BARENTS PROJECT

Age and chemical character of the Perthite monzonite suite in south-western Norrbotten, northern Sweden

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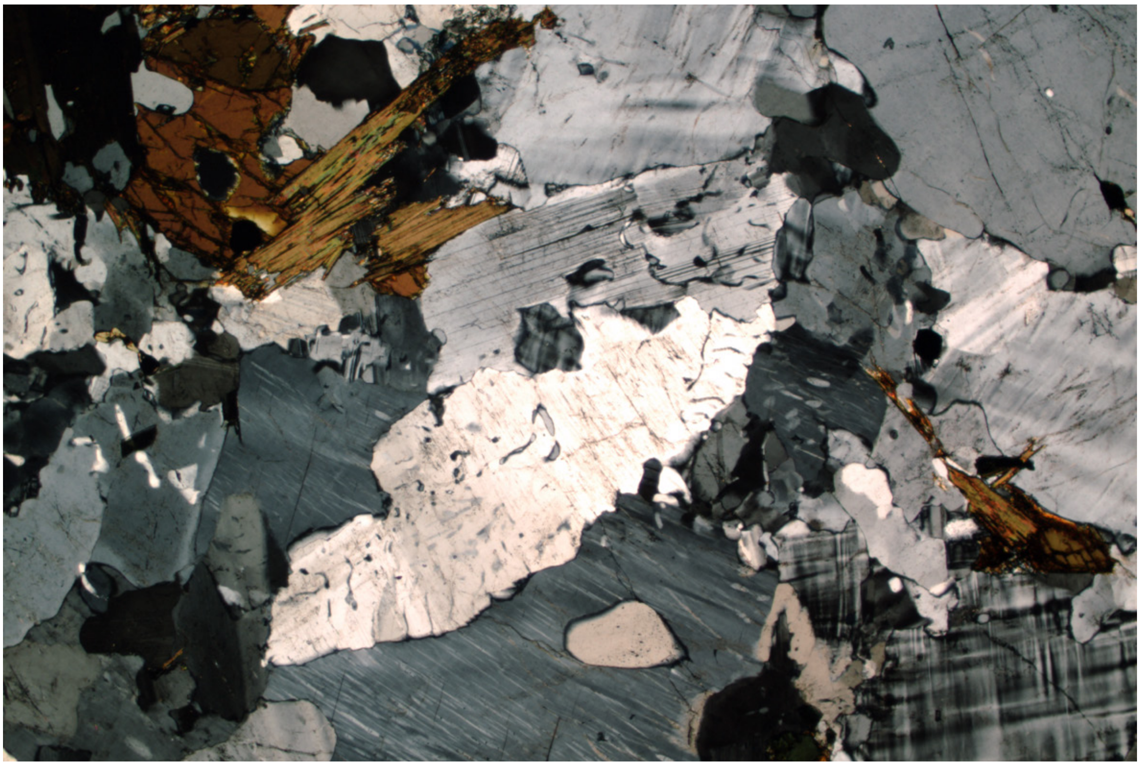

Sveriges geologiska undersökning
Geological Survey of Sweden

Cover: Photomicrograph in cross-polarised light of the
dated sample of Vuolvojaur granite (JEH090297A).
Photo: Fredrik Hellström.

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ABSTRACT

North of the Skellefte ore district in northern Sweden there are large volumes of early Svecokarelian intrusive rocks, divided into the calc-alkaline 1.89–1.88 Ga Haparanda-Jörn GI suite and the alkali-calcic 1.88–1.86 Ga Perthite monzonite suite. These intrusive suites are contemporaneous and comagmatic with Svecofennian volcanic rocks, the latter hosting numerous mineralisations including the world class Kiruna iron ores. In the south-western parts of the Norrbotten County, between Arjeplog and Jokkmokk, there is an 80 × 80 km large area with variably deformed porphyritic to augen-bearing metagranites, which are grouped under the term Vuolvojaur granite and belong to the Perthite monzonite suite. In the western part of this area, the granite is transected by the regional north-north-east trending Karesuando-Arjeplog deformation zone. This part includes strongly recrystallised and deformed, augen-bearing, partly gneissic varieties of granite. The eastern part, in contrast, consists of better preserved potassium feldspar-porphyritic to unevenly grained, weakly deformed granite. One augen-bearing, gneissic granite from the western part and two porphyritic to unevenly grained granites from the eastern part of the area record ages of 1877±5 Ma, 1878±5 Ma and 1876±5 Ma, suggesting a narrow time interval of igneous activity that falls in the 1882±6 to 1867±8 Ma range of previously determined ages of rocks of the Perthite monzonite suite in south-western Norrbotten. This igneous activity corresponds in time with zircon ages obtained from the main ore body in the Kiirunavaara apatite iron oxide deposit, suggesting a connection between the large volumes of the Perthite monzonite suite intrusions and apatite iron ore formation in Norrbotten. The igneous age of the strongly recrystallised sample of Vuolvojaur granite constrains regional amphibolite facies metamorphism in the Arjeplog-Jokkmokk area to be younger than 1877±5 Ma. Heterogeneous, post-1.87 Ga deformation and metamorphism is suggested to have occurred in large areas of Norrbotten.

The Vuolvojaur granite is classified as ferroan, alkali-calcic to calc-alkalic and metaluminous to weakly peraluminous. It falls in the fields of high-potassium, calc-alkaline to shoshonite series, suggesting an A- to I-type signature. Fluorite is a characteristic accessory mineral in the biotite±hornblende bearing granite of syenogranitic to subordinate monzogranitic composition. Syenitoid rocks are rare in this area, unlike in the Fjällåsen-Kiruna area further north. This possibly reflects different source compositions north of the Archean–Proterozoic boundary zone north of Jokkmokk, in addition to thicker crust with possibly deeper and lower degrees of partial melting constraining magma compositions to more alkaline, silica poor compositions. The overall felsic nature of early Svecokarelian magmatism suggests that a Paleoproterozoic basement probably is present south of the Archean boundary, represented by scattered basement windows of 1.96–1.93 Ga old rocks, including the 1.93 Ga Norvijaur intrusion in the Jokkmokk area. The Vuolvojaur granite has an upper crust trace element geochemical signature and it is suggested that the rocks of the Perthite monzonite suite have formed at a convergent margin above a subduction zone dipping to the present north.

Keywords: U-Pb, zircon, Vuolvojaur granite, Svecokarelian, Svecofennian, Fennoscandian Shield

INTRODUCTION

North of the Skellefte ore district in northern Sweden there are large volumes of early orogenic Svecokarelian intrusions, divided into the calc-alkaline 1.89–1.88 Ga Haparanda and Jörn GI suites and the alkali-calcic 1.88–1.86 Ga Perthite monzonite suite (Fig. 1, e.g. Ödman et al. 1949, Ödman 1957, Kathol & Weihed 2005, Witschard 1984, Skiöld & Öhlander 1989, Skiöld 1993, Bergman et al. 2001, Lundmark et al. 2005, González Roldán 2010, Beijgarn et al. 2013). These intrusive rocks are considered to be comagmatic with the Svecofennian volcanic rocks of the Porphyrite and Porphyry groups, which host numerous mineralisations including the world class Aitik porphyry

