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Radiometric dating results 4

Division of Bedrock Geology

Geological Survey of Sweden

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Cover: Dyke of leucotonalite (trondhjemite) crosscutting foliated conglomerate at Pultarliden (Swedish national grid 7223500/1715820). See paper by Lundström et al. (pp. 52–69).

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CONTENTS

EDITOR´S PREFACE

This volume is the fourth in a series of publications comprising radiometric age determinations carried out as an integral part of the bedrock mapping programme of the Geological Survey of Sweden. The seven papers in this volume present data from different geological provinces of the Swedish Precambrian bedrock, from Råstojaure north of Kiruna to Blekinge in the south (see Fig. 1), and ranging in age between Archaean and Mesoproterozoic.

The fruitful co-operation with the following isotope laboratories involved in the present investigations is gratefully acknowledged: the Laboratory for Isotope Geology, Swedish Museum of Natural History, Stockholm (Head, Prof. Stefan Claesson), and the Unit for Isotope Geology, Geological Survey of Finland, Espoo (Head, Dr. Hannu Huhma; analyses performed under the supervision of Dr. Matti Vaasjoki). In each of the papers of this volume, information is given regarding which laboratory is responsible for the isotopic analyses.

Analytical methods for the U-Pb datings performed at the **Laboratory for Isotope Geology in Stockholm** can be summarized as follows. The zircons were separated using standard magnetic and heavy liquid techniques. Most fractions were abraded according to the Krogh (1982) method. They were dissolved in HF:HNO_3 in Teflon® capsules in autoclaves according to Krogh's (1973) method. After decomposition, the samples were dissolved in HCl and aliquoted. A mixed ^{208}Pb–$^{233\text{-}235}U$ tracer was added to the ID-aliquots. Some of the smaller samples were spiked with a mixed ^{205}Pb–$^{233\text{-}235}U$ tracer prior to decomposition. The sample aliquots, dissolved in 3.1 N HCl (ID aliquots and ^{205}Pb-spiked samples) or 2 N HCl (IC aliquots) were loaded onto anion exchange columns with 50 µl resin volume for extraction of Pb and U. Pb was loaded on Re single filaments with silica gel and H_3PO_4. U was loaded on Re double filaments with HNO_3. The isotopic ratios were measured on a Finnigan MAT 261 mass spectrometer equipped with five faraday cups. Most samples were measured in the static mode with the faraday cups. Small Pb and U amounts, yielding low signals, were measured in peak jumping mode on a secondary electron multiplier. The calculation of the corrected isotope ratios and the error propagation were made using the PBDAT program of Ludwig (1991a), and the decay constants recommended by Steiger & Jäger (1977) were used. Calculation of the intercept ages and the drawing of the concordia plot were done with Ludwig's (1991b) ISOPLOT program. The total Pb blank was 5–10 pg and the U blank less than 2 pg. The assigned composition of common Pb is calculated according to the Pb evolution model of Stacey & Kramers (1975). The mass fractionation for Pb is 0.1 % per a.m.u. U mass fractionation was monitored and corrected for by means of the $^{233\text{-}235}U$ ratio of the spike. All analytical errors are given as 2σ.

Monazite was analysed in the same way as zircon with the exception of being decomposed in 6N HCl.

Titanite was analysed in the same way as zircon except from the ion exchange procedure where a HBr step was added for better purification of lead.

For the analytical procedure of the **Unit for Isotope Geology, Geological Survey of Finland**, the reader is referred to Suominen (1991) and Vaasjoki et al. (1991).

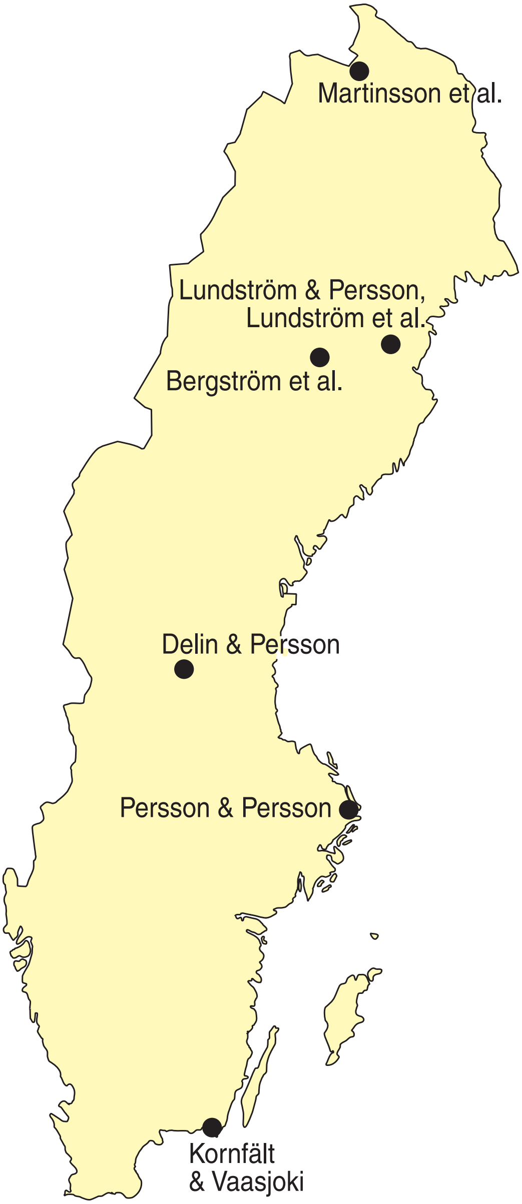

Fig. 1. Location of areas from which papers are presented in this volume.

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Uppsala, October 1998

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Age of the Kristineberg Pluton, western Skellefte District, northern Sweden

By

Ulf Bergström, Kjell Billström and Thomas Sträng

INTRODUCTION

The Skellefte District, interpreted as a Palaeoproterozoic volcanic arc (Weihed et al. 1992, Allen et al. 1996), is one of Sweden's major ore districts. It contains about 100 massive sulphide and gold deposits, occurring in a c. 100 x 30 km belt of metavolcanic and metasedimentary rocks in the northern part of Västerbotten County in northern Sweden. The ores are hosted mainly by metavolcanic rocks of the Skellefte Group.

The age of the different rocks in the Skellefte District has been discussed by several workers and a summary was presented by Billström & Weihed (1996). Three main supracrustal assemblages may be discerned in the district and its immediate surroundings. Volcanic and sedimentary rocks older than c. 1950 Ma are exposed in the Knaften area south of the Skellefte District (Wasström 1993, 1996). A similar age was obtained from a volcanic rock in the Barsele area further to the west (Eliasson & Sträng 1998). In these terrains south of the Skellefte District proper, several generations of granitoids are present with a wide variety of ages (Skiöld 1988, Billström & Weihed 1996, Björk & Kero 1996). The deposition of the Skellefte Group and the VHMS ores within the Skellefte District was interpreted by Billström & Weihed (1996) to have taken place in the interval 1890–1880 Ma. The Skellefte Group is overlain by sedimentary rocks, and at least partly by subaerial volcanic rocks of the Vargfors Group. The latter group has been correlated with the terrestrial, volcanic rocks of the Arvidsjaur Group to the north, and age determinations summarized by Billström & Weihed (1996), Skiöld (1987), and Skiöld et al. (1993) suggest a time interval between 1880 and 1870 Ma for the emplacement of these rocks.

The volcanic rocks of the Skellefte and Arvidsjaur Groups are associated with granitoid plutons of the same age. The Arvidsjaur District, which is the area where the Arvidsjaur Group is exposed, includes a wide variety of intrusions ranging from tonalite to alkali feldspar granites. Some are well defined (rounded) plutons, like the Arvidsjaur pluton (Muller 1980), dated by Skiöld et al. (1993) at 1877+8/-7 Ma, while others form large irregular masses. In the Skellefte District, a limited number of plutons are tentatively associated with rocks of the Skellefte Group. The major Jörn pluton was investigated and the Jörn GI generation was dated at 1888+20/-14 Ma by Wilson et al. (1987). Quartz-feldspar porphyry stocks and dykes form an important component, dated at Tallberg at 1886+15/-9 Ma (Weihed & Schöberg 1991). Few other plutons in the Skellefte District have been so extensively investigated. In this paper, a U-Pb zircon age of the Kristineberg pluton in the western part of the Skellefte District is presented. As all the involved rocks (except the Revsund granitoids) are metamorphosed, the prefix meta- is omitted.

REGIONAL GEOLOGY

The Kristineberg area is composed of rocks belonging to the Skellefte Group volcanic rocks and the Vargfors Group sedimentary rocks which surround the domeshaped Kristineberg pluton (Fig. 1). The Vindelgransele area, to the west just outside the map area, forms another anticlinal structure. The c. 1.8 Ga postorogenic Revsund granitoids border the Kristineberg and Vindelgransele areas to the east, south and west.

The Skellefte Group volcanic rocks in the Kristineberg area may be divided into three separate types: 1) plagioclase-(quartz)-phyric coherent dacites–rhyolites, interpreted as lava- or intrusive crypto-domes, 2) partly porphyritic rhyolitic volcanoclastites and 3) basalts–andesites, mainly emplaced as subvolcanic sills (Bergström & Sträng 1998). Within the upper part of the stratigraphy, intercalations of limestone, calc-silicate rocks and mudstone lenses occur together with massive sulphide deposits within the volcanoclastites. This unit was named the Kimheden Formation by Willden (1986), who proposed deposition in submarine rifts during a late extensional phase. Alteration is widespread in the Kristineberg area. Intensely chlorite-sericite-pyrite altered zones occur close to the ores, but on a regional scale there is also extensive, less intense alteration. The ore assemblages are overlain by mixed felsic–mafic volcanoclastites ("tuffites" is a widely used historical term) with intercalated basalts.

The Skellefte Group is stratigraphically overlain by a laterally extensive argillite formation, the Mörkliden Formation, which is readily observed on geophysical maps due to its graphite and pyrrhotite content (Bergström & Sträng 1998). This marker horizon suggests stagnant, deep water conditions and waning volcanic activity. It is succeeded by greywackes of the Fäbodliden Formation, deposited as typical rhythmic sandy–silty turbidites (Bergström & Sträng 1998). Both the Mörkliden and the Fäbodliden Formations correspond stratigraphically to the Vargfors Group, as defined by Allen et al. (1996).

The Skellefte and Vargfors Group rocks in the Kristineberg area have experienced polyphase deformation during at least three phases. The area is characterized by a strong foliation/banding S_1, which is subparallel to the original bedding and folded around E–W-trending fold axes plunging 20–50° to the west during D_2. The older foliation/banding is present in the Kristineberg pluton as well. A younger crenulation cleavage S_3, with steep lineations, overprints the older structures. A marked tectonic lineament is present just outside the map area in Fig. 1, and separates the strongly folded and sheared rocks of the Kristineberg area from the well preserved rocks to the northwest.

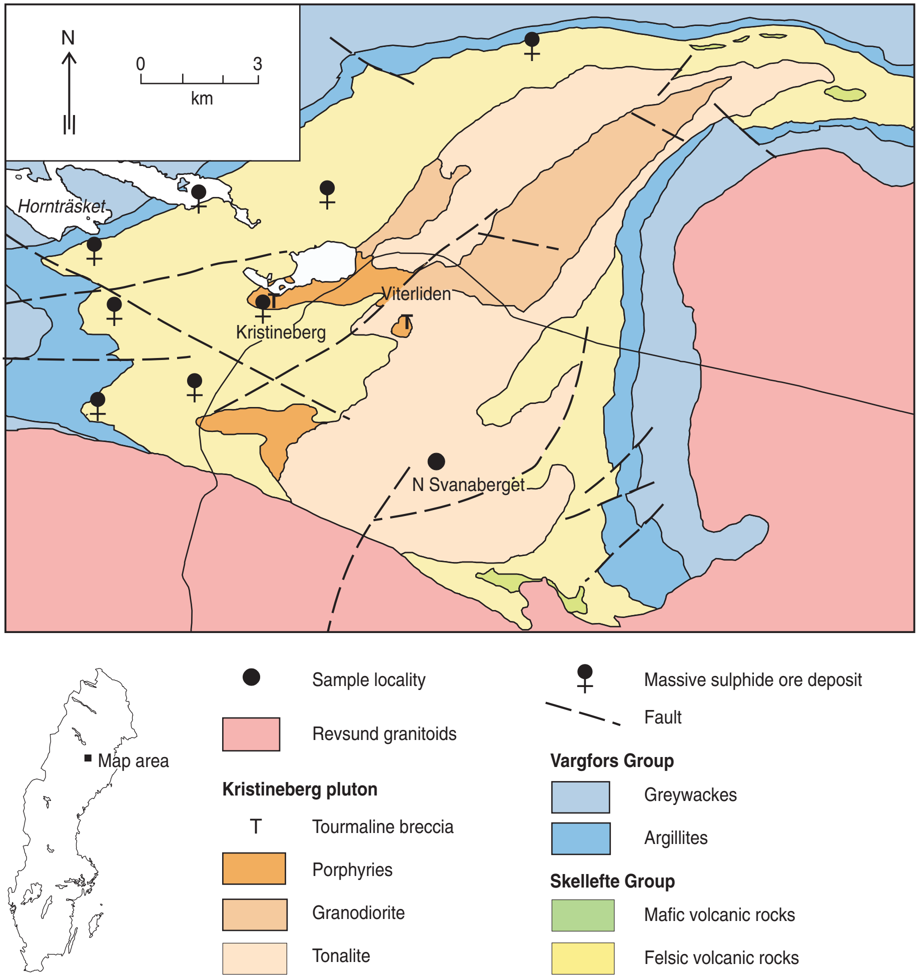

Fig. 1. Simplified map of the geology of the Kristineberg area. From the map sheet Malå SO (Bergström & Sträng, in press).

GEOLOGICAL FEATURES OF THE KRISTINEBERG PLUTON

The Kristineberg pluton was discussed by Du Rietz (1953), Edelman (1967) and Willden (1986). Three principal rock types can be distinguished within the Kristineberg pluton: tonalite which is the dominant rock type, granodiorite which occurs in the north-central core, and porphyry stocks and sills in the western contact towards the volcanic rocks. The tonalite is a dark grey, medium grained granoblastic rock with plagioclase, hornblende, and quartz as main constituents, with subordinate biotite and with magnetite, apatite, and zircon as accessory phases. The hornblende is metamorphic, while plagioclase with An 30–40 may be preserved.

The granodiorite is a grey, medium grained oligoclase-quartz-biotite rock, sometimes with c. 5 mm quartz phenocrysts and minor amounts of microcline.

There are two types of porphyries. The dominant variety is a dark grey, fine-grained, granoblastic biotite tonalite with rare preserved albite twinned plagioclase phenocrysts. Another type discussed by Du Rietz (1953) is a fine-grained, lighter grey rock with a granitic to trondhjemitic composition and with a plagioclase porphyritic texture. This type occurs at the intrusive contact towards the volcanic rocks, while the tonalitic, more coarse-grained type occupies the cores of the porphyry stocks. Tourmaline can occasionally be observed and magnetite occurs as c. 0.5 mm grains.

The strong NNE-trending deformation of the plutonic and volcanic rocks makes the primary contact relationships difficult to interpret. Two main east–west trending porphyry stocks in the western part of the pluton are intrusive into the volcanic rocks (Fig. 1). The internal relation among different units within the pluton is less well known, although aplitic porphyry dykes can be seen to cross-cut the tonalite. No reliable observations have been made on contact relationships between the tonalite in the Kristineberg pluton and the Skellefte Group volcanic rocks. Mafic dykes are also present in the tonalite, and Du Rietz (1953) reported some mafic dykes to be intrusive into the porphyries. Better preserved parts of tonalite and granodiorite are separated by zones with a mylonitic fabric. Generally, the granodiorite has a more massive appearance than the tonalite, possibly due to a smaller mica content. The metamorphic grade increases towards the south and east. The northern porphyry at Kristineberg is sericitized and chloritized, while the southern porphyry exhibits the higher grade biotite-cordierite assemblage (Du Rietz 1953). A specific alteration type is present close to the Kristineberg ore deposit and on the Viterliden hill, c. 3 km east of Kristineberg, where quartz-tourmaline veinlets form stockwork breccias in an aplitic host rock (Edelman 1967).

PETROPHYSICAL FEATURES OF THE PLUTON

The Kristineberg pluton has a much higher magnetization than the surrounding volcanic rocks, due to a distinct magnetite content. This makes it possible to outline the pluton shape, even though there are few outcrops. However, the magnetic susceptibility varies considerably at different sample locations and the number of measurements taken is too small to estimate a statistical mean value. Susceptibility values of the tonalite range from 330 to 35,000 (µSI), while the distribution of the granodiorite values is almost as large, 130 to 18,440 (µSI). However, based on magnetic susceptibility measurements in the field, the tonalite tends to exhibit higher magnetic susceptibility values than the granodiorite. The granodiorite can be seen as a low magnetic core of the pluton on the aeromagnetic maps. The porphyries have similar magnetic properties to the tonalite. Alteration and deformation give the intrusive rocks of the Kristineberg pluton a heterogeneous magnetic pattern. The deformation character of the Kristineberg pluton is also evident on the aeromagnetic anomaly map, where the pluton displays a banded, almost sigmoidal pattern. Remanent magnetization is low for the tonalite and the granodiorite.

