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Constraints over the age of magmatism and subsequent deformation for the Neoarchean Kukkola Gneiss Complex, northern Fennoscandia

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Abstract

The Archean crust in northern Fennoscandia preserves a fragmentary geological record, making direct correlation among Archean domains challenging. This study presents two new zircon U-Pb age determinations from the Archean Kukkola Gneiss Complex (KGC) that straddles the border between Finland and Sweden. The results indicate that crystallization of tonalites within the magmatic core of the complex occurred at 2711±8 Ma, somewhat earlier than previously considered. A new pulse of magmatism occurred at 2675±10 Ma as demonstrated by hornblende-tonalites cutting the 2.71 Ga rocks. The results further indicate that the first deformation event responsible for development of penetrative foliations occurred after the first magmatic event at 2.71 Ga and prior to the subsequent tectonothermal event at 2.68 Ga. These findings are in concert with the known major periods of magmatism (2.8–2.7 Ga) and deformation (2.7 Ga) within better-known Archean domains in northern Fennoscandia, and hence support their correlation with KGC. Three complementary age determinations on the Haparanda-suite granites and tonalites were conducted: the results indicate crystallization ages of 1.90–1.89 Ga, overlapping with the known age range of the suite and supporting its predominance over the 1.8 Ga Lina suite granites in the Tornio-Haparanda area.

Keywords: Peräpohja Belt, Haparanda, Archean, Fennoscandia, magmatism, tonalite, granite

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1. Introduction

Dominantly Neoarchean crust of the Karelian, Kola, Belomorian, Murmansk and Norrbotten provinces in northern Fennoscandia forms the nucleus of the Fennoscandian Shield (Hölttä et al., 2008). The evolution of the larger, relatively coherent easterly provinces has been well-constrained (e.g. Hölttä et al., 2008; Kulikov et al., 2010), but their relationship with the westerly Norrbotten province, and in particular the Archean outliers along the Norwegian coast (Bergh et al., 2014) has been more difficult to understand, due to the overall segmentation of the Archean crust into variably sized blocks detached from the attenuated Archean continent during progressive rifting events at < 2.5 Ga (e.g. Nironen, 2017). Despite their segmented nature and the truncating Caledonian orogeny, the Archean outliers along the Norwegian coast in the west are frequently considered an autochtonous part of the Fennoscandian Shield (Henkel, 1991; Olesen et al., 1997). This interpretation is supported by the continuity of the major NW–SE structural trends and timing constraints over magmatism and deformation within northern Fennoscandia (Fig. 1; Henkel 1991; Doré et al., 1997; Olesen et al., 1997; Bergh et al., 2014). Further correlation with the unexposed south–western margin of the Archean domain in Sweden (e.g. Mellqvist et al., 1999) results in a NW–SE trending Archean-Proterozoic boundary which is partially concealed, relatively linear, and has a substantial lateral continuity across the Fennoscandian area (Fig. 1), comparable to the major NW–SE trending rift systems bounding the Kola and Karelian Cratons (Fig. 1; Melezhik & Hanski, 2013). Consequently, Skyttä et al. (2019) attributed the margin orientation to tensional stresses during the incipient plume-induced active rifting at 2.45 Ga, with later reactivation leading to the final continental break-up at around 2.1 Ga.

This paper aims at constraining the timing of magmatism and subsequent deformation within the westernmost extremity of the semi-coherent Karelian Craton, which is generally less-studied with respect to its eastern counterpart. The target of the investigation is the Kukkola Gneiss Complex (KGC) which underlies the Paleoproterozoic Peräpohja Belt (Piippo et al., 2019), and extends from Tornio in Finland across the Swedish border to the Haparanda area (Fig. 1; Koistinen et al., 2001; Bergman et al., 2014). KGC is an elongated NW–SE trending gneissic dome cored by 2.67–2.69 Ga metatonalitic rocks (Öhlander et al., 1987; Bergström et al., 2015) and bound towards the west by the N–S trending Pajala Shear Zone (Berthelsen & Marker, 1986; Kärki et al., 1993; Luth et al., 2018).

Correlating the results of new zircon U-Pb age determinations and geochemical patterns from two samples of Archean intrusive rocks with contrasting structural settings allows us to i) test whether the KGC is part of the Karelian Craton and whether the model of NW–SE lateral continuity of Archean components within the northern Fennoscandia (Bergh et al., 2014; Bingen et al., 2016) is valid, and ii) provide additional evidence for the possible age trend of Neoarchean igneous magmatism, e.g. sanukitoid igneous magmatism in the Karelian Craton grew younger from east to west (eg. Hölttä et al., 2012). The second main objective of this work is to delineate the occurrence of the 1.88 Ga and the 1.80 Ga intrusives of the Haparanda and Lina suites, which make up a great proportion of the crust of the area. The new age constraints of this study lead to improvement of our knowledge about the Precambrian crustal evolution in Northern Fennoscandia, and are most likely useful also with respect to configuring the past supercontinents (Bleeker, 2003; Bleeker & Ernst, 2006; Pehrsson et al., 2013), including their break-up by continental rifting processes (Skyttä et al., 2019). This work builds upon the MSc Thesis of Maiju Määttä (nee Kaartinen; Kaartinen, 2017).

2. Geological setting

2.1. Overview

The Archean domains of Fennoscandia may be broadly described by major crust-formation periods and orogenic events at approximately 2.9–2.7 Ga, followed by a long period of quiescence and, therefore, are associated with a family of Neoarchean supercratons comprising the Karelia-Kola, Superior, Hearne and Wyoming Cratons (Bleeker & Ernst, 2006; Pehrsson et al., 2013). The Fennoscandian Archean provinces (op. cit.) show a relatively wide range of Meso- to Neoarchean ages, but characteristic for all the provinces is the presence of compositionally versatile, dominantly felsic 2.8–2.7 Ga intrusive rocks (Hölttä et al., 2008 and references therein). The Archean outliers of Norway and the Råstojaure complex of Norrbotten (Sweden) show a comparable evolution characterized by magmatism and cratonisation at 2.9–2.7 Ga, with the dominant tectonothermal events following at 2.70–2.67 Ga (Skiöld, 1979, Skiöld & Page 1998, cf. Martinsson et al., 1999; Bergh et al., 2014 and references therein). The minor exposures of Archean crust in Luleå, southwest of the area of this investigation (Fig. 1), show a range of magmatic ages of 2.71–2.64 Ga (Lundqvist et al., 1996, Wikström et al., 1996).

The studied KGC is one of the scattered remnants of Archean rocks in northern Sweden and forms the apparent lateral continuation of the Archean Pudasjärvi Complex (Fig. 1; Koistinen et al., 2001; Bergman et al., 2014; Bergström et al., 2015) which is the westernmost block of the Archean Karelian Craton in northern Fennoscandia (Hölttä et al., 2008). The Pudasjärvi Complex comprises Archean migmatitic gneisses and amphibolites, the 2.82 Ga Oijärvi greenstone belt, 2.8 Ga tonalites-trondhjemites-granodiorites (TTG), paragneisses with post-2.74 Ga depositional ages, and approximately 2.7 Ga mafic and felsic intrusive rocks, including anatectic granites, migmatites and mantle-derived quartz diorites (Lauri et al., 2011; Huhma et al., 2012). Moreover, it encompasses the oldest rocks of the Fennoscandian Shield, the 3.5 Ga tonalite gneisses within the Siurua Complex (Mutanen & Huhma, 2003). The Archean basement has been intruded by mafic-ultramafic layered intrusions along the NE-SW trending Tornio-Näränkävaara Belt: the Tornio intrusion occurring on the flank of KGC is undated but correlated with the better-studied 2.44 Ga intrusions within the Pudasjärvi Complex (Alapieti et al., 1990; Iljina & Hanski, 2005; Iljina et al., 2015; Halkoaho, 1993; Huhma et al., 2018). Overlying KGC, mafic-ultaramafic rocks of the Tornio intrusion have intruded into pre-2.44 Ga metavolcanic and metasedimentary rocks (Lundmark, 1984) which are unknown elsewhere in the study area, but are likely correlative to the 2.51–2.43 Ga Sumian sediments further east representing the first syn-rift deposited units (Melezhik & Hanski, 2013).

