An Eoarchean continental nucleus for the Fennoscandian Shield, and a link to the North Atlantic Craton

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ABSTRACT

Enabling the build-up of continental crust is a vital step in the stabilisation of cratonic lithosphere. However, these initial crustal nuclei are often either destroyed by recycling or buried by younger rocks. In the Fennoscandian Shield, the oldest rocks are ca. 3.5 Ga, but ca. 3.7 Ga inherited and detrital zircons indicate the presence of an older, unexposed crustal substrate. We present U-Pb, O and Hf isotope data from detrital zircons of three major Finnish rivers, as well as zircon O and Hf isotope data from previously dated rocks of the Archean Suomujärvi and Pudasjärvi complexes, central Finland. Combined, these data indicate a previously un-identified ca. 3.75 Ga felsic crustal nucleus in the Fennoscandian Shield. This adds to the growing number of Eoarchean nuclei recognized in Archean terranes

around the globe, highlighting the importance of such nuclei in enabling the growth of continental crust. The isotopic signatures of the Fennoscandian nucleus correlate with equivalent-aged rocks in Greenland, consistent with a common Eoarchean evolution for Fennoscandia and the North Atlantic Craton (NAC).

INTRODUCTION

The earliest evolution of Archean cratons, and the controls on crustal growth and preservation, are still poorly understood. It is debated whether primordial crust formed from mantle plume activity (Smithies et al., 2005), due to density-driven convective overturn of proto-crust (Johnson et al., 2014) or bolide impacts (Hansen, 2015). It is also unclear if a pre-existing nucleus of sialic continental crust is needed to facilitate larger scale continental growth, or if the initial growth phase of Archean terranes were purely juvenile crustal contributions (Reimink et al., 2014). An oceanic plateau setting with thickened mafic crust, analogous to modern day Iceland has been suggested as a possible way of generating these ancient nuclei, as they are relatively sialic (Jakobsson et al., 2008; Reimink et al., 2014). The Fennoscandian Shield is thought to have formed through repeated episodes of subduction-related magmatism around the margins of an Archean core (e.g. Stephens and Bergman, 2020). Whether these episodes record growth of new continental crust or mainly record reworking of pre-existing crustal blocks is, however, a matter of debate (Rutanen et al., 2011; Petersson et al., 2015a, 2017). This debate focuses on the isotopic composition of the Fennoscandian mantle, and its degree of depletion (Andersen et al., 2009; Rutanen et al., 2011; Petersson et al., 2017). The majority of the zircon Hf isotope data from Fennoscandia yield model crust formation ages that are coeval with known orogenic events, such as the 2.8–2.6 Ga Lopian/Karelian, and the 2.0–1.8 Ga Svecokarelian orogenies. However, the oldest rocks in Fennoscandia, the Siurua gneiss in Pudasjärvi, dates to 3.5 Ga (zircon U-Pb; Mutanen and Huhma, 2003), predating known orogenies. Inherited zircon from rocks of the

Siurua region have negative ε_{Hf} signatures that are consistent with derivation from an ancient protolith (Lauri et al., 2011).

To trace an ancient crustal component within Fennoscandia, we report detrital zircon U-Pb, O and Lu-Hf isotope data from three major rivers draining central and NW Finland, and zircon O and Lu-Hf isotope data from three gneisses, a quartzite and a metagabbro (Evins et al., 2002) from the ca. 2.8 Ga Suomujärvi Complex, just north of the 3.5–2.7 Ga Pudasjärvi Gneiss Complex (Fig. 1). River samples were targeted to increase the sample area and the chances of identifying hereto unknown components within Fennoscandia. The Suomujärvi and Pudasjärvi complexes were targeted due to the evidence for ancient crustal components. We find that ca. 3.4 Ga detrital zircon within a ca. 2.75 Ga sillimanite-bearing meta-arkose have Hf isotope signatures that matches those of the least radiogenic zircon signatures from the Siurua gneiss. These signatures are significantly less radiogenic than other known crust in Fennoscandia requiring a source that is substantially older than the oldest known rocks in the area. Based on this, we infer that the Fennoscandian Shield grew from an ca. 3.75 Ga Eoarchean felsic crustal nucleus. Due to similar trends in their earliest zircon U-Pb and Lu-Hf isotope signatures, we explore the possibility of a linked Eoarchean evolution with that of the NAC.