The density mean of the tonalite is 2.69 (g/cm^3), while the granodiorite has a lower density of 2.65 (g/cm^3). Only one sample of the tonalitic porphyries has been analysed, yielding a density of 2.74 (g/cm^3). Based on the above density values, gravity modelling suggests a depth of at least 6 km for the Kristineberg pluton.

γ-radiometric measurements of the Kristineberg pluton indicate low values regarding the content of potassium and uranium, as well as thorium. The tonalite shows a potassium content of 1.6 %, a uranium content of 2.5 ppm and a thorium content of 6 ppm. A limited number of measurements of the granodiorite gives the following mean values: K = 2 %, U = 1.3 and Th 4.7 ppm.

DESCRIPTION OF THE DATED TONALITE SAMPLE

The sample was taken at Norra Svanaberget (Fig. 1), from a small outcrop c. 100 m from the road between Kristineberg and Björkliden, some 1600 metres southeast of Kronås (RAK 163414E/721693N). This outcrop (MGN930258 in the SGU database) is situated within a structurally well preserved block, surrounded by shear zones. The dated sample is a typical grey to dark-grey tonalite with a granoblastic texture showing weak but distinct foliation. A few preserved sericitized plagioclase crystals can be observed with An 37–44. Green hornblende is more abundant than biotite. Magnetite occurs as c. 0.5 mm grains.

The chemical composition of the dated sample is shown in Table 1. It is similar to that of the Sm-Nd-investigated sample from Viterliden (F 84133), analysed by Öhlander et al. (1987). Geochemical data from a granodiorite and a tonalite porphyry are also included in Table 1. A possible difference in geochemical composition between the tonalites and the tonalite porphyries is manifested by the absence of a negative Eu anomaly and higher P_2O_5 for the porphyry. More data is needed to verify this.

TABLE 1. Geochemistry of the rock types of the Kristineberg pluton. Sample MGN930258 (the dated sample): 721693/163414 (ICP-AES and ICP-MS, Svensk Grundämnesanalys AB, Luleå, 1995), Sample UJB930186: 722492/163904 (XRF and INAA, XRAL, Canada, 1994), Sample UJB930275: 722101/163105 (XRF and INAA, XRAL, Canada, 1993).

		Tonalite MGN930258	Granodiorite UJB930186	Ton. Porphyry UJB93075
SiO_2	wt-%	62.1	74.8	65.3
TiO_2		0.501	0.218	0.642
Al_2O_2		14.5	13.1	15.1
FeO_3t		7.50	2.37	7.66
MnO		0.139	0.06	0.05
MgO		3.94	0.51	2.21
CaO		6.18	2.07	3.24
Na_2O		2.97	4.24	4.94
K_2O		1.02	2.35	0.39
P_2O_5		0.110	0.06	0.28
LOI		0.5	0.48	0.90
Ba	ppm	422	771	207
Rb		23.6	43	10
Sr		424	267	337
Cr		107	110	93
Ni		30.5	3	4
V		172	-	-
Co		25.2	4	9
Sc		20.6	4.6	17
Zr		126	120	135
Y		12.9	17	21
Nb		7.48	10	6
Hf		5.16	3.7	3.8
Ta		0.726	-	-
U		2.59	2.6	2.4
Th		4.66	4.8	3.1
La		24.4	34.5	21.3
Ce		65.4	60	46
Pr		6.69	-	-
Nd		30.4	26	22
Sm		6.14	4.2	4.9
Eu		1.11	0.7	1.6
Gd		5.17	-	-
Tb		0.631	0.4	0.7
Dy		3.57	-	-
Ho		0.673	-	-
Er		2.39	-	-
Tm		0.341	-	-
Yb		2.40	1.4	2.2
Lu		0.307	0.23	0.30
Sum		99.5	100.3	100.7

U-Pb DATING RESULTS

The zircons of the tonalite at Norra Svanaberget (sample 96019 in the LIG database) are euhedral and weakly coloured, with good transparency, although many crystals are slightly turbid and metamict. Dark inclusions are fairly common but such crystals were avoided during the hand-picking procedure. Rarely, slight tendencies for growth zoning were observed, but no obvious cores could be detected in normal light. Quite a few crystals are long-prismatic, approaching a needle-like character (cf. the >106 nål fraction in Table 2), while other crystals are more stubby with a length to width ratio of around 2–3:1 (marked “hel” in Table 2) and rather flat in a view looking perpendicular to the c-axis. Few crystals are completely transparent and have a brilliant lustre (cf. the >74 brilj fraction, Table 2). Certain of the long-prismatic grains have transverse cracks with evidence for having been broken and subsequently healed. In general, the larger crystals have frequently developed cracks, while the smaller grains are more homogeneous.

Four different size fractions were used for the final selection procedure and altogether eight fractions, including two that were abraded (denoted with ”ab” in Table 2), were analysed at the Laboratory for Isotope Geology in Stockholm. The analytical procedure is described in the Editor’s Preface to this volume. The large >150 µm fraction plots in a slightly reverse discordant manner in the concordia diagram (Fig. 2) and, considering its near-concordant position, has a comparatively low ^{207}Pb/^{206}Pb age. This fraction also has a much lower ^{206}Pb/^{204}Pb ratio and a higher Pb content relative to the other analysed fractions. The remaining seven fractions were regressed to yield an age of 1907±13 Ma with a MSWD value of 7.6 (Fig. 2). The high MSWD value indicates a certain internal sample inhomogeneity, an opinion which is strengthened by the deviating data for the large >150 µm fraction. However, we consider the 1907 Ma age, defined by seven separate fractions of various habitus and optical quality, to be a good estimate of the intrusion age of the pluton and possibly the deviating fraction is reflecting an over-growth process at some time subsequent to the intrusive event. Still, the age determined is unusual for a magmatic rock in the Skellefte District, and some zircons from this sample should be analysed with an ion probe in order to check for internal heterogeneities and potential problems such as different generations of zircon growth.

DISCUSSION

The over-printing metamorphic and hydrothermal processes which have affected the rock may also have had an influence on the zircon systematics. Presumably, zircons originally crystallized during a single event, forming a homogeneous magmatic population. Subsequently, post-crystallization processes slightly affected the U-Pb systematics of the zircons, except for the >150 fraction which was more strongly over-printed. In a concordia diagram this shows up as a discordia with a relatively high MSWD value. It is suggested that the anomalous common Pb and total Pb contents shown by the >150 fraction reflects an over-growth episode that was synchro-

TABLE 2. U-Pb zircon data from the Norra Svanaberget sample (96019). See text for abbreviations.

Fraction (µm)	Weight (mg)	U (ppm)	Pb tot (ppm)	$^{206}Pb/^{204}Pb$ measured	^{206}Pb - ^{207}Pb- ^{208}Pb radiog. Pb (at%)	$^{206}Pb/^{238}U$	$^{207}Pb/^{235}U$	$^{207}Pb/^{206}Pb$	$^{207}Pb/^{206}Pb$ ages in Ma
> 150	0.0631	330.5	195.2	466	84.4 - 9.7 - 5.9	0.3511	5.5393	0.1144	1871
>106 hel	0.2052	385.8	112.3	12679	81.9 - 9.3 - 8.8	0.2767	4.3145	0.1131	1850
>106 nål	0.1881	319.2	101.8	5800	81.3 - 9.4 - 9.3	0.2998	4.7407	0.1147	1875
>106 ab	0.0696	310.0	103.8	2878	82.0 - 9.5 - 8.5	0.3142	5.0100	0.1156	1890
>74 hel	0.1789	359.6	111.2	5496	81.2 - 9.3 - 9.5	0.2901	4.5641	0.1141	1866
>74 brilj	0.1076	358.9	105.2	7861	82.7 - 9.5 - 7.8	0.2813	4.4184	0.1139	1863
>74ab	0.0578	340.2	112.5	9799	81.8 - 9.5 - 8.7	0.3143	4.9925	0.1152	1883
>45	0.1857	324.5	103.0	9718	81.7 - 9.4 - 8.9	0.3008	4.7487	0.1145	1872

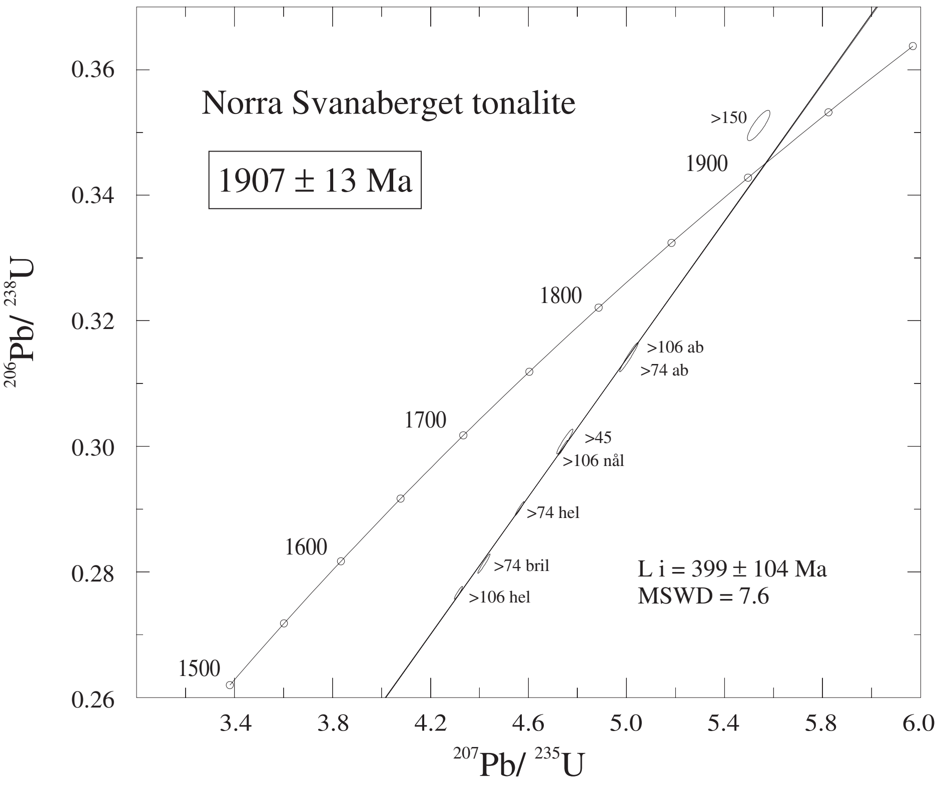

Fig. 2. Concordia diagram for the analysed zircons from the Kristineberg pluton tonalite.

nous with the c. 1.88–1.89 Ga old processes which generated the Skellefte Group volcanic rocks and ultimately the relatively Pb-rich VHMS ore at Kristineberg. This kind of process apparently created rims on the zircons that are not optically detectable.

An epsilon-Nd value of c. +3.2 (calculated at *t* = 1890 Ma) was previously reported for the tonalite at Viterliden (Öhlander et al. 1987) and an analysis of the whole-rock material of the dated zircon sample gave a similar epsilon-Nd value of +3.5 (Kjell Billström, unpublished results). Such a primitive Nd isotope value does not allow any significant incorporation of material much older than 1.9 Ga in the magma source. This is also consistent with the apparent lack of cores in the zircons. In addition, the data of the abraded zircons also fell on the discordia, a feature which is not consistent with the presence of any significant core material. These features give credit to the interpretation that the 1907 Ma age is a good estimate of a magmatic crystallization event.

The obtained age for the tonalite within the Kristineberg pluton correlates well with the 1902 Ma age for the Kattisavan pluton (Björk & Kero 1996), situated c. 20 km to the southwest and separated from rocks of the Skellefte District by Revsund granitoids. Recent investigations of the Kattisavan intrusion (Vesterlund 1996) describe a fractionated tonalite-granodiorite with epsilon-Nd values close to +4, which is similar to values for the Kristineberg pluton. Petrophysical properties (Kero, pers. comm.) are also similar, i.e. high magnetic susceptibility and a density of approximately 2.7 g/cm^3, even though there seems to be a larger variation of the radiometric values, in particular for thorium.

The above age and Sm-Nd isotope characteristics suggests the existence of a suite of geochemically primitive granitoid plutons with ages slightly above 1900 Ma. Such an age is definitely higher than that of the Jörn GI granitoids (cf. Wilson et al. 1987). On a district scale, the Skellefte Group volcanism is interpreted to be c. 1890–1880 Ma (Billström & Weihed 1996) and the early-stage Jörn plutons are believed to be deep equivalents to the volcanic rocks and more or less coeval in age. Given the age of 1907 Ma for the Kristineberg pluton, it is possible that also spatially associated supracrustal rocks in the area have similar ages >1890 Ma, as the spatial relationship between plutonic and volcanic rocks is valid also in the Kristineberg area. The volcanic rocks and the Kristineberg pluton also share the same deformation history. Age differences of 20–30 million years within the Skellefte District are compatible with the variable Pb isotope data obtained from galenas across the district (Billström & Vivallo 1994). However, the recognition of magmatic zircon ages slightly exceeding 1900 Ma for plutons to the south of the Skellefte District (Björk & Kero 1996), without any known connection with the Skellefte Group volcanism, is consistent with an alternative hypothesis, where a crystalline basement to the 1.89–1.88 Ga volcanism is present. This means that the local Skellefte Group rocks in the Kristineberg area may have ages within the 1.89–1.88 Ga age span and that the Kristineberg pluton constitutes a basement. Until new age information on volcanic rocks becomes available from the western Skellefte District, it is difficult to conclude which of the two hypotheses is correct.

The porphyries show good intrusive contacts towards the Skellefte Group volcanic rocks in the Kristineberg mine. Dykes of porphyry also intruded the tonalite-granodiorite parts of the Kristineberg pluton. This suggests that the porphyries may not be related to the tonalite-granodiorite part. The small difference in composition between the porphyries and the tonalite–granodiorite is possibly important, as they might represent two different magma groups. Possibly, the porphyries formed a subvolcanic component of the Skellefte Group volcanic rocks. Supporting this is the sodic character of the Kristineberg pluton granitic-trondhjemitic porphyries, which is similar to that of the coherent plagioclase phyric volcanic rocks (Du Rietz 1953). The described tonalite–porphyry relationship is similar to the situation in the Tallberg area (Weihed 1992) within the Jörn pluton. Here, a tonalite is intruded by porphyry stocks and dykes with a different geochemical composition, but the age difference is quite small, 1888+20/-14 Ma (Wilson et al. 1987) for the Jörn G1 tonalite, and 1886+15/-9 Ma for the porphyry (Weihed & Schöberg 1991). The porphyry intrusions are spatially related to a large tonnage/low grade porphyry copper type of mineralization at Tallberg, which was suggested to be related to volcanism above the porphyry dykes (Weihed 1992). Evidence for similar mineralization types in the Kristineberg pluton was suggested by Lindberg (1983).

CONCLUSIONS

A tonalite from the Kristineberg pluton has been dated by the U-Pb method on zircons. The obtained age, 1907±13 Ma, is interpreted as the magmatic crystallization age. The epsilon value for the same sample is +3.5. This value and the lack of observed cores in the zircons contradict that inherited older material in the zircons is responsible for the comparatively high U-Pb age. The >150 µm fraction deviates from the other fractions and is interpreted to record an overprinting process at some post-crystallization event.

The Kristineberg pluton is spatially related to the volcanic rocks of the Skellefte Group and a genetic relationship has been suggested by Bergström & Sträng (1988). The 1907±13 Ma age is somewhat older than the 1880–1890 Ma interval suggested by Billström & Weihed (1996) for the emplacement of the Skellefte Group. Two hypotheses are possible: 1) The Kristineberg tonalite is slightly older than the Skellefte Group and forms a basement for the volcanism. The volcanic rocks are coeval only with the porphyry stocks in the western part of the pluton. The overgrowth episode shown by the >150 µm fraction is correlated with the volcanism. 2) The Kristineberg tonalite is coeval with the Skellefte Group, and the volcanic rocks are older in this part of the Skellefte District. The porphyries represent a late-stage intrusive component similar to the situation in the Jörn pluton. The overprinting episode could be related to the strong deformation evident in the Kristineberg pluton.

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U-Pb zircon ages of three Palaeoproterozoic igneous rocks in the Loos-Hamra area, central Sweden

By

Hans Delin and Per-Olof Persson

INTRODUCTION

The bedrock of the region of southern Norrland, of which the Loos–Hamra area is a part, is predominated by rocks belonging to the Svecokarelian orogen, in particular high-grade metamorphic and strongly deformed granitoids, metasedimentary and metavolcanic rocks. In the western parts of the area, these rocks have been cross-cut by late- to postorogenic granitoids of the Transscandinavian Igneous Belt (TIB). The Svecokarelian early orogenic granitoids have zircon ages of 1843–1858 Ma (Delin 1993, 1996, Welin et al. 1993 and Delin & Aaro 1994). The TIB is represented here by the Rätan granitoid intrusion and, further southwest, by the Dala Volcanite Complex and granites belonging to the Dala Granite Group. The Rätan intrusion is about 1700 Ma old, according to datings by Wilson et al. (1985), Patchett et al. (1987) and Delin (1996). Closely associated with the eastern margin of the Rätan intrusion, three separate younger intrusions of porphyritic granitoids occur. Two of these have been dated and classified by Delin (1996). Yielding zircon ages of c. 1800 Ma, the granitoids were regarded as probable members of the Revsund Granitoid Suite.