The depositional evolution of the Peräpohja Belt occurred during a prolonged period of 500 Ma and may be subdivided into three basin stages: i) the 2.4–2.1 Ga Early Basin Stage comprises coarse continental sediments and flood basalts, ii) the 2.1 Ga Middle Basin Stage is characterized by numerous relatively thin sedimentary and volcanic units and, iii) the 2.0–1.88 Ga Late Basin Stage is characterized by deposition of finer-grained material in a deepening ocean basin (Perttunen, 1991; Laajoki, 2005; Kyläkoski et al., 2012; Vanhanen et al., 2015). No systematic comparison of rocks across the Finnish-Swedish border has been conducted, but Kaartinen (2017) suggests correlation of the greenstone-dominated lower part and the compositionally more variable central (2.1 Ga) and upper parts of the Sockberget and Kalix Groups (Wikström, 1996) with the > 2.25 Ga metavolcanic Runkaus Formation) (Fm), and the > 2.22 Ga Palokivalo Fm and the > 2.14 Ga Petäjäskoski Fm in Finland (Perttunen et al., 1996; Kyläkoski et al., 2012), respectively. Moreover, Kaartinen (2017) correlated the Karlsborg Fm and the Råneå Group (Bergman et al., 2014) with the 2.15–2.05 Ga Jouttiaapa Fm and 1.9 Ga

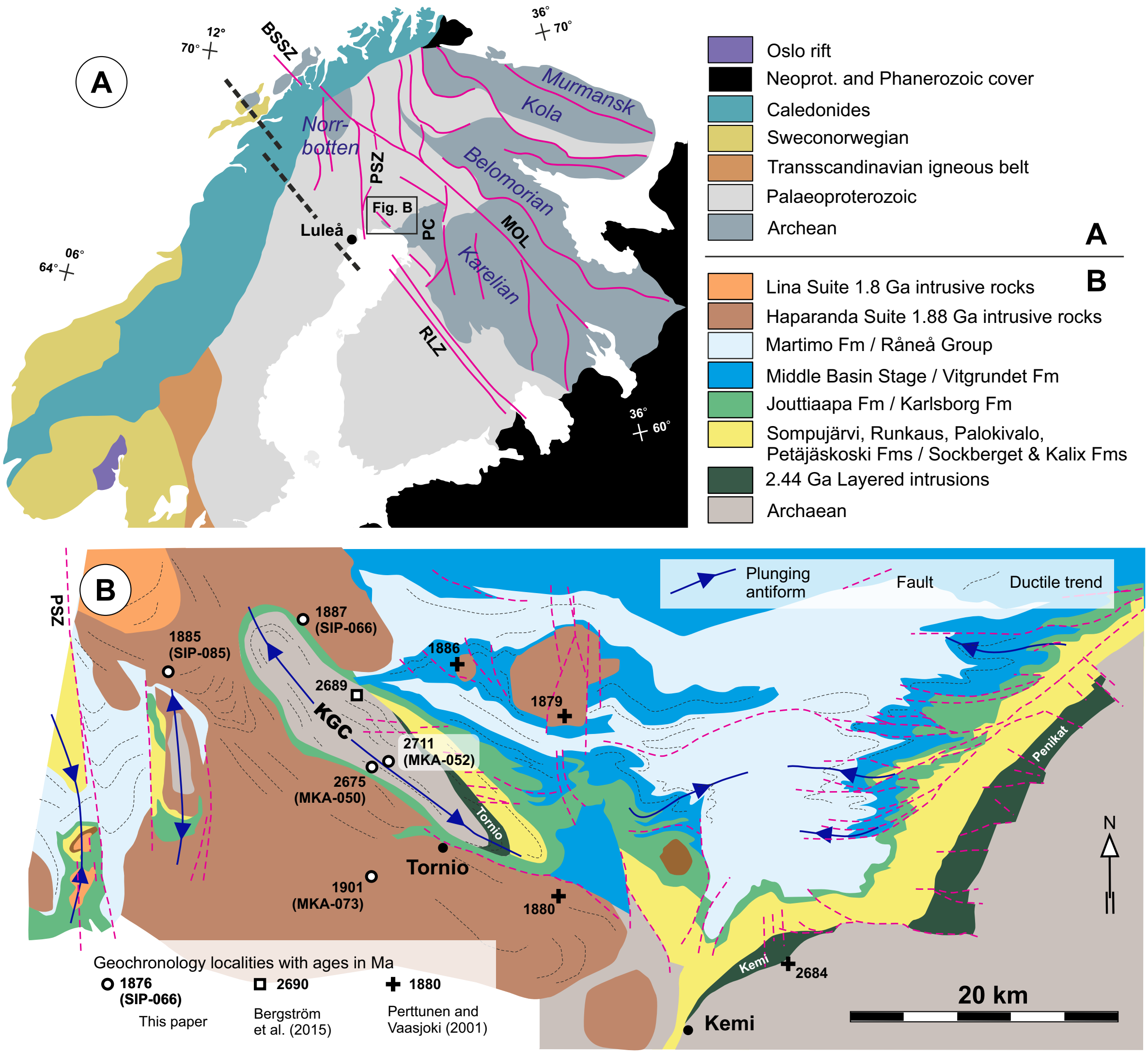

Figure 1. a) An overview of the major geological domains of Fennoscandia. The purple lines are major deformation zones and the thick dashed line indicates the south-western extent of the concealed Archean crust (Mellqvist et al., 1999). BSSZ = Bothnia-Senja shear system, MOL = Malangen-Onega Lineament, PC = Pudasjärvi Complex, PSZ = Pajala Shear Zone, RLZ = Raahe-Ladoga Zone (modified after Bergh et al. 2014). b) Geology of the study area with reference to geochronology work conducted in this investigation and relevant previous investigations. The simplified lithology is drawn according to the cross-border correlations by Kaartinen (2017) and structure by Piippo et al. (2015; 2019). KGC = Kukkola Gneiss Complex. The occurrences of pre-2.44 Ga metavolcanic and metasedimentary rocks are too thin to be shown on the map.

Martimo Fm (Ranta et al., 2015; Huhma et al., 2018), respectively, and the Vitgrundet Fm with the Middle Basin stage of the Peräpohja Belt (Vanhanen et al., 2015; Piippo et al., 2019).

Several generations of mafic dykes clustering at least at 2.22, 2.14 and 2.1 Ga transect both the Archean basement, and the stratigraphically basal parts of the Paleoproterozoic Peräpohja rocks (Perttunen & Vaasjoki, 2001; Perttunen & Hanski, 2003; Hanski et al., 2010; Kyläkoski et al., 2012). Paleoproterozoic intrusive rocks within the study area comprise approximately 1.88 Ga Haparanda granitoids, dioritoids and gabbroids (Ödman et al., 1949; Ödman, 1957; Lehtonen et al., 1998; Perttunen & Vaasjoki, 2001), the 1.8 Ga Lina Suite granites (Holmqvist, 1905; Bergman et al., 2014) and the 2.1–1.77 Ga Central Lapland Granitoid Complex rocks (Fig. 1; Ahtonen et al., 2007; Lauri et al., 2012).

Structurally, the extent of the Archean rocks is bound by the Pajala Shear Zone in the west and, overall, much of the distribution and structural overprint of the overlying Paleoproterozoic rocks is controlled by movements of the underlying Archean basement blocks (Nironen, 2017; Piippo et al., 2019; Skyttä et al., 2019). The prolonged depositional history of the Peräpohja Belt from 2.4 to 1.9 Ga is attributed to either a failed rift (Gaál, 1990) or a pull-apart basin initiated at the onset of rifting of the Archean continent at approximately 2.45 Ga (Skyttä et al., 2019).