SAMPLES AND ANALYTICAL METHODS

U-Pb, O and Lu-Hf isotopes were analyzed in detrital zircon from three major rivers (the Torne, Iil and Oulu rivers) draining central and NW Finland. Additionally, zircon O and Hf isotopes of five previously dated rocks, three TTG gneisses (Samples 3, 4, and 47), a quartzite (TVSED) and a metagabbro (Sample 888) of the Suomujärvi Complex (Evins et al., 2002, Fig. 1) were obtained, as well as complementary zircon U-Pb analyses on the previously dated Siurua gneiss (Mutanen and Huhma, 2003, A1602). U-Pb and O isotopes in zircon were measured using a CAMECA IMS1280 ion microprobe at the Swedish Museum of Natural History (Stockholm, Sweden) and zircon Lu-Hf isotopes were analyzed using a Cetac Analyte G2 laser and a Thermo Scientific Neptune Plus multicollector–inductively coupled plasma–mass spectrometer (MC-ICP-MS) at the University of Western Australia. Zircon from the Suomujärvi rock samples, were analyzed for O and Lu-Hf isotopes on the same zircon separates investigated for U-Pb age determinations by Evins et al. (2002). Oxygen isotope analyses were performed at the WiscSIMS Lab., University of Wisconsin-Madison, (USA) using a CAMECA IMS1280 and Hf analyses at the University of Bristol using a Thermo Finnigan Neptune MC-ICP-MS attached to a New Wave 193 nm laser system. All analytical data are found in DR Tables 3-7. Full analytical procedures are described in Appendix DR 1, and zircon BSE images with analysis spot locations, as well as U-Pb concordia and probability density plots for the detrital zircon, are in Appendix DR 2.

AGE CONSTRAINTS ON THE OLDEST COMPONENTS IN FENNOSCANDIA

Zircon U-Pb age data from the Siurua gneisses (samples A1602 and A1813) are complex (Fig. 2). A1602, the oldest rock so far identified in Fennoscandia, has been interpreted to have a 3.5 Ga crystallisation age (Mutanen and Huhma, 2003), but contains a significant portion of >3.5 Ga zircon. A combined data set of Mutanen and Huhma (2003) and our new data shows <5% discordant $^{207}Pb/^{206}Pb$ dates between 3.73 Ga and 3.08 Ga, with our new data identifying 15 >3.5 Ga grains. The main age group spreads between ca. 3.5 Ga and ca. 3.0 Ga. A second data cluster has $^{207}Pb/^{206}Pb$ dates between 3.66 Ga and 3.58 Ga, and one concordant analysis gives a $^{207}Pb/^{206}Pb$ date of ca. 3.73 Ga (Fig. 2A). There is a positive correlation between Th/U and $^{207}Pb/^{206}Pb$ dates, where older grains generally have higher

Th/U (Fig. 2). Zircon with the highest Th/U in their respective rock give >3.5 Ga $^{207}Pb/^{206}Pb$ dates (Fig. 2), and are compatible with >3.5 Ga crystallisation and subsequent Pb-loss. These zircon grains are interpreted as relicts of eroded or buried (meta)igneous rocks that attest to the existence of Eoarchean crust within the Fennoscandian Shield. These zircon define a near-horizontal array for $^{176}Hf/^{177}Hf$ versus $^{207}Pb/^{206}Pb$ date (Fig. 3B), which is typically produced in Archean rocks by Pb-loss or age resetting of a single magmatic zircon component (e.g., Zeh and Gerdes, 2009; Vervoort and Kemp, 2016). In ε_{Hf} versus age space, this steep trend ($^{176}Lu/^{177}Hf \approx 0$) projects back to a chondritic composition at ca. 3.75 Ga (Fig. 3A–B), compatible with derivation from an Eoarchean crustal nucleus. Similarly-aged (ca. 3.7–3.3 Ga) inherited zircon grains are found in a 2.7 Ga leucogranite (A1813) of the Siurua region (Lauri et al., 2011). These data plot along two discordia lines with upper intercepts at ca. 3.65 Ga and 2.7 Ga, with grains in the older (inherited) group having generally higher Th/U (Fig. 2C–D), strengthening the interpretation of a 3.5 Ga crystallisation age of the neighboring gneiss A1602 and the inherited nature of the high Th/U grains in both these samples. It also noteworthy that the >3.5 Ga detrital zircon in the TVSED quartzite have Th/U >1.3. Zircon with > 3.2 Ga dates are, however, absent from the detrital river populations in this study, possibly reflecting incomplete sampling of the catchment, and/or changing drainage patterns due to post-glacial isostatic rebound.

