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SHORT COMMUNICATION

New U-Pb zircon data for Maarianvaara granite and Tohmajärvi volcanic complex, eastern Finland: geologic implications

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Abstract

New U-Pb zircon ages reported for samples from the *Maarianvaara granite* and Tohmajärvi volcanic complex (TVC) corroborate previous estimates of their magmatic emplacement at ca. 1.85 Ga and 2.11 Ga, respectively. The ca. 1.85 Ga age of the largely undeformed Maarianvaara granite, which cuts the Proterozoic protomylonitic foliation in the Archean basement gneisses, sets a minimum age for the basement-involved thrusting in North Karelia. Geological evidence and geochemical data for the Kylmäkallio sill, dated at ca. 2.11 Ga from Tohmajärvi, indicate it is cogenetic/coeval with mafic metavolcanic/hypabyssal intercalations occurring in both the TVC and the surrounding black schist layered metasedimentary rocks of the *Tohmajärvi suite*. Thus, burial of organic carbon in the sedimentary protoliths of the Tohmajärvi succession was evidently occurring at ca. 2.11 Ga, about 50 Ma earlier than has been assumed in some recent time-stratigraphic interpretations.

Keywords: Zircon, U-Pb age, Paleoproterozoic, Maarianvaara granite, Tohmajärvi volcanic complex, regional deformation, stratigraphy, carbon burial

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1. Introduction

In this short communication we report and discuss two new U-Pb zircon ages for two geologically significant rock units in North Karelia, eastern Finland. One is the batholith size granodiorite-granite body between Outokumpu and Kaavi (Fig. 1a) known as the *Maarianvaara granite* (Huhma 1975, 1976) or granodiorite (Koistinen 1993). The other is the *Kylmäkallio dolerite* (Bedrock of Finland - DigiKP) in the Tohmajärvi volcanic complex/TVC (Nykänen 1968, 1971) within the southern part of the Höytiäinen belt (Fig. 1b).

The *Maarianvaara granite* consists of relatively Na_2O rich ('adamellitic') granitic and granodioritic rocks that tend to occur with gradational rather than cross-cutting intrusive relationships; both phases are commonly intruded by pegmatitic and aplitic granite dykes. The granitoids occur near the interface between the Archean basement and the Paleoproterozoic cover, intruding gneissic basement granitoids and autochthonous cover quartzites in the east, and allochthonous cover schists in the south and west (e.g., Huhma 1975, 1976; Park & Bowes 1983; Koistinen 1981). Granitoid emplacement was plausibly controlled by the disposition of pre-existing thrust-related structures and generally gently dipping enveloping surfaces of surrounding rock units. Enclaves of the host rocks are common throughout the main intrusive body, and the granite occurs in the flanking gneisses and schists both as cross-cutting and foliation-concordant small stocks and dykes. Neither the main intrusive body nor the granite in the surrounding smaller bodies show any distinct tectonic fabric.

The age of the *Maarianvaara granite* was first estimated to be 1857 ± 8 Ma (Huhma 1986), more recently revised to 1850 ± 6 Ma (Lahtinen, et al. 2016), based on zircons dated from sample A60 Vihtajärvi (Huhma 1976). However, this sample is from an imprecisely known location about 17 km NW of Maarianvaara (Fig. 1a), rising concerns about the validity of the assumed correlation to the main pluton, which is accordingly represented by our new sample (Fig. 1a). Knowing the magmatic emplacement/crystallization age of the largely undeformed *Maarianvaara granite* (Huhma 1976; Koistinen 1993) is an important constraint on establishing the timing of cessation of Svecofennian ductile deformation in the Kaavi-Outokumpu area (cf. Park & Bowes 1983).

The bedrock in the Tohmajärvi area hosting the *Kylmäkallio dolerite* consists of the intrusive and extrusive mafic rocks of the TVC (Nykänen 1968, 1971; Nykänen et al. 1994; Torvinen 2008), which intercalate with and are surrounded by a dominantly metasedimentary assemblage of pelitic schist ('phyllite'), carbonaceous schist, coarse arkosic-lithic metawacke, mafic metatuff–tuffite and minor carbonate rocks (Nykänen 1968, 1971; Damstén 2010a, 2010b; Kousa, 2014). All these rocks are currently included in the lithodemic *Tohmajärvi suite* (Bedrock of Finland – DigiKP). The *Kylmäkallio dolerite*, generally considered a sill, is mostly surrounded by the metasedimentary schists, but in the southeast, it is flanked by metabasalts of the TVC. However, the exact contact relationships of the intrusion are unknown. Mapping and exploration drilling (Torvinen 2008; Damstén 2010a) have revealed mafic intercalations in the interbedded succession of psammitic–pelitic schist and black schist on the western side of the intrusion. Chemical analyses indicate that at least one of these intercalations is compositionally similar with our age sample from the Kylmäkallio intrusion.