2.2. The Kukkola Gneiss Complex (KGC)

Archean rocks on the Swedish part of the study area are present within the NW–SE trending elongated dome-shaped KGC, and based on a distinct magnetic low in geophysical data, within the unexposed core of a structurally similar dome further to the south-west (Bergman et al., 2014). KGC is lithologically and structurally variable, comprising metamorphosed tonalite, trondhjemite, gabbro and granite, displaying gneissose structures, banding, recrystallization, alteration and felsic dykes (Bergman et al., 2014). The single-grain SIMS dating by Bergström et al. (2015) confirmed the earlier magmatic age of 2670±18 Ma (Öhlander et al., 1987) and further tightened the constraint about the magmatic crystallization of the complex at 2689±3 Ma. The dated sample was an equigranular, medium-grained, gneissic metatonalite with no migmatising veins present at the sample locality along the north-eastern flank of the NW–SE trending dome (Fig. 1b). Besides the 2689±3 Ma magmatic crystallization age, two contrasting zircon rim domains characterized by dark signatures in cathodoluminescence imaging yielded an age of 2667±5 Ma which was taken to reflect a subsequent metamorphic overprint (Bergström et al., 2015).

3. Methods and data

Geological observations from a total of 217 localities were collected during the field mapping campaign in Finland and Sweden. We collected a total of five geochronology samples: Two structurally constrained geochronology samples (MKA-050, MKA-052) to determine the age of magmatic, tectonic and metamorphic events within the Archean KGC, and three further geochronology samples (MKA-073, SIP-066, and SIP-085) to refine the distribution of the 1.88 Ga Haparanda suite and the 1.80 Ga Lina suite intrusive rocks.

Petrographical analyses of geochronology samples, comprising observations on the mineralogy and rock fabric were conducted from regular 30 µm polished thin sections. Geochemical composition of the geochronology samples were analysed to provide further tools for correlation with known Archean intrusive rocks within the Karelian Craton. The analyses were conducted in Acme Analytical Laboratories Ltd. (Bureau Veritas Group) in Vancouver, Canada, from an approximately 4 cm^3 of material/sample. The rocks were cut in a way that only pristine and homogeneous samples were sent for analysis. In the laboratory the whole rock samples were pulverized to pass a diameter 200 µm mesh and 36 elements were analyzed with the ICP-MS method. We plotted the geochemical data using GCDkit 6.00 (Janoušek et al., 2019).

For the age determinations, we separated ~ 150 zircons from each geochronology sample, BSE-imaged the zircons to target the spot analysis sites and eventually performed the U-Pb dating analyses using a Nu Plasma AttoM single collector ICP-MS connected to a Photon Machine Excite laser ablation system. We plotted the U-Pb isotopic data and conducted the age calculations using

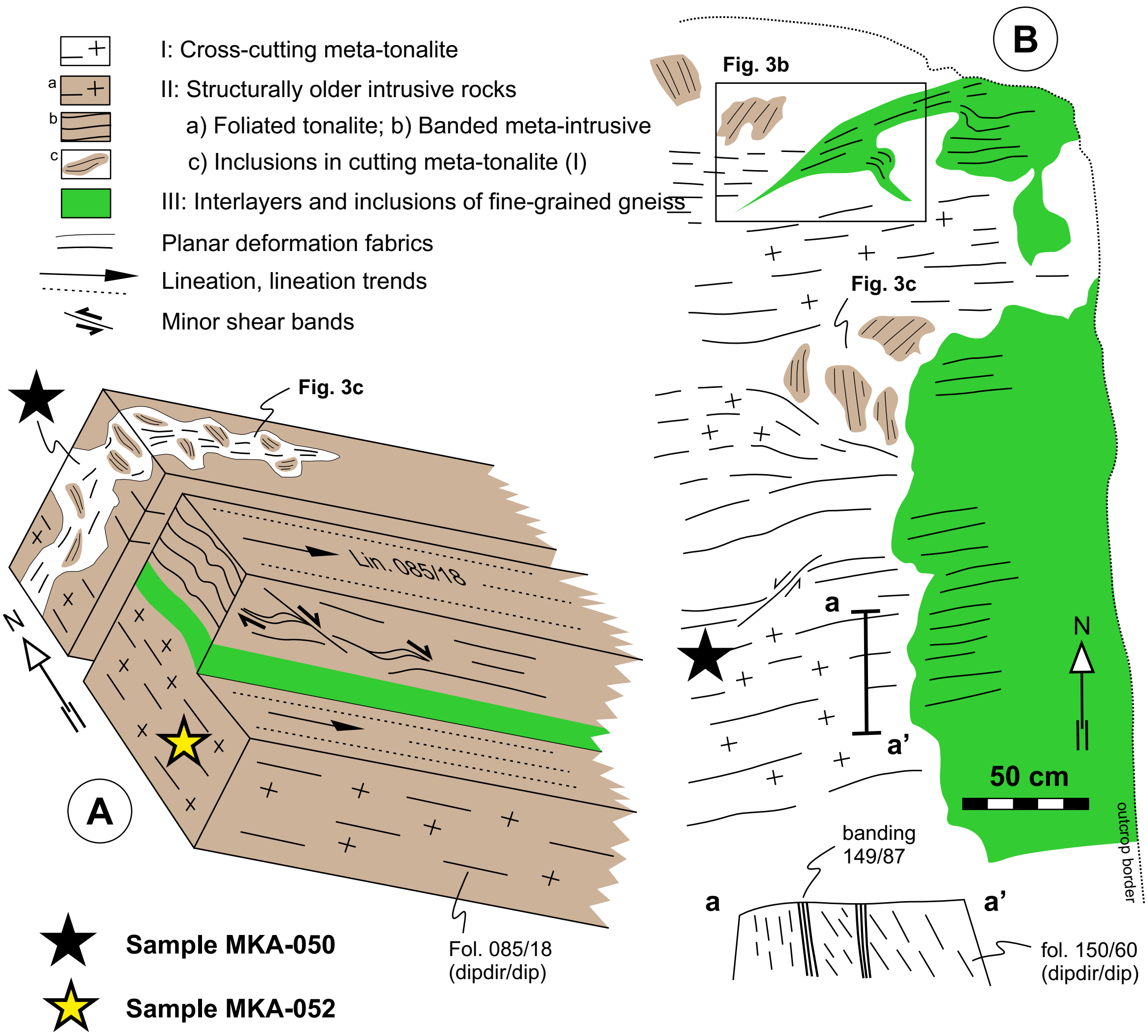

Figure 2. Structural setting of the intrusive rocks sampled for age determinations. a) A schematic block drawing illustrating the relationship between the older foliated (MKA-052) and younger cross-cutting (MKA-050) intrusive rocks. Notice that samples MKA-050 and MKA-052 are spatially separated (see Fig. 1B). b) Sampling locality for MKA-050 displaying the presence of larger coherent and smaller brecciated inclusions of older banded metatonalite within the younger, heterogeneously deformed intrusive units (sample MKA-050).

the Isoplot/Ex 3 program (Ludwig, 2003). All the ages were calculated with 2σ errors and without decay constants errors. Data-point error ellipses in the figures are at the 2σ level. A more detailed description of the preparation, imaging and analysis of the geochronology samples is given in Electronic Appendix A.

4. Sample descriptions

The geological setting of the geochronology samples is described below and an overview of their petrography is given in Table 1. The used rock names are those determined in the field, without subsequent validation by other methods.