The Svecokarelian rocks of the region are generally affected by strong, ductile (and brittle) deformation, the most conspicuous structural element being the Storsjön–Edsbyn Deformation Zone (SEDZ). The complex deformation history, in particular concerning the SEDZ, has been thoroughly analysed and defined by Bergman & Sjöström (1994). The SEDZ is a multi-phase, ductile to semi-ductile deformation zone that intersects the area in a roughly NS direction with a total length of some 200 km. In the western part of the Loos–Hamra area (map-sheet 15F Voxna, Fig. 1), the Svecokarelian metamorphism is low to medium grade and the deformation is rather weak. Here, a partly well preserved synclinal supracrustal sequence occurs, composed mainly of metasedimentary rocks and products of a bimodal volcanism. The general stratigraphy here is, from older to younger formations, meta-argillite, quartzite, metarhyolite and metabasalt. The geology of the Loos–Hamra area has been studied in a comprehensive work by Lundqvist (1968) and is also described in field work reports from the 15F Voxna map-sheet (Delin 1995, Delin & Aaro 1996). A regional geological map with description of the Gävleborg County, including the Loos–Hamra area, was prepared by Lundegårdh (1967).

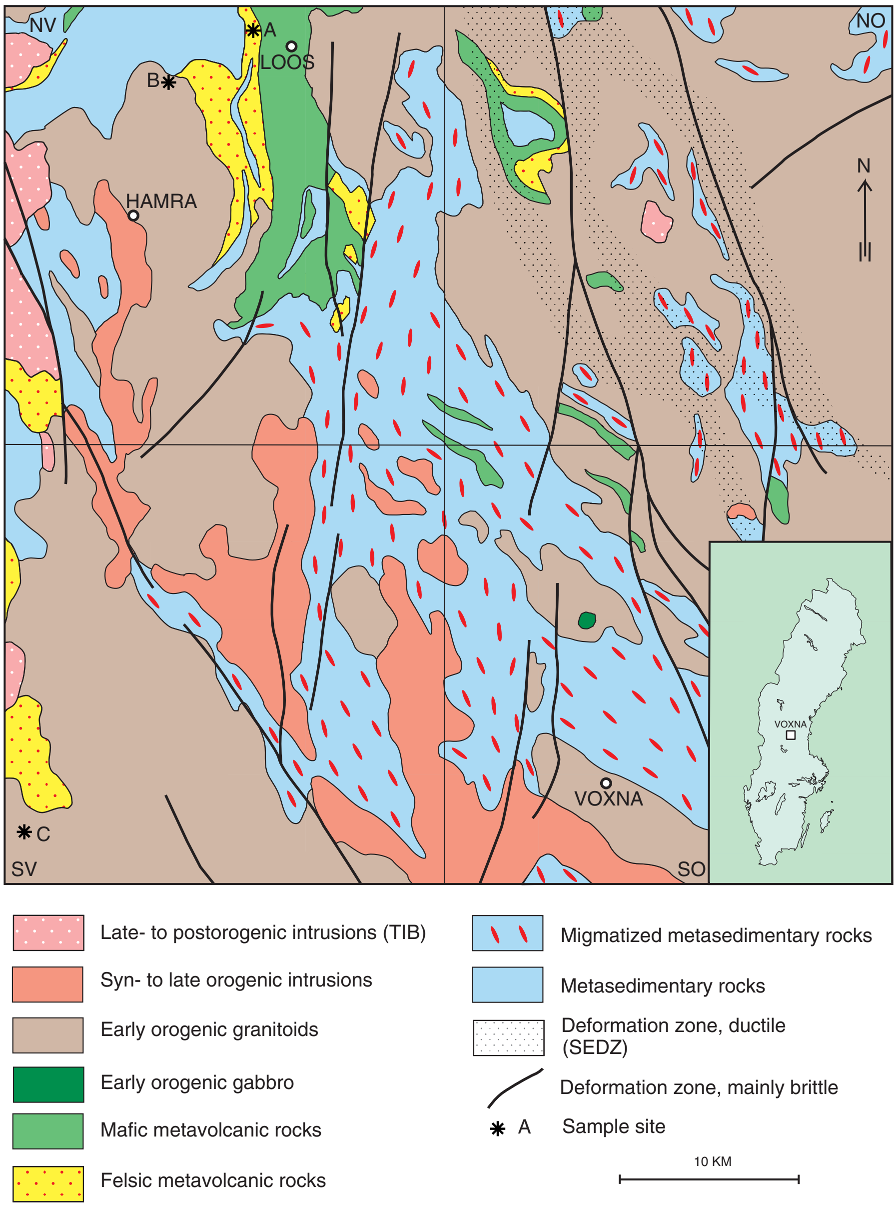

Fig. 1. Schematic map of the bedrock geology of the 15F Voxna map-sheet, simplified from Delin & Aaro (in prep.) and Bergman & Sjöström (1994). A, B and C refer to dating samples HLD940484, HLD930222 and HLD940488, respectively.

GEOLOGICAL BACKGROUND

During regional bedrock mapping of the southern Norrland region, central Sweden, a number of radiometric zircon datings have been carried out, some of these yielding encouraging results. As a complement to these previous works, and to increase our knowledge of the Svecokarelian evolution in the region, three new targets (Fig. 1) were selected for U-Pb zircon dating. Selection and sampling were carried out in connection with bedrock mapping of the map-sheet 15F Voxna (Delin & Aaro, in prep.), and the dating results are reported in this study.

The Loos and the Noppikoski (c. 30 km SW of Loos) supracrustal sequences partly show similar lithologies, viz. a quartzite formation overlain by metarhyolite. They have been correlated stratigraphically by Lundqvist (1968), but no isotopic data have so far been available concerning the Loos metavolcanic rocks. For the ignimbritic Noppikoski metarhyolite, Welin (1987) reported a zircon age of 1867±9 Ma. At Hortesberget in the 17F Ånge map-sheet area (c. 70 km north of Loos), a porphyritic metarhyolite was sampled for zircon dating by H. Delin (unpubl.). The purpose of this dating attempt was to get useful data for later correlations with the Loos metarhyolite and other occurrences of metarhyolite in southern Norrland, central Sweden. Unfortunately the isotopic analysis failed due to strongly uranium-enriched zircons.

In order to ascertain the absolute age of the Loos volcanism and, if possible, correlate the Loos and the Noppikoski sequences, U-Pb zircon dating was carried out on a sample (HLD 940484) collected in the Loos metarhyolite. Additionally, a U-Pb dating of titanite in the same sample was done. As, according to field evidence, the Loos metabasalt formation overlies the metarhyolite stratigraphically, the extrusion age of the latter would also give a maximum age of the metabasalts.

At the small Lake Laxtjärnen, about 6 km west of Loos community, there is an occurrence of a fine-grained, quartz-porphyritic felsic rock with a subvolcanic appearance and no sign of foliation. According to Lundqvist (1968), the rock forms the northern marginal phase of an early orogenic granite intrusion (here called the Hamra intrusion). The granite has an intrusive relationship with respect to meta-argillitic rocks in the north and has formed a contact metamorphic aureole, which is one of very few reported, concerning early orogenic granitoids of the Swedish Svecokarelian bedrock. There is no observed lithological contact between the granite and the more easterly located Loos metarhyolite. However, xenoliths of metarhyolite have been observed in the porphyritic granite, a fact that indicates an intrusive relationship with the former.

Rocks of the Laxtjärnen granite type occur at a few other localities in the Loos–Hamra area, mostly in a marginal position near meta-supracrustal rocks. In contradiction to Lundqvist's opinion (1968), some of these occurrences have been interpreted as late orogenic granites in earlier, unpublished prospecting reports. As an attempt to resolve the problem, a sample (HLD930222) was selected for U-Pb zircon dating. This dating ought also to yield the age of the intrusive phase that cross-cuts the central parts of the Loos supracrustal area.

In the southwestern corner of map-sheet 15F Voxna, an area with a red granite was identified during bedrock mapping. The granite differed from all previously mapped Svecokarelian early orogenic granitoids in the region and displayed absence of pegmatites and very weak or no foliation. It also seemed to cross-cut the basal, conglomeratic layers of the Dala Volcanite Complex. The latter forms a volcanic–sedimentary complex, which was deposited unconformably on top of the older, deformed Svecokarelian rocks. The red granite was considered to be a Dala type granite by Hjelmqvist (1966) and in some other previous mapping works, according to which the granite could form an easterly intrusion belonging to the Dala Granite Group. To verify this suggestion, U-Pb zircon dating was carried out on a sample (HLD940488) of the red granite, taken 1 km west of Lake Kölsjön.

SAMPLE DESCRIPTION AND ANALYTICAL RESULTS

The analyses were performed at the Laboratory for Isotope Geology in Stockholm. The analytical procedure is described in the Editor's Preface to this volume.

Loos metarhyolite

Sample HLD 940484 was taken from a small road cut c. 1 km west of Loos village (map-sheet 15F Voxna NV, coordinates 684832/146430 in the Swedish National Grid). The rock sample is a very fine-grained, dark greyish violet to reddish brown metarhyolite with a well-preserved porphyritic texture, the phenocrysts consisting mainly of plagioclase. It also displays some auto-brecciation and flow structures. The chemical composition of the rock is reported in Table 1.

The rock sample yielded very few zircons. Most of them are colourless to dark brown and have length/width ratios of about 3, but shorter, as well as more elongate, crystals are also present. The morphology varies from euhedral to slightly rounded forms. Some crystals have a distinct core. Four fractions were analysed, all of which were strongly abraded.

Zr 1 consists of four colourless to pale brown crystals. Two are clear and free from cracks; the other two have a few cracks and some dark inclusions.

Zr 2 consists of six dark brown, rather fractured and turbid crystals. Some have small inclusions.

Zr 3 consists of three crystals, which are lighter brown than in fraction 2. They are clear and have few cracks.

Zr 4 consists of six beige to pale brown crystals. Most of them are turbid and metamict.

TABLE 1. Chemical composition of investigated rocks. The analyses were performed by Svensk Grundämnesanalys AB, Luleå, using a combination of ICP-AES and ICP-MS.

Sample no.	HLD 930222	HLD 940488	HLD 940484
SiO_2 (wt.%)	77.4	70.7	71.7
Al_2O_3	11.8	13.4	12.9
TiO_2	0.161	0.361	0.562
Fe_2O_3	1.40	3.77	4.55
MgO	0.481	0.306	0.742
CaO	0.554	2.16	1.47
Na_2O	3.29	3.52	3.51
K_2O	4.83	5.27	4.40
MnO	0.0249	0.0821	0.0438
P_2O_5	0.179	0.227	0.239
LOI	0.3	1.1	0.5
Total	100.1	99.8	100.1
Ba (ppm)	872	813	802
Be	1.79	1.65	1.75
Ce	31.0	90.8	57.4
Co	<5.35	<5.96	<5.66
Cr	16.9	20.3	43.9
Cu	11.2	10.3	13.2
Dy	4.43	10.6	5.77
Er	3.13	6.82	3.34
Eu	0.216	1.15	0.625
Ga	<10.7	<11.9	<11.3
Gd	3.37	10.6	5.19
Hf	3.50	9.46	5.81
Ho	0.933	2.22	1.11
La	13.1	44.8	28.1
Lu	0.495	1.08	0.546
Mo	1.15	<0.716	2.20
Nb	13.6	14.2	9.51
Nd	14.8	43.2	25.4
Ni	12.2	<11.9	<11.3
Pr	3.62	10.8	6.39
Rb	131	162	124
Sc	8.39	5.79	8.83
Sm	3.22	9.72	5.35
Sn	2.31	7.22	2.43
Sr	35.9	69.9	84.3
Ta	1.14	1.48	1.15
Tb	0.655	1.66	0.891
Th	8.91	20.5	16.1
Tm	0.477	1.00	0.546
U	4.11	5.34	7.82
V	<2.14	5.98	23.9
W	0.542	1.02	1.54
Y	38.9	87.3	42.7
Yb	3.25	7.62	2.94
Zn	19.0	83.6	18.0
Zr	112	354	215

TABLE 2. U-Pb isotopic data.

Mineral, analysis No., size fraction (µm)	No. of crystals	Weight (µg)	U (ppm)	Pb tot. (ppm)	Common Pb (ppm)	$\frac{^{206}Pb^{a}}{^{204}Pb}$	^{206}Pb-^{207}Pb-^{208}Pb Radiog. (atom%)^{b}	$\frac{^{206}Pb^{b}}{^{238}U}$	$\frac{^{207}Pb^{b}}{^{235}U}$	$^{207}Pb/^{206}Pb$ age (Ma)
HLD 940484. Loos metarhyolite.										
Zr 1	4	4	348	115.1	0.45	3354	82.7 - 9.4 - 7.9	0.3163±15	4.964±29	1861±6
Zr 2	6	7	1309	352.1	3.86	4047	82.3 - 9.0 - 8.7	0.2543±10	3.838±17	1790±4
Zr 3	3	2	931	311.8	0.81	4402	82.9 - 9.4 - 7.7	0.3219±20	5.020±34	1850±5
Zr 4	6	3	1430	423.8	2.46	5153	85.5 - 9.6 - 4.9	0.2932±9	4.521±17	1829±3
Ti 1	2	56	55	17.0	0.32	1751	84.3 - 8.7 - 7.0	0.2956±17	4.199±31	1679±8
Ti 2	31	102	59	17.8	0.40	1984	86.2 - 8.9 - 4.9	0.2964±10	4.208±18	1679±5
HLD 930222. Quartz-porphyritic granite.										
Zr 1	12	12	166.4	54.7	0.01	3012	82.7 - 9.4 - 7.9	0.3162±19	4.958±33	1860 ±5
Zr 2	1	6	89.5	27.8	0.31	703	83.6 - 9.6 - 6.8	0.2999±36	4.740±66	1874 ±12
Zr 3	40	30	247.1	78.8	0.05	9507	84.2 - 9.6 - 6.2	0.3120±9	4.906±16	1865 ±3
Zr 4	18	10	230.4	75.9	0.38	5384	83.9 - 9.6 - 6.5	0.3200±17	5.030±29	1864 ±4
HLD 940488. Red granite.										
Zr 1 74-106	10	13	517.6	168.4	0.37	8142	83.4 - 9.4 - 7.2	0.3149±8	4.903±15	1847 ±3
Zr 2 74-106	17	23	425.3	138.6	0.05	16586	83.7 - 9.4 - 6.9	0.3169±9	4.934±16	1847 ±3
Zr 3 74-106	10	18	499.0	162.7	0.45	9034	83.5 - 9.4 - 7.1	0.3154±9	4.912±17	1847 ±4
Zr 4 74-106	7	11	415.1	135.7		2278	82.0 - 9.2 - 8.7	0.3063±10	4.760±20	1843 ±4

a) corrected for mass fractionation (0.1% per a.m.u).
b) corrected for mass fractionation, blank and common Pb.

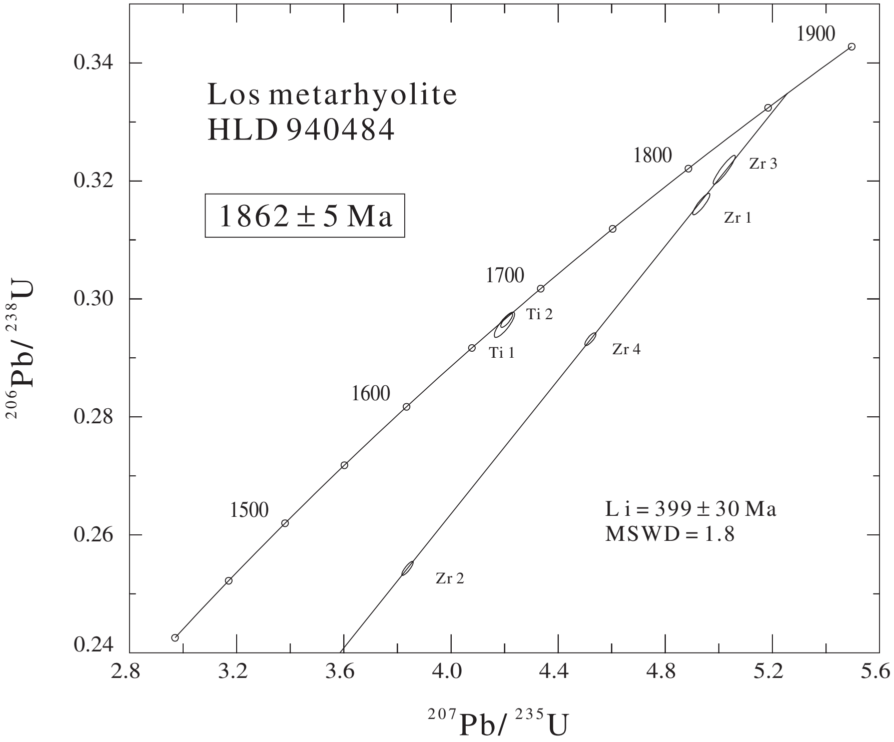

Fig. 2. Concordia diagram for analysed zircon and titanite fractions from the Loos metarhyolite, sample HLD940484.

