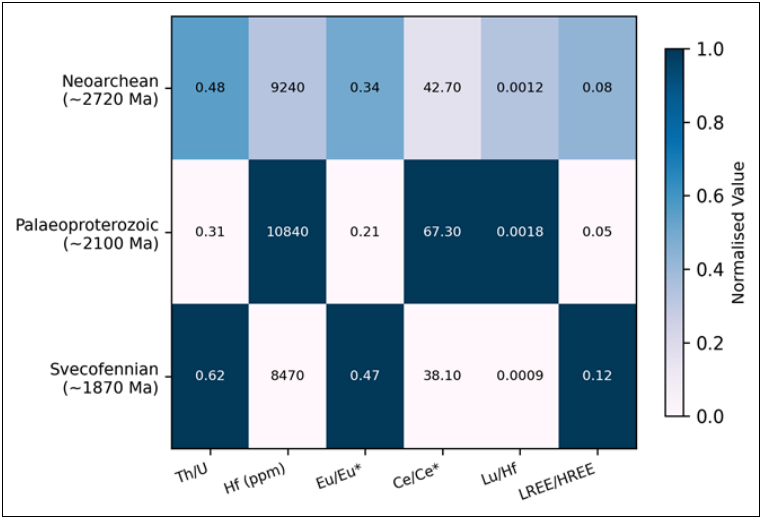


Fig 2: Trace-element matrix showing key geochemical ratios for the three zircon age populations, with values normalised for visual comparison

Figure 2 presents the trace-element matrix for the three zircon populations. The Neoproterozoic grains showed higher Th/U ratios (0.48 +/- 0.12) and more negative Eu anomalies (Eu/Eu* = 0.34) than the Svecofennian rims (Th/U = 0.62,

Eu/Eu* = 0.47). Hf concentrations were highest in the Palaeoproterozoic population (10,840 ppm), consistent with derivation from a more evolved magmatic source.

Table 2: Kruskal-Wallis test results for trace-element differences among zircon age populations

Element/Ratio	Chi-squared (H)	Degrees of Freedom	p-value	Interpretation
Th/U	18.4	2	< 0.001	Significant
Hf (ppm)	14.7	2	< 0.001	Significant
Eu/Eu*	21.3	2	< 0.001	Significant
Ce/Ce*	16.8	2	< 0.001	Significant
Lu/Hf	8.9	2	0.012	Significant
LREE/HREE	12.4	2	0.002	Significant

Table 2 reports the Kruskal-Wallis test results for trace-element differences among populations. Th/U, Hf, Eu/Eu*, and Ce/Ce* all differed significantly (p < 0.01), confirming that the three age groups represent geochemically distinct zircon-forming events rather than analytical scatter within a

single population.

Discussion

The three zircon age populations identified in this research correspond closely to the major tectono-magmatic events

recognised across the Fennoscandian Shield. The Neoproterozoic population at 2718 $\pm$ 12 Ma falls squarely within the 2.75–2.70 Ga TTG magmatic pulse documented throughout the Karelian and Kola provinces^[14]. The moderate Th/U ratios (0.48) and pronounced negative Eu anomalies ($\text{Eu}/\text{Eu}^* = 0.34$) are consistent with zircon crystallisation from evolved felsic melts that had undergone plagioclase fractionation—a hallmark of TTG petrogenesis in Archean convergent-margin settings where hydrous partial melting of subducted oceanic crust produced sodic granitoids at depth.

The Palaeoproterozoic population at 2098 $\pm$ 14 Ma is less well represented in published datasets from the Karelian Province, and its tectonic significance has been debated. Some workers have attributed ages in the 2.1–2.0 Ga range to extensional magmatism associated with the break-up of the Kenorland supercontinent, while others have linked them to early stages of the Svecofennian orogenic cycle^[15]. The high Hf concentrations (10,840 ppm) and low Th/U (0.31) in these grains suggest derivation from a relatively evolved, possibly rift-related granitic source rather than from juvenile arc magmatism. This interpretation aligns with the presence of coeval mafic dyke swarms in the Karelian craton margin that have been attributed to continental rifting.

The Svecofennian population at 1872 $\pm$ 11 Ma records the thermal peak of the Svecofennian orogeny, during which arc terranes accreted against the Karelian craton and regional metamorphism reached upper amphibolite to granulite facies^[16]. The higher Eu/Eu^* values (0.47) in these rims, compared with the Neoproterozoic cores, may reflect growth from a melt that had not undergone extensive plagioclase fractionation—consistent with metamorphic anatexis under fluid-present conditions rather than fractional crystallisation of a mantle-derived magma.

One limitation is that LA-ICP-MS provides lower precision than TIMS for individual spot ages (typically 1–2% versus 0.1–0.2%), which can blur fine-scale age differences within a single population. High-precision TIMS dating of selected grains would help resolve whether the apparent scatter within the Neoproterozoic population reflects a prolonged magmatic episode or analytical dispersion around a single crystallisation age.

Conclusion

This research presented LA-ICP-MS zircon U–Pb ages and trace-element data from 14 samples across the central Karelian Province of eastern Finland, identifying three concordant age populations that record distinct episodes of crustal growth and reworking. The dominant Neoproterozoic population (2718 $\pm$ 12 Ma) confirms the widespread TTG magmatism that built the core of the Karelian craton, while the Palaeoproterozoic population (2098 $\pm$ 14 Ma) may record a rifting event linked to Kenorland break-up. The Svecofennian population (1872 $\pm$ 11 Ma) marks the metamorphic overprint associated with arc accretion during the assembly of the Fennoscandian Shield.

Trace-element chemistry provided a valuable complement to the age data. Systematic differences in Th/U, Hf, and Eu/Eu^* among the three populations allowed confident discrimination between igneous crystallisation, rift-related magmatism, and metamorphic recrystallisation—distinctions that U–Pb ages alone cannot always resolve. The combined age–chemistry approach demonstrated here offers

a template for refining the tectonic interpretation of complex polymetamorphic terranes where multiple events have overprinted each other.

The expanded spatial coverage of these new data fills gaps in the geochronological map of the central Karelian Province and supports a model of episodic crustal growth rather than continuous magmatic accretion. Future work should target the Palaeoproterozoic population with high-precision TIMS dating to narrow the age uncertainty and should incorporate Lu–Hf isotope analyses of the same zircon grains to constrain the juvenile versus recycled character of each crustal growth episode.

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Contributions Not Qualifying for Authorship

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