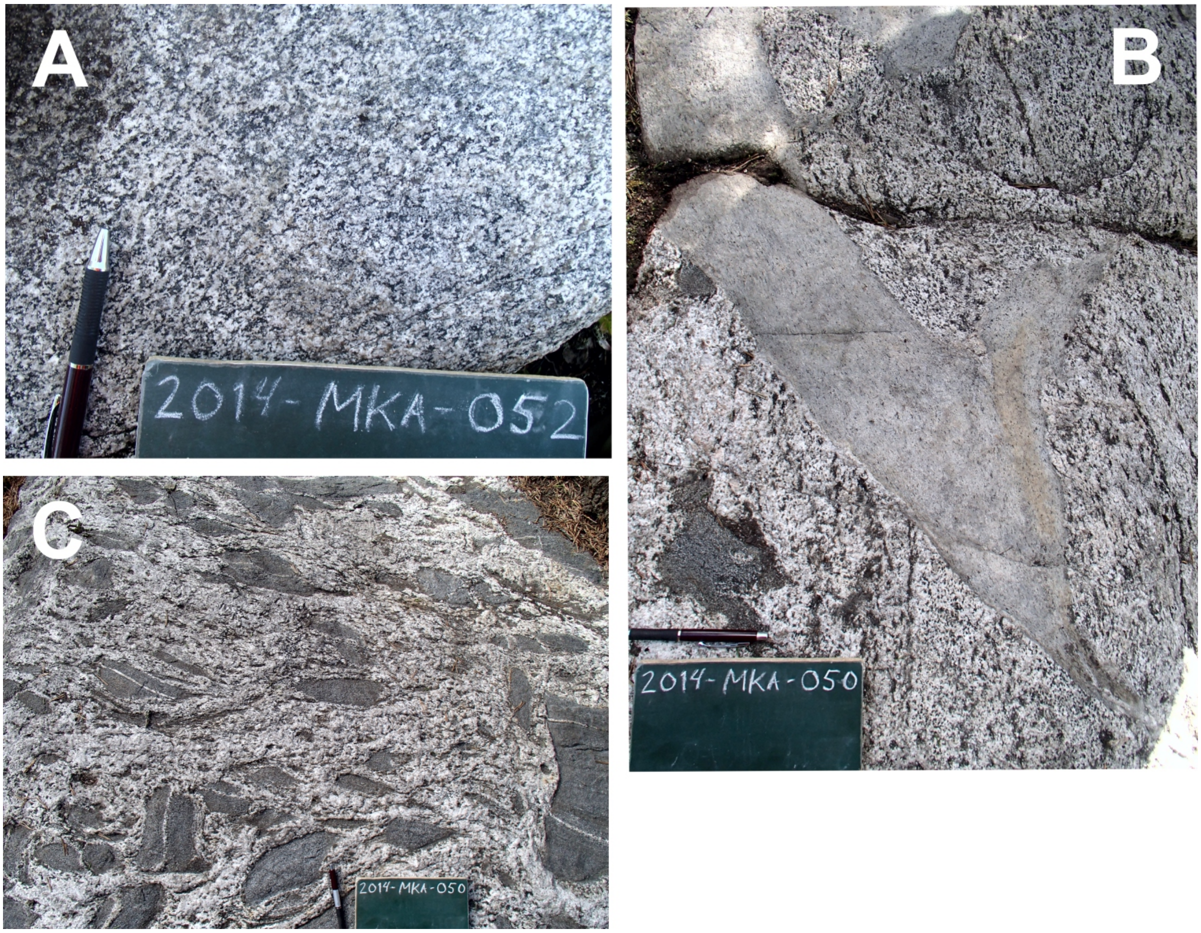

Figure 3. a) Sampling locality MKA-052. Homogeneous tonalite with a rather weak, penetrative, gently-dipping foliation. b–c) Sampling locality MKA-050. b) A folded inclusion of gneiss within the foliated hornblende-tonalite. c) Variably transposed inclusions of banded, medium-grained, intermediate rocks within the hornblende-tonalite sampled for age determination. The width of the plate is approximately 15 cm.

4.1. Archean rocks

The tonalite sample **MKA-052** was collected approximately from the centre of the KGC (Figs. 1b, 2a). The outcrop is characterized by a medium- and even-grained lower part, overlain by a horizon of fine-grained intermediate gneiss and locally more banded meta-granitoids on the top of the outcrop. All these rocks are foliated with gentle easterly dips and display clear mineral lineations with down-dip attitudes. Minor shear bands within the banded portions indicate east-block-down movement senses (Fig. 2a). No signs of later cross-cutting fabrics were observed. The geochronology sample taken from the basal portion of the outcrop is even-grained and homogeneous (Fig. 3a) and considered to provide a crystallisation age for the intrusive rocks and also a maximum age of the gently-dipping fabric.

The sampled hornblende-tonalite **MKA-050** is located on the south-western flank of KGC (Fig. 1b). The outcrop is characterised by an overall brecciated appearance with larger coherent and smaller brecciated fragments of older metatonalite and fine-grained gneisses intruded by the hornblende-bearing migmatizing tonalitic melt (Figs. 2b, 3 b,c).

Table 1. The geological character, setting and petrography of the rocks sampled for geochronology analyses.

ID	Northing*	Easting*	Age Ma**	Lithology	Field relations	Def. Fabric	Colour	Texture	Grainsize	Main minerals***
MKA-052	7339029	910276	2711±8	Tonalite	Oldest intrusive unit in KGC centre	Foliated & lineated	Grey	Even-grained	Medium (1-5mm)	qtz, kfs, pl, bt
MKA-050	7339334	911908	2675±10	Hbl.-tonalite	KGC flank, younger migmatising melt pulse	Variably foliated	Black/ white	Weakly porphyritic	Medium (1-5 mm) / coarse (> 5 mm)	pl, hbl, px, bt, qtz, kfs
MKA-073	7330605	912551	1901±10	Granite	Granite cross-cuts older gabbro	Weakly foliated	Reddish	Porphyritic	Medium (1-5 mm) / coarse (> 5 mm)	qtz, kfs, pl, bt, px
SIP-066	7348543	903431	1887±9	Tonalite	Immediately NE of KGC	Foliated & lineated	Grey	Even-grained	Fine (< 1mm)/ medium (1-5 mm)	pl, qtz, px, hbl, kfs, opaq
SIP-085	7342767	893874	1885±9	Granite	North of an unexposed Archean dome	Magm. fol., no tectonic fabric	Reddish	Porphyritic	Coarse (>5 mm)	kfs, qtz, pl, bt

* Coordinates in SWEREF99

** See Section 6 for results

*** pl = plagioclase, qtz= quartz, kfs = K-feldspar, bt = biotite, px = pyroxene, hbl = hornblende, opaq = opaques

The brecciating hornblende-tonalite is somewhat heterogeneously deformed as shown by the foliation patterns (Fig. 2b, including the cross-section) and the arrangement of the older inclusions: some have been folded (Fig. 3b) whereas others show variable degrees of transposition towards parallelism with the tonalite foliation (Fig. 3c). The sampled brecciating, black-and-white, mesocratic, medium to coarse grained hornblende-tonalite (MKA-050) is considered to provide the age for the younger magmatic and structural overprint on the older intrusive event observed at MKA-052.

4.2. Paleoproterozoic rocks

Sample **MKA-073** was collected from an abandoned quarry south-west of Tornio (Fig. 1b). The sampled rock is a granite which cross-cuts an older gabbro. The sampling spot was located 10 metres east of the contact. The sampled granite is reddish, leucocratic, medium to coarse-grained and has a porphyritic texture (Fig. 4a).

Sample **SIP-066** was taken from the immediate vicinity of KGC, on its north-eastern side (Fig. 1b). The sampled rock is a grey, mesocratic, fine to medium-grained tonalite (Fig. 4b). The rock has observable linear and planar fabrics and may be described as an L-S tectonite.

Sample **SIP-085** was taken north of the smaller, unexposed Archean dome (Fig. 1b). The sampled rock is a porphyritic granite with clearly discernible magmatic foliation (Fig. 4c). The alignment of the K-feldspar grains within the close vicinity of the sampling point was systematic and parallel with the regional foliation. The sampled rock is reddish, leucocratic, coarse-grained, porphyritic granite, which does not show any signs of tectonic deformation. The outcrop also contains several parallel finer-grained aplitic veins (Fig. 4c) which were not included in sampling.