The analytical data are presented in Table 2 and Fig. 2. The zircons are rich in U and radiogenic Pb, making the analyses of the individual fractions precise, despite the small sample size. The data points define a straight line with intercept ages of 1862±5 and 399±30 Ma. The upper intercept age is interpreted as the crystallization age of the rock.

Two analyses of titanite were performed. The titanite crystals are pale yellow to yellowish brown. Their habits vary from euhedral to anhedral.

Ti 1 consists of two large, brown crystals. Parts of the grains are transparent. Both grains are fragments of originally larger grains and cracks are common.

Ti 2 consists of thirteen small, pale yellow to pale brown grains. Most of them are fragments of larger grains. They are generally transparent, but some grains have turbid domains.

The data points plot practically concordant. A discordia with a fixed lower intercept of 0±400 Ma yields an upper intercept age of 1679±4 Ma.

Quartz–porphyritic granite (Laxtjärnen)

Sample HLD 930222 represents the northern margin of the Hamra granitoid intrusion, and the sample site is located at the southern end of Laxtjärnen (map-sheet 15F Voxna NV, coordinates 684515/145975 in the Swedish National Grid). The granite is light red, fine-grained, porphyritic and unfoliated, with an abundance of small, rounded quartz phenocrysts and a partly granophyric matrix. The granite also contains a considerable amount of tourmaline, detected by the mineral separation phase of the isotopic analyses. The chemical composition of the rock is reported in Table 1.

The zircon content is very meagre and the zircon grains recovered constitute a rather heterogeneous population. Many crystals are brownish or yellowish brown and short prismatic (length/width = 1–3) and euhedral to subhedral. Some grains are colourless to pink, and some of those are euhedral while others are rounded or of irregular shape. Most zircons are strongly metamict. The grain size is small and the majority fall within the <74 µm sieve fraction. A few crystals show possible overgrowths, and were avoided when selecting grains for analysis. Some grains have dark, rounded inclusions.

Zr 1 consists of colourless euhedral, fairly elongate (length/width»3) grains with some dark inclusions. They are moderately abraded.

Zr 2 consists of one clear crystal of good quality and is strongly abraded.

Zr 3 consists of small, clear and short crystals of good quality. Some of them have small inclusions and are strongly abraded.

Zr 4 consists of small, good-quality crystals, that are strongly abraded.

The analytical results are shown in Table 2 and Fig. 3. The four data points define a discordia with a rather poor linear fit (MSWD = 3.3). A regression gives intercept ages of 1857±36 and -231±1033 Ma. The negative lower intercept is caused by fraction 2. This has a larger analytical uncertainty than the others due to small sample size, low contents of U and radiogenic Pb and to a low ^{206}Pb/^{204}Pb ratio. Hence, less weight should be attached to this data point. It is therefore preferable to draw the discordia through the origin with an arbitrary error of ±200 Ma, which yields an upper intercept age of 1866±17 Ma. This discordia is shown in Fig. 3 and the age is interpreted as the crystallization age of the granite.

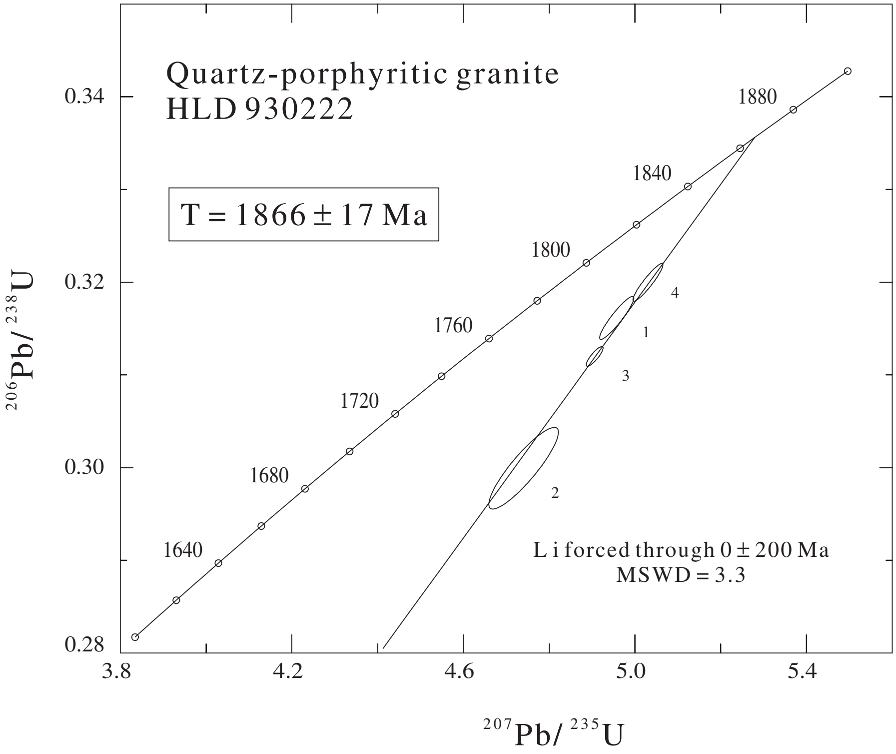

Fig. 3. Concordia diagram for analysed zircon fractions from the quartz–porphyritic granite, sample HLD930222.

Red granite

Sample HLD940488 was collected in a road cut c. 1 km west of Lake Kölsjön (mapsheet 15F Voxna, coordinates 680254/145108 in the Swedish National Grid). The rock sample is a very homogeneous deep red, markedly felsic, medium-grained and weakly foliated granite. The chemical composition of the rock is reported in Table 1.

The zircons are colourless to brownish yellow. They are euhedral and have prism and pyramid faces with low crystallographic indices. A minor proportion of the crystals display cores. Magmatic zonation is common. Most crystals are short prismatic with length/width ratios of 1–3. The zircons are strongly metamict and very few are suitable for geochronology. Of the analysed fractions, no. 1 consists of crystals with few fractures and inclusions, whereas no. 4 has the most fractured ones. All fractions were selected from the middle size fraction (74–106 µm) and were strongly abraded.

The analytical results are shown in Table 2 and Fig. 4. The four data points are slightly discordant and define a straight line, although three points plot closely together. The upper intercept age of 1853±9 is interpreted as the crystallization age of the granite.

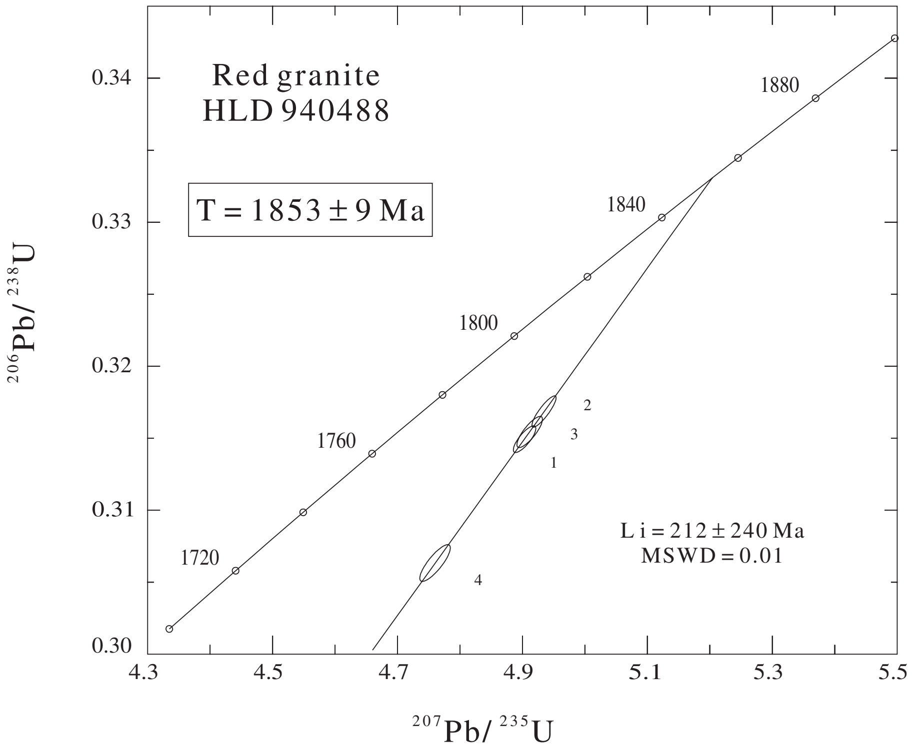

Fig. 4. Concordia diagram for analysed zircon fractions from the red granite west of Lake Kölsjön, sample HLD940488.

CONCLUSIONS

The zircon age of the Loos metarhyolite, 1862±5 Ma, clearly agrees with that of the ignimbritic Noppikoski metarhyolite (Welin 1987). It is also possibly coeval with several scattered, undated occurrences of felsic metavolcanic rocks further north within the southern Norrland region. If so, all these rocks are probably products of widespread volcanic activity of rather short duration in southern Norrland. Furthermore, the dating result of the Loos metarhyolite yields a maximum age of the Loos metabasalt formation.

From the sample of the Loos metarhyolite, a titanite age of 1679±4 Ma was also obtained. The most likely geological event corresponding to this age is a heat pulse from the 1700 Ma old Rätan granitoid intrusion, located at a horizontal distance of c. 10 km northwest of the sampling site. It cannot be excluded that the Rätan intrusion could be located closer to the metarhyolite, at depth. Another indication of a thermal event at the time around 1700 Ma in this area was reported by Welin (1966), concerning a U-Pb dating of pitchblende from a calcite vein in the Loos cobalt mine. This analysis yielded an age of 1690 Ma, which was later recalculated to 1670 Ma by Welin (1980).

The quartz-porphyritic marginal phase of the Hamra granitoid intrusion yielded a zircon age of 1866±17 Ma, which defines the rock as an early orogenic Svecokarelian granite, in spite of the obvious lack of foliation. As field evidence (viz. xenoliths) indicates the granite to be intrusive into the metarhyolite, the somewhat older age of the granite must be due to the larger analytical error. Thus, the Loos metarhyolite and the porphyritic Hamra granite could be regarded as roughly coeval, with the granite as the slightly younger of the two. The zircon age of the granite also fits well within the age range of other felsic Svecokarelian granitoids in this region (Delin & Aaro 1994, Delin 1996 and this study).

The zircon age of the red granite from west of Lake Kölsjön is 1853±9 Ma, which contradicts the original suggestion, supported by field appearance and previous mapping work, that this rock ought to belong to the Dala Granite Group. Instead, the granite must be classified among the early orogenic Svecokarelian granitoids mentioned above. It can therefore be concluded that field characteristics of granites in this region are not always reliable as a basis for a tectonic classification.

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U-Pb zircon datings of Småland and Karlshamn granites from southeasternmost Sweden

By

Karl-Axel Kornfält and Matti Vaasjoki

INTRODUCTION

Dating of a Småland granite, belonging to the Transscandinavian Igneous Belt (TIB), just north of the E–W trending Småland–Blekinge deformation zone (Fig. 1) yielded an age of 1778±11 Ma (Kornfält 1993). Another dating of a Småland granite c. 14 km ESE of Växjö has given a similar age (1769±9 Ma, Jarl & Johansson 1988). Also the Tving granitoid, south of the Småland–Blekinge zone, has yielded ages of c. 1770 Ma (Johansson & Larsen 1989, Kornfält 1996), and can be regarded as a more basic variety of Småland granite.

During the mapping of map-sheet Kristianopel NV a granite was found that was considered the youngest Småland granite in the region, as it cuts through all other Småland granite varieties, except the fine-grained ones. For the interpretation of the regional geology it was important to establish the age of this alleged youngest Småland granite.

Rocks belonging to the Karlshamn granite group have been dated earlier, and the age of the massive Karlshamn granite proper has been reported as c. 1400 Ma (Springer 1980, Åberg et al. 1985a, b, Åberg & Kornfält 1986). In western and central Blekinge the rocks of the Karlshamn granite group are, as a rule, massive, but in eastern Blekinge, and above all in the southeasternmost archipelago, foliated Karlshamn granite occurs which can be mistaken for the likewise foliated and c. 1770 Ma old Tving granite. It was therefore of great interest to verify that this foliated granite really belongs to the Karlshamn granites. A previous dating of foliated Karlshamn granite, from map-sheet Karlskrona NO, yielded an age of 1445±10 Ma (Kornfält 1996).

SAMPLE DESCRIPTIONS AND ISOTOPIC DATA

The isotope analyses were performed at the Unit for Isotope Geology, Geological Survey of Finland. Regarding the analytical procedure, see Suominen (1991) and Vaasjoki et al. (1991).

The *Sample KK 94:33* of Småland granite was taken in a road cut at Väghyltan, map-sheet 3G, Kristianopel NV (9b) (Fig. 1). Coordinates in the Swedish National Grid are 624651/150992. The granite is rather heterogeneous, greyish red to red, medium-grained, with characteristic, granulated quartz grains, which are often whitish on weathered surfaces (Fig. 2). Its chemical composition is shown in Table 1.

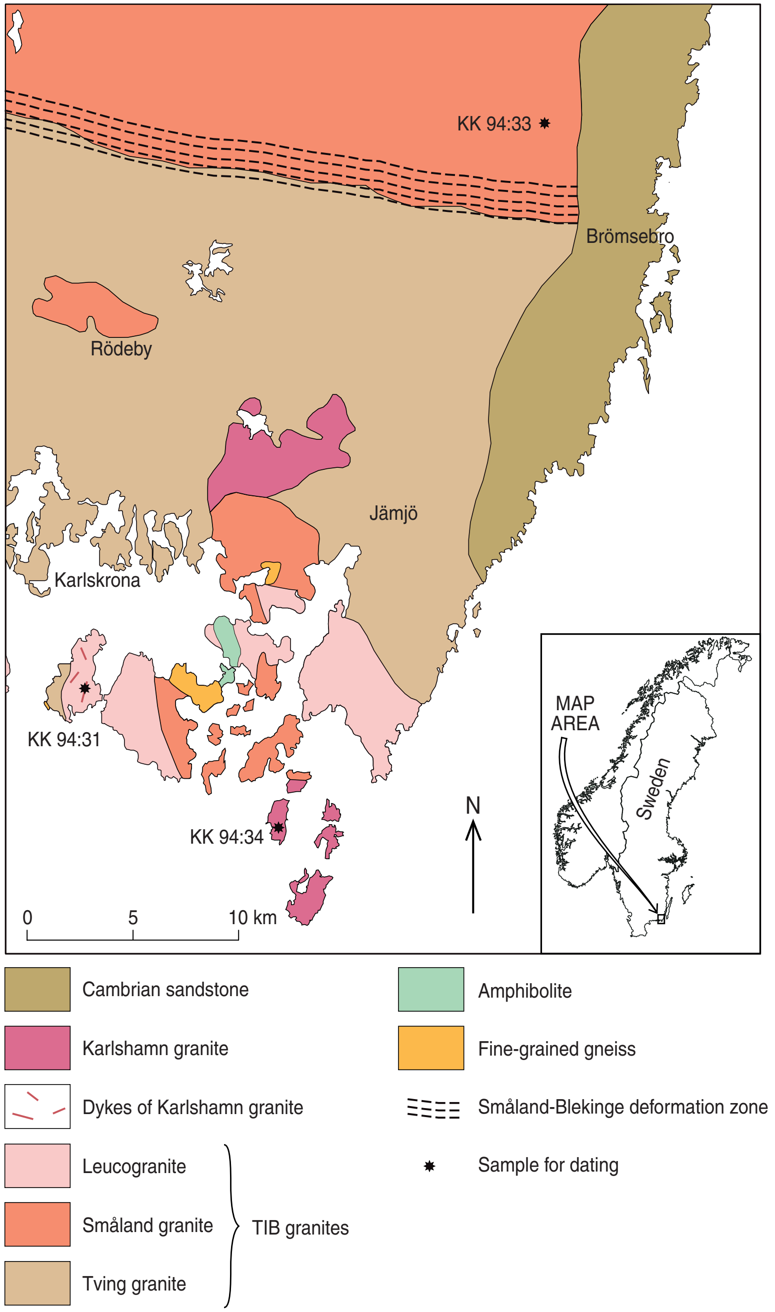

Fig. 1. Sketch map of the geology of the Karlskrona area with sampling sites indicated.

Fig. 2. Medium-grained Småland granite from sample locality KK 94:33, Väghyltan. (The diameter of the coin is 20 mm.)

The zircons separated from the rock are pale brown and of medium (c. 100 µm in length) grain size. There are some (<1 %) reddish crystals which were removed by hand-picking prior to analysis. The zircons are euhedral, with simple prismatic and pyramidal faces predominating. They are relatively long, with a length/width ratio of c. 5. The zonation is weak and a few (<1 %) crystals contain visible cores. Both opaque and transparent, rod-like inclusions of undetermined nature occur frequently.