ZIRCON ISOTOPE SIGNATURES

The Hf isotope data from the detrital river zircon and the Suomujärvi Complex give predominantly juvenile signatures at around 2.7 Ga (majority of data with ε_{Hf} between ca. +5 and -1) and unradiogenic signatures at ca. 1.8 Ga (ε_{Hf} between -0.5 and -13). The two oldest detrital river zircons (ca. 3.2 and 3.1 Ga) have near chondritic Hf, while the ca. 3.6–3.2 Ga inherited grains in Pudasjärvi (A1602 and A1813) and the oldest grains in the Suomujärvi

TVSED quartzite have Hf isotope compositions that define a Pb-loss trend from near chondritic at around 3.75–3.60 Ga to strongly un-radiogenic at 3.4 Ga (ε_{Hf} = ca. -9: Fig. 3A–B). Excluding the inherited zircon from Pudasjärvi and the oldest TVSED zircon, remaining zircon Hf data in this study largely overlap with published Fennoscandian zircon Hf isotope data (Fig. 3A). As shown in figure 3B, the $^{176}Hf/^{177}Hf$ of the inherited zircon in sample A1602 are virtually identical, while $^{207}Pb/^{206}Pb$ dates range from ca. 3.45 Ga to ca. 3.22 Ga, attesting to variable degrees of Pb-loss, with a poorly defined lower intercept (Fig. 2A). The Hf isotope composition of the ca. 3.4 Ga TVSED zircon are virtually identical to A1602, and all these zircon have high Th/U, consistent with a common source (Fig. 3A–B). It should, however, be noted that some of the zircon analyzed by Mutanen and Huhma, (2003) yielded both slightly normally and reversely discordant data, so interpretations of Pb-loss, possibly combined with zircon recrystallisation, are not straightforward, even if $^{207}Pb/^{206}Pb$ dates are used. Mutanen and Huhma (2003) suggest that the reversely discordant data are an analytical artifact.

Hf isotope data from the oldest Fennoscandian zircon, from the Pudasjärvi Complex (Lauri et al., 2011) and the previously dated (Evins et al., 2002) detrital zircon in the TVSED quartzite in this study, yield strongly negative ε_{Hf} that, taken out of context, could be interpreted as evidence for very old (Hadean) evolved crust of unknown origin. However, the homogeneous $^{176}Hf/^{177}Hf$ define a Pb-loss trend, in ε_{Hf} versus age space, that traces back to a ca. 3.75 Ga chondritic source. This Pb-loss trend projects to strongly unradiogenic signatures ($\varepsilon_{Hf} \approx -20$) at 2.75 Ga (Fig. 3A), which is coeval with the Lopian/Karelian Orogeny, the age of surrounding bedrock in both Pudasjärvi and Suomujärvi, and the maximum depositional age of the TVSED quartzite (2731±8 Ma, Evins et al., 2002). These observations point to a previously un-identified Eoarchean nucleus within the Fennoscandian Shield. We speculate that this 3.75 Ga sialic nucleus facilitated the preservation of the 3.5 Ga Siurua suite within the Pudasjärvi complex. This crustal nucleus does not appear to have been a major source of subsequent magmatism within the Fennoscandian Shield, as strongly sub-chondritic Hf isotope signatures are virtually absent in Mesoarchean and younger crust (Fig. 3).

A GROWING NUMBER OF IDENTIFIED EOARCHEAN NUCLEI

Similarly-aged >3.7 Ga nuclei have been inferred for several other major Archean cratons, including the West African and São Francisco Cratons (see Santos-Pinto, 2012); North China Craton (Nutman et al., 2009); the Muzidian complex (Wang et al., 2023); the Kaapvaal Craton (Schneider et al., 2018); the Slave Craton (Reimink et al., 2014); the Wyoming Craton (Frost et al., 2017); the Tarim Craton (Ge et al., 2018); the Napier complex (Guitreau et al., 2019); the Superior Craton (Stevenson et al., 2006); and the Pilbara and Yilgarn Cratons (Petersson et al., 2019). Several different processes have been suggested for the formation of these ancient crustal nuclei, including radiogenic heating of thickened hydrated basalt (Kamber et al., 2005), mantle upwellings (Reimink et al., 2014), bolide impacts (Hansen, 2015) and some version of subduction leading to reworking of a stagnant lid (Kamber et al., 2003). The growing number of Archean cratons for which an Eoarchean crustal component has been recognized highlights the importance of these nuclei for stabilization of cratonic lithosphere and enabling the subsequent accretion of continental material in the early Earth. This work, for the first time, identifies such an Eoarchean nuclei to the Fennoscandian Shield, and emphasizes the value of inherited zircon for deciphering the enigmatic early evolution of Archean cratons.