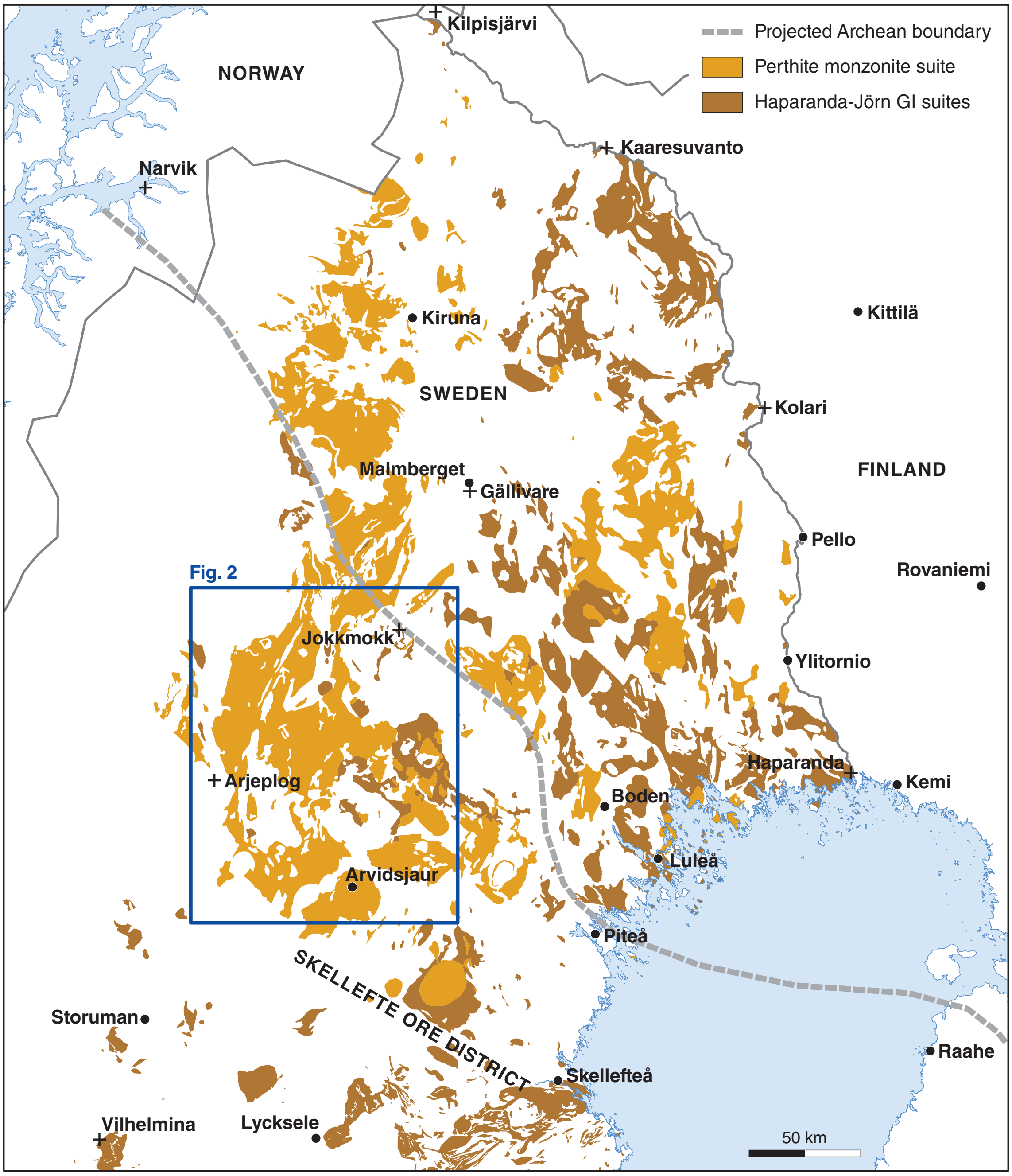


Figure 1. Early orogenic Svecokarelian intrusions of northern Sweden. Modified from the SGU 1:1 million bedrock geology database. The square outlines the extent shown in Figures 2 and 3.

copper deposit and the Kiruna-Malmberget iron ores (Martinsson & Wanhainen 2013, Weihed et al. 2008). The Perthite monzonite suite is mainly found in the western part of Norrbotten County (further on referred to as Norrbotten), where it forms a broad, north-south trending belt. The Haparanda suite is mainly found in the eastern parts of Norrbotten. The criteria for subdivision of the rocks into either one of the suites is not well defined. Commonly, red granitic to syenitoid rocks are assigned to the Perthite monzonite suite, whereas grey granodioritic to dioritic rocks are assigned to the Haparanda suite. However, also syenitoid rocks have been allocated to the Haparanda suite (see Bergman et al. 2001 and references therein, Bergman et al. 2015).

Sm-Nd isotope 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. This paleoboundary has been referred to as the Luleå-Jokkmokk zone, and it is located c. 100 km north of the Skellefte district (Fig. 1, Öhlander et al. 1993, Mellqvist et al. 1999). In southern Norrbotten, south of the Luleå–Jokkmokk zone, the early orogenic intrusions have been subdivided in a similar way into the 1.89–1.88 Ga old Jörn GI suite, coeval with the Skellefte group, and the 1.88–1.86 Ga old granites of the Perthite monzonite suite which are comagmatic with the volcanic rocks of the Arvidsjaur group. The calc-alkaline Jörn GI 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 $\varepsilon_{Nd(t)}$ values, a calcic, calc-alkaline trend and was formed in a juvenile island arc-terrane that was accreted onto the Archean craton (Mellqvist et al. 2003).

Ongoing bedrock mapping by SGU south of the Luleå–Jokkmokk zone, in the 26I Luvos area between Arjeplog and Jokkmokk in the south-western part of Norrbotten (Fig. 1), reveals large parts of variably deformed potassium-feldspar porphyritic granites to augen-bearing, gneissic granites, referred to as the Vuolvojaur granite (Berndtsson 1983). Field characteristics and the geochemical signature of the rocks of the Perthite monzonite suite are similar to rocks of the younger, 1.80–1.79 Ga old Edefors-Revsund suites (Öhlander & Skiöld 1994) and assigning rocks to either suite without radiometric dating is difficult. Two different varieties of the Vuolvojaur granite were sampled for geochronology (Fig. 2) to investigate if the Vuolvojaur granite belongs to the Perthite monzonite suite or the Edefors-Revsund suite. Two samples (ARN120006A, DLA130010A) were taken of a weakly deformed, potassium-feldspar porphyritic to unevenly grained granite from the north-eastern and south-eastern parts of the mapped area 26I Luvos (Fig. 2), and one sample (JEH090297A) was taken from a gneissic, strongly recrystallised granite from the south-western part of the mapped area.

The aims of this study are to date igneous crystallisation of the Vuolvojaur granite and to characterise the petrography and geochemistry of the granite. A protolith age of the gneissic granite will also constrain a maximum age of regional, amphibolite facies metamorphic recrystallisation and deformation of the area, which is transected by the north-north-east trending Karesuando-Arjeplog deformation zone.

The Vuolvojaur granite

The Vuolvojaur granite is outlined by a c. 80 × 80 km large, low-magnetic area between Arjeplog and Jokkmokk. It is bordered by Svecofennian supracrustal rocks and c. 1.80 Ga old intrusive rocks (Figs. 2–3). The western part of the granite is transected by the Karesuando-Arjeplog deformation zone (KADZ), which is a steeply dipping regional deformation zone that strikes north-north-east. West of and within the KADZ, the Vuolvojaur granite is generally strongly foliated or lineated and recrystallised into a finer grain size. Locally there are, however, also areas with more well-preserved potassium-feldspar porphyritic textures, as in the south-western part