As to the analytical results (Table 2) the abraded fraction A is least discordant, the degree of deviation increasing with increasing uranium content and decreasing density. The upper intercept age is 1800±13 Ma, with a large MSWD of 9.3 (Fig. 3). If the very discordant data point D is omitted from the calculation, the upper intercept becomes 1793±3 Ma and the MSWD decreases to 1.1. However, we prefer the former age (1800±13 Ma), based on 4 data points in spite of the large analytical error.

Sample KK 94:31 of finely medium-grained Karlshamn granite occurring as dykes or small massifs in older rocks, was taken in a road cut on the island of Tjurkö, mapsheet 3F, Karlskrona SO (4h). Coordinates in the Swedish National Grid are 622028/148837. The granite, which cuts through a strongly foliated leucogranite (Tjurkö granite), is greyish red, finely medium-grained and weakly foliated. The chemical composition is reported in Table 1.

The zircons from the rock are relatively small (c. 80 % <70 µm broad), light brown, transparent with simple prismatic–pyramidal crystal form. Under oil immer-

TABLE 1. Chemical analyses of dated samples. The analyses have been performed at Svensk Grundämnesanalys AB in Luleå by ICP-spectroscopy (ICP-AES and ICP-MS).

Sample no.	KK 94:33	KK 94:31	KK 94:34
Location	Väghyltan	Tjurkö	Inlängan
Coordinates	624651/150992	622028/148837	621390/149747
SiO_2 (wt. %)	70.6	69.5	66.8
TiO_2	0.63	0.50	0.73
Al_2O_3	13.8	13.2	14.9
Fe_2O_3	3.56	1.44	5.10
FeO		1.91	
MnO	0.09	0.08	0.11
MgO	0.61	0.65	1.01
CaO	1.56	1.69	2.27
Na_2O	3.32	3.04	3.89
K_2O	5.86	6.07	4.78
P_2O_5	0.18	0.20	0.35
BaO		0.13	
F		0.18	
LOI	0.5		0.5
Total	100.1	98.6	99.9
Ba (ppm)	1160		1090
Be	1.75		5.31
Co	<5.82		<5.98
Cr	<11.6		<12.0
Cu	15.3		21.3
Ga	16.2		23.6
Hf	13.2		17.5
Mo	1.83		1.66
Nb	21.4	32	26.0
Ni	<5.82		6.30
Rb	98.9	219	201
Sc	2.38		<2.39
Sn	1.11		2.91
Sr	236	221	256
Ta	1.15		2.24
Th	16.1	39	19.5
U	1.67	6	6.32
V	24.2		33.8
W	0.302		0.416
Y	33.1	63	50
Zn	68.2		107
Zr	513	477	715
La	118	132	104
Ce	229	251	223
Pr	22.9		24.4
Nd	82.0	112	89.4
Sm	10.4	15.2	13.1
Eu	1.23	2.54	2.28
Gd	8.18	14.1	11.3
Tb	1.21		1.63
Dy	6.34	9.63	8.92
Ho	1.23	1.98	1.76
Er	3.73	5.64	5.15
Tm	0.577		0.810
Yb	3.73	5.92	5.88
Lu	0.543	0.78	0.892

TABLE 2. U-Pb zircon data from samples KK 94:33 (Småland granite), KK 94:31 and KK 94:34 (Karlshamn granite).

Sample	Fraction (density)	Uconc ppm	Pbconc ppm	206/204 meas.	206 - 207 - 208 Radiogenic atom%	206/238 Corrected for blank	207/235	207/206 Age (Ma)
KK 94:33 Småland granite (Väghyltan)								
A	+4.5/ABR	214.3	70.00	1636	80.94 - 8.86 - 10.20	.2981±18	4.495±27	1790±3
B	+4.5	250.9	74.93	4031	81.91 - 8.95 - 9.15	.2810±16	4.231±26	1786±3
C	4.3-4.5	520.6	135.69	3133	82.22 - 8.89 - 8.89	.2452±14	3.646±22	1763±3
D	4.2-4.3	1151.4	208.33	914	80.34 - 8.20 - 11.46	.1596±10	2.234±14	1652±2
KK 94:31 Karlshamn granite (Tjurkö)								
A	+4.5/ABR	85.6	30.74	200.1	76.75 - 7.04 - 16.21	.2504±15	3.149±18	1451±9
B	+4.5	112.4	37.46	218.7	77.53 - 7.07 - 15.40	.2387±14	2.989±17	1442±5
C	4.3-4.5	119.8	37.63	247.0	78.24 - 7.11 - 14.65	.2328±14	2.905±17	1436±9
D	4.2-4.3	150.6	46.59	247.9	77.86 - 7.07 - 15.07	.2274±14	2.834±17	1433±8
KK 94:34 Karlshamn granite (Inlängan)								
A	+4.5/ABR	191.7	46.65	995.0	82.05 - 7.51 - 10.44	.2203±13	2.766±17	1448±2
B	+4.5	280.9	58.57	881.7	83.43 - 7.54 - 9.04	.1903±11	2.359±14	1423±2
C	4.3-4.5	581.7	96.59	881.0	84.62 - 7.52 - 7.86	.1534±9	1.870±11	1391±1
D	4.2-4.3	1456.5	188.85	282.9	81.40 - 6.83 - 11.77	.1016±6	1.171±7	1282±25

Common lead correction: ^{206}Pb/^{204}Pb:15.7; ^{207}Pb/^{204}Pb:15.4; ^{208}Pb/^{204}Pb:35.2 (KK 94:33 Väghyltan)
^{206}Pb/^{204}Pb:16.1; ^{207}Pb/^{204}Pb:15.4; ^{208}Pb/^{204}Pb:35.8 (KK 94:31 Tjurkö and KK 94:34 Inlängan)

ABR = abraded fraction

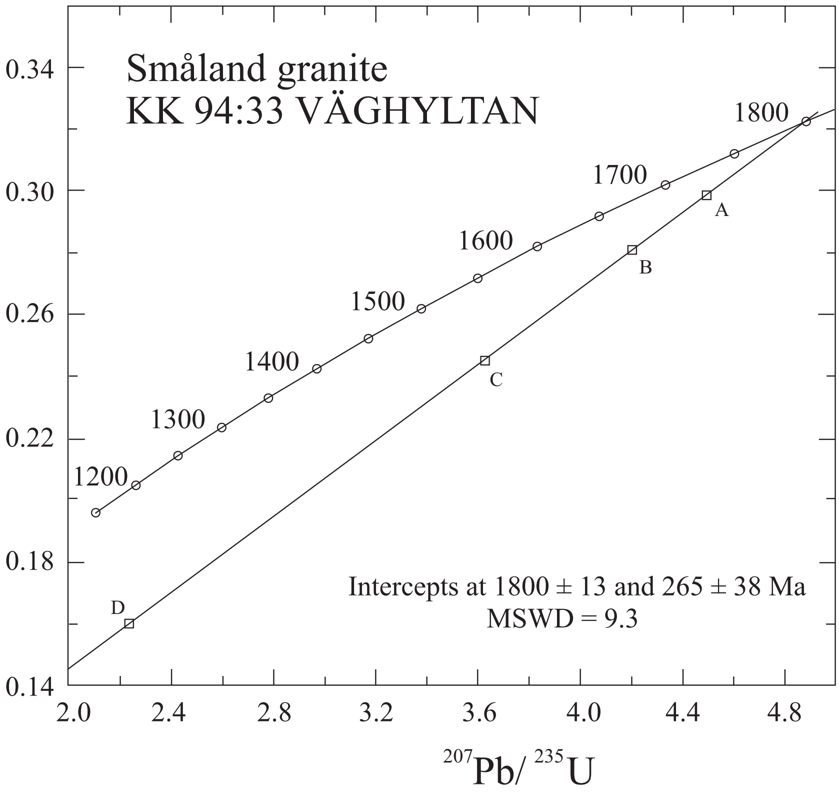

Fig. 3. U-Pb concordia diagram for zircons from Småland granite, sample KK 94:33.

sion, the crystals exhibit oscillatory zoning, and contain no significant inclusions.

The analysed fractions contain little uranium (85–150 ppm, Table 2), and exhibit a discordance pattern typical of magmatic rocks, i.e. increasing discordance as the uranium concentration increases. Nevertheless, as a result of the low uranium concentrations, even the most discordant fraction (D) has a fairly low degree of discordance, and the fraction containing least uranium (A) is practically concordant within experimental error. The common lead contents are high, as indicated by the measured $^{206}Pb/^{204}Pb$ ratios, which range from 200 to 250. However, if the common lead compositions are kept within reason, no significant effect on the age result can be observed.

The upper and lower intercept ages with the concordia curve are 1452±8 and 281±142 Ma, respectively, and the MSWD value is very low at 0.09 (Fig. 4), indicating that analytical uncertainty accounts for all of the observed scatter. Thus it is obvious that sample KK 94:31 represents a rock belonging to the Karlshamn granite group. Considering the low MSWD and the near concordance of fraction A, the result is probably the best age estimate for the Karlshamn granite group obtained so far.

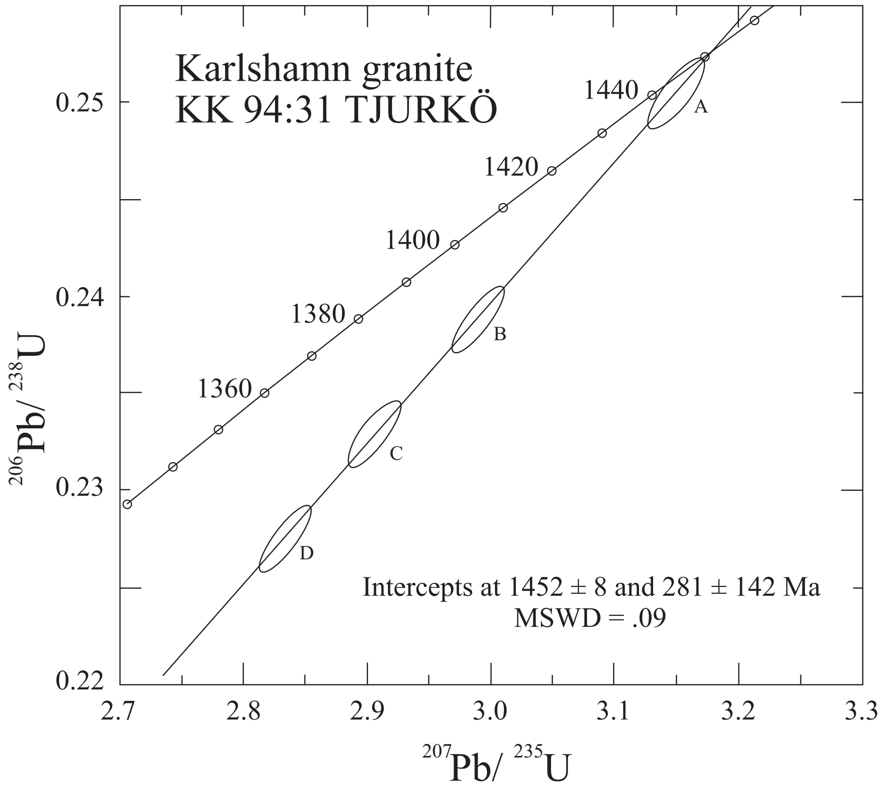

Fig. 4. U-Pb concordia diagram for zircons from Karlshamn granite, sample KK 94:31.

Sample KK 94:34 of foliated, medium-grained Karlshamn granite was taken on the island of Inlängan quite close to a military ‘pillbox’, where the bedrock had been blasted during its construction. Coordinates in the Swedish National Grid are 621390/149747, map-sheet 3F Karlskrona SO (2j). The granite is reddish grey, medium-grained, with megacrysts of potash feldspar (<1 cm). It is weakly foliated and contains some hornblende. The chemical composition of this granite is reported in Table 1.

Four fractions of zircon were analysed (Table 2). The separated zircons range from 50 to 200 µm in size and are generally pale brown, although there is also a reddish variety (<2 %) which was removed by hand-picking. The crystal form is predominantly euhedral with simple prismatic–pyramidal habit. The crystals in the heavy fraction are mostly transparent, but the lighter fractions become increasingly turbid. Study under oil immersion revealed rod-like liquid-gas inclusions and weak oscillatory zoning. No cores were detected. The length/width ratio varies between 1.5 and 7, with a median at c. 3.

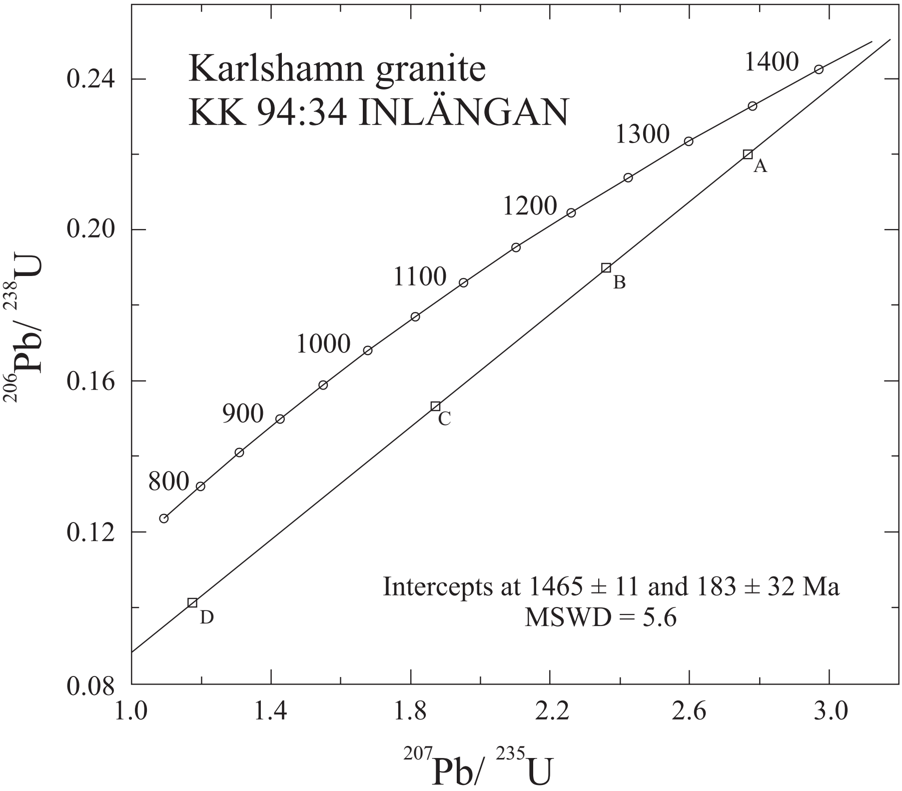

Fig. 5. U-Pb concordia diagram for zircons from Karlshamn granite, sample KK 94:34.

The discordance pattern of the analysed zircons is normal, i.e. the abraded fraction A is least discordant and the degree of discordance increases as the uranium content increases. Although the common lead contents are rather high, the estimated common lead composition has no significant bearing on the dating result. The upper and lower intercept ages are 1465±11 and 182±32 Ma, respectively (Fig. 5). The high MSWD of 5.6 may suggest a slight heterogeneity in the source of the zircons, but could equally well be a result of the considerable amounts of lead loss in the lighter fractions C and D. The upper intercept most likely represents the time of the emplacement of the Inlängan granite, but the lower intercept is of no geological significance.

DISCUSSION

The obtained age, 1800 Ma, of the Småland granite sample from Väghyltan is surprisingly old. This granite variety should be the youngest medium-grained Småland granite in the area according to the observed field relations. (Still younger is a greyish red to red, fine-grained to finely medium-grained granite occurring as dykes or small massifs in the older rocks.) A dating of a Småland granite sampled c. 20 km west of Väghyltan has, as mentioned above, yielded an age of 1778±11 Ma (Kornfält 1993). Datings of granitoids which from field evidence are interpreted as older than the granite from Väghyltan might solve the ambiguity. Further studies are required to establish whether the old age of the granite is due to inheritance.

Åberg et al. (1985b) have published zircon U-Pb analyses of two samples of Karlshamn granite from central Blekinge. Four of the analyses from the 'normal' type are only slightly discordant and exhibit $^{207}Pb/^{206}Pb$ ages in the range 1420–1440 Ma, while a fifth fraction is reversely discordant. Four fractions from a leucogranitic type are quite discordant and have a relatively narrow range of discordance, but define a good (MSWD = 0.38) linear trend yielding an upper intercept of 1403±36 Ma, which Åberg et al. (1985b) consider the best age estimate for the Karlshamn granite intrusion.

However, the results of the present study suggest an age of the order of 1450–1460 Ma for the Karlshamn type granites. The dating on the Tjurkö sample is especially very reliable, the MSWD being 0.09, with the abraded fraction nearly concordant. Thus there seems to be a discrepancy of about 50 Ma between the present age determinations and the hitherto accepted age of the Karlshamn granite.

