SIMS geochronology of a 1.93 Ga basement metagranitoid at Norvijaur west of Jokkmokk, northern Sweden

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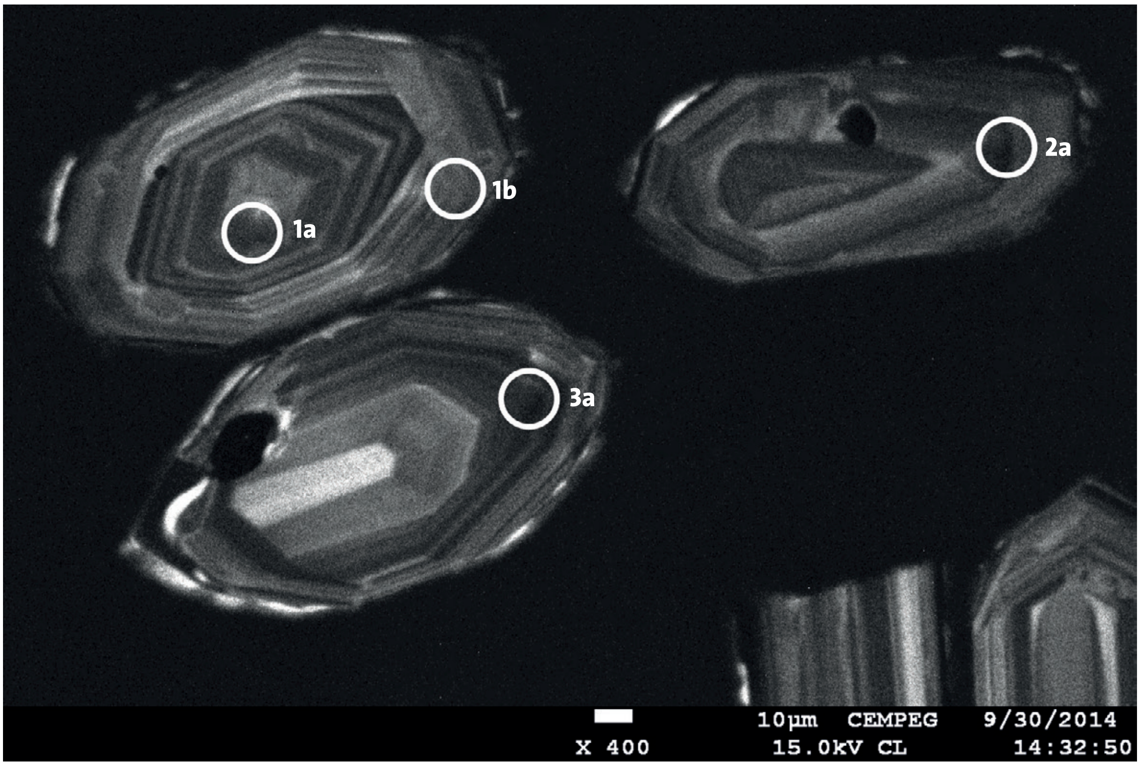

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Cover: Cathodoluminescence image of selected zircon grains from the Norvijaur metagranodiorite. Ellipses mark the locations of SIMS U-Pb analyses. Numbers refer to analytical spot number.

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ABSTRACT
West of Jokkmokk, an older generation of metagranitoids forms the basement of a metasedimentary sequence which, in turn, is cut by younger c. 1.88 Ga metagranitoids. The older generation of granitoids, represented by the Norvijaur granodioritic to tonalitic intrusion, is herein re-dated with U-Pb SIMS techniques to evaluate previous age determinations, which used strongly discordant U-Pb TIMS zircon data. The new U-Pb zircon SIMS age is concordant at 1930±6 Ma (2σ) and dates igneous crystallisation of the Norvijaur granodiorite at 1.93 Ga in agreement with the old TIMS age of 1926^{+13}_{-11} Ma. The age of the Norvijaur intrusion also constrains the maximum depositional age of the c. 800 m thick overlying supracrustal sequence. Igneous rocks of similar age and composition to the Norvijaur granodiorite are rare in the Svecokarelian orogen, but are found in the Savo schist belt within the Raahe-Ladoga zone in Finland, and in the Rombak-Sjangeli basement window of the Caledonides, all along the Archean-Paleoproterozoic boundary. In addition, 1.96–1.94 Ga calc-alkaline rocks with island arc affinity occur in the northern part of the Bothnian basin, south of the Skellefte district. The overall felsic nature of the Skellefte and Arvidsjaur volcanic and intrusive rocks suggests that a Paleoproterozoic basement is likely to be present beneath the Skellefte-Arvidsjaur magmatic domain south of the Archean boundary, represented by scattered basement windows of 1.96–1.93 Ga rocks, including the 1.93 Ga Norvijaur intrusion in the Jokkmokk area.