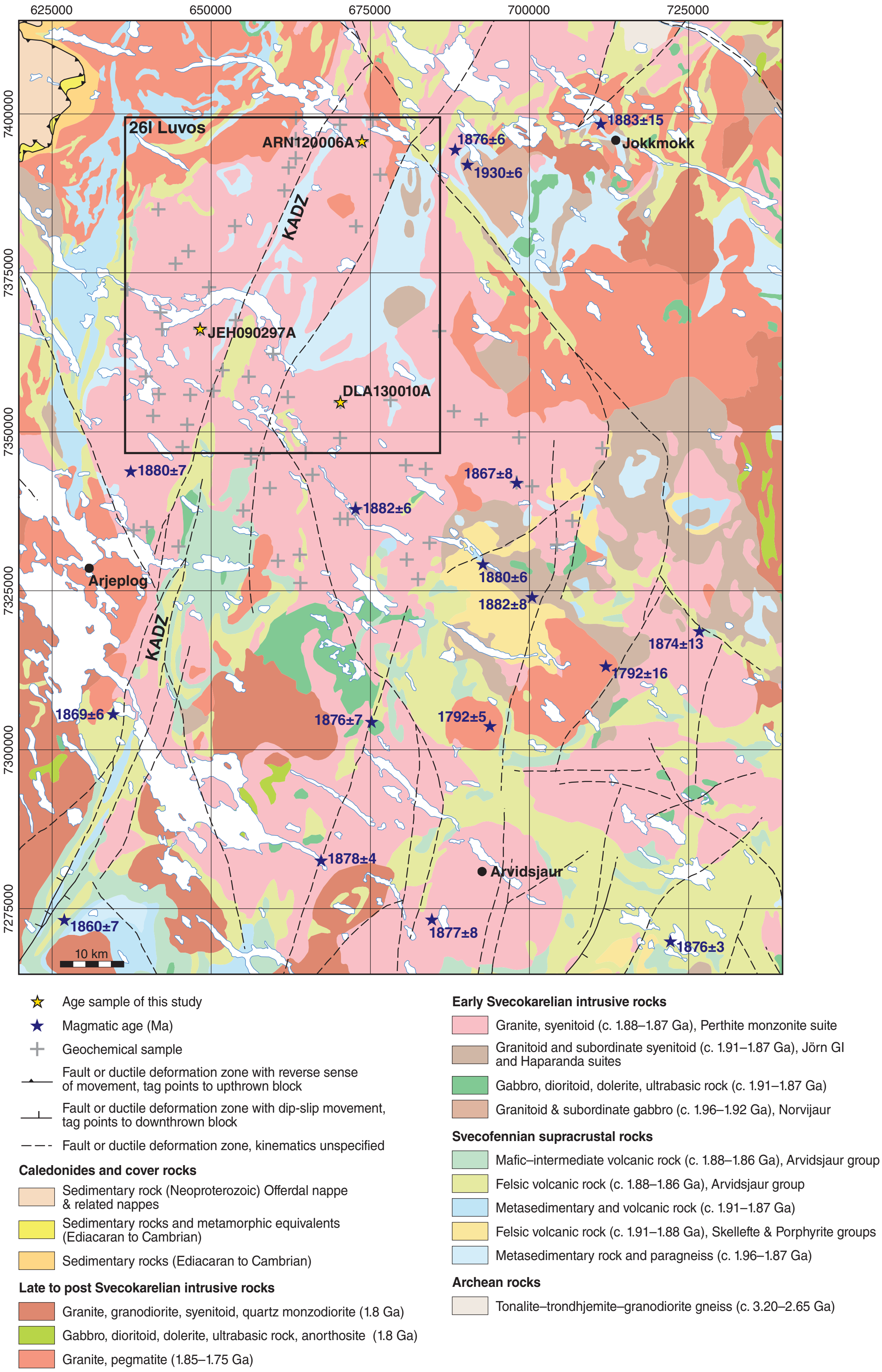

625000
650000
675000
700000
725000
7400000
7375000
7350000
7325000
7300000
7275000
26I Luvos
ARN120006A
JEH090297A
DLA130010A
KADZ
KADZ
1883±15
Jokkmokk
1876±6
1930±6
1880±7
1867±8
1882±6
Arjeplog
1880±6
1882±8
1874±13
1792±16
1869±6
1876±7
1792±5
1878±4
Arvidsjaur
1860±7
1877±8
1876±3
10 km
Age sample of this study
Magmatic age (Ma)
Geochemical sample
Fault or ductile deformation zone with reverse sense of movement, tag points to upthrown block
Fault or ductile deformation zone with dip-slip movement, tag points to downthrown block
Fault or ductile deformation zone, kinematics unspecified
Caledonides and cover rocks
Sedimentary rock (Neoproterozoic) Offerdal nappe & related nappes
Sedimentary rocks and metamorphic equivalents (Ediacaran to Cambrian)
Sedimentary rocks (Ediacaran to Cambrian)
Late to post Svecokarelian intrusive rocks
Granite, granodiorite, syenitoid, quartz monzodiorite (1.8 Ga)
Gabbro, dioritoid, dolerite, ultrabasic rock, anorthosite (1.8 Ga)
Granite, pegmatite (1.85–1.75 Ga)
Early Svecokarelian intrusive rocks
Granite, syenitoid (c. 1.88–1.87 Ga), Perthite monzonite suite
Granitoid and subordinate syenitoid (c. 1.91–1.87 Ga), Jörn GI and Haparanda suites
Gabbro, dioritoid, dolerite, ultrabasic rock (c. 1.91–1.87 Ga)
Granitoid & subordinate gabbro (c. 1.96–1.92 Ga), Norvijaur
Svecofennian supracrustal rocks
Mafic–intermediate volcanic rock (c. 1.88–1.86 Ga), Arvidsjaur group
Felsic volcanic rock (c. 1.88–1.86 Ga), Arvidsjaur group
Metasedimentary and volcanic rock (c. 1.91–1.87 Ga)
Felsic volcanic rock (c. 1.91–1.88 Ga), Skellefte & Porphyrite groups
Metasedimentary rock and paragneiss (c. 1.96–1.87 Ga)
Archean rocks
Tonalite–trondhjemite–granodiorite gneiss (c. 3.20–2.65 Ga)

Figure 2. Bedrock geological map of the Arjeplog-Jokkmokk-Arvidsjaur area in south-western Norrbotten, modified from the SGU 1:1 million bedrock geology database. The mapped area of 26I Luvos is outlined by the square. KADZ=Karesuando-Arjeplog deformation zone. Selected U-Pb age determinations are from SGU's radiometric age database. References to age determinations: Bergström & Triumf 2002, Hellström 2015, Kathol & Aaro 2006, Kathol & Persson 2007, Kathol et al. 2008, Kathol et al. 2012, Lundmark et al. 2005, Mellqvist & Aaro 2006, Morris et al. 2015, Skiöld et al. 1993.

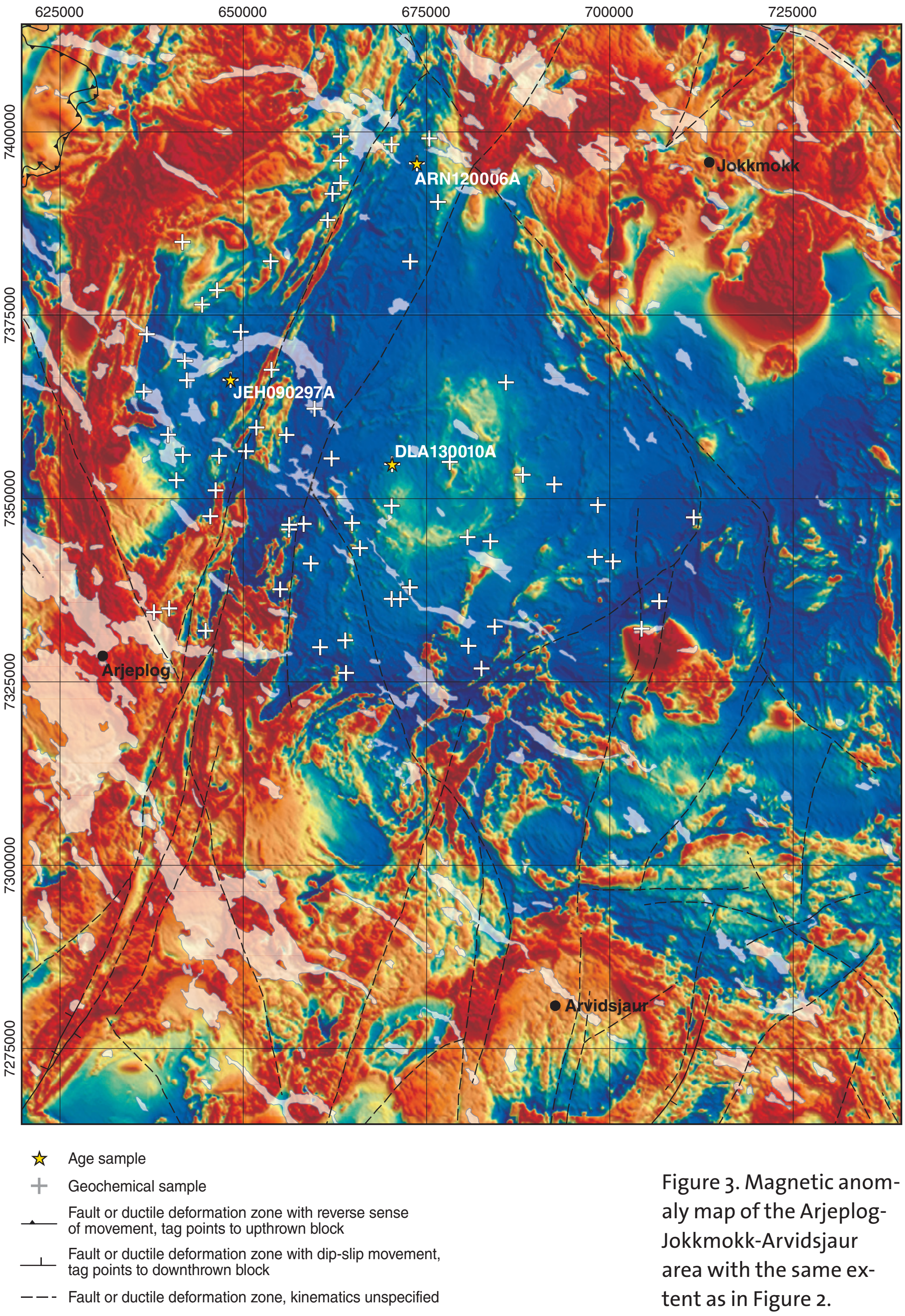


Figure 3. Magnetic anomaly map of the Arjeplog-Jokkmokk-Arvidsjaur area with the same extent as in Figure 2.

of the mapping area, west of KADZ, with a variety of rocks previously referred to as Hällnäs granite (Welin et al. 1977), but which are now considered to be part of the Vuolvojaur granite according to recent mapping by SGU (Fig. 4A).

Biotite±amphibole in the gneissic variety of the granite are accumulated in extended and parallel oriented aggregates between recrystallized quartz-feldspar domains, giving an augen bearing appearance (Fig. 4B). This suggests a relict potassium-feldspar porphyritic to unevenly, coarse grained texture. Within the KADZ, there are zones of protomylonitic Vuolvojaur granite, but also supracrustal gneisses outlined as high magnetic north-north-east trending strings.

The metamorphic grade in the western part of the area reached amphibolite facies conditions with the formation of sillimanite, cordierite and garnet in the paragneisses. Partial melting occurred locally in the supracrustal gneisses. Locally, there are melt mobilisates in the gneissic granites (Fig. 4C).

Figure 4. Typical textures of Vuolvojaur granite. **A.** Potassium feldspar porphyritic metagranite (former Hällnäs granite). **B.** Gneissic, recrystallised metagranite (JEH090297A). **C.** In the gneissic metagranite there are locally diffuse irregular pockets with evenly grained, isotropic leucogranite, possibly representing anatectic melt mobilisate. Photo: Fredrik Hellström.

In the area east of the KADZ, the degree of deformation and metamorphic recrystallisation is generally lower, with a potassium-feldspar porphyritic, unevenly medium- to coarse-grained texture of the granite. In the central part of the Vuolvojaur granite, around the sample site of DLA130010A, there is a circular magnetic structure which is interpreted as one or two distinct magmatic pulses within the Perthite monzonite suite (Kathol & Aaro 2006). To the south, in the map area 25I Stensund NO, the bedrock inside this structure is composed of evenly medium-grained granite, surrounded by finely to coarsely porphyritic granite.

The Vuolvojaur granite is biotite-bearing and commonly contains hornblende. Fluorite, titanite, zircon and magnetite are common accessory phases. The potassium feldspar is a tartan-twinned microcline or an orthoclase, and both partly contain perthitic intergrowths.