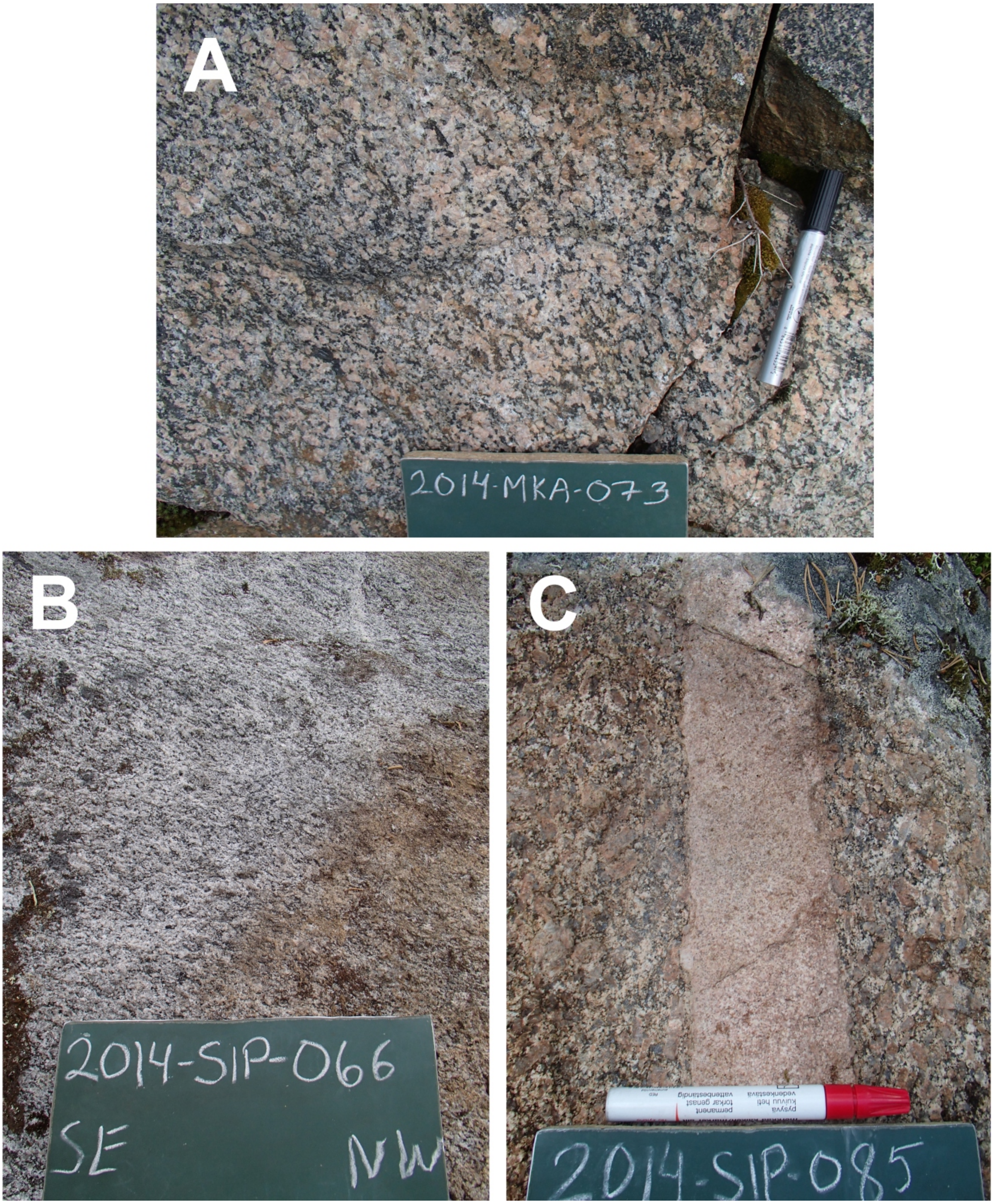

Figure 4. Sampled Haparanda-suite intrusive rocks. a) The porphyritic texture of the granite at locality MKA-073. b) Fine-grained, homogeneous tonalite of sampling locality SIP-066. c) Sample SIP-085 with a magmatic foliation and a cross-cutting fine-grained aplite dyke.

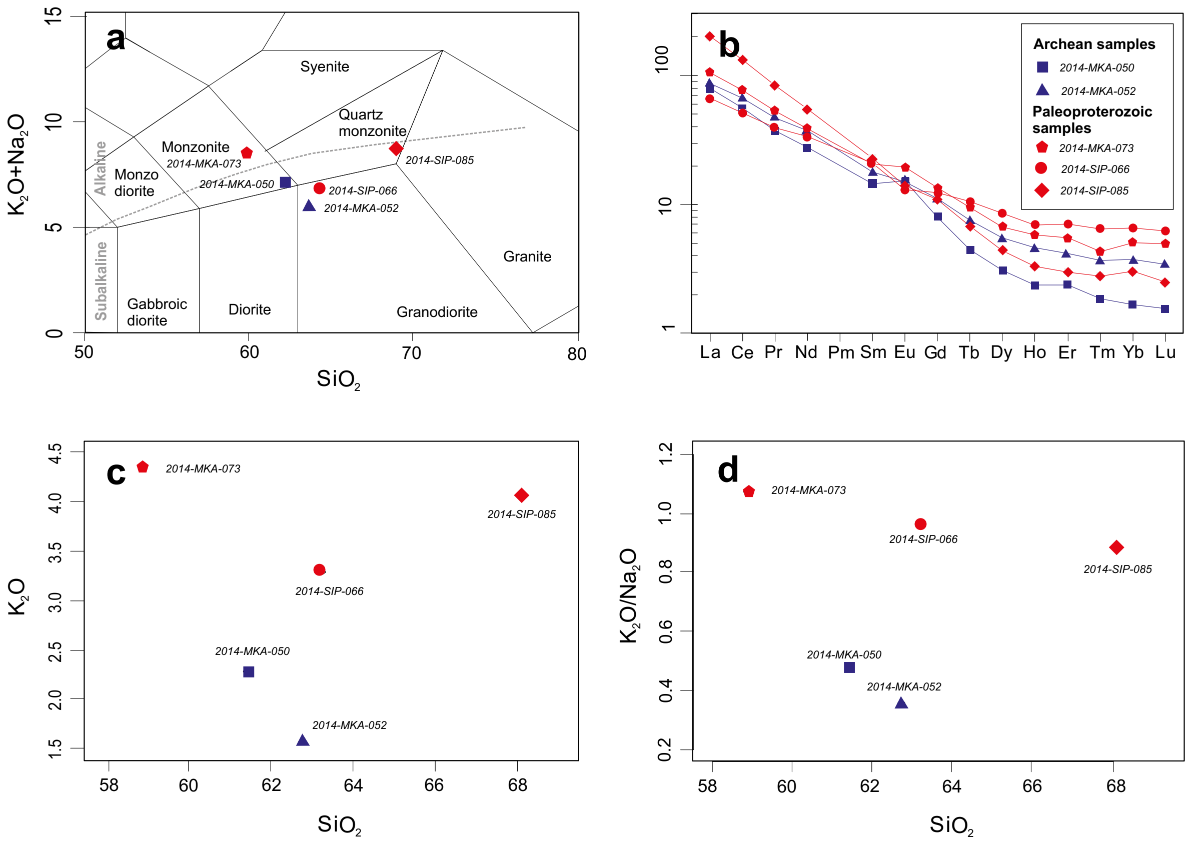

Figure 5. Composition of the studied samples shown a) Na_2O+K_2O vs. SiO_2 (TAS fields from Middlemost, 1994). b) chondrite-normalized REE diagram (Boynton, 1994). c) K_2O vs. SiO_2; d) K_2O/Na_2O vs. SiO_2.

5. Geochemistry

Elemental compositions of the five studied samples are shown in Figure 5 and the geochemical data are provided in Electronic Appendix B. The TAS diagram (Fig. 5a) shows mainly intermediate to felsic compositions (SiO_2 = 58.89–68.12 wt %) and subalkaline characteristics with one outlier (014-MKA-073) plotting in the monzonite field. The REE patterns of chondrite normalized analyses are fractionated [$(La/Lu)_N$ ~ 10–50] without a major Eu anomaly (Fig. 5b). The Archean and Paleoproterozoic samples can be distinguished based on their K_2O contents ranging at 1.56–2.27 wt % and 3.29–4.34 wt %, respectively (Fig. 5c). Na_2O and K_2O contents emphasize the difference between the Archean and Paleoproterozoic granitoid compositions, best demonstrated with K_2O/Na_2O ratios (Fig. 5d).