Keywords: Svecokarelian orogen, Svecofennian, radiometric age, zircon, U-Pb, Norvijaur, the Archean-Proterozoic boundary

INTRODUCTION
According to Skiöld et al. (1993), the Norvijaur area west of Jokkmokk features two generations of granitoids (Figs. 1 & 2). The stratigraphically lower and older granitoid generation forms the basement of a metasedimentary sequence which, in turn, is cut by the younger granitoid generation. The metasedimentary rocks and the older granitoids have undergone polyphase deformation, whereas the younger granitoids only show a diffuse foliation. The older granitoids have been weathered in situ and the weathering surface is overlain by an immature, arkosic metasandstone with graded bedding and by polymict conglomerates. The metaarkose grades upwards into a metagreywacke with additional conglomerates and intercalations of tuffites and mafic lavas. In the upper part of the sedimentary sequence there are meta-argillites with graphitic schists and, at the top, a recrystallised calcite limestone. The current thickness of the sedimentary sequence is estimated to c. 800 m (Markkula 1977, Skiöld et al. 1993). The present interpretation of the bedrock geology of the Jokkmokk area is under revision by ongoing SGU mapping (Claeson & Antal Lundin 2013).

The Norvijaur gneissic granodiorite, i.e. the older generation of granitoid, was dated at 1926^{+13}_{-11} Ma (MSWD = 1.8, U-Pb TIMS zircon data), whereas the younger generation of granitoids, represented by the Juoksjokko granite, was dated at 1876±6 Ma by Skiöld et al. (1993). An early attempt to date the Norvijaur intrusion was done by Skiöld & Larsson (1978), who also used discordant U-Pb TIMS zircon data with a resulting upper intercept age of 2010±40 Ma. The current age of the Norvijaur granodiorite is older than most ages of Svecokarelian granitoids, but similar in age to the c. 1.96–1.94 Ga intrusive and extrusive rocks in the northern part of the Bothnian basin south of the Skellefte district (Wasström 1993, 1996, Lundqvist et al. 1998, Eliasson et al. 2001, Skiöld & Rutland 2006). The old TIMS U-Pb age of the Norvijaur granodiorite by Skiöld et al. (1993) is, however, based on analyses of seven, strongly discordant (12.5–16.7%) zircon fractions. It was also stated that an explanation of the relatively large error in the calculated age could be due to the presence of zircon cores despite efforts to eliminate complex core-overgrowth in the euhedral, transparent, long and short prismatic crystals selected for analysis. Zircon from the Norvijaur granodiorite is herein reanalyzed with U-Pb SIMS techniques to better constrain the protolith age.

GEOLOGICAL OUTLINE

The Precambrian bedrock in northern Sweden includes a c. 3.2–2.6 Ga Archean granitoid-gneiss basement, which is unconformally overlain by Paleoproterozoic volcanic and sedimentary successions (e.g. Ödman 1957, Witschard 1984, Bergman et al. 2001, Martinsson 2004, Kathol & Weihed 2005, Weihed et al. 2005, Martinsson & Wanhainen 2013). Sm-Nd isotopic analyses of Proterozoic granitoids and metavolcanic rocks approximately delineate the Archean paleoboundary zone between the reworked Archean craton in the north and more juvenile Paleoproterozoic domains to the south along the Luleå–Jokkmokk zone in Sweden and along the Raahe–Ladoga zone in Finland (Fig. 1, Öhlander et al. 1993, Mellqvist et al. 1999, Vaasjoki & Sakko 1988, Nironen 1997). This approximate boundary zone defines the border between the Norrbotten and the Bothnia-Skellefteå lithotectonic provinces (Stephens pers. comm).

In the Norrbotten province there are rift-related 2.5–2.0 Ga Karelian basic metavolcanic rocks and associated metasedimentary rocks of the Kovo- and Greenstone groups that occur at the lowest stratigraphic level. These are overlain by terrestrial to shallow water, c. 1.89–1.87 Ga arc-related Svecofennian successions, represented by the calc-alkaline, andesite-dominated Porphyrite group, the mildly alkaline volcanic rocks of the Kiruna Porphyry group and, in the uppermost stratigraphic level, younger clastic sedimentary rocks. The Greenstone group contains stratiform–stratabound base metal and iron deposits in the middle and upper parts (Martinsson & Wanhainen 2013), whereas the Porphyry group hosts economically important apatite iron ores, e.g. the Kiirunavaara and Malmberget deposits.

Sub-aerial volcanic rocks extend south of the Archean paleoboundary, in the dominantly volcanic 1.88–1.87 Ga Arvidsjaur group (Skiöld et al. 1993, Kathol & Triumf 2004, Kathol & Weihed 2005, Kathol & Persson 2007). The volcanic rocks of the Arvidsjaur group are commonly grouped together with similar volcanic rocks north of the Archean paleoboundary, as the Kiruna-Arvidsjaur Porphyry group (Perdahl & Frietsch 1993).

Further south, the turbiditic greywackes and argillites and subordinate metavolcanic rocks of the Bothnian supergroup form the inferred basement to the 1.89–1.88 Ga mainly felsic volcanic and volcaniclastic Skellefte group, which is the main host to the VMS deposits of the Skellefte district (Allen et al. 1996, Billström & Weihed 1996, Rutland et al. 2001a, 2001b, Kathol & Weihed 2005, Montelius 2005, Skiöld & Rutland 2006, Skyttä et al. 2011, Bauer et al. 2014). Rocks of the Bothnian supergroup extend from the Skellefte district in the north to at least the Ljusdal lithotectonic province (Stephens pers comm) in the south and are characterised by marine metasedimentary rocks with an estimated total thickness of 10 km (Hietanen 1975, Lundqvist 1987, Kousa & Lundqvist 2000, Kumpulainen 2009). At least part of the sedimentary-volcanic succession in the northern part of the Bothnian basin was deposited before the intrusion of 1.95–1.94 Ga granitoids (Wasström 1993, 1996, Skiöld & Rutland 2006). The sedimentary Vargfors group (1.88–1.87 Ga) overlies the Skellefte group and is considered coeval with and a lateral facies of the Arvidsjaur group (Kathol & Weihed 2005, Bauer et al. 2013).