The supposed age of mafic magmatic rocks in the TVC (2103 ± 8 Ma) has been based on the U-Pb zircon age of a relatively coarse-grained metagabbro (sample A0398, Fig 1b) from the *Oravaara sill* (Huhma 1986; Huhma et al. 2018; Bedrock of Finland - DigiKP). However, it has remained unclear whether the sedimentary rocks surrounding the TVC are of the same age or perhaps significantly younger. Dating of the *Kylmäkallio dolerite* was considered to offer an opportunity to obtain a minimum age also for the sedimentary rocks.

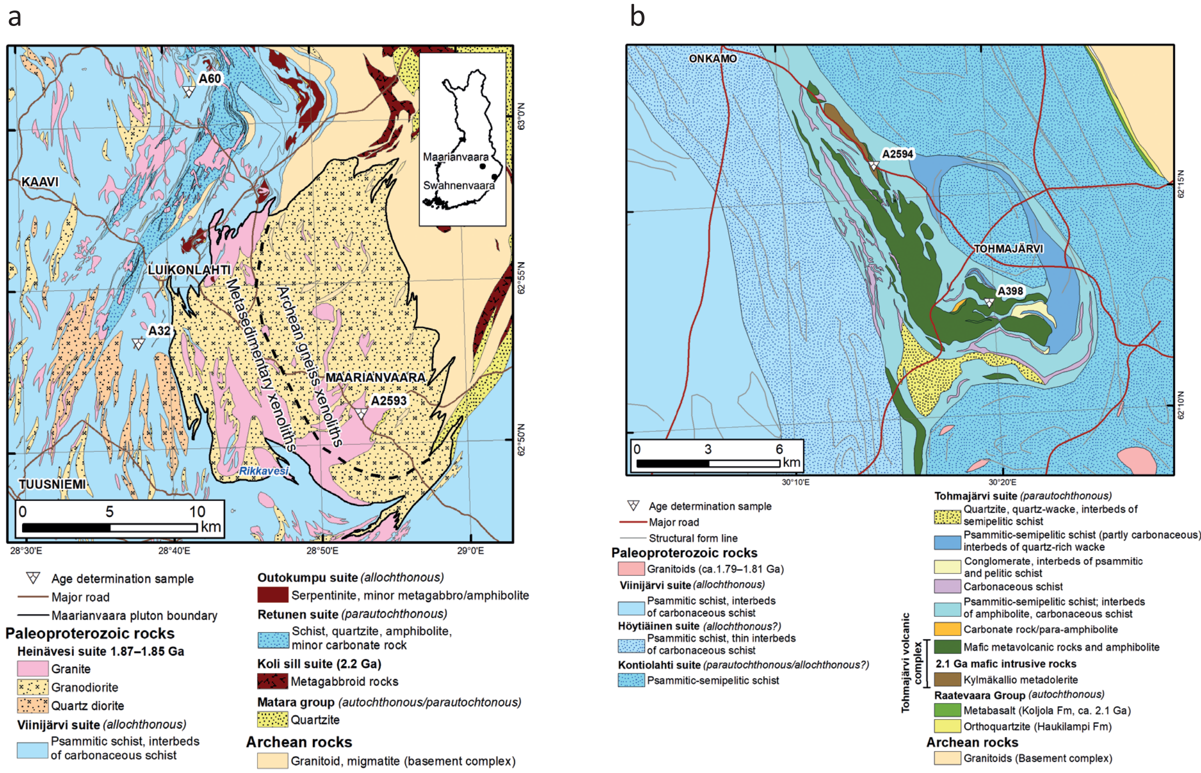

Fig. 1. Geological maps of (a) Maarianvaara-Kaavi and (b) Tohmajärvi areas showing locations of the studied samples A2593 Maarianvaara and A2594 Swahnenvaara and previous age samples discussed in the text. The maps are modified after Bedrock of Finland - DigiKP.

2. Samples

Sample A2593 Maarianvaara is from a 100 m long road-cut in the SE part of the Maarianvaara granodiorite-granite pluton (Fig. 1a) It represents a grey, medium, even-grained, undeformed, sub-leucocratic biotite (5 vol.%) granite, abundantly injected by a three-dimensional network of interconnected, sharply-bounded dykes of pink muscovite-biotite granite pegmatite varying in width from centimeters to meters. The sample has a chemical composition (Electronic Appendix A) placing it near the granite-granodiorite boundary in both QAP and TAS diagrams. Criteria by Debon and Le Fort (1983) define it as a sub-leucocratic, sodic-potassic adamellite. ASI at 1.05 and minor corundum in the CIPW norm indicate a slightly peraluminous composition. The zirconium content of A2593 is 271 ppm.