Geochemistry

Sample preparation was carried out by ALS Minerals in Piteå (Sweden) and subsequent analytical work performed at ALS Minerals and at ACME labs in Vancouver (Canada). Preparation involved crushing of the sample and pulverising it to a powder using low-chrome steel grinding mills.

The lithogeochemical analysis at ALS was conducted using the whole rock major and trace element package CCP-PKG01, which is a combination of different methods. Lithium metaborate fusion ICP-AES (ME-ICP06) was used for major elements. Total carbon and sulphur was analysed using a LECO sulphur analyser (ME-IR08). The sample (0.01 to 0.1 g) is heated to approximately 1350 °C in an induction furnace while passing a stream of oxygen through the sample. Total sulphur and carbon is measured by an IR detection system. Trace elements including the full rare earth element suites are reported from three digestions with either ICP-AES or ICP-MS finish: a lithium borate fusion for the resistive elements (ME-MS81), a four acid digestion for the base metals (ME-4ACD81), and an aqua regia digestion for the volatile gold related trace elements (ME-MS42).

The lithogeochemical analysis at ACME labs used the whole rock major and trace element package 4A+4B, where total abundances of the major oxides and several minor elements are reported on a 0.2 g sample analysed by ICP-emission spectrometry following a lithium metaborate or tetraborate fusion and dilute nitric digestion. Loss on ignition (LOI) is by weigh difference after ignition at 1000 °C. Rare earth and refractory elements are determined by ICP mass spectrometry following a lithium metaborate or tetraborate fusion and nitric acid digestion of a 0.2 g sample (same decomposition as Group 4A). In addition, a separate 0.5 g split is digested in aqua regia and analysed by ICP-MS to report the precious and base metals. Geochemical diagrams were made using software GCD-kit (Janoušek et al. 2006).

Geochemical character of the Vuolvojaur granite

Altogether, there are geochemical analyses of 64 samples classified as Vuolvojaur granite. Five of these show weak K-alteration according to the diagram of Hughes (1973), and are not discussed further (Fig. 5). Two quartz-syenitic samples with high potassium content are also outlined as different from the remaining group. Excluding the quartz-syenitic samples, most samples classify as syenogranites to subordinate monzogranites in the Q-ANOR diagram of Streckeisen & LeMaitre (1979), which is a CIPW normative equivalent to the IUGS classification of Streckeisen (1976). The Q-ANOR diagram provides the closest approximation to plutonic rock names obtained from the modal IUGS quartz-plagioclase-K-feldspar diagram (Whalen & Frost 2013). The P-Q diagram of Debon & Lefort (1983) shows similar results (Fig. 5). Samples of the Vuolvojaur granite have high silica, >70 wt% SiO_2 (70.3–77.8 wt%) and high potassium content, in average 5.0 wt% K_2O (3.5–6.1 wt%). The Zr content is moderate, 131–510 ppm, and zircon saturation temperatures are calculated at 771–885 °C (Watson & Harrison 1983).

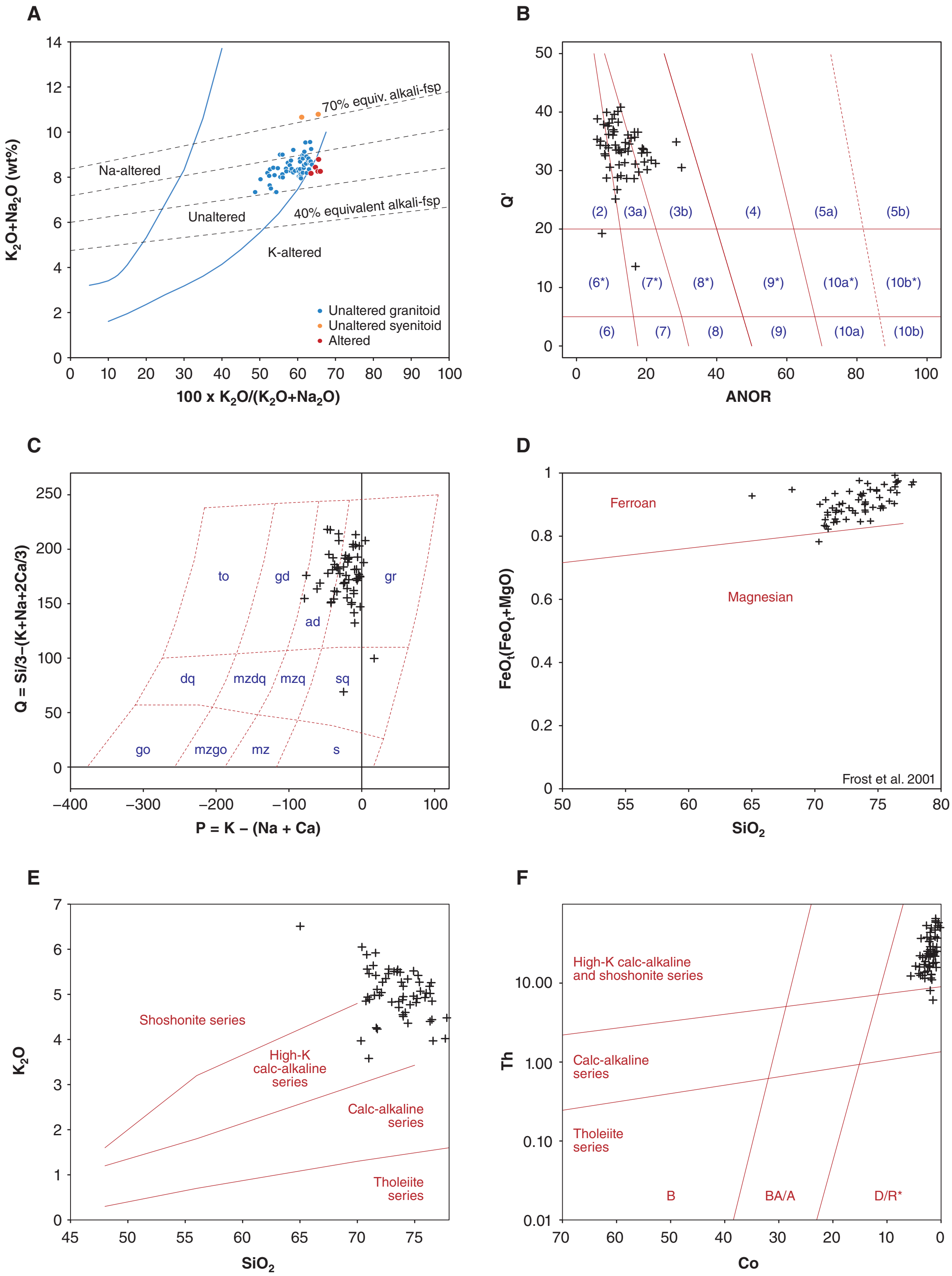
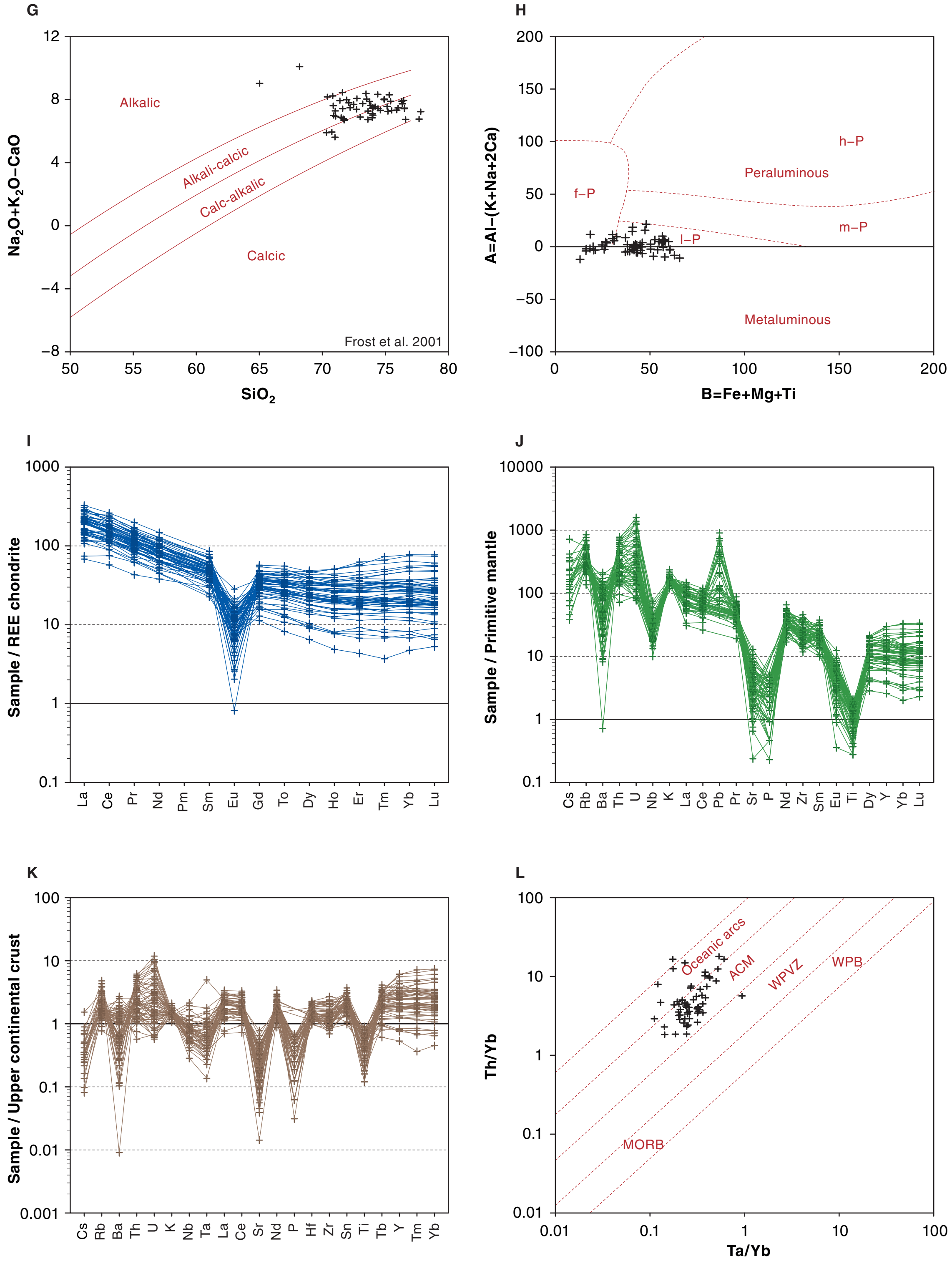