The Paleoproterozoic supracrustal rocks are intruded by the calc-alkaline 1.89–1.88 Ga Haparanda suite and the alkali-calcic 1.88–1.86 Ga Perthite monzonite suite, considered comagmatic with the Svecofennian volcanic rocks of the Porphyrite and Porphyry groups, respectively (Bergman et al. 2001, Witschard 1984). The Aitik Cu-Au-Ag deposit has been suggested to represent a porphyry copper system related to a 1.89 Ga quartz monzodiorite, which was later modified by hydrothermal and metamorphic events (Wanhainen et al. 2012).

Figure. 1. Lithotectonic map of the Fennoscandian Shield modified from Koistinen et al. (2001).

In the Bothnia–Skellefteå province, the early orogenic Svecokarelian inrusions can be subdived in a similar way into the 1.90–1.88 Ga Jörn suite, coeval with rocks of the Skellefte group, and the 1.88–1.87 Ga Arvidsjaur granites which are comagmatic with the Arvidsjaur group rocks. The calc-alkaline Jörn suite shows similarities to the Haparanda suite which occurs further north, but the Haparanda suite displays mainly negative $\varepsilon_{Nd(t)}$ values, an alkalic, calc-alkaline trend, and was formed within or at the margin of the Archean craton. The Jörn suite, in contrast, displays positive $e_{Nd(t)}$ values, a calcic, calc-alkaline trend, and was formed in a juvenile island arc-terrane that was accreted to the Archean craton (Mellqvist et al. 2003). 1.80–1.79 Ga minimum-melt granites and pegmatites referred to as Lina granite occupy large areas of Norrbotten (Öhlander et al. 1987). These are not easily distinguished from older 1.86 Ga leucocratic granites.

Coeval with the S-type rocks of the Lina suite are c. 1.80 Ga I- to A-type GSDG-type (Granite-syenite-diorite-gabbro) magmatic rocks in Norrbotten belonging to the Edefors suite. These rocks are related to of the Transscandinavian igneous belt that forms a 1500 km long, north–south trending belt along the western part of the Svecokarelian orogen (Högdahl et al. 2004).

SAMPLE DESCRIPTION

The Norvijaur intrusion is outlined by a positive magnetic anomaly shaped as a heart-like, c. 100 km^2 large body, and it is surrounded by metasupracrustal rocks (Figs. 2–3). According to Skiöld et al. (1993), the Norvijaur intrusion can be classified as a calcic to calc-alkaline granodiorite to tonalite with a magnesian, metaluminous, major element geochemical character. It is similar to granitoids of the Jörn suite in the Skellefte district (Skiöld 1993, Mellqvist et al. 2003, Lundmark et al. 2005a, b). A sample (FHM130111A) for SIMS geochronology was taken from the same outcrop as previous datings by Skiöld & Larsson (1978) and Skiöld et al. (1993), i.e. c. 1 km east of the contact to overlying metasedimentary rocks (Fig. 2, Table 1). The sampled rock is a finely medium-grained, light grey, gneissic granodiorite with a steep mineral lineation (Fig. 4). Accessory minerals are, according to Skiöld & Larsson (1978), apatite, sphene, zircon and opaque minerals, together with small amounts of colourless amphibole. The metagranodiorite is cut by leucogranitic dykes as well as an isotropic, 4–5 m wide, garnet-bearing pegmatite. A 0.5 cm large aggregate of molybdenite was noted in the pegmatite.

ANALYTICAL RESULTS AND INTERPRETATION OF GEOCHRONOLOGICAL DATA

Zircons were obtained from a density separate of a crushed rock sample using a Wilfley water table. The magnetic minerals were removed by a hand magnet. Handpicked crystals were mounted in transparent epoxy resin together with chips of reference zircon 91500. The zircon mounts were polished and after gold coating examined by cathodoluminescence (CL) imaging using electron microscopy at the Swedish Museum of Natural History in Stockholm. High-spatial resolution secondary ion mass spectrometer (SIMS) analysis was done in 2013 using a Cameca IMS 1270 at the Nordsim facility at the Swedish Museum of Natural History in Stockholm. Detailed descriptions of the analytical procedures are given in Whitehouse et al. (1997, 1999). Pb-U ratios, elemental concentrations and Th-U ratios were calibrated relative to the Geostandards zircon 91500 reference, which has an age of c. 1065 Ma (Wiedenbeck et al. 1995, 2004). Common lead corrected isotope values were calculated using a modern common lead composition (Stacey & Kramers 1975) and the measured ^{204}Pb. Decay constants follow the

Table 1. Summary of sample data.