6. Results of the age determinations

6.1. Archean rocks

Sample MKA-052: (Tonalite) The separation of the sample MKA-052 produced subhedral to euhedral zircon grains 100 to 350 µm in grain size. The Back Scattered Electron (BSE) images reveal oscillatory zoning for many of the grains (Fig. 6a). A total of 50 spots were analysed (Electronic Appendix C) and 41 of these analyses were concordant at 2σ-level. The concordant data plot in two separate clusters. The older cluster is defined by three analyses deriving from three separate grainsresulting in is a concordia age of 2931±26 Ma (95% confidence)

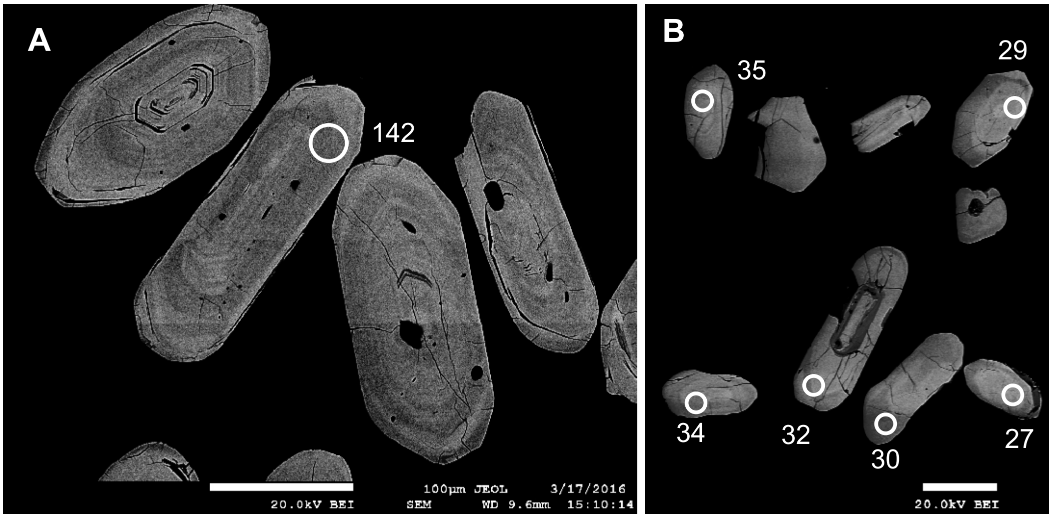

Figure 6. BSE-images of the Archean samples. a) MKA-052. Oscillatory zoning textures. b) MKA-050. Characteristic fractured appearance of zircon. The BSE images further reveal brighter zoned internal and homogeneous darker outer areas or rims. The rings exemplify sites of the conducted analyses. The white scale bar in both images is 100 µm.

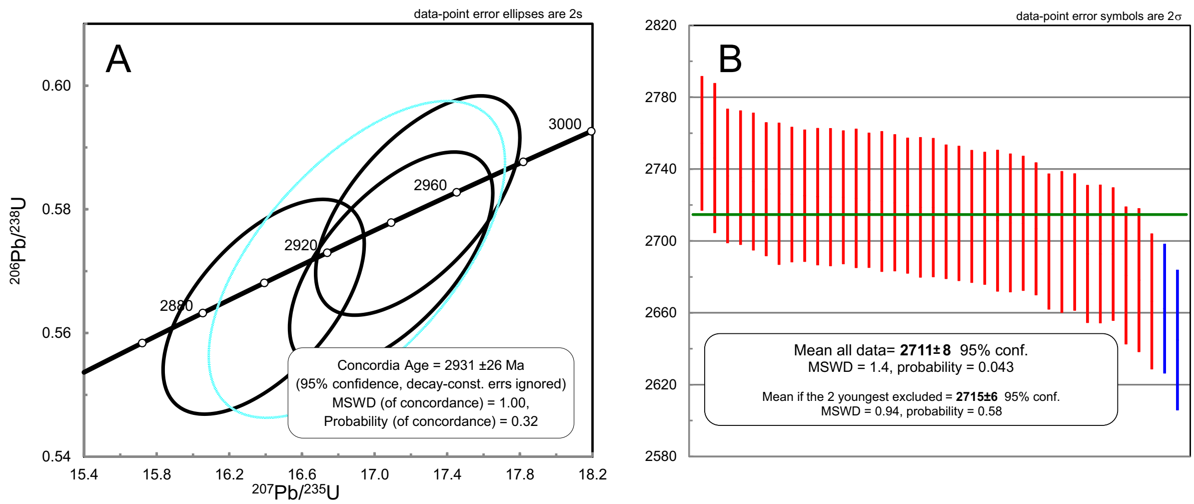

Figure 7. Age results for sample MKA-052. a) Concordia diagram of the three separate zircon grains interpreted to be of inherited origin with an age of 2931±26 Ma. b) Weighted average of the $^{207}Pb/^{206}Pb$ ages representing the crystallization age (2711±8 Ma) of the rock.

with MSWD of concordance = 1.00 and probability of concordance = 0.32 (Fig. 7a). The main cluster consists of 38 analyses with $^{207}Pb/^{206}Pb$ ages varying from 2754±37 Ma to 2645±39 Ma (Fig. 7b). No single concordia age for these data can be calculated. Textural classification of the grains does not allow classification of this cluster into meaningful subclusters. Weighted average for all these data yields a mean age of 2711±8 Ma (95% conf.) with MSWD = 1.4, probability = 0.043. Excluding the two youngest analyses, deriving from the same grain (67a and b; Electronic Appendix C), results in a nearly same age of 2715±6 (95% conf.) but with a better MSWD value of 0.94 and probability of 0.58. Based on the above, we consider the age of 2931±26 Ma to show inheritance and the age of 2711±8 Ma is considered as the best estimate of the crystallization age of the rock.

Sample MKA-050 (Hornblende-tonalite): The separation of the sample MKA-050 produced mostly subhedral, rounded, and typically fractured zircon grains ranging in size from 100 to 250 µm. BSE images reveal bright oscillatory zoned central areas and in some instances homogeneous darker outer areas (Fig. 6b). A total of 39 spots were analyzed (Electronic Appendix C) and plotting the data reveals that it is heterogenous in age (Fig. 8a). Using all the data a discordia age of 2709±23 Ma with high MSWD of 6.6 can be calculated. This age is not considered meaningful due to the heterogeneity of the population. 15 of the analyses were concordant at 2σ-level. These data can be divided into two groups on the basis of the textures at the analytical location; (1) BSE bright mostly inner domains of the grains that sometimes show oscillatory zoning and (2) outer domains of the grains that often are homogeneous and darker (compared to inner domains) in BSE images. A concordia age of 2676±15 Ma (95% confidence, decay-const. errs ignored) can be calculated for the first group, containing 10 analyses. The MSWD of concordance is relatively high (8.0) and the probability of concordance is low (0.005) for this sample set. The second group (n=5) has a concordia age of 2671±17 Ma with low MSWD of concordance (0.00025) and high probability of concordance (0.99). Taking into account all the data from the two texturally different groups that are concordant at the 2σ level a concordia age of 2675±10 Ma can be calculated (MSWD of concordance) = 5.4, probability (of concordance) = 0.020). If the two least concordant data points are ignored there is no significant difference in the calculated concordia age; 2677±10 Ma, but the MSWD of concordance increases to 1.5, and probability of concordance is higher (0.22).

Taking into account the 2σ error limits of the concordia ages calculated for the two textural groups, we cannot observe any clear age difference between the groups. Although it may be possible that these textural domains represent geologically different events, we interpret that the best estimate of the igneous age of rock is the calculated concordia age of 2675±10 Ma.