Figure 5. Geochemistry of the Vuolvojaur granite. Data of unaltered samples of Vuolvojaur granite is plotted in diagrams B–L (crosses). **A.** Hughes igneous spectrum (Hughes 1973). **B.** Q'–ANOR plot (Streckeisen & Le Maitre 1979). 2 = alkali feldspar granite, 3a = syenogranite, 3b = monzogranite, 6* = quartz alkali feldspar syenite, 7* = quartz syenite. **C.** Debon and Le Fort P–Q. gr = granite, ad = adamellite (monzogranite), gd = granodiorite, sq = quartz syenite. **D.** FeO_{tot}/(FeO_{tot} + MgO) vs. wt% SiO_2 diagram (Frost et al. 2001). **E.** SiO_2–K_2O plot (Peccerillo & Taylor 1976). **F.** Co–Th plot (Hastie et al. 2007). B = basalt, BA/A = basaltic andesite and andesite, D/R* = dacite and rhyolite. **G.** Modified alkali-lime index diagram (Frost et al. 2001). **H.** B–A plot (modified by Villaseca



et al. 1998). l-P = low peraluminous, f-P = felsic peraluminous. **I.** Spider plot – REE chondrite (Boynton 1984). **J.** Spider plot – primitive mantle (Sun & McDonough 1989). **K.** Spider plot – upper continental Crust (Taylor & McLennan 1995). **L.** Th/Yb–Ta/Yb geotectonic classification diagram (Schandl & Gorton 2002, originally used for volcanic rocks). ACM= Active continental margin, WPVZ = within-plate volcanic zones, WPB = within-plate basalt, MORB = mid-oceanic ridge basalts.

The Vuolvojaur granite can be classified as ferroan (A-type), alkali-calcic to calc-alkalic and metaluminous to low peraluminous (I-type), and falls in the fields of high-K, calc-alkaline to shoshonite series (Fig. 5). The chondrite normalised REE spider diagram shows a variably negatively tilted REE pattern with enrichment of LREE over HREE ($[La/Lu]_N$ = 1.2–41.7, average 10.2), and a negative Eu anomaly (Eu/Eu* = 0.02–0.68, average 0.28). The HREE end shows a negatively tilted to horizontal pattern.

A primitive mantle normalised multi-element spider diagram shows an enrichment in the large ion lithophile elements and distinct negative anomalies in Ba, Nb, Sr, P and Ti. The spider pattern thus shows a typical upper continental crustal signature, except the low amounts of Sr, P, Ti and partly Ba. The geotectonic Th/Yb vs. Ta/Yb discrimination diagram of Schandl & Gorton (2002) suggests an active continental margin signature, but is possibly inherited from the source rock.

Zircon U-Th-Pb geochronology

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 back scattered electron (BSE) and cathodoluminescence (CL) imaging using electron microscopy at the Department of Geology, Uppsala University, and at the Department of Geology, Lund University. High-spatial resolution secondary ion mass spectrometer (SIMS) analysis was made in March 2010 (JEH090297A), in May 2013 (ARN120006A) and in November 2014 (DLA130010A) using a Cameca IMS 1280 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) and Whitehouse & Kamber (2005). A c. 6 nA O^{2-} primary ion beam was used, yielding spot sizes of c. 15–20 µm. 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 Pb corrected isotope values were calculated using modern common Pb composition (Stacey & Kramers 1975) and measured ^{204}Pb. Decay constants follow the recommendations of Steiger & Jäger (1977). Diagrams and age calculations of isotopic data were made using software Isoplot 4.15 (Ludwig 2012). All age uncertainties are presented at the 2σ or 95% confidence level.

ARN120006A

The rock sampled in the north-eastern part of the study area (26I Luvos) is a foliated, porphyritic granite with 1–2 cm large potassium-feldspar phenocrysts in a medium-grained groundmass containing 5–10% mafic minerals in aggregates, mainly biotite (Fig. 6). Fluorite is an accessory mineral.

Zircons in the sample have subhedral to euhedral, prismatic shapes and show an oscillatory zonation that in some grains are irregular or patchy. Some grains may contain inherited cores (Fig. 6). One analysis (no 62) is rich in uranium, 1592 ppm. It records a high value of common lead and is probably metamict. The other analyses have has 159–380 ppm U (Table 1). Th/U ratios are 0.11–0.42. Two analyses (59, 62) are 15% and 43% discordant. Six analyses are concordant at the 2σ limit, with a concordia age of 1880±5 Ma (Fig. 6, 2σ, MSWD of conc. & equiv = 1.5, probability = 0.11). Including also two weakly discordant (4%) analyses (25, 57), the weighted average ^{207}Pb/^{206}Pb age is calculated at 1878±5 Ma (MSWD = 1.6, probability = 0.13, n = 8), i.e. within error identical to the concordia age. The weighted average age is chosen as the best age estimate, interpreted to date igneous crystallisation of the granite at 1.88 Ga.

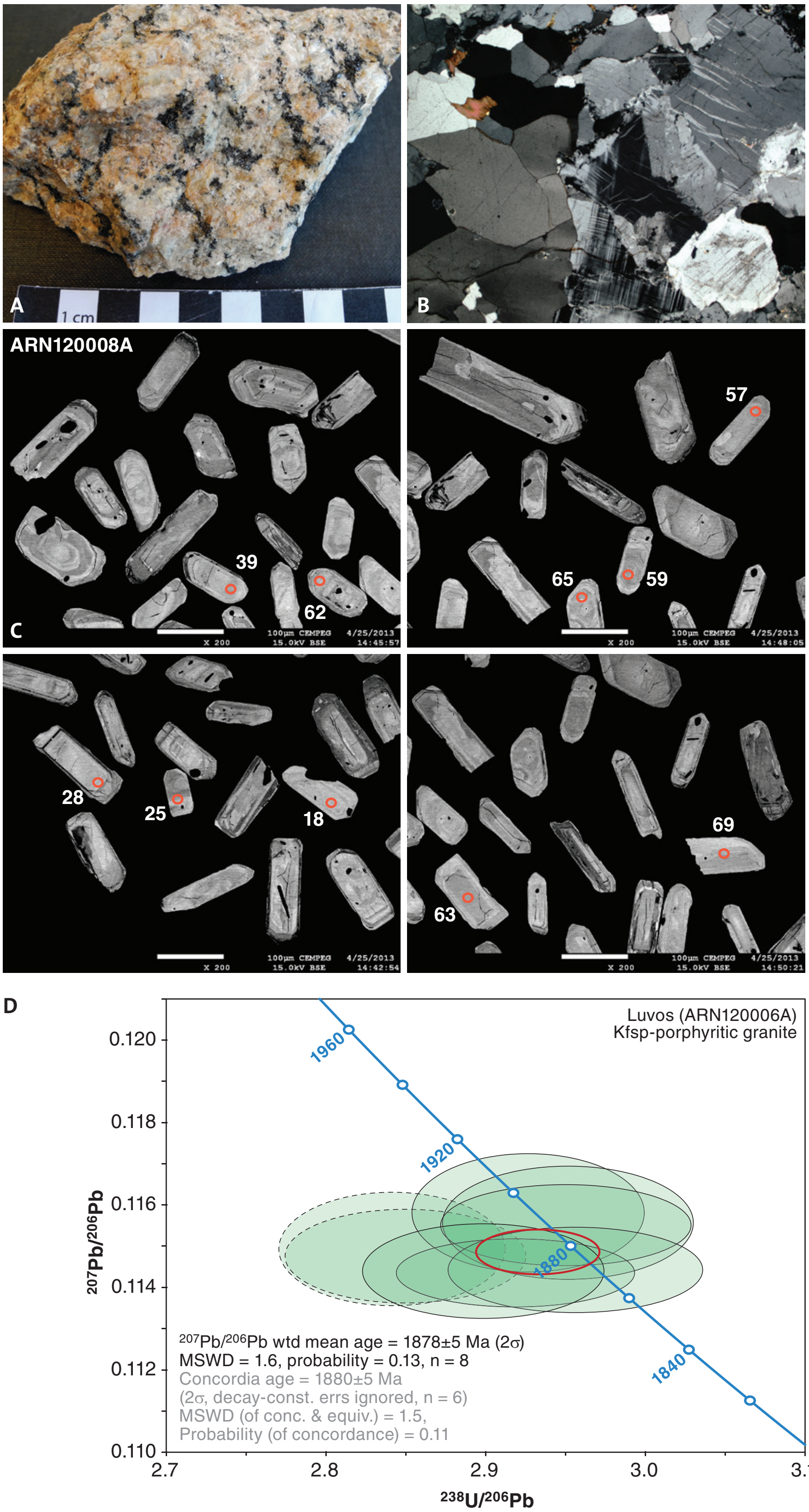


Figure 6. **A.** The dated sample (ARN120006A) of potassium-feldspar porphyritic granite. **B.** Photomicrograph in cross-polarised light. Long side of the image is 5.8 mm. **C.** BSE-images of zircon. Red circles mark the approximate location of analysed spots. Numbers refer to analytical spot number in Table 1. **D.** Tera-Wasserburg diagram showing U-Pb SIMS zircon data. Discordant analysis is marked with broken lines. Error ellipse of calculated weighted mean age is shown in red.