Rock type:	Metagranodiorite
Tectonic domain:	Svekokarelian orogen
Tectonic subdomain:	Bothnia–Skellefteå province
Lithodem:	Norvijaur granitoid
Sample number:	FHM130111A
Laboratory id:	n4823
Coordinates:	7392041 / 690272(SWEREF99 TM)
Map sheet:	27J Jokkmokk NV (RT90)
Locality:	Norvijaur
Project:	Sydvästra Norrbotten

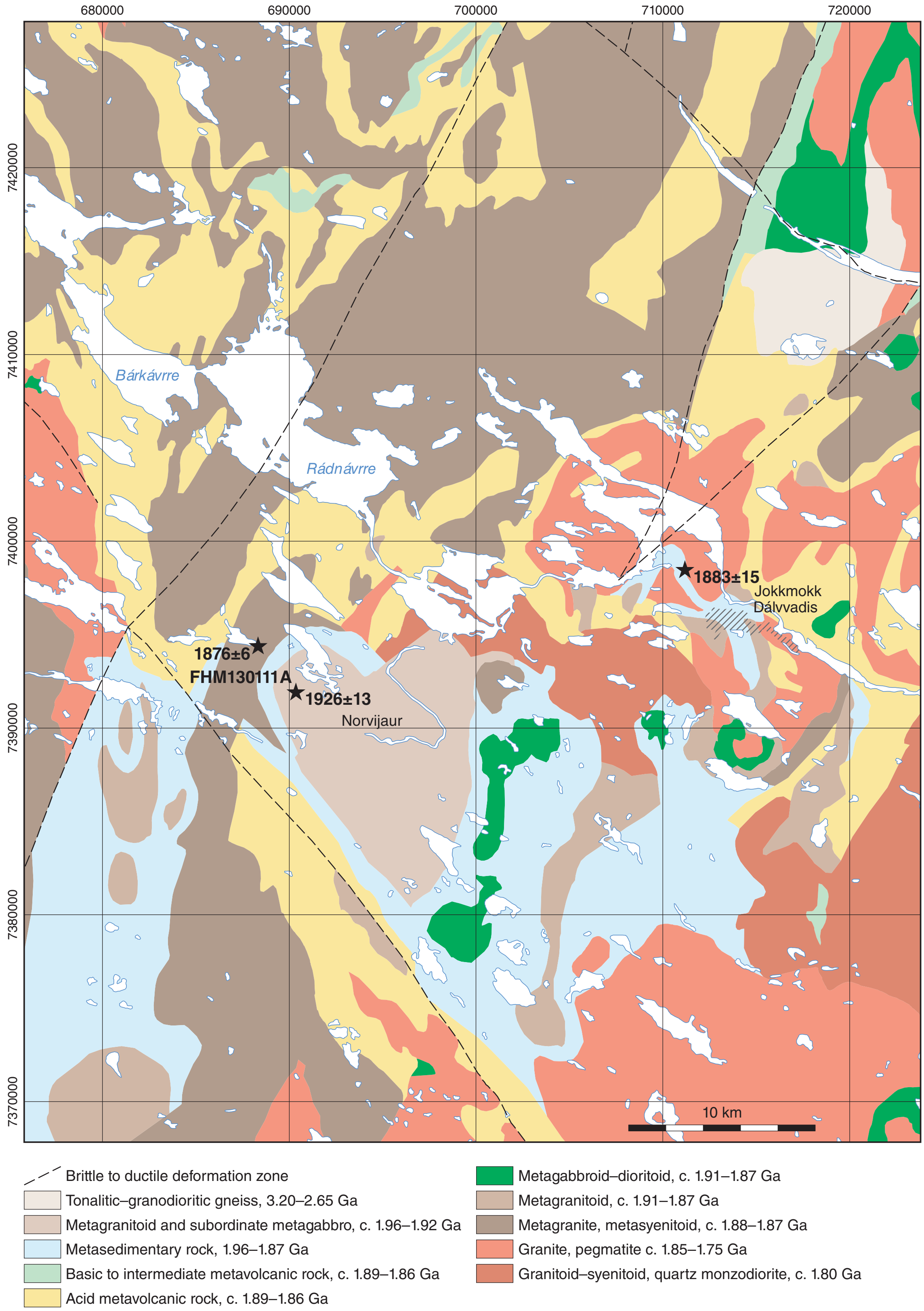

Figure. 2. Bedrock geology of the Jokkmokk area, modified after the SGU 1:1 million bedrock geology database. Selected U-Pb age determinations are from SGU's radiometric age database. References to age determinations: Skiöld et al. (1993), Lundmark et al. (2005a).