Sample A2594 Swahnenvaara represents a medium-grained, blasto-diabasic mafic rock from the SE part of the 4 km long and 250–400 m wide *Kylmäkallio dolerite* (Fig. 1b), in which the present main mineral constituents comprise amphiboles and sodic plagioclase. Seven whole rock analyses from the intrusion (Torvinen 2008; Rasilainen et al. 2007; this work; see Electronic Appendix A) show differentiation from gabbroic to ferrodioritic compositions. Chondrite-normalized REE patterns of all the analyzed samples are nearly flat, but display variable concentration levels, which suggests the cause for the compositional variation is low-P fractional crystallization. A2594 is among the most evolved samples with 55.51 wt.% SiO_2, 3.52 wt.% MgO and 20.20 wt.% Fe_2O_3tot. The high Na_2O value of 5.07 wt.% indicates the sample has been affected by Na-metasomatism/albitization. The zirconium content of A2594 is 226 ppm.

3. Analytical methods

Zircon separation and sample preparation were done using the standard methods routinely applied at GTK (Geological Survey of Finland). Before the analysis, the epoxy mounted, intersected, and polished zircons were imaged with both BSE and CL methods for morphological characterization and selection of analytical spots. Isotope analyses were performed using a Nu Plasma AttoM® laser ablation single-collector inductively coupled plasma mass spectrometer (LA-SC-ICPMS) at the Finnish Geoscience Laboratory (SGL). Analytical procedures were those as described by Molnár et al. (2018). The obtained data are presented in Electronic Appendix A.

A general tendency towards slight reverse discordance can be seen in the common Pb corrected data, presumably due to matrix effects between unknowns and the standard reference zircon GJ1 (609 ± 1 Ma, Belousova et al. 2006) used in the calibration. It is worth noting that the unknowns and the Archean reference sample A1772, which tend to plot reversely discordant, have on average higher Pb and U contents than the calibration standard GJ1, whereas the Proterozoic reference sample A382, which has Pb and U contents much closer to GJ1, plots concordantly. However, as the reference samples yield intercept ages that are accurate within analytical uncertainties (Electronic Appendix A), we consider that the $^{207}Pb/^{206}Pb$ dates from the target zircons are reliable for age calculations.

4. Results

Separation of the sample A2593 Maarianvaara produced a relatively large amount of prismatic zircon grains that are mostly 150–200 µm long, about 50 µm wide and show weak oscillatory zoning. In addition, there is a smaller population of grains displaying smaller length/width ratios and commonly distinct core-rim textures.

Of the total 60 spots, analyzed from 56 grains, two were excluded due to high common Pb ($^{206}Pb/^{204}Pb$ <1000). The remaining 58 analyses from 54 grains are mostly reversely discordant (1–18 %, centrally), 3 are concordant and 12 normally discordant (1–19 %). The obtained $^{207}Pb/^{206}Pb$ ages fall into two main age groups: (1) from 1752 to 1882 Ma (other than the grey bars in Fig. 2a) and (2) from 1898 to 2707 Ma (the grey bars in Fig. 2a). Most of the older ages (n = 18) are from apparent cores or crystals with the smaller length/width ratio, whereas the younger ages (n = 40) come mainly from the apparently core-free, longer prismatic grains, and in two cases from overgrowths on the older >1898 Ma zircon. Based on the obvious magmatic nature of the sampled rock and distinct difference in the ages of the zircon populations, we interpret the younger ages to represent mainly magmatic, and the older mainly xenocrystic zircon.

Excluding the youngest analysis from the 1752–1882 Ga group as an outlier, the remaining 39 analyses (1788–1882 Ma, the pink and red bars in Fig. 2a) define a weighted mean $^{207}Pb/^{206}Pb$ age of 1834 ± 8 Ma (MSWD = 7.5). However, the relatively high MSWD of 7.5 Ma implies scatter exceeding analytical uncertainty alone. If the mixing algorithm in the radial plot module of Isoplot-R (Vermeesch 2018) is applied in a two-component mode, identified peaks of the components are at 1808 ± 5 Ma and 1851 ± 4 Ma. Twenty-five analyses in the older grouping (the red bars in Fig. 2a) give a weighted mean $^{207}Pb/^{206}Pb$ age of 1852 ± 6 Ma (MSWD = 2.4) and 14 analyses in the younger grouping (the pink bars in Fig. 2a) 1808 ± 5 Ma (MSWD = 1.5), respectively. Given the geologic context of A2593, it seems reasonable to assume that these ages imply magmatic crystallization at ca. 1.85 Ga and a stage of fluid inflow and zircon dissolution–precipitation at ca. 1.81 Ga. The latter event may have been related to the emplacement of the plentiful pegmatite dykes in the Maarianvaara granite.