Table 1. SIMS U-Pb-Th zircon data (n3576 = JEH090297A, n4590 = ARN120003A, n5172 = DLA130010A).

Analysis	U (ppm)	Th (ppm)	Pb (ppm)	Th/U calc.[1]	^{207}Pb/^{235}U	±σ (%)	^{208}Pb/^{232}Th	±σ (%)	^{238}U/^{206}Pb	±σ (%)	^{207}Pb/^{206}Pb	±σ (%)	ρ^2	Disc. % conv.[3]	Disc. % 2σ lim.[4]	^{207}Pb/^{206}Pb age (Ma)	±σ	^{206}Pb/^{238}U age (Ma)	±σ	^{206}Pb/^{204}Pb measured	f_{206}%[5]
n3576-03	565	215	200	0.36	4.451	1.23	0.0916	3.94	3.493	1.19	0.1128	0.30	0.97	−13.6	−11.1	1844.3	5.5	1623.0	17.1	9144	0.20
n3576-04a	270	384	85	0.30	4.076	1.25	0.0208	5.18	3.885	1.19	0.1148	0.38	0.95	−23.9	−21.4	1877.5	6.8	1476.4	15.7	48459	0.04
n3576-05	457	124	167	0.26	4.787	1.00	0.0917	3.86	3.264	0.95	0.1133	0.30	0.95	−8.0	−5.8	1853.1	5.4	1723.0	14.4	18527	0.10
n3576-07	199	70	82	0.37	5.387	1.04	0.1008	3.85	2.950	0.96	0.1153	0.41	0.92	−0.2		1884.1	7.3	1881.6	15.6	147821	{0.01}
n3576-12b	279	96	115	0.35	5.326	1.03	0.0984	3.83	2.962	0.95	0.1144	0.39	0.92	0.3		1870.5	7.1	1875.2	15.5	72516	0.03
n3576-12c	265	115	107	0.33	5.267	1.02	0.0730	4.10	2.999	0.96	0.1146	0.35	0.94	−1.1		1873.0	6.2	1855.0	15.5	62470	0.03
n3576-12d	210	60	85	0.29	5.316	1.05	0.0995	3.85	2.983	0.98	0.1150	0.37	0.94	−1.0		1880.1	6.6	1863.6	15.9	122849	{0.02}
n3576-14	167	61	68	0.37	5.237	1.19	0.0970	3.91	3.015	1.09	0.1145	0.46	0.92	−1.6		1872.5	8.2	1846.4	17.6	111508	{0.02}
n3576-16	315	89	129	0.29	5.418	1.02	0.1004	3.84	2.924	0.97	0.1149	0.32	0.95	1.1		1878.4	5.8	1896.1	16.0	92350	0.02
n3576-19	219	156	84	0.37	4.879	1.12	0.0500	3.92	3.213	1.02	0.1137	0.46	0.91	−6.9	−4.0	1859.2	8.3	1746.7	15.7	7161	0.26
n3576-20	343	104	140	0.30	5.375	1.06	0.0984	3.84	2.952	1.01	0.1151	0.34	0.95	−0.0		1881.1	6.0	1880.7	16.5	71655	0.03
n4590-18	264	102	110	0.40	5.398	1.14	0.0997	3.3	2.950	1.08	0.1155	0.35	0.95	−0.4		1887.9	6.3	1881.5	17.7	237551	{0.01}
n4590-25	159	53	68	0.36	5.577	1.13	0.1056	3.3	2.842	1.02	0.1149	0.49	0.90	4.0	0.9	1878.9	8.8	1943.7	17.1	92262	{0.02}
n4590-28	297	93	124	0.33	5.441	1.14	0.1027	3.3	2.899	1.06	0.1144	0.41	0.93	2.5		1870.4	7.4	1910.5	17.6	99577	0.02
n4590-39	223	88	93	0.40	5.337	1.16	0.0999	3.3	2.956	1.10	0.1144	0.37	0.95	0.5		1870.9	6.7	1878.2	18.0	270906	{0.01}
n4590-57	192	58	81	0.32	5.552	1.15	0.1042	3.7	2.850	1.08	0.1148	0.40	0.94	3.9	0.9	1876.1	7.3	1938.7	18.1	419295	{0.00}
n4590-59	380	41	116	0.11	3.954	1.27	0.0955	8.3	3.754	1.17	0.1077	0.49	0.92	−15.2	−12.1	1760.3	8.9	1522.2	15.9	6375	0.29
n4590-62	1592	809	308	0.31	2.027	1.78	0.0486	4.1	6.494	1.51	0.0955	0.93	0.85	−42.8	−37.7	1537.1	17.3	923.2	13.0	674	2.77
n4590-63	179	74	75	0.42	5.398	1.19	0.0993	3.3	2.952	1.09	0.1156	0.49	0.91	−0.5		1888.8	8.7	1880.8	17.7	156216	{0.01}
n4590-65	202	72	84	0.37	5.456	1.13	0.1013	3.4	2.927	1.01	0.1158	0.51	0.89	0.1		1892.6	9.1	1894.7	16.7	115669	{0.02}
n4590-69	358	66	143	0.19	5.402	1.08	0.1011	3.3	2.919	1.04	0.1144	0.30	0.96	1.8		1869.7	5.3	1899.1	17.2	219443	{0.01}
n5172_01a	7106	2106	3449	0.35	6.421	1.15	0.1154	2.3	2.472	1.14	0.1151	0.10	1.00	19.3	16.6	1881.8	1.8	2189.9	21.3	281753	0.01
n5172_02a	129	34	52	0.27	5.332	1.09	0.0979	2.2	2.960	0.99	0.1144	0.46	0.91	0.3		1871.2	8.3	1876.4	16.2	350381	{0.01}
n5172_03a	197	84	84	0.44	5.424	1.08	0.1012	2.1	2.929	0.98	0.1152	0.46	0.91	0.6		1883.5	8.2	1893.4	16.1	16817	0.11
n5172_03b	435	118	177	0.28	5.395	1.03	0.1007	2.1	2.945	0.98	0.1152	0.31	0.95	0.1		1883.2	5.6	1884.7	16.0	215589	{0.01}
n5172_04a	184	78	77	0.43	5.294	1.16	0.0981	2.2	2.980	1.05	0.1144	0.50	0.90	−0.3		1870.7	9.0	1865.3	17.0	>1e6	{0.00}
n5172_04b	201	51	48	0.17	3.158	1.40	0.0649	3.0	4.960	1.23	0.1136	0.66	0.88	−39.6	−36.2	1857.5	11.9	1184.1	13.3	1347	1.39
n5172_05a	409	176	169	0.43	5.228	1.13	0.0973	3.1	3.003	1.08	0.1139	0.33	0.96	−0.5		1861.8	5.9	1853.1	17.4	3641	0.51
n5172_06a	120	35	49	0.30	5.288	1.08	0.0991	2.2	2.959	0.98	0.1135	0.47	0.90	1.3		1855.9	8.4	1876.9	15.9	>1e6	{0.00}
n5172_06b	1424	395	184	0.15	1.259	1.12	0.0335	2.3	9.032	0.97	0.0824	0.56	0.87	−48.5	−45.0	1256.2	10.8	676.9	6.2	963	1.94
n5172_07a	190	84	81	0.46	5.382	1.07	0.0999	2.1	2.924	1.01	0.1141	0.37	0.94	1.9		1865.9	6.7	1896.4	16.5	>1e6	{0.00}
n5172_08a	183	44	73	0.25	5.362	1.02	0.0996	2.1	2.955	0.95	0.1149	0.38	0.93	0.1		1878.2	6.8	1879.2	15.5	520454	{0.00}
n5172_08b	158	61	65	0.40	5.340	1.07	0.0993	2.3	2.967	0.99	0.1149	0.40	0.93	−0.4		1878.3	7.3	1872.5	16.1	>1e6	{0.00}

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 corrected for Pbcom, 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. % of common ^{206}Pb in measured ^{206}Pb, estimated from ^{204}Pb assuming a present day Stacey and Kramers (1975) model.
Figures in parentheses are given when no correction has been applied.