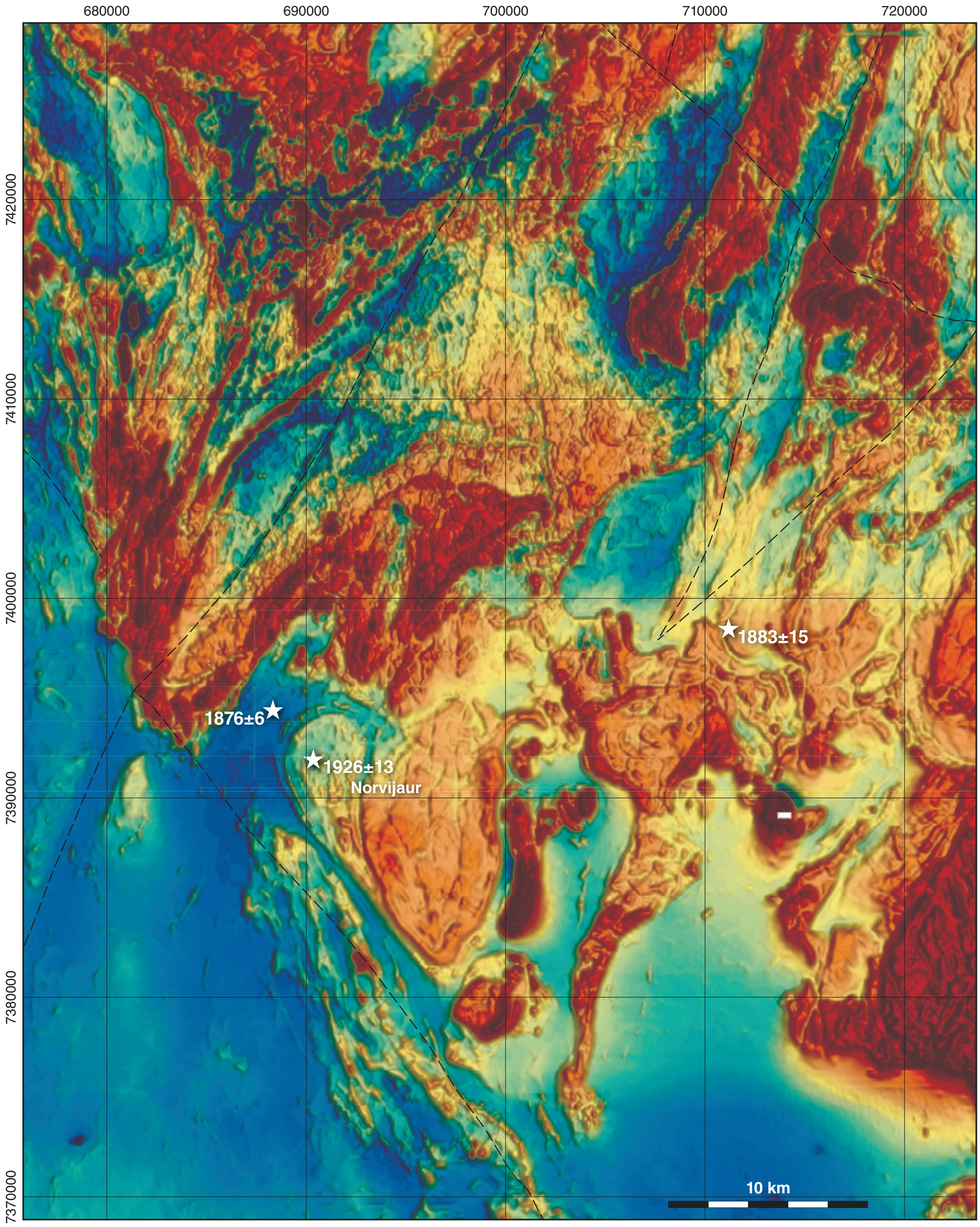

Figure. 3. Magnetic anomaly map of the Jokkmokk area showing the heart-like shape of the Norvijaur intrusion (SGU data).

recommendations of Steiger & Jäger (1977). Diagrams and age calculations of isotopic data were made using the software Isoplot 4.15 (Ludwig 2012).

The heavy mineral concentrate is rich in zircon. Most grains are fractured and turbid, but there are also clear, transparent and colorless grains which were selected for analysis. The zircon grains have subhedral to euhedral prismatic shapes. There is also titanite in the sample.

Figure 4. The dated metagranodiorite sample from Norvijaur, west of Jokkmokk.

Table 2. SIMS U-Pb-Th zircon data of the Norvijaur metagranodiorite (FHM130111A, laboratory id n4823).

Analysis	U (ppm)	Th (ppm)	Pb (ppm)	Th/U calc.	$^{207}Pb/^{235}U$	±σ %	$^{238}U/^{206}Pb$	±σ %	$^{207}Pb/^{206}Pb$	±σ %	ρ[1]	Disc. % conv.[2]	Disc. % 2σ lim.[3]	$^{207}Pb/^{206}Pb$ age (Ma)	±σ	$^{206}Pb/^{238}U$ age (Ma)	±σ	$^{206}Pb/^{204}Pb$ measured	f_{206}%[4]
01a	162	129	75	0.69	5.721	1.63	2.845	1.33	0.1181	0.95	0.82	0.9		1927	17	1942	22	24503	{0.08}
01b	120	62	51	0.43	5.507	1.89	2.905	1.39	0.1160	1.28	0.74	0.7		1896	23	1907	23	7502	0.25
02a	349	325	165	0.83	5.637	1.50	2.862	1.34	0.1170	0.68	0.89	1.3		1911	12	1932	22	14861	0.13
03a	284	132	125	0.42	5.815	1.51	2.819	1.32	0.1189	0.73	0.88	1.0		1940	13	1957	22	15308	0.12
04a	258	217	119	0.72	5.7t34	1.68	2.883	1.50	0.1199	0.77	0.89	–2.1		1955	14	1920	25	16424	0.11
05a	207	101	89	0.43	5.588	1.64	2.883	1.35	0.1168	0.93	0.82	0.7		1908	17	1920	22	9918	0.19
06a	174	77	74	0.36	5.657	1.66	2.884	1.34	0.1183	0.98	0.81	–0.8		1931	17	1919	22	9711	0.19
07a	144	93	66	0.58	5.775	1.74	2.784	1.32	0.1166	1.13	0.76	4.5		1905	20	1979	23	14331	0.13
08a	123	25	49	0.16	5.443	2.32	2.928	1.62	0.1156	1.66	0.70	0.3		1889	30	1894	27	10102	0.19
09a	151	214	75	1.11	5.718	1.70	2.898	1.34	0.1202	1.04	0.79	–2.8		1959	18	1911	22	20018	{0.09}
10a	112	49	51	0.49	5.991	1.29	2.725	1.17	0.1184	0.55	0.91	5.0	1.5	1932	10	2015	20	465427	{0.00}
11a	315	328	157	1.05	5.752	1.02	2.839	0.99	0.1184	0.26	0.97	0.8		1933	5	1945	17	249478	*0.01
12a	359	304	161	0.71	5.518	0.93	2.951	0.88	0.1181	0.32	0.94	–2.8	–0.5	1928	6	1881	14	15291	{0.12}