A COMMON EOARCHEAN EVOLUTION FOR THE FENNOSCANDIAN SHIELD AND THE NORTH ATLANTIC CRATON

The Meso- to Paleoproterozoic zircon Hf isotope record of the North Atlantic Craton and the Fennoscandian Shield are very similar, with periods of growth, reworking and magmatic lulls more or less overlapping (Fig. 3A). In both the NAC and Fennoscandia, the formation of gneisses with sub-chondritic ε_{Hf}, coincided with the onset of juvenile (slightly supra-chondritic) crustal additions at 3.2 Ga. The ca. 3.2 Ga gneisses of these terranes have very similar zircon Hf isotope signatures with a majority of the data clustering between $\varepsilon_{Hf} = +2$ and -2 (see Whitehouse et al., 2022), and a connection between Fennoscandia and NAC has been proposed as far back as the earliest Mesoarchean, based on similarities in zircon Hf isotope data (Whitehouse et al., 2022). A Proterozoic connection between these cratons has been inferred based on both isotopic, metamorphic and petrographic similarities (e.g. Park, 1994; Whitehouse et al., 2022). Now this Fennoscandia–NAC connection can be traced back to the Eoarchean, with a shared crustal nucleus.

The tightly clustered zircon Hf isotope signatures from the ca. 3.8–3.6 Ga gneisses of NAC suggest a near chondritic source for the initial crustal nucleus. The least radiogenic zircon Hf isotope signatures of NAC between ca. 3.6 and 2.7 Ga plot along a Pb-loss trend in ε_{Hf} vs. time space (Fig. 3A–B). In Fennoscandia, the 2.7 Ga event corresponds to the Lopian/Karelian Orogeny, and is evident as growth and Pb-loss in zircon of the Pudasjärvi gneisses (Fig. 2A and C) as well as the appearance of Fennoscandian zircon with $\delta^{18}O$ signatures above mantle values, attesting to the onset of reworking of supracrustal materials (Appendix DR 1). In the Pudasjärvi Gneiss Complex, inherited zircon cores with $^{207}Pb/^{206}Pb$ dates between 3.73 and 3.6 Ga (Mutanen and Huhma, 2003, this study) support the existence of a ≥3.7 Ga source. Additionally, the oldest remnants of the Fennoscandian Shield, inherited zircon from the Pudasjärvi Gneiss Complex and detrital zircon from the Suomujärvi Complex (TVSED), give Hf isotope signatures that suggest a ca. 3.75 Ga protolith, similar to some of the oldest crust in NAC (Fig. 3A). Zircon Hf isotope signatures from NAC (e.g. Godthåbsfjord, Kemp et al., 2019) and samples TVSED and A1602 Finnish Karelia (Pudasjärvi and Suomujärvi) define a Pb-loss array extending back to a ca. 3.75 Ga near-chondritic source (green arrow in Fig. 3A). We propose that these above-listed isotopic similarities between these two regions are evidence for a common Eoarchean origin and that the oldest (3.75 Ga) felsic crust of the Fennoscandian Shield originated from a precursor reservoir similar to that of the NAC.