Based on an Isoplot-R radial plot, the population considered inherited (n = 18, 31 % of all accepted analyses, the grey bars in Fig. 2a), and

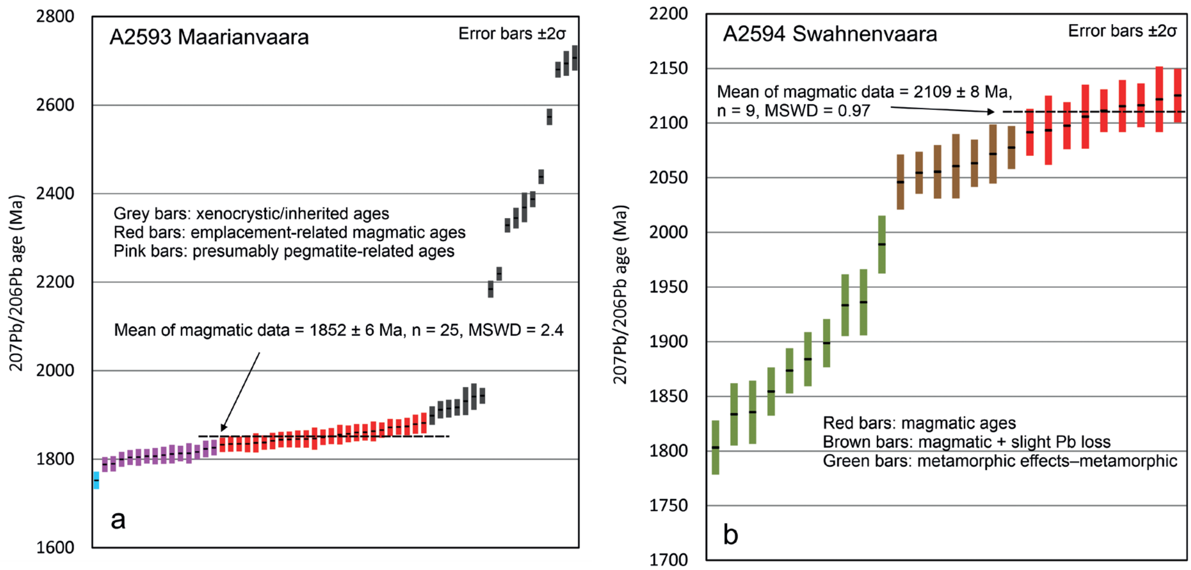

Fig. 2. Distribution and interpretation of $^{207}Pb/^{206}Pb$ ages (a) from sample A2593 Maarianvaara, and (b) from sample A2594 Swahnenvaara. For respective concordia diagrams, see Electronic Appendix A.

possibly reset to variable degrees, is distributed in four groups with $^{207}Pb/^{206}Pb$ age peaks at 1921 ± 8 Ma (39 %), 2206 ± 12 Ma (11 %), 2379 ± 9 Ma (28 %) and 2650 ± 11 Ma (22 %).

Separation of the sample A2594 Swahnenvaara produced a small amount of both intact zircon grains and fragments. Two main grain types are present, one comprising rather small (<100 µm), elongated prismatic crystals, and the other somewhat larger (100–150 µm), rounder crystals or their fragments. No grains with core-rim structures were observed. In total, 30 analyses from as many grains were made. Four analyses were rejected due to high common Pb ($^{206}Pb/^{204}Pb$<1000). As in the case of the previous sample most of the accepted analyses plot reversely discordant (1–17 % centrally), only 2 analyses being concordant and 3 slightly normally discordant (2 %).

The 26 analyses considered acceptable fall into two age groups: (1) with $^{207}Pb/^{206}Pb$ ages ranging from 1803 to 1989 Ma (n = 10, the green bars in Fig. 2b) and (2) from 2046 to 2125 Ma (n = 16, the brown and red bars in Fig. 2b). The ages have no obvious correlation with morphological characteristics. Considering the igneous origin of the sampled rock and that regional Svecofennian metamorphism of the North Karelia belt occurred between 1.90–1.80 Ga (Hölttä & Heilimo 2017), the ages in the younger group likely record metamorphic effects, whereas those in the older group probably are from isotopically less modified parts of magmatic grains. The magmatic nature of the older group zircon is supported by its high Th/U ratio (2.00 ± 0.58). In contrast, 6 of the 10 analyses with younger $^{207}Pb/^{206}Pb$ ages have much lower Th/U ratios (0.01–0.46), supporting the inference that the respective grains record metamorphism-related alteration and growth of zircon (cf. Rubatto, 2017; Yakymchuk et al. 2018).

Taken together, the 16 analyses in the older group yield a weighted average $^{207}Pb/^{206}Pb$ age of 2088 ± 13 Ma (MSWD = 5.0). We interpret the overdispersion with this result to reflect presence of both well-preserved magmatic zircon, and those registering ancient partial lead loss. If this assertion is correct, the weighted $^{207}Pb/^{206}Pb$ average age of 2109 ± 8 Ma (MSWD = 0.97) for the oldest statistical sub-group (cf. Coutts et al. 2019) of 9 dates (the red bars in Fig. 2b) should provide a reasonable estimate of the age of the magmatic zircon and emplacement and solidification of the Kylmäkallio sill.