It is probable that the hitherto accepted age of the Karlshamn granite intrusion is based on an overly confident interpretation of data and should be revised. We suggest that the new age for the Karlshamn granite intrusion should be 1452±8 Ma. This age proposal is based on the very reliable dating of sample KK 94:31 from Tjurkö, supported by the two datings of Karlshamn granite KK 94:34 from Inlängan, and KK 90:3 from NNE of Ramdala (Kornfält 1996) giving 1465±11 Ma and 1445±10 Ma, respectively. The existence of a somewhat younger generation of Karlshamn granite in western and central Blekinge cannot be ruled out, but as long as good datings from that region are missing, we think that the proposed new age, 1452±8 Ma, should be valid for the Karlshamn granite intrusion.

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The Brännbergsliden gneiss - an exotic block of a plastically deformed Arvidsjaur metavolcanic rock? Field geologic and radiometric dating results

By

Ingmar Lundström & Per-Olof Persson

INTRODUCTION

The area north of the Skellefte district (Weihed et al. 1992) is dominated by well preserved metavolcanic and intrusive rocks. The metavolcanic rocks belong to the Arvidsjaur group of Allen et al. (1996) and are predominantly felsic volcaniclastic rocks, mostly ash-flow tuffs (cf. Grip 1935). Various intermediate and mafic varieties also occur. The intrusive rocks comprise deep-seated granitoids of Jörn GI and GIII type (cf. Wilson et al. 1987) and more or less shallow, subvolcanic intrusive rocks. Kathol & Rapp (1996) presented evidence that some of these intrusive rocks are co-magmatic with the extrusive rocks.

Having suffered only greenschist facies metamorphism, these rocks have experienced very little structural and metamorphic overprinting and are generally extremely well preserved. Thus, Grip (1935) gives numerous examples of delicate volcanic structures and textures, whose preservation is comparable to what is found in recent volcanic rocks. Such well preserved, felsic volcaniclastic and intrusive rocks occur around Klintån and Kamsån rivulets, some 20 km northeast of Jörn (see Fig. 1a and Lundström & Antal 1998). In the vicinity of these rocks, penetratively deformed, recrystallized, highly metamorphosed, almost gneissic rocks occur on and around the Brännbergsliden hill. This complex unit of tectonometamorphically strongly deviating rocks is here called the "Brännbergsliden gneiss complex". The exotic nature of the Brännbergsliden gneiss made an age determination highly desirable.

GEOLOGICAL SETTING AND SAMPLE DESCRIPTION

Geological setting of the Brännbergsliden gneiss complex

The Brännbergsliden gneiss complex is bordered by northwest-striking, plastic shear zones on its northeastern and southwestern sides (see Fig. 1b). Both the shear zones and the interior of the complex are characterized by gently southeast-dipping lineations. The northeastern zone shows a sinistral sense of shear, the southwestern zone dextral (cf. Fig. 2). These shear kinematics indicate that the complex was moved almost horizontally towards the southeast. The western and eastern borders of the complex are poorly known because of lack of exposures, but geophysical data indicate brittle deformation zones. Small, more or less undeformed areas occur inside the complex. Fine-grained, basic to intermediate metavolcanic and intrusive rocks can some-

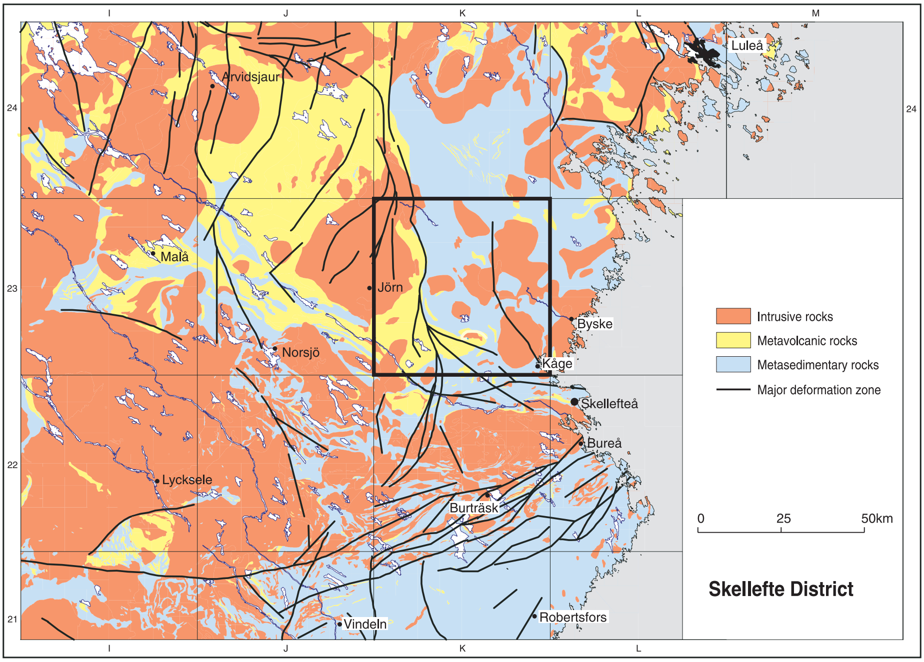

Fig. 1a. The Skellefte field. Boliden map-sheet indicated by thick square. Side of squares 50 km.

times be discerned in such areas. Kinematic indicators are unknown from the interior of the complex. In many places, the deformation fabric is cross-cut by isotropic, reddish granites, similar to the Jörn GIII granite (see Fig. 3, cf. Wilson et al. 1987), which occurs immediately to the west of the Brännbergsliden complex.

Description of dated sample

The sample to be dated was taken from a road-cut, some 500 m north of lake Grundträsk. The rock is a strongly lineated to foliated tonalitic gneiss, consisting of quartz, plagioclase, biotite and amphibole as main minerals. It has a granoblastic, well recrystallized texture. Some 10 % of relict (?) plagioclase megacrysts, of mm-size, occur within a fine-grained (0.1–0.5 mm) matrix. Compositional, textural and grain size variations give rise to a diffuse lensoid pattern. Macroscopically, winged porphyroclasts indicate a dextral sense of shear (Fig. 2), which is also supported by a vague c/s fabric, seen in thin section. The chemical composition (see Table 1) is dioritic or andesitic, but the rock is sufficiently quartz-rich to give it a tonalitic or dacitic modal composition.

The analysed sample was extremely poor in zircons. About 50 crystals were obtained, most of which were of poor quality (metamict and fractured). Approximately

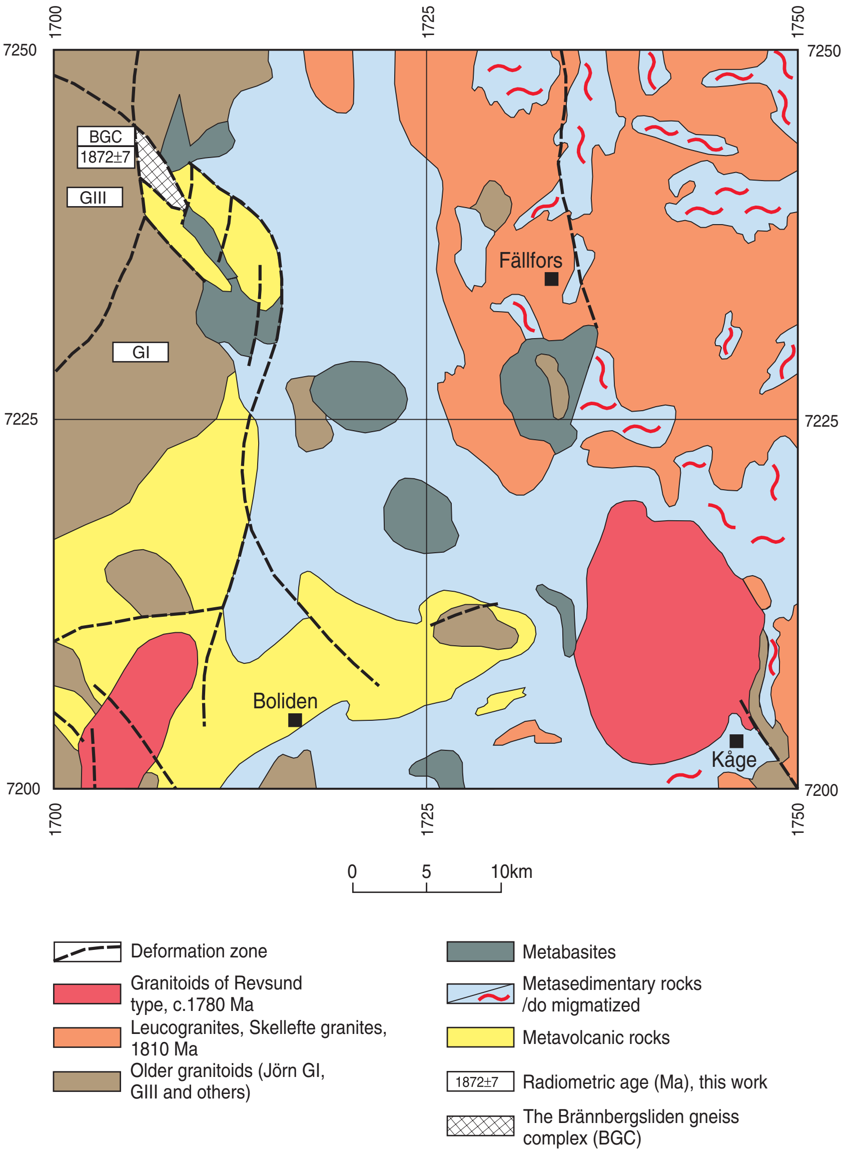

Fig. 1b. The Boliden map-sheet. BGC: The Brännbergsliden gneiss complex (hatched pattern).

half of the population is colourless and the other half is brown. The length/width ratio is mostly c. 1–2 but grains with ratios of 3–4 also occur. Both euhedral and substantially rounded crystals are found. Several of the rounded crystals display small,

Fig. 2. Winged plagioclase megacryst indicating dextral movement. Sampling site at road cut 500 m north of lake Grundträsket, Swedish national grid coordinates: 724219/170602.

Fig. 3. Veins of granite of Jörn GIII type, cross-cutting the planar fabric of the Brännbergsliden gneiss. Sampling site at road cut 500 m north of lake Grundträsket, Swedish national grid coordinates: 724219/170602.

TABLE 1. Chemical analysis of the dated sample. The analysis was performed by Svensk Grundämnesanalys AB, Luleå, using a combination of ICP-AES and ICP-MS.

Sample nr	FRS960027
N-coord.	7242190
E-coord.	1706020
Reference:	SGU
SiO_2 (wt-%)	57.3
TiO_2	0.894
Al_2O_3	16.4
Fe_2O_3	7.95
MnO2	0.144
MgO	4.91
CaO	5.64
Na_2O	4.07
K_2O	1.85
P_2O_5	0.329
LOI	0.4
Total	99.5
Ba (ppm)	750
Be	0.797
Co	51.8
Cr	126
Cu	31
Ga	15.4
Hf	6.86
Mo	2.12
Nb	7.92
Ni	48.2
Rb	34.5
Sc	19.1
Sn	1.21
Sr	592
Ta	0.91
Th	5.7
U	3.56
V	129
W	210
Y	19.5
Zn	305
Zr	142
La	24.7
Ce	51.6
Pr	6.41
Nd	27
Sm	4.52
Eu	0.961
Gd	3.88
Tb	0.691
Dy	3.51
Ho	0.663
Er	1.98
Tm	0.305
Yb	1.95
Lu	0.418
Lab.	SGAB97388-9

TABLE 2. U-Pb isotopic data

Mineral and analysis No.	No. of crystals	Weight (µg)	U (ppm)	Pb tot. (ppm)	Common Pb (ppm)	$\frac{^{206}Pb^{a}}{^{204}Pb}$	^{206}Pb - ^{207}Pb - ^{208}Pb Radiog. (atom %)^{b}	$\frac{^{206}Pb^{b}}{^{238}U}$	$\frac{^{207}Pb^{b}}{^{235}U}$	$^{207}Pb/^{206}Pb$ age (Ma)
FRS 960027	**Tonalitic gneiss, Brännbergsliden**									
Zircon 1	22	9	680	221	0.13	8442	85.2 - 9.8 - 5.0	0.3213±14	5.075±23	1873±2
Zircon 2	10	4	1741	599	6.63	3649	85.7 - 9.8 - 4.5	0.3389±14	5.338±22	1868±3
Monazite 1	20	20	1782	6644	0.45	32974	7.9 - 0.9 - 91.2	0.3386±15	5.325±24	1866±1
Monazite 2	35	31	1907	7591	0.80	31740	7.4 - 0.8 - 91.8	0.3400±14	5.365±22	1871±1
Titanite 1	40	7	360	151	3.36	2014	72.3 - 8.3 - 19.4	0.3451±7	5.470±19	1879±5
Titanite 2	25	10	382	160	3.84	1782	70.9 - 8.1 - 21.0	0.3350±10	5.303±21	1877±4

a) corrected for mass fractionation (0.1% per a.m.u).
b) corrected for mass fractionation, blank and common Pb.

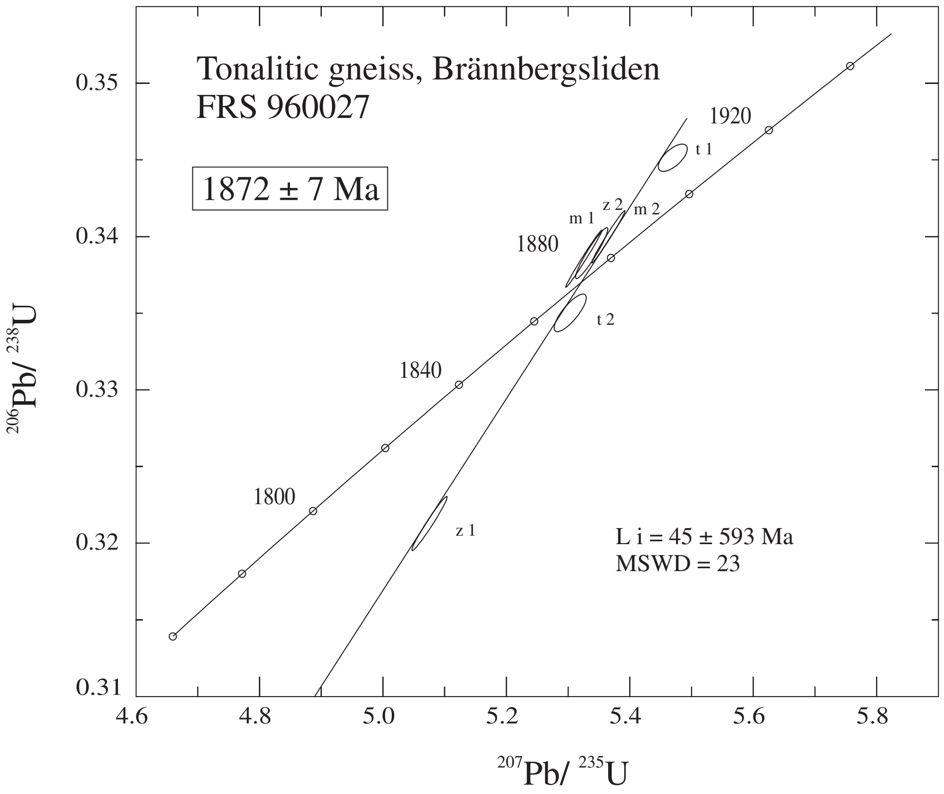

Fig. 4. Concordia plot for the Brännbergsliden gneiss zircons, titanites and monazites.

high-index faces. The brown zircons are generally of poorer quality than the colourless ones. A few crystals have brown cores and colourless rims. Because of the small amount of material, abrasion was not carried out. Two zircon fractions were analysed:

z 1: 22 small, euhedral, colourless crystals, most of them fractured.

z 2: 10 euhedral to subrounded, small crystals, in various shades of brown. The dark brown crystals are turbid whereas the lighter ones are transparent.

The rock also contains small amounts of greenish yellow monazite, two analyses of which were made:

m 1: 20 small rather clear crystals. Some have crystal faces, the rest are irregular.

m 2: 35 small crystals. They are more turbid than those in fraction 1.

Two fractions of titanite were analysed. The titanite of the Brännbergsliden tonalitic gneiss is dark brown, often reddish brown. Most of the grains in the mineral separate are fragments of larger grains.

t 1: 7 rather large crystals. They are fragments, but two crystals show crystal faces. The largest parts of the grains are transparent but turbid domains occur. Few cracks are present. Two of the grains are reddish brown, the rest brown.

t 2: 10 small grains that are fragments of larger crystals. They are transparent, with only a few turbid domains.

The analyses were made at the Laboratory for Isotope Geology in Stockholm. The analytical procedure is described in the Editor's Preface to this volume. The results of the isotopic analyses are shown in Table 2 and Fig. 4. One zircon fraction plots somewhat discordantly while the other one and the two monazite fractions are slightly reversely discordant. The latter three have a spread in their $^{207}Pb/^{206}Pb$ ages exceeding analytical uncertainty (Table 2). The U content of the two analysed zircon populations varies greatly. Contrary to what normally is the case, the U-rich fraction is less discordant than the fraction with moderate U content. One of the two titanite fractions is marginally discordant and the other reversely discordant. The $^{207}Pb/^{206}Pb$ ages of the titanites are slightly older than the zircon and monazite ages, just outside the error limits. A regression calculated on all six points gives an upper intercept age of 1872±7 Ma and a lower intercept close to zero. The MSWD is large due to the poor linear fit, but the small discordance makes the age determination precise.