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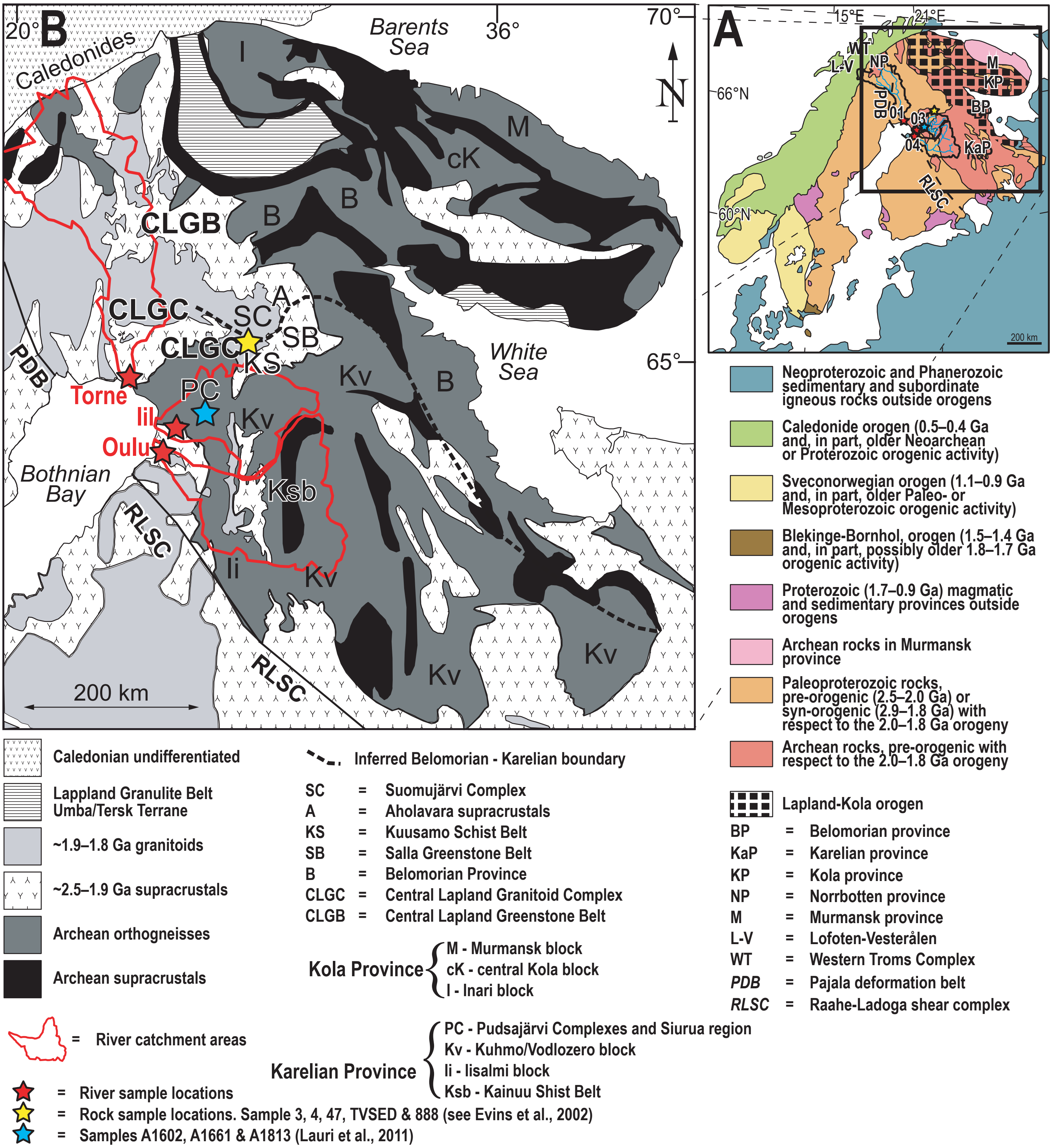
Captions