5. Significance of the results

Our interpretation of the A2593 zircon U-Pb data involves emplacement and solidification of the *Maarianvaara granite* at ca. 1.85 Ga, the presence of a sizeable inherited population with $^{207}Pb/^{206}Pb$ dates from 1.92 to 2.69 Ga and an additional younger population after zircon dissolution–precipitation at ca. 1.81 Ga. The interpreted 1851 ± 6 Ma magmatic age of the A2593 is correlative with the 1850 ± 6 Ma age obtained from the sample A60 by Lahtinen et al. (2016). The genetic link is reinforced by the nearly identical petrographic features and chemical compositions of these two rocks (Huhma 1976; Lahtinen et al. 2016; this work, see Electronic Appendix A). Nevertheless, data in Lahtinen et al. (2016) suggest that, unlike A2593, A60 does not contain inherited nor 1.81 Ga zircon. However, due to the small number of grains analyzed from A60 (n = 11), it is possible that even large subpopulations may have gone undetected, especially if grains with supposed magmatic morphology were favored in the selection of grains to be analyzed.

The proposition that the zircon age population present in A2593 would be common in Maarianvaara type granitoids is supported by multigrain U-Pb TIMS data for a granodiorite sample (A32) from Kaavinkoski, about 3 km west of the main pluton. Namely, this sample has a subpopulation of prismatic zircon grains, probably magmatic, yielding an age of 1856 ± 21 Ma, and a subpopulation of darker, roundish, and probably xenocrystic/inherited grains producing an age of 2470 ± 19 Ma (Huhma 1976). Regarding the source of the xenocrystic grains, we note that the surrounding Viinijärvi suite schists (Fig. 1a) commonly contain detrital zircon grains with similar ages to those of the xenocrystic grains in A2593 (see Lahtinen et al. 2010, 2013; Mikkola et al. 2022).

The abundance of sharply cross-cutting pegmatite dykes in the A2953 granite implies a post-emplacement thermal pulse and related inflow of aqueous fluid, which could have facilitated the speculated ca. 1.81 Ga zircon dissolution and regrowth. However, in the absence of age data for the pegmatites, which typically contain only little zircon, their true significance in generation of the 1.81 Ga zircon in A2953 remains uncertain. But if the scenario is correct, differences in the amount of pegmatite could explain differences in subsolidus zircon growth between granite occurrences, such as that apparently found between samples A60 and A2593.

The Maarianvaara granite, for which the U-Pb zircon data in Lahtinen et al. (2016) for sample A60, and now obtained for A2593, provide a credible ca. 1.85 Ga age, is presently included in the *Heinävesi suite* (Bedrock of Finland - DigiKP). Other dated components in the *Heinävesi suite* comprise the ca. 1.87 Ga (Lahtinen et al. 2016) Kermajärvi (Koistinen 1993) and Suvasvesi granitoids (Rantanen 2021) about 50 km S of Maarianvaara. The magmatic activity in the suite thus seems to cover a period of ca. 20 Ma. A genetically important aspect of the *Heinävesi suite* is the presence of dioritic rocks, which are especially plentiful in the Kermajärvi area (Koistinen 1993) but also in the Kaavi area west of the Maarianvaara batholith (Huhma 1975, Fig. 1a). There are no age data for the diorites, but they seem to be related to the early ca. 1.87 Ga phase of the *Heinävesi suite* magmatism and be completely missing from the 1.85 Ga Maarianvaara batholith.

Field evidence from the N-part of the Maarianvaara area (Onnivaara, Niinivaara) show that the *Maarianvaara granite* post-dates the protomylonitic foliation developed in the local Archean granitoids during the main phase of Proterozoic (D2) thrusting (Koistinen 1981; Park & Bowes 1983). This limits the absolute minimum age of the main thrusting and D2 to 1.85 Ga. The proper tectonic setting, as well as mode and depth of emplacement of the Maarianvaara intrusion remain important subjects to be clarified in future. More generally, it seems obvious that the 1.87–1.85 Ga *Heinävesi suite* granitoids divide the Svecofennian tectonic development in the Heinävesi and Kaavi areas in two major stages: (1) antecedent with regionally pervasive deformation and (2) subsequent with deformation focused in shear zones. Due to their emplacement in the transition stage, it is not surprising these granitoids have been classified as syn- to post-orogenic (Huhma 1976; Koistinen 1993) but also post-kinematic (Nironen, 2005; Rantanen, 2021).

The age of 2109 ± 8 Ma obtained by the A2594 Swahnenvaara sample for the Kylmäkallio sill corresponds, within the limits of error, to the 2103 ± 8 Ma age previously reported for the gabbroic sample A0398 from mafic rocks at the Oravaara hill (Huhma et al. 2018). The Kylmäkallio intrusion shares also the characteristic chemical features of Oravaara gabbro and most other mafic rocks of the TVC, which include flat chondrite-normalized REE, low Th/Sc, Th/Nb and La/Nb (Nykänen et al. 1994; Torvinen 2008; Electronic Appendix A), together indicating minimal crustal contamination. Combined the available age determinations and chemical information strongly support the proposition that the Tohmajärvi mafic magmatism was ca. 2.11 Ga in age (Huhma 1986; Huhma et al. 2018).