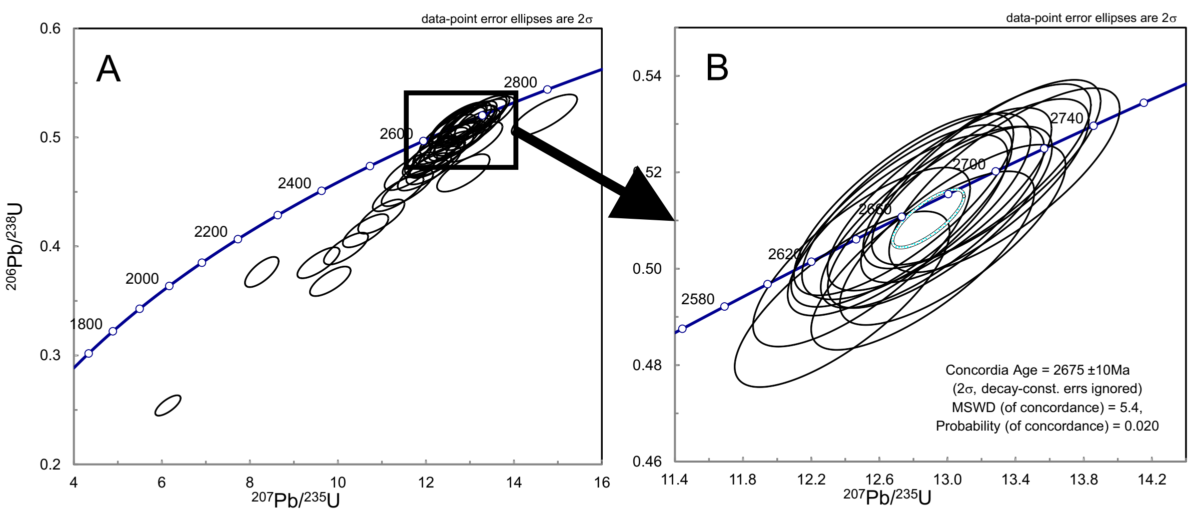

Figure 8. Sample MKA-050. a) Concordia diagram showing all the data. b) Concordia diagram of the concordant analyses from both the inner zoned and outer homogeneous, BSE-darker domains (Fig. 6b) giving an age of 2675±10 Ma.

6.2. Paleoproterozoic rocks

Sample MKA-073 (granite): The sample contains subhedral and semi-angular zircon grains varying from 100 to 300 µm in size. The zircon grains are mainly transparent with a shade of pink though darker ones are also present. BSE images (Fig. 9a) show inclusions, fracturing and zoning in most of the grains. Zoning is present mainly in the xenocrystic core parts.

25 analyses were conducted on the sample MKA-073 (Electronic Appendix D). All these data plot fairly close to the concordia curve, but no concordia age can be calculated. Taking all the data, a discordia age of 1899±16 Ma can be calculated (Fig. 10a). However, after filtering for data quality (% concordance must be >95% and $^{206}Pb/^{204}Pb$ must be > 5000), 17 analyses remain. These provide a $^{207}Pb/^{206}Pb$ age of 1901±10 (Fig. 10b), equivalent within error to the discordia age. We consider the age of 1901±10 Ma to be the best estimate for the crystallisation age of this granite.

Sample SIP-066 (tonalite): Separation of the sample provided 147 zircon grains varying in size from 75 to 250 µm. The grains are subherdal, subrounded and relatively fractured. They are transparent with a pinkish tint, and occasionally contain inclusions. Xenocrystic cores are present in approximately one third of them (Fig. 9b).

Altogether 24 U-Pb analyses were made on zircon and 22 analyses of them were concordant at 2σ-level (Electronic Appendix D). The data are heterogeneous and no single concordia age could be calculated. The calculated discordia age of 1890±9 Ma (MSWD=1.3) is in line with the mean age of 1887±9 Ma (Figs. 10c,d) that is derived from 22 data points after excluding the two analyses with oldest ^{207}Pb-/^{206}Pb ages (1997±40 Ma and 1914±42 Ma at the 2σ level) that indicate inheritance. We consider the mean age of 1887±9 Ma as the best estimate for the crystallization of the tonalite.

Sample SIP-085 (granite): Separation of the sample SIP-085 produced zircons with grain sizes varying between 100 and 350 µm. Majority of the grains are subhedral and sub-angular, fractured and partly heavily altered while some euhedral and needle-like grains are also present. The grains are typically grayish in color, with some transparent grains present as well. Some cores can also be seen in BSE images (Fig. 9c).

A total of 21 U-Pb analyses were done on the sample SIP-085 (Electronic Appendix D). 5 of these analyses provide discordant data at 2σ-level. Even if they were excluded no single concordia age can be calculated. Calculating discordia age for all the data we get an age of 1882±11 Ma is equivalent to the mean age of 1885±9 Ma derived from calculation

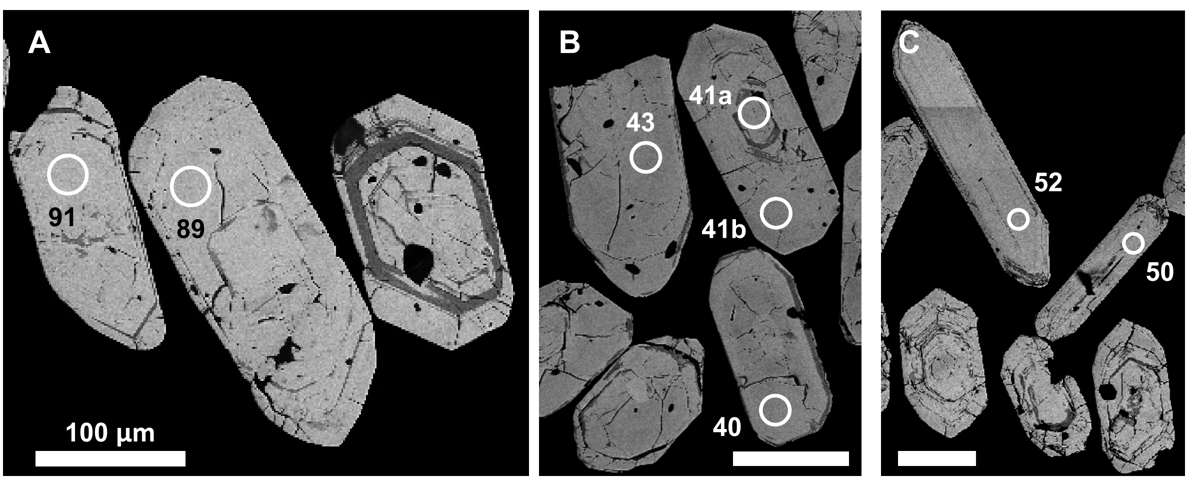

Figure 9. BSE-images of the Palaeoproterozoic zircons with selected analysis spots shown. a) MKA-073. b) SIP-066. c) SI-085. The white scale bar in all the images is 100 µm. The rings exemplify sites of the conducted analyses.