JEH090297A

The dated rock from the south-western part of the study area (26I Luvos) is a relict medium- to coarse-grained, weakly augen-bearing, foliated to lineated granite (Fig. 7). Hornblende and biotite are concentrated in dispersed, parallel orientated aggregates between elongated, recrystallised quartz-feldspar domains. There is a tendency of incipient melting of the rock. Traces of fluorite occur.

The zircon grains in the sample have subhedral to euhedral prismatic shapes with aspect ratios of about 1.5–4.0. Most grains have inclusions and cracks and are generally turbid. There are also transparent grains which were selected for analysis. BSE-images show an internal oscillatory zonation in the selected zircon (Fig. 7). Some grains have structurally older cores and in

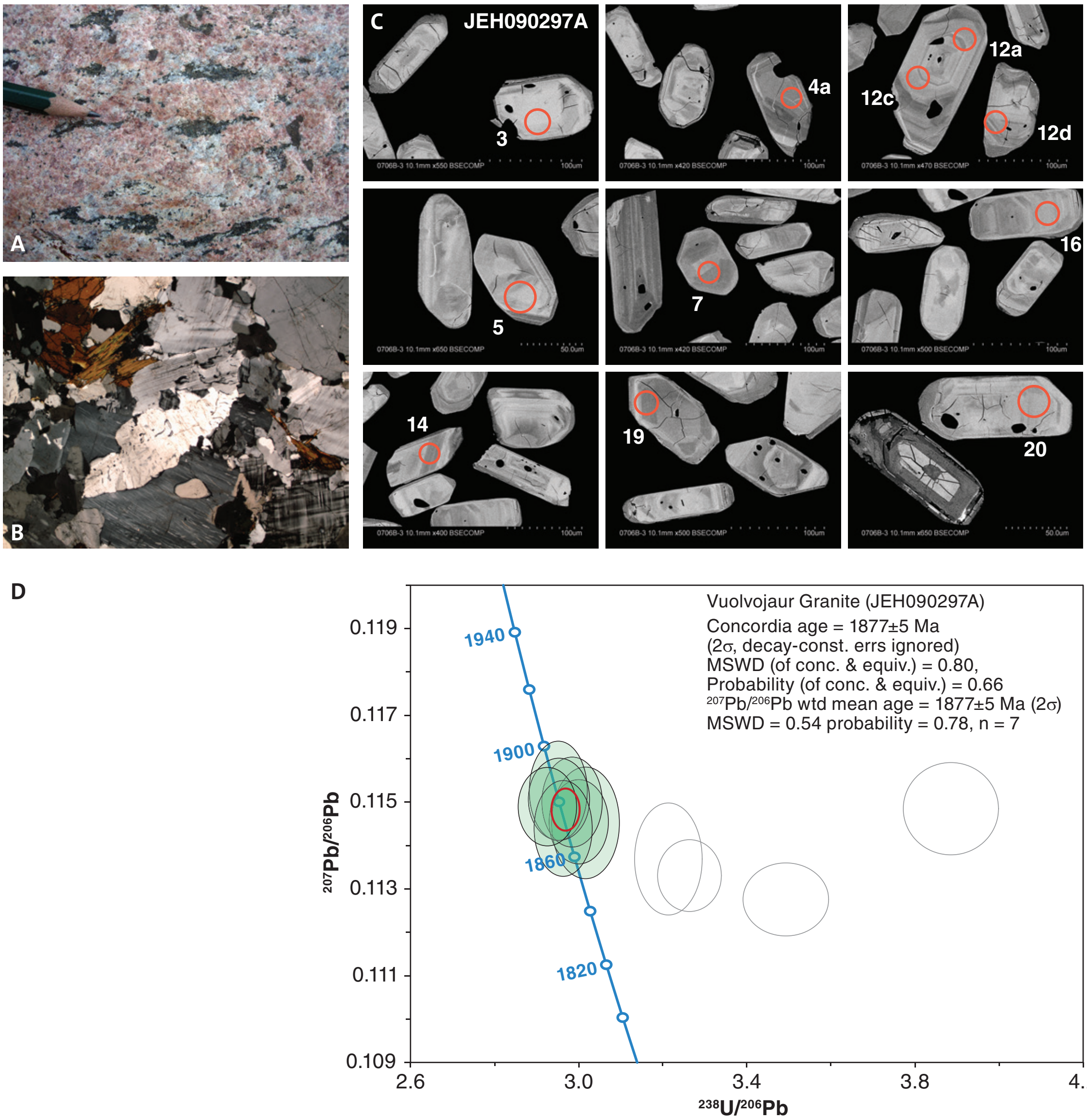


Figure 7. **A.** The dated sample (JEH090297A) of recrystallised, augen-bearing metagranite. **B.** Photomicrograph in cross-polarised light. Long side of the image is 5.8 mm. **C.** BSE-images of zircon (image: Andreas Petersson). Red circles mark the approximate location of analysed spots. Numbers refer to analytical spot number in Table 1. **D.** Tera-Wasserburg diagram showing U-Pb SIMS zircon data. Discordant analyses marked in gray are not used in age calculation. Error ellipse of calculated weighted mean age is shown in red.

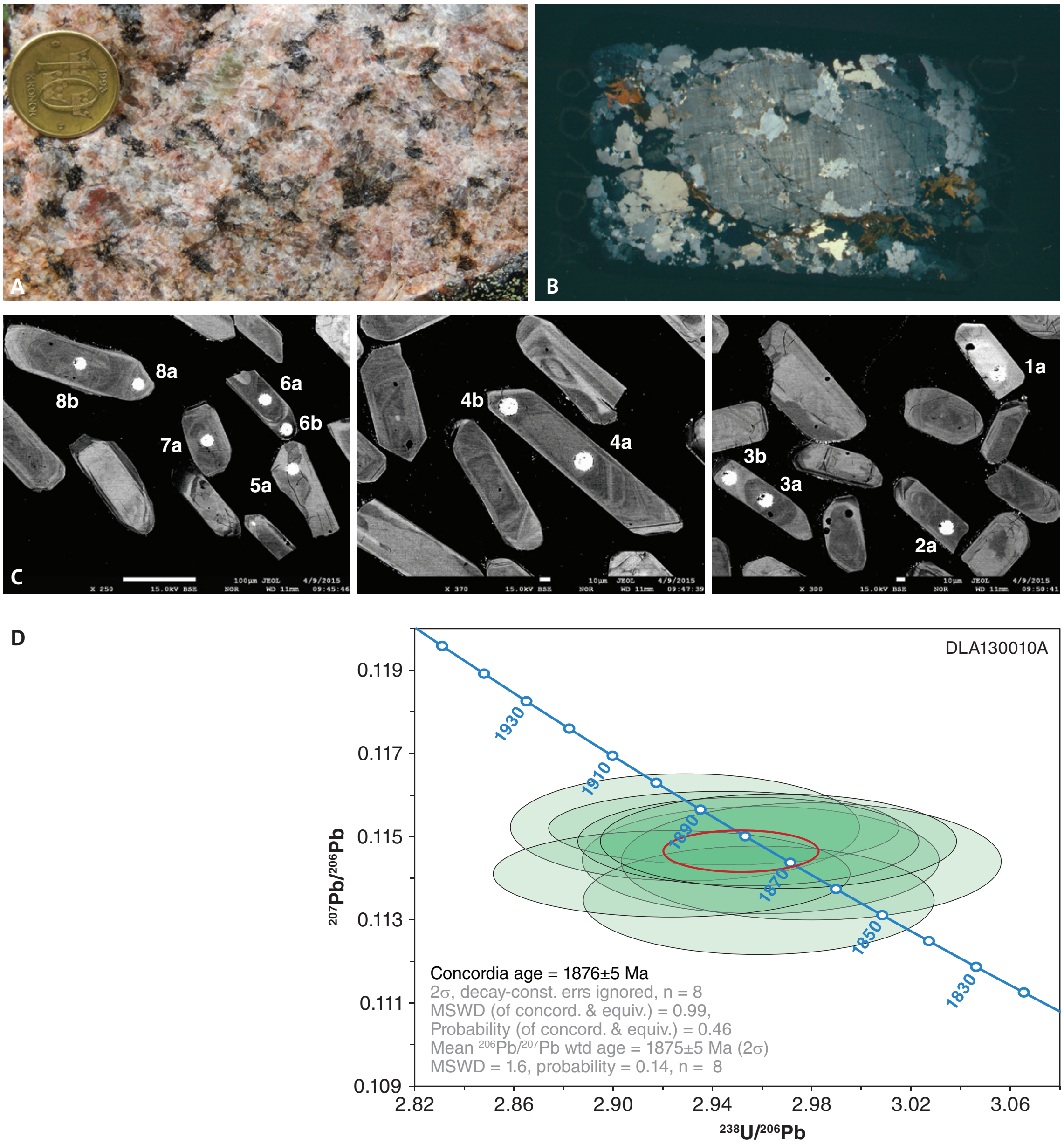


Figure 8. **A.** The dated sample (DLA130010A) of unevenly-grained to potassium-feldspar porphyritic granite. **B.** Photomicrograph in cross-polarised light. Long side of the image is 4.5 cm. **C.** BSE-images of zircon. Numbers refer to analytical spot number in Table 1. **D.** Tera-Wasserburg diagram showing U-Pb SIMS zircon data. Discordant analyses marked in gray are not used in the age calculation. Error ellipse of calculated weighted mean age is shown in red.

part also metamict zircon domains. The U content of the analysed zircon varies between 167 and 565 ppm and Th/U ratios are 0.26–0.37 (n=11, Table 1). The data points define a discordia line with intercept ages of 1875±9 Ma and 137±170 Ma (2σ, MSWD = 3.9, n = 11) indicating no significant post igneous isotopic disturbance in addition to recent Pb-loss. Seven analyses are concordant and yield a concordia age of 1877±5 Ma (2σ, MSWD of conc. & equiv = 0.80), identical to the weighted average ^{207}Pb/^{206}Pb age of 1877±5 Ma (2σ, MSWD = 0.54). The concordia age of 1877±5 Ma is interpreted to date igneous crystallisation of the studied metagranite.