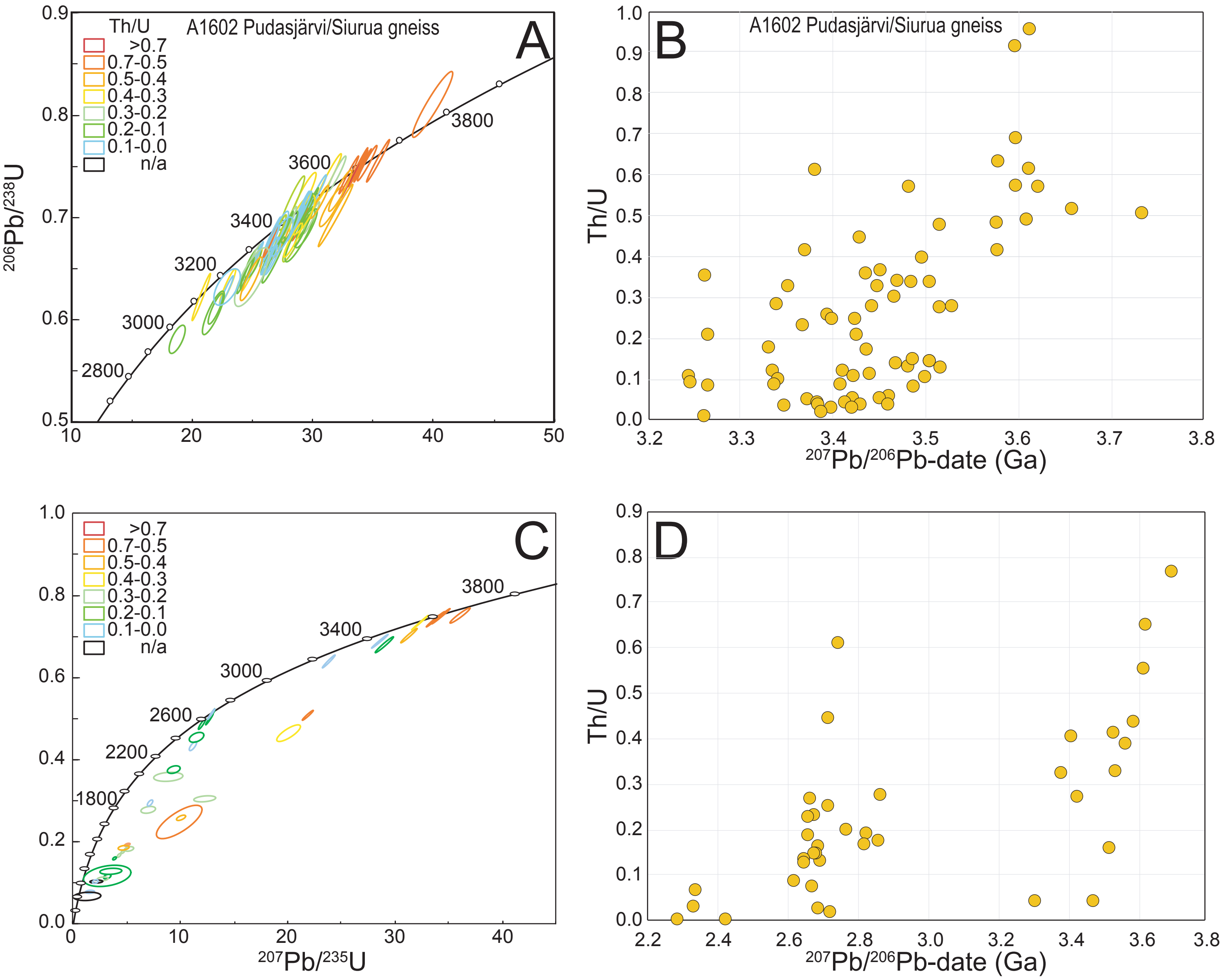
Figure 1. (A) Simplified geological map of the Fennoscandia showing the main geological units, based on Stephens and Bergman (2020). (B) Simplified geological map of the northern Fennoscandia showing individual blocks and complexes, based on Evins et al. (2002).

Figure 2. (A and C) Concordia plot of zircon U-Pb data from sample A1602 (A) and A1813 (C) including our new data (n = 61) and published data (Mutanen and Huhma, 2003, n = 8). Colours denote different Th/U ratios. (B and D) Th/U versus $^{207}Pb/^{206}Pb$ dates of the same analyses showing the positive correlation between Th/U and age. Reversely discordant data from Mutanen and Huhma (2003) have been omitted.