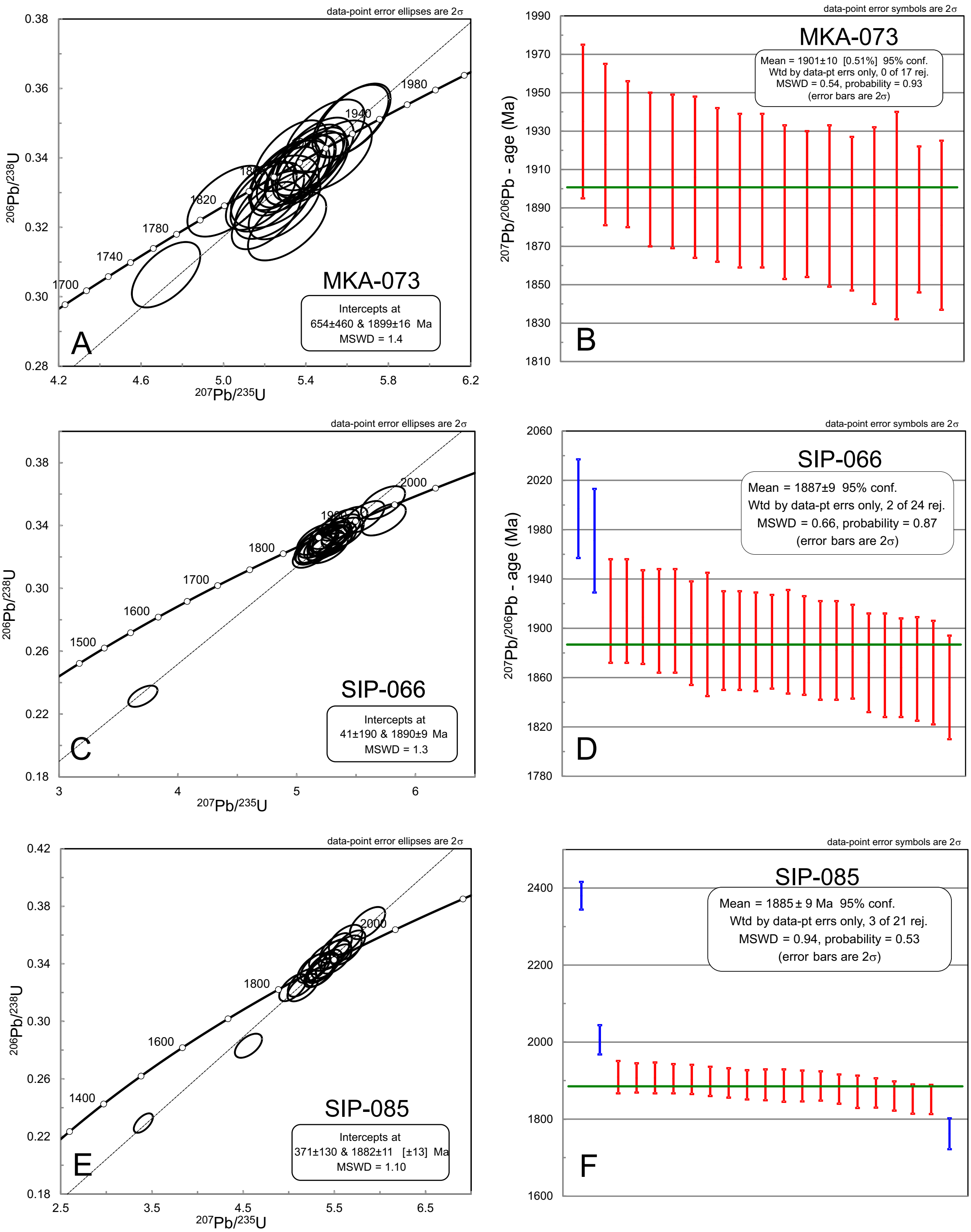

Figure 10. Discordia diagrams and $^{207}Pb/^{206}Pb$ mean ages for samples MKA-073 (a–b), SIP-066 (c–d) and SIP-085 (e–f). The blue bars in d) and f) indicate the outliers in the data excluded from the calculations.

excluding the two analyses having the lowest $^{206}Pb/^{204}Pb$-ratios and the one normally discordant grain having $^{207}Pb/^{206}Pb$ -age of 1762±40 Ma (Figs. 10e,f). We consider that the age of 1885±9 Ma is the best estimate of the crystallization age of the granite.

7. Discussion

The 2711±8 Ma age result (sample MKA-052) within the KGC core is clearly older than the previously determined 2.69 Ga and 2.67 Ga ages by Bergström et al. (2015) and Öhlander et al. (1987), respectively, as well as the new age of 2675±10 Ma (sample MKA-050). The 2.67 Ga by Öhlander et al. (1987) correlates with the younger 2.68 Ga tectonothermal event recognized in this study. On the cratonic scale, the 2.68 Ga event also correlates with the migmatisation and the so-called anatectic granitoids (Käpyaho et al., 2007; Mikkola et al., 2011 and references therein) and the peak of thermal metamorphism at least within the Lentua Complex occurring in the eastern part of the Karelian Craton. However, the composition of the Archean samples of this study is atypical within the regional context when considering their age. Overall, the most voluminous Archean granitoid type is Na-rich TTGs, which forms the majority of the Archean crust. In the Karelian Craton, Halla et al. (2009) proposed subdivision for TTGs based on their composition into: low- and high-HREE TTGs. Additionally, Mikkola et al. (2011) defined a minor group of younger intermediate quartz diorites with SiO_2 51.1–63.9 wt %, MgO 2.5–4.0 wt %, and high levels of LREE. In this study, mainly based on the MgO contents of 2.49 wt % and 2.16 wt % of the Archean samples, the studied Archean rocks are the most likely part of quartz diorite group. However, it is worth mentioning that the HREE content (Lu = 0.05 ppm) of sample MKA-50 is untypically low for the quartz diorite group, and more typical of the low-HREE TTGs subgroup. Temporally the Archean TTGs within the Eastern Karelian Craton (e.g. Lentua complex) are typically > 2.74 Ga. i.e. older than the 2.71–2.68 Ga Archean rocks of this investigation, which are instead roughly coeval with the sanukitoids, quartz diorites and anatectic granitoids of the Eastern Karelian Craton. Moreover, the Archean rocks dated in this study occur close to the migmatisation and metamorphic peak that are often considered to be related with SiO_2 and K_2O enriched anatectic granitoids (Käpyaho et al., 2007; Mikkola et al., 2012). Overall, our data support the proposed idea of younging Neoarchean igneous magmatism in the Karelian Craton from east to west that is indicated by a documented younging direction from east to west of sanukitoid magmatism (Hölttä et al., 2012).

Bearing in mind the ±10 Ma error margin in the younger Archean age of this study, we may not differentiate whether the suggested 2.67 Ga metamorphic event (Bergstörm et al., 2015) was a separate event or prolonged metamorphic overprint over the tightly constrained primary magmatic event at 2689±3 Ma (Bergström et al., 2015). Bergström et al. (2015) base the presence of the metamorphic event on 2.67 Ga ages of two CL-brighter rim domains. Our data do not, however, give us possibility to discuss on this matter as the texturally contrasting core and margin domains of sample MKA-050 show similar ages when taking into account the 2σ-errors (see e.g. Spots 67a and b; Electronic Appendix C).

Comparing geochronological data is one of the typical ways of comparison between crustal blocks. In the Lofoten-Vesterålen and Råstojaure complexes in Norrbotten the crystallisation of granitoids is constrained at 2.8–2.7 Ga, and a regional metamorphic event at 2.7 Ga (Welin et al., 1971; Skiöld 1979; Skiöld & Page 1998; cf. Martinsson et al., 1999). Considering the age difference between the segments of e.g. the Karelian Craton, the slight misfits with the ages from the Lofoten-Westerålen area and the Norbotten do not seem to be highly significant. Moreover, despite the older 2.98–2.78 Ga ages of crystallization and reworking within the Archean Jergul complex and the associated Goldenvárri Formation in northern Norway, Bingen et al. (2016) assign these units as part of the Karelian Craton based on their "Karelian affinity", supporting the presence of an initially continuous but subsequently segmented Karelian Craton.

The results provide also some new viewpoints towards the structural interpretation of the domal structure of KGC: The sheared base of the Tornio (and Kemi) intrusion(s) (Söderholm & Inkinen, 1982) has been attributed to focussing of Proterozoic compressional overprint of syn-rift normal faults and strain localization into the vicinity of the intrusions' basal contacts (Skyttä et al., 2019). Recognition of the Archean deformation event (this paper) provides an alternative explanation where the doming could be of Archean age, associated with the 2.68 Ga tectonothermal event. However, the inferred sub-horizontal primary orientation of 2.44 Ga mafic-ultamafic layered intrusions (Karinen, 2010) makes an Archean age for the doming less likely.

Crystallization of the Haparanda series intrusives at 1.90–1.89 Ga within the Haparanda-Tornio area occurred slightly earlier than the average 1.88 Ga age for the suite, and also the granitic composition deviates from the more common dioritic or quartz-dioritic compositions (Bergman et al., 2014). The oldest 1.90 Ga intrusive rock (sample MKA-073) may be correlated with the Uusivirka supersuite and the interpreted metamorphic event at 1.92–1.90 Ga within the Pajala area (Lahtinen et al., 2015).

8. Conclusions

1) Crystallization age of the oldest intrusive rocks within the core of the Kukkola Gneiss Complex is 2.71 Ga.
2) Generation of the first deformation fabric within the oldest intrusive rocks within the Kukkola Gneiss Complex is constrained between 2.71 and 2.67 Ga.
3) A subsequent tectonothermal event occurred at 2.67–2.68 Ga and was associated with structural overprint; this is approximately the same age previously determined as the crystallization age of the Kukkola Gneiss Complex.
4) The geochemical compositions of the Archean samples are mainly comparable to the Archean quartz diorites described within the Karelian Craton.
5) The results support the correlation of KGC with the eastern part of the Karelian Craton, and the overall NW–SE continuity of the Archean continent.
6) The dated Haparanda-suite magmatic rocks range from 1.90 to 1.89 Ga in the Haparanda-Tornio area, overlapping with the average 1.88 Ga age of the suite in earlier studies.

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Supplementary data

Electronic Appendices A–D for this article are available via Bulletin of the Geological Society of Finland web page.

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