Isotope values are common Pb corrected using modern common Pb composition (Stacey & Kramers 1975) and measured ^{204}Pb.
1. Th/U ratios calculated from $^{208}Pb/^{206}Pb$ and $^{207}Pb/^{206}Pb$ ratios, assuming a single stage of closed U-Th-Pb evolution
2. Error correlation in conventional concordia space. Do not use for Tera-Wasserburg plots.
3. Age discordance in conventional concordia space. Positive numbers are reverse discordant.
4. Age discordance at closest approach of error ellipse to concordia (2σ level).
5. Figures in parentheses are given when no common lead correction has been applied and indicate a value calculated assuming present-day Stacey-Kramers common Pb.

Cathodoluminescence images show oscillatory zoned zircon (Fig. 5). In some grains there are texturally older cores. Analyses of the inner and outer oscillatory domains in grain no 1 reveal, however, within error no difference in age between the different domains. In the remaining eleven analyses, the texturally older core domains were avoided. The analyses contain 112–359 ppm uranium and have variable Th/U ratios of 0.16–1.11 (Table 2). Ten analyses are con-

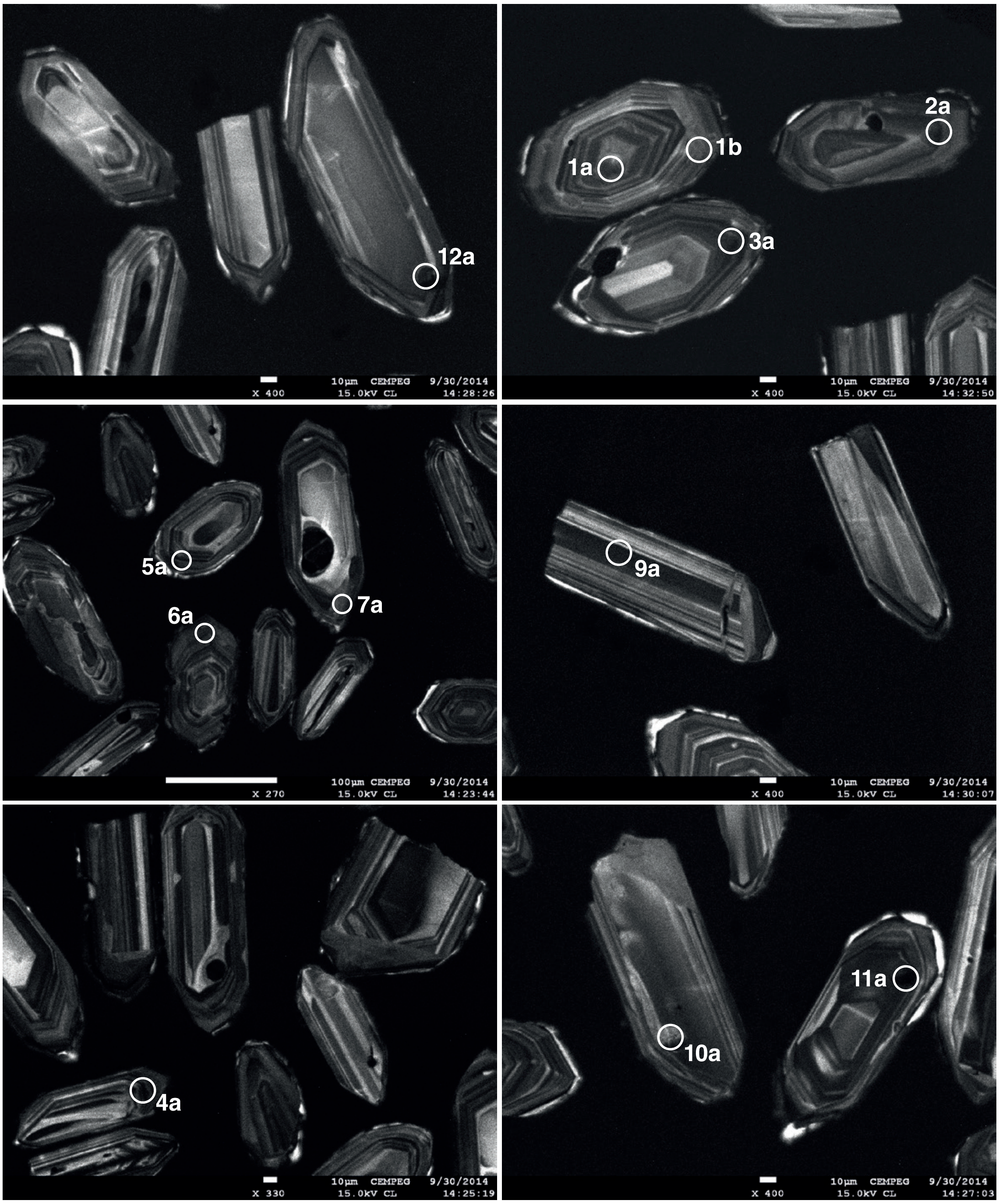

Figure 5. Cathodoluminescence images of analysed zircon grains. Ellipses mark the locations of analyses. Numbers refer to analytical spot number in Table 2.