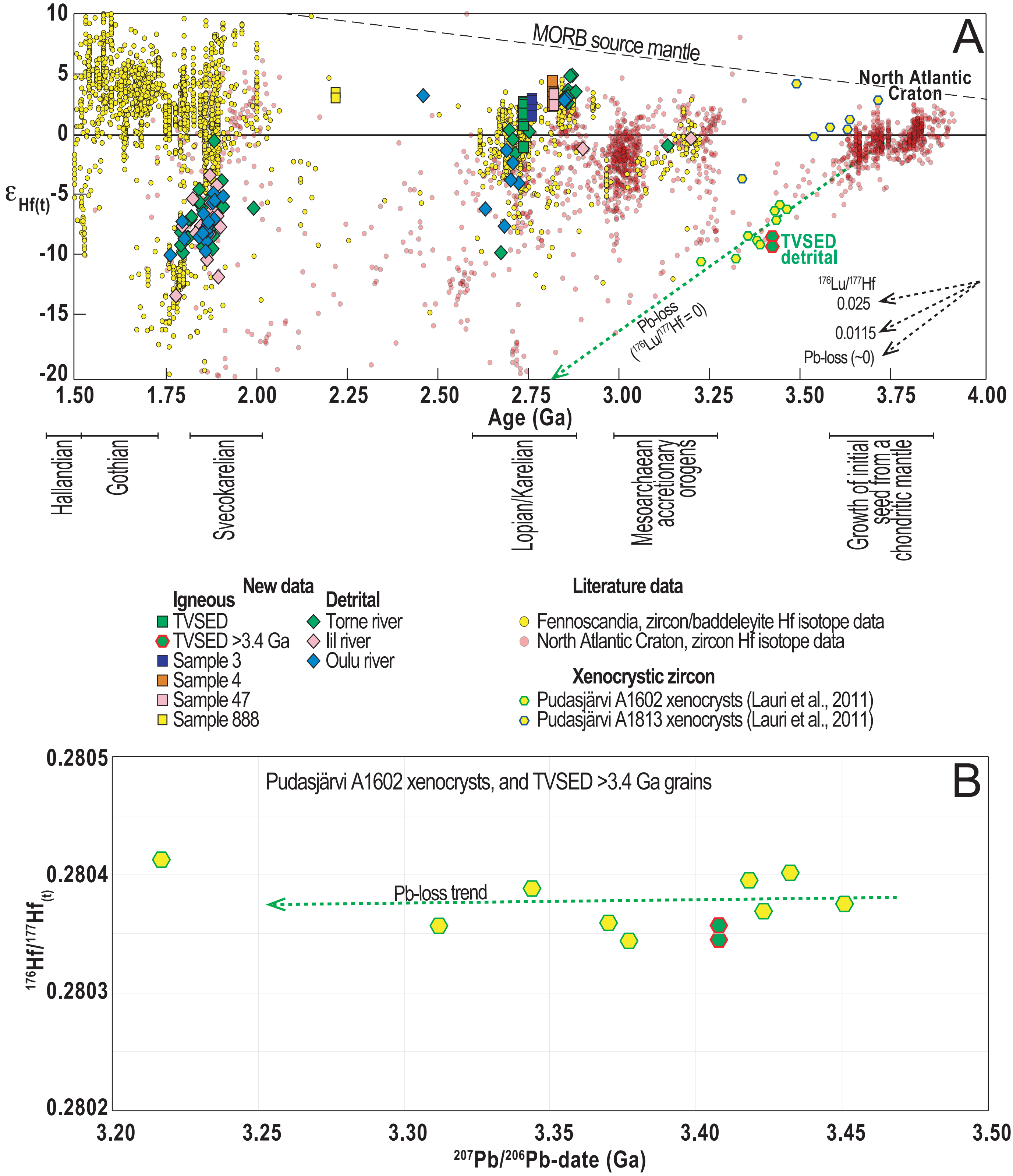
Figure 3. (A) Zircon $\varepsilon_{Hf(t)}$ versus date (Ga). Squares denote rock samples (this study) and diamonds denote river samples (this study). Circles represent literature data. Yellow circles: 3733 Fennoscandian zircon/baddeleyite Hf isotope data. Red circles: 2477 zircon Hf isotope data from southern W Greenland. Hexagons depict inherited zircon. Green arrow defines a Pb-loss trend ($^{176}Lu/^{177}Hf = 0$) from ca. 3.75 Ga to ca. 2.7 Ga. References to data found in Appendix DR 1. (B) $^{176}Hf/^{177}Hf_{(t)}$ versus $^{207}Pb/^{206}Pb$ dates (Ga) of the Siurua gneiss A1602 and TVSED showing a horizontal trend indicative of Pb-loss, with unchanged Hf isotope composition.