Table 2. Ages of the Perthite monzonite suite granites in south-western Norrbotten (see Figure 2 for location of samples).

Sample	N	E	Map	Lithodem or locality	Age (Ma)	Method	Reference
ARN120006A	7395713	673708	26I NE	Vuolvojaur granite (Luvos)	1878±5	SIMS	This study
JEH090297A	7366179	648256	26I SW	Vuolvojaur granite (Njuolas)	1877±5	SIMS	This study
DLA130010A	7354680	670292	26I SE	Vuolvojaur granite (Dájdavárre)	1876±5	SIMS	This study
UJB970167A	7282610	667259	24I NE	Avaviken granite	1878±4	TIMS	Bergström & Triumf 2002 (SGU unpublished data)
CMT030001U	7337929	672637	25I NE	Njuorokvaratj	1882±6	TIMS	Kathol & Aaro 2006 (SGU un-published data)
CHB020195Y	7304441	675191	25I SE	Strittjebäcken	1876±7	TIMS	Kathol & Aaro 2006 (SGU un-published data)
CLU040256	7342018	697995	25J NW	Reuna	1867±8	TIMS	Kathol et al 2012 (SGU unpub-lished data)
CMT030026U	7343825	637359	25I NW	Hällnäs granite	1880±7	TIMS	Mellqvist & Aaro 2006 (SGU unpublished data)
88106	7394421	688335	26J NW	Juoksjokko granite	1876±6	TIMS	Skiöld et al 1993
80017	7273345	684645	24I SE	Arvidsjaur granite	1877±8	TIMS	Skiöld et al 1993

DLA130010A

The sampled rock is an isotropic, unevenly medium- to coarse-grained, reddish granite (Fig. 8). The magnetic susceptibility ranges between 400 and 600 × 10^{-5} SI units. The heavy mineral concentrate is rich in zircon. Most crystals are fractured, turbid and contain mineral inclusions. There are also clear, transparent, colorless grains, which were selected for analysis. The zircon shapes are subhedral to euhedral prismatic. BSE-images show oscillatory zoned zircon and some grains have texturally older cores in the central parts of the crystals (Fig. 8). Two analyses (6b, 1a) are rich in uranium, 1 424 and 7 106 ppm, whereas the remaining ten analyses have 120–435 ppm U. Th/U ratios are rather uniform, 0.15–0.46. Three analyses (4b, 5a, 6b) have high values of common lead, and two of these (4b, 6b) are highly discordant, as well as analysis 1a which is reversely discordant. These four analyses (1a, 4b, 5a, 6b) were excluded from the age calculations and diagram (Fig. 8, Table 1). The remaining eight analyses are concordant at the two sigma level with a concordia age of 1876±5 Ma (Fig. 8, 2σ, MSWD of conc. & equiv. = 0.99, probability of conc. & equiv = 0.46, n = 8). The weighted average $^{207}Pb/^{206}Pb$ age records a similar age of 1875±5 Ma (2σ, MSWD = 1.6, probability = 0.14, n = 8). The concordia age of 1876±5 Ma is chosen as the best age estimate and is interpreted to date igneous crystallisation of the Dájdavárre granite at 1.88 Ga.

DISCUSSION AND CONCLUSION

In the area between Arjeplog and Jokkmokk, three samples of variably deformed porphyritic to augen bearing granites, referred to as Vuolvojaur granite, have been dated at 1878±5 Ma, 1877±5 Ma and 1876±5 Ma. The igneous age of the Vuolvojaur granite falls in the 1882±6 to 1867±8 Ma range of previously determined ages of early Svecokarelian intrusions of the Perthite monzonite suite (PMS) in south-western Norrbotten and the Vuolvojaur granite thus belongs to this suite (Fig. 9). This igneous activity corresponds in time with zircon ages obtained from the main ore body in the Kiirunavaara apatite iron oxide deposit (Westhues et al. 2014, Hanchar et al. 2015), suggesting a connection between the large volumes of the Perthite monzonite suite intrusions and apatite iron ore formation in Norrbotten.

The igneous age of the strongly recrystallised, gneissic variety of Vuolvojaur granite in the western part of the Arjeplog–Jokkmokk area constrains regional amphibolite facies metamor-

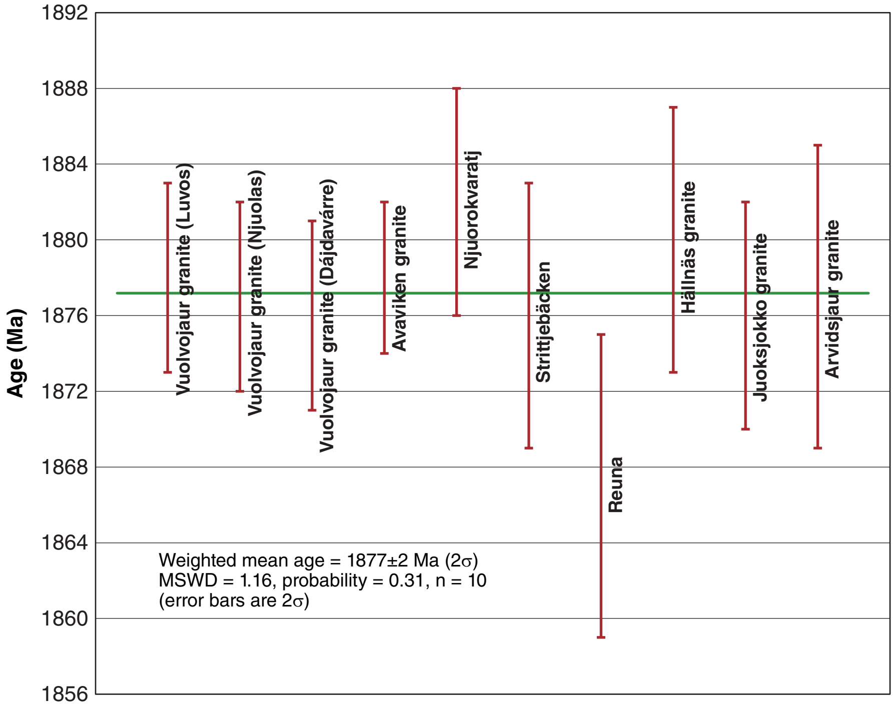


Figure 9. Ages of the Perthite monzonite suite granites in south-western Norrbotten (see Figure 2 for location of samples).

phism in that area to be younger than 1877±5 Ma. Low to high degrees of deformation and metamorphic recrystallisation of rocks of the Perthite monzonite suite in the central and south-western parts of Norrbotten suggest heterogenous, post 1.87 Ga deformation and metamorphism in large areas of Norrbotten (Hellström et al. 2012). In contrast, Bergman et al. (2001) suggested an early orogenic event at 1.89–1.87 Ga, based on the observation of markedly different degrees of deformation between rocks of the Haparanda and the Perthite monzonite suites in the north-western part of Norrbotten. Overall, ages of metamorphism and deformational events in the Svecokarelian orogen north of the Skellefte district are poorly constrained.

The Vuolvojaur granite is classified as ferroan, alkali-calcic to calc-alkalic and metaluminous to low peraluminous, and it falls in the fields of high-potassium, calc-alkaline to shoshonite series, suggesting an A- to I-type signature. Fluorite is a characteristic accessory mineral in the biotite±hornblende bearing granite of syenogranitic to subordinate monzogranitic composition.

Syenitoid rocks are rare in the Perthite monzonite suite in south-western Norrbotten, in contrast to those parts of this suite in the Fjällåsen–Kiruna area further north (Witschard 1975, Witschard 1984, Bergman et al. 2001), possibly reflecting different compositions of melt source rocks north of the Archean–Proterozoic boundary zone north of Jokkmokk, in addition to thicker crust with possible deeper and lower degrees of partial melting constraining magma compositions to more alkaline, silica-poor compositions. Gabbroic rocks seem also to be more abundant to the north.

The overall felsic nature of early Svecokarelian magmatism suggests that a Paleoproterozoic basement probably is present south of the Archean boundary, represented by scattered basement windows of 1.96–1.93 Ga old rocks, including the 1.93 Ga old Norvijaur intrusion in the Jokkmokk area (Hellström 2015). The Vuolvojaur granite has an upper crust trace element geochemical signature and is suggested to have formed at a convergent margin above a subduction zone dipping to the present north. An intra-plate emplacement setting of the rocks of the Perthite monzonite suite has alternatively been suggested by Billström et al. (2010).

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