Most importantly, the 2.11 Ga age obtained for the *Kylmäkallio dolerite* and the presence of compositionally similar mafic interlayers and/or sills in the adjacent sedimentary rocks suggest corresponding age for the entire Tohmajärvi succession, including parts containing carbonaceous schists. If correct, this constrains the onset of organic carbon-burying sedimentation in the North Karelia schist belt significantly earlier (>50 Ma) than presently assumed. In a broader context this would mean that the occurrence of black shales or carbonaceous, dark colored intercalations in Karelian formations could not be considered a reliable, diagnostic indication of their Ludikovian (2060–1960 Ma) or younger age (cf. Melezhik et al. 1997; Hanski & Melezhik 2013).

The 2.11 Ga age and distinctive chemical characteristics of the Tohmajärvi mafic metavolcanic rocks provide a useful basis for correlations across eastern Finland. The age correlation to the metabasalts of Koljola Formation in the nearby Kiihtelysvaara area is obvious (see Pekkarinen & Lukkarinen 1991). However, the Koljola metabasalts and their assumed feeder dykes show, unlike the majority of Tohmajärvi metabasalts, strong LREE enrichment and evidence for crustal contamination (Pekkarinen & Lukkarinen 1991; Nykänen et al. 1994; Huhma et al. 2018) and were thus probably emplaced in a tectonic environment significantly different to that of the TVC (Nykänen et al. 1994). Other potentially correlative successions occur in the Sortavala (Kirjavalahti), Paltamo (Horkankallio), Pohjois-Pohjanmaa (Vepsä-Pyyräselkä, Martimojoki, Kiiminki, Haukipudas), Perä-Pohja (Jouttiaapa, Tikanmaa) and Kuusamo (Liikasenvaara) areas. As all these successions contain units compositionally close to Tohmajärvi basalts (Honkamo 1988; Rasilainen et al. 2007), and the Tikanmaa formation has been dated at 2106 ± 8 Ga (Karhu et al. 2007), we consider that they all may have been deposited in broadly similar tectonic settings at ca. 2.1 Ga. Noting that all these units contain carbonaceous/black schists, this would mean that organic-carbon burying sedimentation at 2.1 Ga was not restricted to North Karelia.

6. Final remarks

1. The zircon age of 1.85 for sample A2593 from Maarianvaara vindicates the interpretation of the emplacement age of *the Maarianvaara granite* and sets the minimum age for the main thrusting events in North Karelia.

2. In addition to significant inherited zircon population, A2593 contains grains recording an apparent 1.81 Ga hydrothermal event that possibly was linked to emplacement of the cross-cutting pegmatite dykes.

3. The new age determination for sample A2594 from the *Kylmäkallio dolerite* with crystallization age estimate of 2.11 Ga confirms the 2.1 Ga age for the volcanic rocks in the Tohmajärvi area.

4. The available map and geochemical data force that the Kylmäkallio sill and the surrounding metavolcanic and black schist intercalated metasedimentary rocks are coeval. This implies that sedimentary burial of organic carbon was already occurring in North Karelia at ca. 2.11 Ga.

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Supplementary Data

Electronic Appendices are available via Bulletin of the Geological Society Finland web page.

Appendix A: U-Pb zircon and whole rock chemical data.

References

Bedrock of Finland - DigiKP. Digital map database [Electronic resource], Geological Survey of Finland [referred 30.11.2023). https://gtkdata.gtk.fi/mdae/index.html

Belousova, E. A., Griffin, W.L. & O'Reilly, S.Y., 2006. Zircon crystal morphology, trace element signatures and Hf isotope composition as a tool for petrogenetic modeling: examples from eastern Australian granitoids. Journal of Petrology 47, 329–353. https://doi.org/10.1093/petrology/egi077

Coutts, D.S., Matthews, W.A. & Hubbard, S.M., 2019. Assessment of widely used methods to derive depositional ages from detrital zircon populations. Geoscience Frontiers 10, 1421–1435. https://doi.org/10.1016/j.gsf.2018.11.002

Damstén, M., 2010a. Diamond drillings in the Tohmajärvi area year 2008 on the map sheet 4232 05. Geological Survey of Finland, Report M19/4232/2010/30, 14 p (in Finnish with English abstract). https://tupa.gtk.fi/raportti/arkisto/m19_4232_2010_30.pdf

Damstén, M., 2010b. Diamond drillings at the schist belt between Tohmajärvi and Joensuu year 2009 on the map sheets 4223 10, 4241 03 and 4232 02 and 05. Geological Survey of Finland, Report M19/4223/2010/31, 18 p (in Finnish with English abstract). https://tupa.gtk.fi/raportti/arkisto/m19_4223_2010_31.pdf

Damstén, M., 2013. Diamond drillings at the schist belt between Tohmajärvi and Hammaslahti on the map sheets N534 and N543 years 2010-2011. Geological Survey of Finland, Report 124/2013, 17 p (in Finnish with English abstract). https://tupa.gtk.fi/raportti/arkisto/124_2013.pdf

Debon, F. & Le Fort, P., 1983. A chemical-mineralogical classification of common plutonic rocks and associations. Transactions of Royal Society of Edinburgh, Earth Sciences 73, 135–149.