B
A
20°
36°
70°
65°
15°E
21°E
66°N
60°N
200 km
Barents Sea
White Sea
Bothnian Bay
Caledonides
CLGB
CLGC
SC
A
SB
KS
PC
B
I
M
cK
Kv
Ksb
Ii
PDB
RLSC
Torne
Iil
Oulu
WT
L-V
NP
PDB
01
03
04
M
KP
BP
KaP
RLSC
N
Neoproterozoic and Phanerozoic sedimentary and subordinate igneous rocks outside orogens
Caledonide orogen (0.5–0.4 Ga and, in part, older Neoarchean or Proterozoic orogenic activity)
Sveconorwegian orogen (1.1–0.9 Ga and, in part, older Paleo- or Mesoproterozoic orogenic activity)
Blekinge-Bornhol, orogen (1.5–1.4 Ga and, in part, possibly older 1.8–1.7 Ga orogenic activity)
Proterozoic (1.7–0.9 Ga) magmatic and sedimentary provinces outside orogens
Archean rocks in Murmansk province
Paleoproterozoic rocks, pre-orogenic (2.5–2.0 Ga) or syn-orogenic (2.9–1.8 Ga) with respect to the 2.0–1.8 Ga orogeny
Archean rocks, pre-orogenic with respect to the 2.0–1.8 Ga orogeny
Lapland-Kola orogen
BP = Belomorian province
KaP = Karelian province
KP = Kola province
NP = Norrbotten province
M = Murmansk province
L-V = Lofoten-Vesterålen
WT = Western Troms Complex
PDB = Pajala deformation belt
RLSC = Raahe-Ladoga shear complex
Caledonian undifferentiated
Lappland Granulite Belt Umba/Tersk Terrane
~1.9–1.8 Ga granitoids
~2.5–1.9 Ga supracrustals
Archean orthogneisses
Archean supracrustals
Inferred Belomorian - Karelian boundary
SC = Suomujärvi Complex
A = Aholavara supracrustals
KS = Kuusamo Schist Belt
SB = Salla Greenstone Belt
B = Belomorian Province
CLGC = Central Lapland Granitoid Complex
CLGB = Central Lapland Greenstone Belt
Kola Province
M - Murmansk block
cK - central Kola block
I - Inari block
= River catchment areas
Karelian Province
PC - Pudsajärvi Complexes and Siurua region
Kv - Kuhmo/Vodlozero block
Ii - Iisalmi block
Ksb - Kainuu Shist Belt
= River sample locations
= Rock sample locations. Sample 3, 4, 47, TVSED & 888 (see Evins et al., 2002)
= Samples A1602, A1661 & A1813 (Lauri et al., 2011)



A
Th/U
A1602 Pudasjärvi/Siurua gneiss
>0.7
0.7-0.5
0.5-0.4
0.4-0.3
0.3-0.2
0.2-0.1
0.1-0.0
n/a
2800
3000
3200
3400
3600
3800
0.9
0.8
0.7
0.6
0.5
10
20
30
40
50
206Pb/238U
B
A1602 Pudasjärvi/Siurua gneiss
Th/U
207Pb/206Pb-date (Ga)
C
>0.7
0.7-0.5
0.5-0.4
0.4-0.3
0.3-0.2
0.2-0.1
0.1-0.0
n/a
1800
2200
2600
3000
3400
3800
207Pb/235U
D
Th/U
207Pb/206Pb-date (Ga)



A
MORB source mantle
North Atlantic Craton
TVSED detrital
176Lu/177Hf
0.025
0.0115
Pb-loss (~0)
Pb-loss (176Lu/177Hf = 0)
εHf(t)
10
5
0
-5
-10
-15
-20
1.50
1.75
2.00
2.25
2.50
2.75
3.00
3.25
3.50
3.75
4.00
Age (Ga)
Hallandian
Gothian
Svecokarelian
Lopian/Karelian
Mesoarchaean accretionary orogens
Growth of initial seed from a chondritic mantle
New data
Igneous
TVSED
TVSED >3.4 Ga
Sample 3
Sample 4
Sample 47
Sample 888
Detrital
Torne river
Iil river
Oulu river
Literature data
Fennoscandia, zircon/baddeleyite Hf isotope data
North Atlantic Craton, zircon Hf isotope data
Xenocrystic zircon
Pudasjärvi A1602 xenocrysts (Lauri et al., 2011)
Pudasjärvi A1813 xenocrysts (Lauri et al., 2011)
B
Pudasjärvi A1602 xenocrysts, and TVSED >3.4 Ga grains
Pb-loss trend
176Hf/177Hf(t)
0.2805
0.2804
0.2803
0.2802
3.20
3.25
3.30
3.35
3.40
3.45
3.50
207Pb/206Pb-date (Ga)