DISCUSSION AND CONCLUSIONS

Zircon fraction 1 and most of fraction 2 comprise zircons of euhedral crystal habit, characteristic of magmatic and non-metamorphic formation. As zircon, monazite and titanite yield virtually identical ages and plot almost concordantly, we interpret the intercept age of 1872±7 Ma as the crystallization age of the tonalite.

It is not possible, with the available information, to tie the different mineral ages to discrete geological events. The usual case is that titanite yields younger or equal ages than the other two minerals. It has generally been considered to have a lower closure temperature for the U-Pb system than zircon and monazite, but recent studies (e.g. Zhang & Schärer 1996) have demonstrated that titanite may survive temperatures above 700° C and that magmatic titanite records the crystallization age of the rock and not a cooling age. The fact that the titanite of the Brännbergsliden tonalitic gneiss gives a marginally older age than zircon and monazite should therefore not be regarded as anomalous, although such cases appear to be rare. The old titanite ages in this study cannot be explained by erroneous common-lead correction, since choosing a markedly different isotopic ratio for initial lead would merely alter the $^{207}Pb/^{206}Pb$ age by less than 1 Ma. It can be concluded that all three minerals are of magmatic origin and that crystallization of zircon, monazite and titanite occurred during a time interval of about 10 million years, possibly suggesting that elevated temperatures prevailed over a substantial period of time. An explanation in terms of underestimated analytical errors, e.g. due to larger variation than usual of the mass fractionation, cannot be totally discarded. However, by giving a conservative error of ±7 Ma for the crystallization age, establishing the exact order of formation of the dated minerals becomes less relevant.

This age is surprisingly young, because the fabric of the rock is cross-cut by Jörn GIII-type granites (see above), the only available age determination of which gave 1873+18/-14 Ma. Obviously, the error has to be taken into account in order to allow time enough for the fabric to develop between the formation of the precursor of the Brännbergsliden gneiss and the intrusion of the Jörn GIII granite. Evidently a more precise age determination of the Jörn GIII granite is urgently needed.

The origin of the exotic Brännbergsliden gneiss complex remains enigmatic. According to age and chemistry it can possibly be correlated with the Arvidsjaur metavolcanic rocks. However, the latter are nowhere known to be as highly strained and metamorphosed as the Brännbergsliden gneiss.

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Indications of early deformational events in the northeastern part of the Skellefte field. Indirect evidence from geologic and radiometric data from the Stavaträsk–Klintån area, Boliden map-sheet

By

Ingmar Lundström, Per-Olof Persson & Ulf Bergström

INTRODUCTION

Weihed et al. (1992) demonstrated that two phases of deformation have affected the rocks in the Skellefte District. Time constraints are poor, but deformation must have persisted after 1859 Ma, which is the age of the Sikträsk gneissose granitoid (Weihed & Vaasjoki 1993), and ended before the intrusion of the 1.78 Ga old, undeformed Revsund granite (see Weihed et al. 1992). According to Billström & Weihed (1996), peak metamorphic conditions culminated between 1.84 and 1.82 Ga ago. From the structural homogeneity throughout the entire stratigraphic pile, Weihed et al. (1992) also concluded that the first phase of deformation affected the uppermost strata in the Vargfors area and probably did not commence until deposition of these rocks was complete, i. e. after 1875 Ma.

However, in the Norrbotten area, north of the Skellefte field, an earlier (pre 1.85–1.87 Ga) metamorphic peak and deformation has been suggested by Skiöld (1988), demonstrated by Wikström et al. (1996) and implied by Bergman (1998).

Combined with existing and new radiometric age data, recently concluded field work for the bedrock mapsheet Boliden in the eastern part of the Skellefte District (see Figs. 1, 2 and Lundström & Antal 1998a, b, c, d) likewise indirectly indicate deformation before c. 1870. These indications were obtained from the Stavaträsk–Klintån area around the eastern border of the Jörn Granitoid Complex (the JGC of Wilson et al. 1987, cf. Lundström & Antal 1998 a, c, see Fig. 1). The purpose with this paper is to present these new data and to introduce a preliminary discussion thereof.

GEOLOGIC AND RADIOMETRIC DATA

Age of deformation and recrystallization within and east of the Jörn Granitoid Complex

The Jörn Granitoid Complex (JGC) was described and its different intrusive phases were dated by Wilson et al. (1987). The complex consists of a series of consecutive intrusions, labelled GI to GIV. Only the GI, which Wilson et al. (1987) dated at 1888+20/-14 and the GIII, which was dated at 1873+18/-14 (both U-Pb age determination on zircons), are significant in the study area and context considered here. The GI is mostly a greyish, medium-grained, even-grained granodiorite to tonalite with a

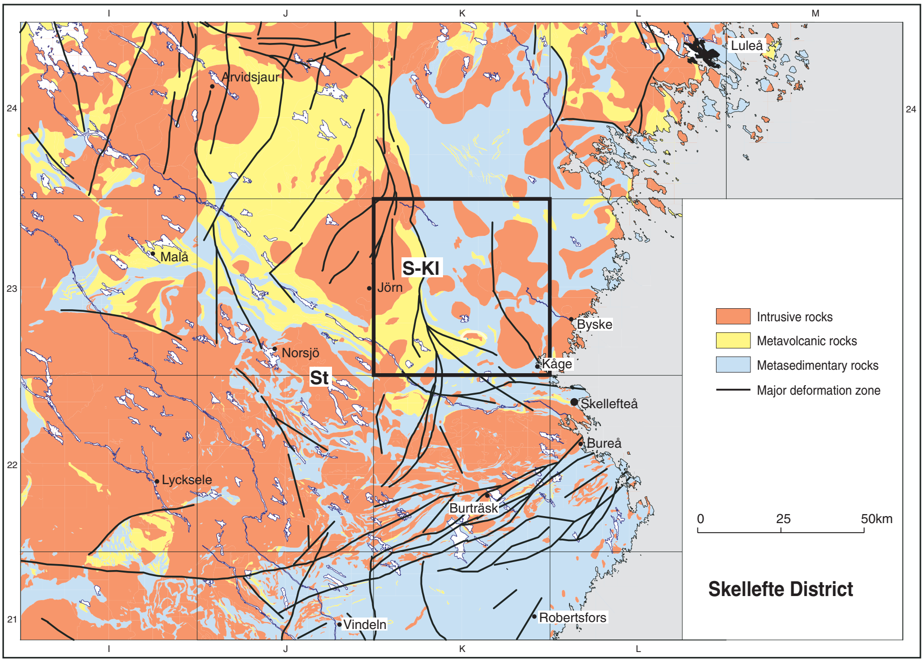


Fig. 1a. The Skellefte District. Boliden map-sheet indicated by thick square. Side of squares 50 km. St: Sikträsk; S-Kl: the Stavaträsk–Klintån area.

granoblastic, isotropic texture. It is frequently cut by mafic and felsic dykes which are sometimes fine-grained enough to be subvolcanic. The GIII is a reddish, homogeneous, even-grained granite with an isotropic, hypidiomorphic–granular texture which shows no signs of recrystallization.

Field relationships of the GI and GIII granitoids in the Stavaträsk–Klintån area

Locally, GIII granitoids clearly post-date older structures in the GI. Thus, at Slevbäcken (coordinates 723234/170278), a foliated, granoblastic granitoid of GI-type occurs as inclusions within isotropic granite of GIII type (see Fig. 3). South of the Klintån rivulet, a foliated, recrystallized granitoid occurs along a northwest-striking ductile shear zone (for kinematic details, see Bergman Weihed 1997). At Bastulundsberget (coordinates 723464/170866), this deformed granitoid is cross-cut by an isotropic, reddish granite of GIII type. Taking the error limits of the above GIII age determination into account, the conclusion is that the foliation in the granitoid must predate 1.86 Ga (see Fig. 2). This is corroborated by the nearby and similar Hobergsliden granite, which is at least 1862 Ma old (Lundström et al. 1997). The age

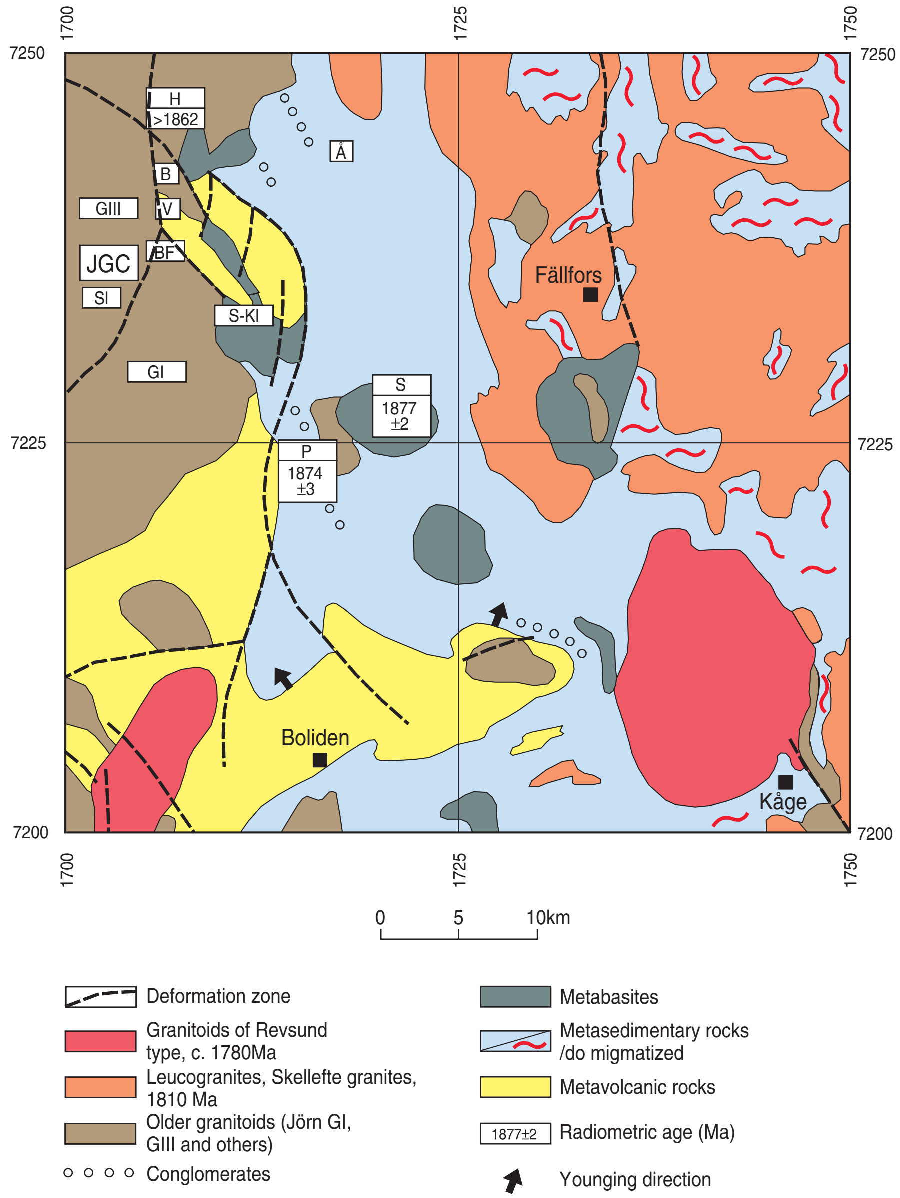
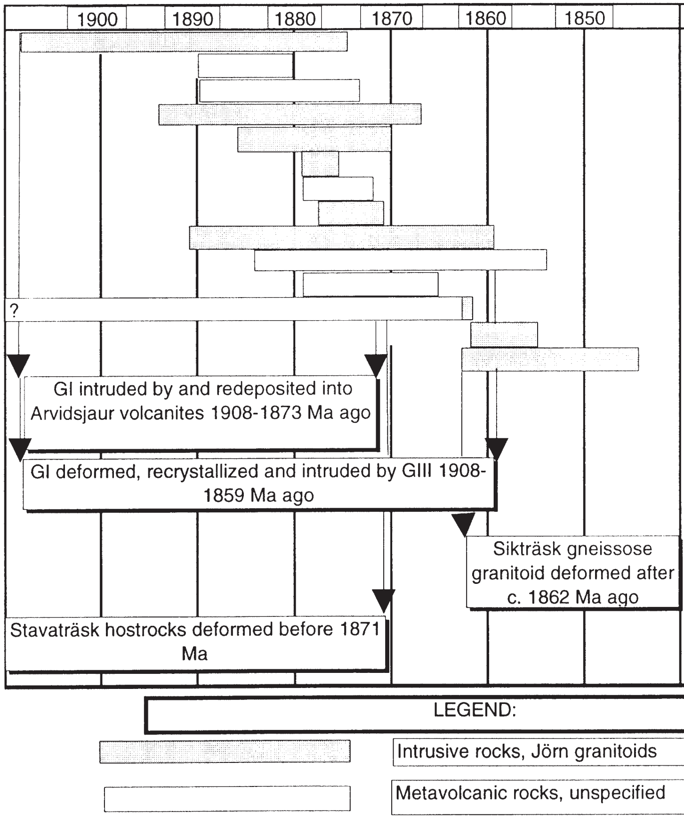


Fig. 1b. The Boliden map-sheet: Å: Åselet, B: The Brännbergsliden gneiss complex; BF: Bastulundsberget and Furuberget hills; H: Hobergsliden; JGC: The Jörn Granitoid Complex; S: Stavaträsk; S-Kl: the Stavaträsk–Klintån area; Sl: Slevbäcken; P: Pultarliden; V: Valliden.



Age (Ma)	Rock and location	Reference
1888+20/-14	Jörn GI granitoid	Wilson et al. 1987
1885+/-5	Bjurvattnet Skellefte volcanite	Billström & Weihed 1996
1882+/-8	Nicknoret Skellefte volcanite	Welin 1987
1879+15/-12	Antak granite	Kathol & Persson 1997
1877+8/-7	Arvidsjaur granite	Skiöld, et al. 1993
1877+/-2	Stavaträsk diorite	Lundström et al. 1997
1876+/-3	Arvidsjaur metavolcanite	Skiöld et al. 1993
1874+/-3	Pultarliden (tonalitic) trondhjemite	This work
1873+18/-14	Jörn GIII granite	Wilson et al. 1987
1869+/-15	Boliden Skellefte volcanite	Bergman Weihed et al. 1996
1872+/-7	Brännbergsliden gneiss	Lundström & Persson 1998
>1862	Hobergsliden granite	Lundström et al. 1997
1859+/-3	Sikträsk granitoid	Weihed & Vaasjoki 1993
1854+/-9	Sikträsk granitoid	Billström & Weihed 1996

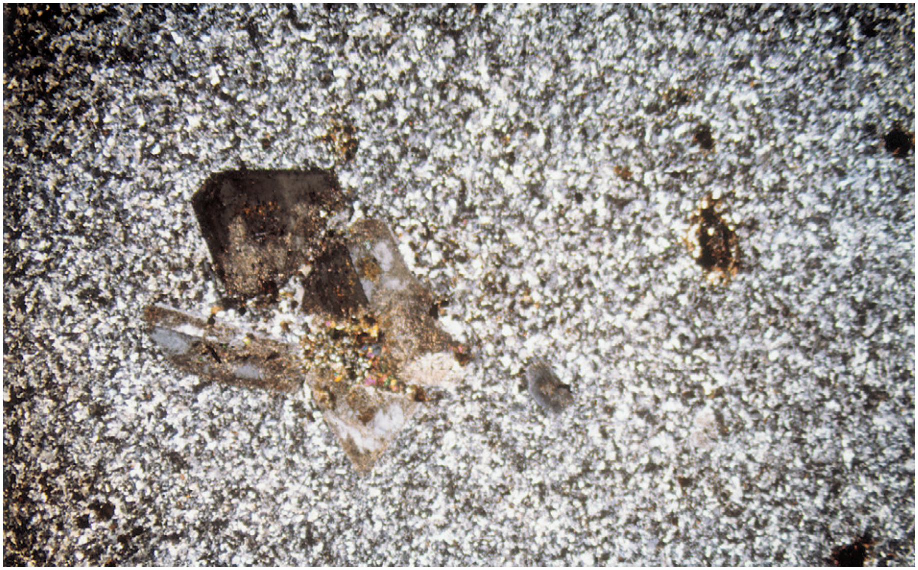
Fig. 2. Compilation of relevant radiometric data.

Fig. 3. Reddish, isotropic GIII-type granite, crosscutting foliation in GI-type granitoid. Slevbäcken (coordinates 723234/170278).