Hanski, E.J. & Melezhik, V.A., 2013. Litho- and chronostratigraphy of the Palaeoproterozoic Karelian formations. In: Melezhik, V.A., Prave, A.R., Hanski, E.J., Fallick, A.E., Lepland, A., Kump, L.R., and Strauss, H. (eds.), Reading the Archive of Earth's Oxygenation. Volume 1: The Palaeoproterozoic of Fennoscandia as Context for the Fennoscandian Arctic Russia – Drilling Early Earth Project, Springer-Verlag, Berlin, Heidelberg, pp. 39–110. https://doi.org/10.1007/978-3-642-29682-6_4

Honkamo M., 1988. Haukipudas and Kiiminki. Explanation to the Geological map of Finland 1:100 000, pre-Quarternary rocks, Sheets 2533 and 2511. Geological Survey of Finland, 46 p (in Finnish with English summary). https://tupa.gtk.fi/kartta/kallioperakartta100/kps_2533_3511.pdf

Hölttä, P. & Heilimo, E., 2017. Metamorphic map of Finland. In: Nironen, M. (ed.), Bedrock of Finland at the scale 1:1000 000 – Major stratigraphic units, metamorphism and tectonic evolution. Geological Survey of Finland, Special Paper 60, 77–128. https://tupa.gtk.fi/julkaisu/specialpaper/sp_060_pages_077_128.pdf

Huhma, A. 1975. Outokumpu, Polvijärvi and Sivakkavaara. Explanation to the Geological map of Finland 1:100 000, pre-Quarternary rocks, Sheets 4222, 4224 and 4311. Geological Survey of Finland, 151 p (in Finnish with English summary). https://tupa.gtk.fi/kartta/kallioperakartta100/kps_4222_4224_4311.pdf

Huhma, A., 1976. New aspects to the geology of the Outokumpu region. Bulletin of the Geological Society of Finland 48, 5–24. https://www.geologinenseura.fi/sites/geologinenseura.fi/files/sgs_bt_048_1_2_pages_005_024.pdf

Huhma, H., 1986. Sm-Nd, U-Pb and Pb-Pb isotopic evidence for the origin of the Early Proterozoic Svecokarelian crust in Finland. Geological Survey of Finland, Bulletin 337, 48 p. https://tupa.gtk.fi/julkaisu/bulletin/bt_337.pdf

Huhma, H., Hanski, E., Kontinen, A., Vuollo, J., Mänttäri, I. & Lahaye, Y., 2018. Sm–Nd and U–Pb isotope geochemistry of the Palaeoproterozoic mafic magmatism in eastern and northern Finland. Geological Survey of Finland, Bulletin 405, 150 p. https://tupa.gtk.fi/julkaisu/bulletin/bt_405.pdf

Karhu, J., Kortelainen. N., Huhma, H., Perttunen, V. & Sergeev, S., 2007. New time constraints for the end of the Paleoproterozoic carbon isotope excursion. 7th International Symposium on Applied Isotope Geochemistry, Stellenbosch, South Africa, 10th–14th September 2007, Abstracts, pp. 76–77.

Koistinen, T.J., 1981. Structural evolution of an early Proterozoic stratabound Cu-Co-Zn deposit, Outokumpu, Finland. Transactions of the Royal Society of Edinburgh: Earth Sciences 72, 115–158. https://doi.org/10.1017/S0263593300009949

Koistinen, T., 1993. Heinävesi. Explanation to the Geological map of Finland 1:100 000, pre-Quarternary rocks, Sheet 4211. Geological Survey of Finland, 64 p (in Finnish with English summary). https://tupa.gtk.fi/kartta/kallioperakartta100/kps_4221.pdf

Kousa, J., 2014. Diamond drilling at Soppi village, Tohmajärvi, years 2012 and 2013 on the map sheet N534. Geological Survey of Finland, Report 59/2014, 23 p (in Finnish with English abstract). https://tupa.gtk.fi/raportti/arkisto/59_2014.pdf

Lahtinen, R., Huhma, H., Kontinen, A., Kohonen, J. & Sorjonen-Ward, P., 2010. New constraints for the source characteristics, deposition and age of the 2.1–1.9 Ga metasedimentary cover at the western margin of the Karelian Province. Precambrian Research 176, 77–93. https://doi.org/10.1016/j.precamres.2009.10.001

Lahtinen, R., Huhma, H., Lahaye, Y., Kontinen, A., Kohonen, J. & Johanson, B., 2013. Long-lived LREE mobility in the cratonic, rift and foredeep to foreland sedimentary cover at the western margin of the Karelia Province. Lithos 175–176, 86–103. https://doi.org/10.1016/j.lithos.2013.05.003