cordant at the two sigma level with a concordia age of 1930±6 Ma (Fig. 6, 2σ, MSWD of concordance = 0.12, probability of concordance = 0.72, n = 11). Including also the two remaining, weakly discordant analyses (<5.1%), the weighted average $^{207}Pb/^{206}Pb$ age is 1930±6 Ma (2σ, MSWD = 1.4, probability = 0.16, n = 13), which is identical to the concordia age. The concordia age of 1930±6 Ma (2σ) is chosen as the best age estimate, interpreted to date igneous crystallisation of the Norvijaur granodiorite at c. 1.93 Ga.

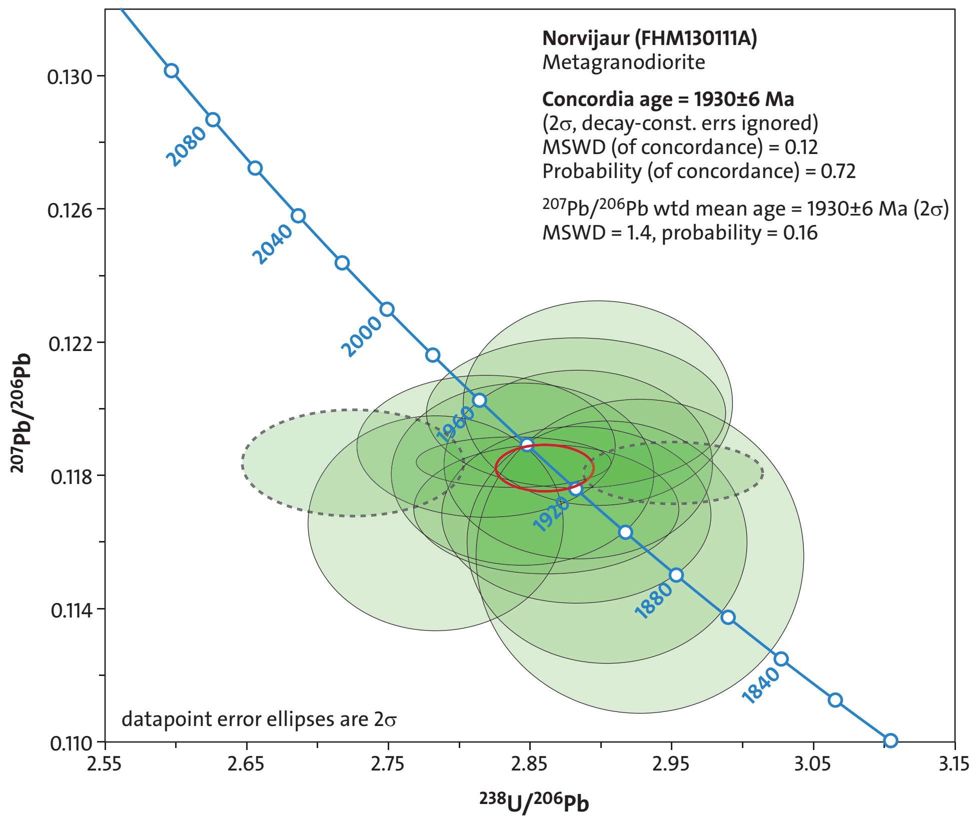

Figure 6. Tera Wasserburg diagram showing U-Pb SIMS data of zircon analyses of the Norvijaur metagranodiorite. Discordant analyses are shown with broken lines. Error ellipse of calculated weighted mean age is shown in red.

DISCUSSION AND CONCLUSIONS

The new U-Pb zircon SIMS age is concordant at 1930±6 Ma (2σ) and dates igneous crystallisation of the Norvijaur granodiorite, and it confirms the old 1926^{+13}_{-11} Ma TIMS age of Skiöld et al. (1993). The age of the Norvijaur metagranodiorite also constrains the maximum depositional age of a c. 800 m thick overlying supracrustal sequence of metaarkose, metagreywacke interlayered with metabasalt, graphite-bearing meta-argillite and recrystallised, calcitic limestone marble (Skiöld et al. 1993).