Lahtinen, R., Huhma, H., Lahaye, Y., Lode, S., Heinonen, S., Sayab, M. & Whitehouse, M.J., 2016. Paleoproterozoic magmatism across the Archean-Proterozoic boundary in central Fennoscandia: Geochronology, geochemistry and isotopic data (Sm-Nd, Lu-Hf, O). Lithos 262, 507–525. https://doi.org/10.1016/j.lithos.2016.07.014

Melezhik, V.A., Fallick, A.E., Makarikhin, V.V. & Lyubtsov, V.V., 1997. Links between Palaeoproterozoic palaeogeography and rise and decline of stromatolites: Fennoscandian Shield. Precambrian Research 82, 311–348. https://doi.org/10.1016/S0301-9268(96)00061-7

Mikkola, P., Aatos, S., Halkoaho, T., Heinonen, S., Hietava, J., Hietala, S., Kurhila, M., Jäsberg, J., Laine, E., Luukas, J., Niskanen, M., Nousiainen, M., Nygård, H., Piispanen, A., Pirinen, H., Rantanen, H. & Romu, I., 2022. Geological evolution and structure along the western boundary of the Outokumpu allochthon. GTK Open File Research Report 23/2022, 117 p. https://tupa.gtk.fi/raportti/arkisto/23_2022.pdf

Molnár, F., Middleton, A., Stein, H., O'Brien, H., Lahaye, Y., Huhma, H., Pakkanen, L. & Johanson, B., 2018. Repeated syn- and post-orogenic gold mineralization events between 1.92 and 1.76 Ga along the Kiistala Shear Zone in the Central Lapland Greenstone Belt, northern Finland. Ore Geology Reviews, 936–956. https://doi.org/10.1016/j.oregeorev.2018.08.015

Nironen, M., 2005. Proterozoic orogenic granitoid rocks. In: Lehtinen, M., Nurmi, P.A. & Rämö, O.T. (eds.), Precambrian Geology of Finland – Key to the Evolution of the Fennoscandian Shield. Elsevier B.V., pp. 443–480.

Nykänen, 0., 1968. Tohmajärvi. Explanation to the Geological map of Finland 1:100 000, pre-Quarternary rocks, Sheet 4232–4234. Geological Survey of Finland, 66 p (in Finnish with English summary). https://tupa.gtk.fi/kartta/kallioperakartta100/kps_4232_4234.pdf

Nykänen, O. 1971: On the Karelides in the Tohmajärvi area, eastern Finland. Bulletin of Geological Society of Finland 43, 93–108. https://www.geologinenseura.fi/sites/geologinenseura.fi/files/sgs_bt_043_1_pages_093_108.pdf

Nykänen, V. M., Vuollo, J. I., Liipo, J. P. & Piirainen, T. A., 1994. Transitional (2.1 Ga) Fe-tholeiitic-tholeiitic magmatism in the Fennoscandian Shield signifying lithospheric thinning during Palaeoproterozoic extensional tectonics. Precambrian Research 70, 45–65. https://doi.org/10.1016/0301-9268(94)90020-5

Park, A.F. & Bowes, D.R., 1983. Basement-cover relationships during polyphase deformation in the Svecokarelides of the Kaavi district, eastern Finland. Transactions of the Royal Society of Edinburgh: Earth Sciences 74, 95–118. https://doi.org/10.1017/S0263593300010191

Pekkarinen, L. J. & Lukkarinen, H. 1991. Paleoproterozoic volcanism in the Kiihtelysvaara – Tohmajärvi district, eastern Finland. Geological Survey of Finland, Bulletin 357, 30 p. https://tupa.gtk.fi/julkaisu/bulletin/bt_357.pdf

Rantanen, H. 2021. Mineralogy, Petrology, and Petrogenesis of the Suvasvesi Granitoid Intrusion. M.Sc. Thesis, University of Helsinki, Finland, 77 p. http://tupa.gtk.fi/opinnayte/rantanen_hanna_gradu.pdf

Rasilainen, K., Lahtinen, R. & Bornhorst, T. J., 2007. The Rock Geochemical Database of Finland Manual. Geological Survey of Finland, Report of Investigation 164, 38 p. https://tupa.gtk.fi/julkaisu/tutkimusraportti/tr_164.pdf

Rubatto, D. 2017. Zircon: the metamorphic mineral. Reviews in Mineralogy and Geochemistry 83, 261–296. https://doi.org/10.2138/rmg.2017.83.9

Torvinen, A. 2008. Geology and geochemistry of the Palaeoproterozoic Tohmajärvi igneous complex, eastern Finland. M.Sc. Thesis, University of Turku, Finland, 91 p.

Vermeesch, P. 2018. IsoplotR: a free and open toolbox for geochronology, Geoscience Frontiers 9, 1479–1493, https://doi.org/10.1016/j.gsf.2018.04.001

Yakymchuk, C., Kirkland, C.L. & Clark, C. 2018. Th/U ratios in metamorphic zircon. Journal of Metamorphic Geology 36, 715–737. https://doi.org/10.1111/jmg.12307