The Norvijaur intrusion is situated close to the proposed Archean–Proterozoic transition zone delineated by extensive Sm-Nd isotope work on granitoids in the Jokkmokk area with a steep gradient to highly negative $\varepsilon_{Nd(1.9\ Ga)}$ just north-east of Jokkmokk. Archean gneisses ($\varepsilon_{Nd(1.89\ Ga)}$ = –6.3 to –10.4) were also shown to occur in the Muddus area just north of Jokkmokk (Mellqvist et al. 1999). Two samples from the Norvijaur metagranitoid record $\varepsilon_{Nd(1.93\ Ga)}$ values of +0.6 and +0.8, and thus have no obvious major Archean component in the source rock (Öhlander et al. 1993). Within the Raahe-Ladoga zone at the Archean–Proterozoic paleoboundary in Finland, 1.93–1.91 Ga gneissic tonalities and related acid metavolcanic rocks in the Savo schist belt show a juvenile character with $\varepsilon_{Nd(t)}$ values of +1 to +4 and represent primitive island arc magmatism (Helovuori 1979, Korsman et al. 1984, Vaasjoki & Sakko 1988, Kousa et al. 1994, Lahtinen & Huhma 1997, Vaasjoki et al. 2003, Kousa et al. 2013). To the west, the Archean–Paleoproterozoic boundary is suggested to continue beneath the Caledonian orogen, passing through or between the basement culminations at Tysfjord, Rombak-Sjangeli and Kvaløya (Öhlander et al. 1987). Archean gneiss has been recognised in the Rombak-Sjangeli window and a tonalite (Gautelis tonalite) there records a zircon age of 1940±26 Ma (Romer et al. 1992, MSWD = 46, lower intercept age at 404±18 Ma, n = 7). The Gautelis tonalite is stratigraphically overlain by the Gautelis supracrustal belt, which is a sequence of impure marble and turbiditic psammitic to pelitic sedimentary rocks with intercalated basic to acid volcanic rocks (Romer et al. 1992).

Rocks similar in age to the Norvijaur intrusion also occur south of the Skellefte district in the northern part of the Bothnian basin, i.e. 100 km south of the Archean–Proterozoic boundary. One of the Knaften granitoids in the Lycksele area has been dated at 1954±6 Ma and an associated quartz-feldspar porphyritic dyke at 1940±14 Ma (Wasström 1993, 1996). Both ages are determined from discordant U-Pb ID-TIMS analyses on multi-grain zircon fractions. The granite-granodiorite-tonalite-trondhjemite (TTG) rocks intruded mafic–intermediate volcanic and volcaniclastic rocks. An evolution from MORB to primitive island arc type affinity has been suggested for the Knaften rocks (Wasström 1989, 1990, 2006). In the Barsele area, c. 85 km north-west of Knaften, a quartz-feldspar porphyritic metadacite was dated at 1959±14 Ma (U-Pb TIMS zircon age) by Eliasson et al. (2001), and in the Robertsfors group south-east of the Skellefte district, the Rönnskär granitoid was dated at 1944±5 Ma (Skiöld & Rutland 2006, SIMS U-Pb zircon age, MSWD = 1.7, n = 10, complex zircon data). In the central part of the Bothnian basin, the Seltjärn and Husum granodiorites are poorly dated at c. 1.93 Ga using U-Pb TIMS zircon data (Lundqvist et al. 1998).

The 1.96–1.91 Ga Knaften-Barsele, Savo, Inari and Tersk units have been interpreted as early Svecofennian island arcs accreted onto different Archean cratonic units at 1.92–1.90 Ga (Nironen 1997, Daly et al. 2001, Lahtinen et al. 2005, Tuisku & Huhma 2006, Tuisku et al. 2012). Hafnium isotope data on single zircons from rocks of the Skellefte district and the presumed Knaften-Barsele basement all show similar depleted mantle signatures indicative of a common source and comparable conditions of emplacement (Guitreau et al. 2014). Overall, the hafnium data was suggested to be compatible with reworking of the Knaften-Barsele arc with possible involvement of 2.2–2.0 Ga oceanic crust to produce the Skellefte rocks over a short time interval from 1.90 to 1.87 Ga in a context of crustal extension with ongoing subduction. It was further suggested to fit into general tectonic models of Svecokarelian orogenic evolution in which the juvenile Knaften-Barsele arc formed between 1.96 and 1.94 Ga and became accreted onto the Karelian continent located further north at about 1.92–1.91 Ga. Accretion at this time is supported by dating of the earliest deformation in strongly deformed and metamorphosed, c. 1.95–1.94 Ga granitoids south-east of the Skellefte district (Skiöld & Rutland 2006).

Skiöld et al. (1993) suggested that the Norvijaur granitoid represents volcanic island-arc magma formed by subduction beneath the Archean craton. The Norvijaur intrusion has a granodioritic to tonalitic, calc-alkaline, juvenile geochemical character similar to granitoids of the Jörn suite in the Skellefte district but also to the Knaften metagranitoids (Skiöld 1993, Mellqvist et al. 2003, Lundmark et al. 2005a, b, Wasström 2006, Guitreau et al. 2014). The overall felsic nature of the Skellefte and Arvidsjaur volcanic and intrusive rocks suggests that there probably is a Paleoproterozoic basement beneath the Skellefte–Arvidsjaur magmatic domain south of the Archean–Paleoproterozoic boundary, as represented by scattered basement windows of 1.96–1.93 Ga rocks, including the 1.93 Ga Norvijaur intrusion in the Jokkmokk area.

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