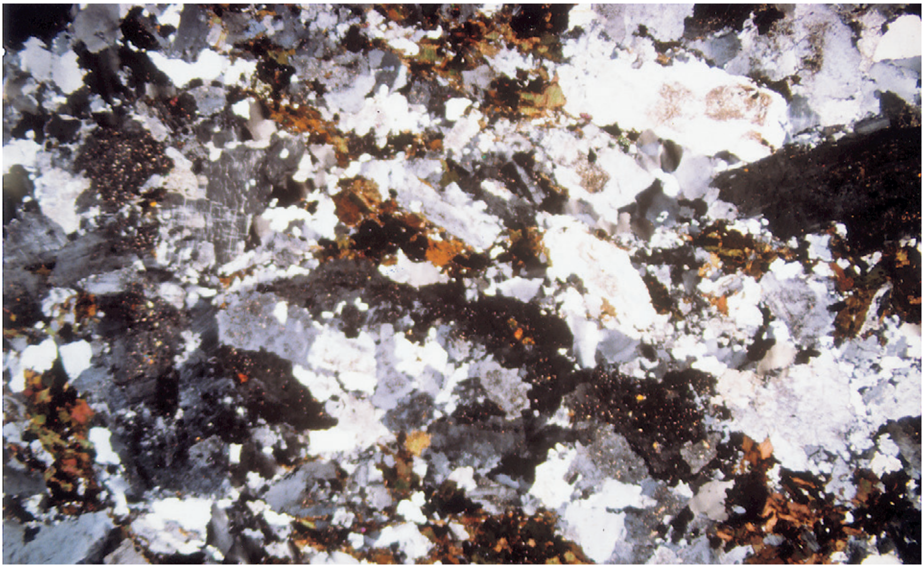
determination of the similar Antak granite (Kathol & Persson 1997) would put the minimum age limit for this deformation at 1867 Ma and the minimum age limit of the related Arvidsjaur granite (Skiöld et al. 1993) would put it at 1870 Ma. Consequently, this deformation must have taken place before 1.86–1.87 Ga.

Field relationships of the GI granitoid and the subvolcanic intrusions in the Stavaträsk–Klintån area

At Furuberget (coordinates 723554/170762), the same shear zone and foliated, recrystallized granitoid as at Bastulundsberget, is cross-cut by a straight dyke of a plagioclase-phyric, fine-grained, isotropic rock (Fig. 4). As Arvidsjaur-type volcanic rocks occur just to the north of the shear zone (cf. Lundström & Antal 1998a), it is tempting to believe that the dyke is a synvolcanic feeder dyke to these rocks. Clearly, the fabric of the granitoid must have been imposed before the dyke solidified, i.e. probably before the Arvidsjaur volcanic rocks were extruded. Additional evidence was obtained at Valliden (723804/170778) just north of the shear zone, where volcanic rocks of Arvidsjaur type are associated with a well-preserved conglomeratic, volcanic sandstone with occasional clasts of a recrystallized, isotropic, typical GI tonalite (Fig. 5a). Table 1 shows that the chemical composition of one of these clasts is very similar to a GI analysis by Wilson et al. (1987). As is shown by Fig. 5b, c, there is a very evident difference in the metamorphic overprint of textures in the clast, compared with



a)



b)

Fig. 4. Subvolcanic dyke crosscutting foliated granitoid of GI type. Furuberget (coordinates 723554/170762)
a) Photomicrograph of the subvolcanic intrusion. Length of micrograph: 13 mm. Crossed nicols.
b) Photomicrograph of the foliated, granoblastic granitoid of GI type. Length of micrograph: 13 mm. Crossed nicols.

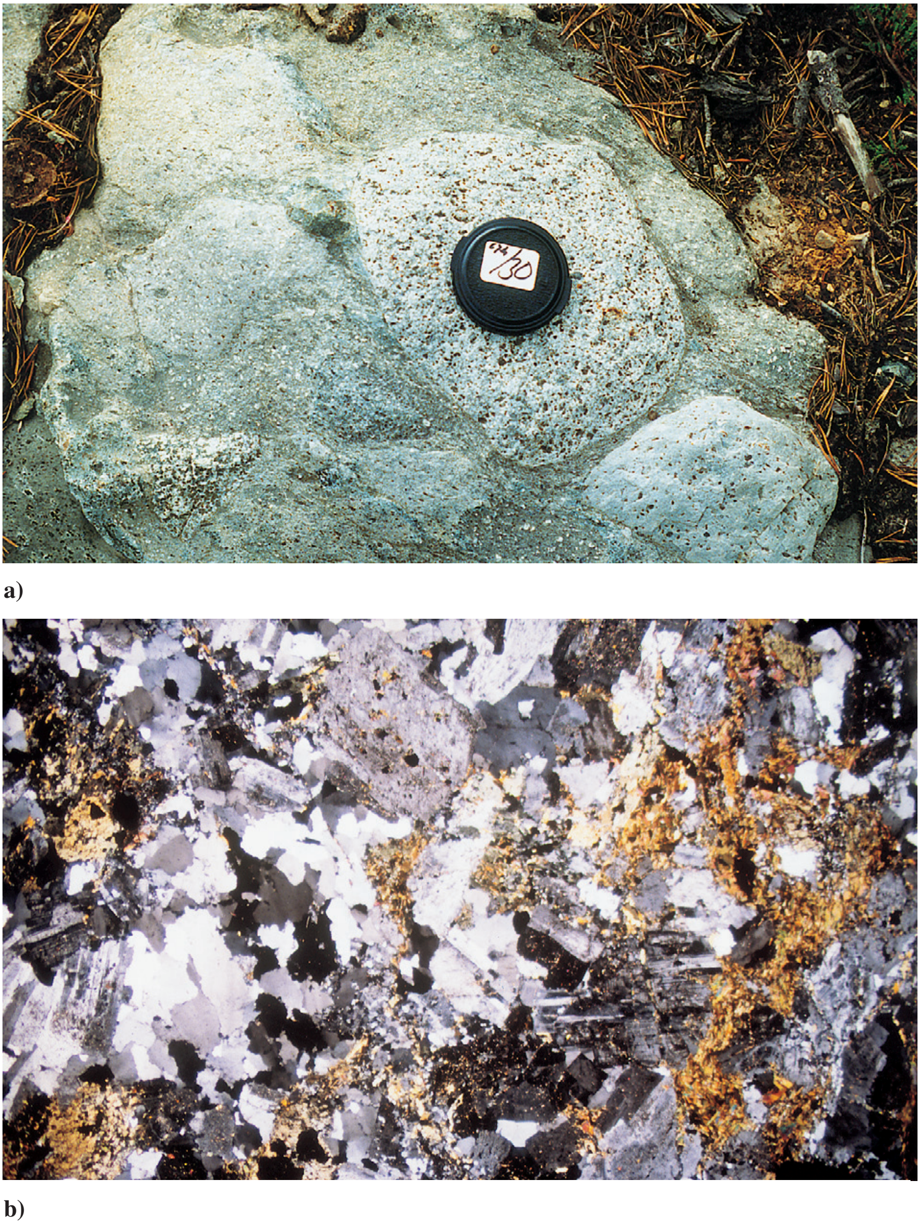
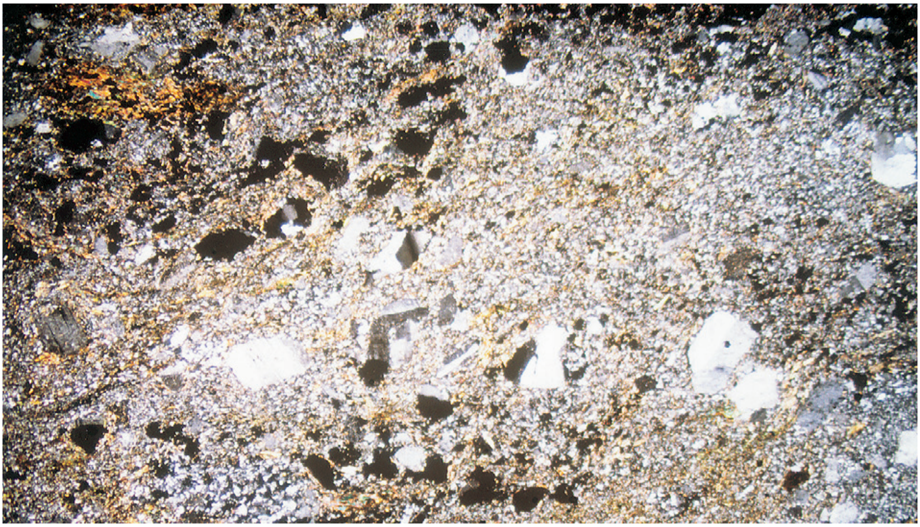


Fig. 5. Polymictic conglomerate with clasts of Jörn GI granitoid. Roadside exposure E of Valliden (coordinates 723804/170778).
a) Clast of Jörn GI granitoid.
b) Photomicrograph of granoblastic texture within clast of Jörn GI. Length of micrograph 13 mm. Crossed nicols.
c) Photomicrograph of conglomerate matrix. Length of micrograph 13 mm. Crossed nicols.



c)

its matrix. Evidently, the GI granitoid was deformed, recrystallized, uplifted, and eroded before the Arvidsjaur volcanic rocks erupted and the conglomerate was deposited. According to Skiöld et al. (1993), a pooled age determination of Arvidsjaur volcanic rocks gave the age 1876±3 Ma. Therefore, the above processes should have taken place before c. 1873 Ma ago.

Consequently, the field relationships and presently available radiometric datings within and around the Jörn Granitoid Complex indicate that a tectonometamorphic event affected the Jörn GI granitoid probably before 1.87 Ga, but certainly before 1.86 Ga. Furthermore, the Jörn GI must have been uplifted and eroded at about 1873 Ma as also suggested by Billström & Weihed (1996) from evidence in the Vargfors area.

Contact relationships around the Stavaträsk massif and age of deformation

North of Stavaträsk a composite pluton has intruded into fine-grained, mostly strongly foliated, quartz-plagioclase-biotite rich, metasedimentary rocks of medium metamorphic grade (see Fig. 1 and Lundström & Antal, 1998a, c). These rocks may also carry chlorite or graphite and can be cordierite- or andalusite porphyroblastic, especially in the vicinity of the intrusive rocks. The grain size is sometimes submicroscopic, but in most cases, a grano- or lepidoblastically recrystallized clastic texture can be recognized. Clastic textures and sedimentary structures can also mostly be recognized in the field. The pluton consists of a diorite, which was dated at 1877±2 Ma by Lundström et al. (1997) and a (tonalitic) trondhjemite. Both appear to cross-cut pre-

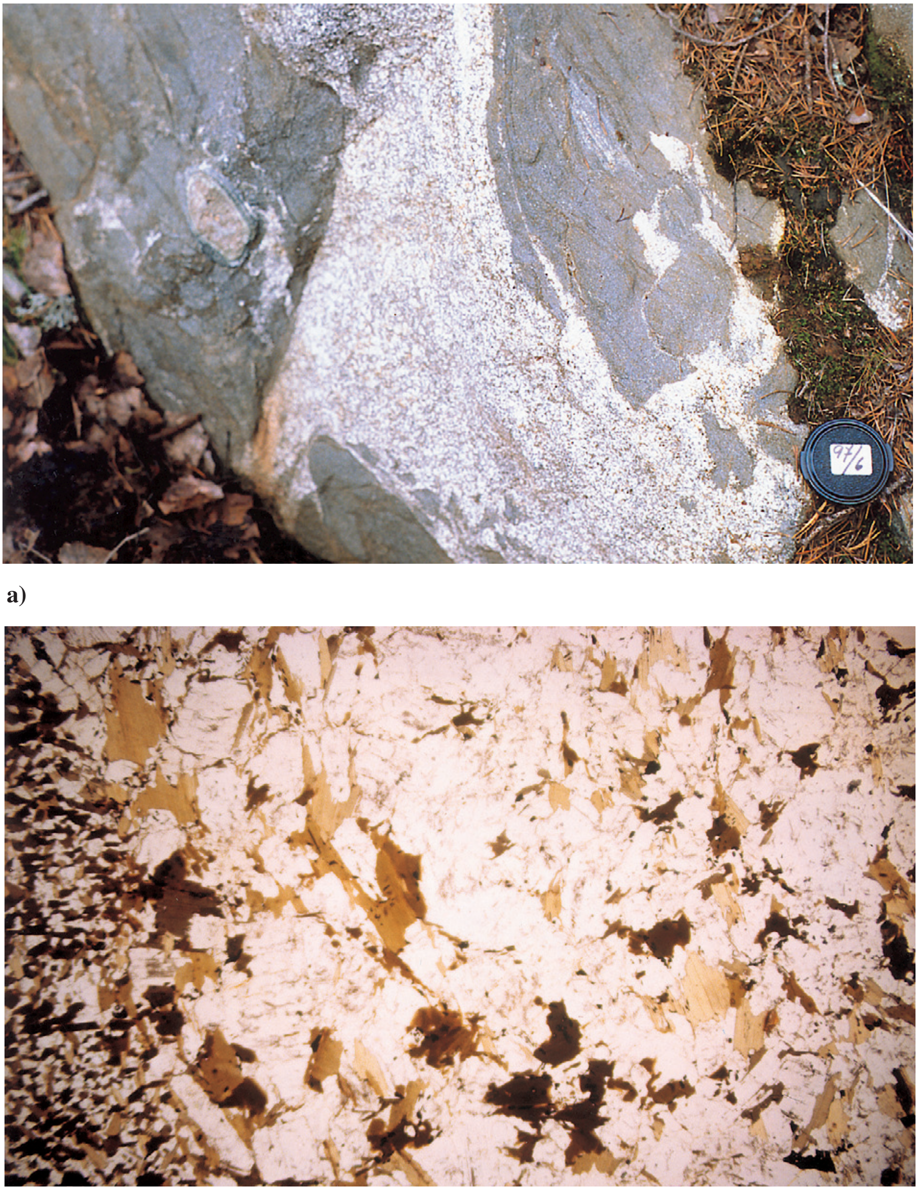


Fig. 6. Contact relationship between the Stavaträsk diorite and metasedimentary roof pendants. Southern slope of Norsberget hill (coordinates 722410/172680), 1 km E of Stavaträsk village.
a) Field relationships between diorite and hornfels altered, foliated metasedimentary roof pendant.
b) Microphotograph of diorite/metasediment contact. Length of micrograph 13 mm. 1 nicol. Notice contact and contact foliation in diorite (right and central part of picture) at right angle to relict, tectonic foliation in metasedimentary rock (left part of picture).

existing fabrics in the metasedimentary rocks. For further petrographic details, see Lundström et al. (1997).

The Norsberget area

At Norsberget (coordinates 722410/172680), some km east of Stavaträsk hamlet, the diorite cross-cuts and causes a hornfels recrystallization of an older foliation in the metasedimentary roof pendants found close to the diorite/metasediment contact (see Fig. 6). Consequently, the pre-hornfels foliation of the metasedimentary rocks should be older than the minimum intrusive age of the Stavaträsk diorite, i.e. 1875 Ma (see Fig. 2).

The Pultarliden area

The field relationships between the trondhjemite and the Stavaträsk diorite are unknown, but at Pultarliden (coordinates 722350/171582), 4 km west of Stavaträsk, trondhjemite dykes cross-cut and most probably post-date a planar fabric within a conglomerate (Fig. 7). In order to confirm the pre-1875 Ma age of the hornfels-overprinted foliation at Norsberget, described above, the trondhjemite also was dated.

Fig. 7. Pultarliden trondhjemite, crosscutting foliated Pultarliden conglomerate. Pultarliden (coordinates 722350/171582). Cf. cover photograph.

Description of dated sample

The trondhjemite (sample no. HCA930062) is a light grey to whitish, medium-grained, even-grained rock with a hypidiomorphic-granular, weakly foliated to isotropic, somewhat recrystallized, but still recognizable, crystallization texture. It contains quartz and albitic oligoclase as main minerals, subordinate amounts of microcline and biotite, with apatite, titanite, zircon and monazite as accessory minerals. The chemical composition is presented in Table 1 (cf. analysis HCA930060 of the same rock from a different locality in Table 1 and Fig. 4 of Lundström et al. 1997).

The rock has few zircons, all of which are of poor quality, i.e. metamict and with numerous fractures and inclusions. They are colourless to light yellowish brown. Many are euhedral, with prism faces with low crystallographic indices. Both sharp and rounded terminations occur. The length/width ratio varies between 1 and 4 but also more elongate crystals are common. Many show cores or overgrowths. The cores can be of euhedral as well as rounded outline. Crystals with visible cores or overgrowths were avoided when selecting crystals for analysis. All fractions were thoroughly abraded. Two fractions with euhedral and one with rounded zircons were analysed:

Zircon 1: 3 rather large, euhedral, brownish somewhat turbid crystals;

Zircon 2: 7 small, euhedral, elongate, colourless crystals. Half of the crystals have fractures;

Zircon 3: 4 rounded crystals. One is spherical and three oval with length/width ratio 3.

The monazites are greenish yellow and vary from transparent to turbid. Some grains have crystal faces while others are anhedral. Several are fragments of larger grains.

Analytical results

The analyses were made at the Laboratory for Isotope Geology in Stockholm. The procedure is described in the Editor's Preface to this volume. The results of the isotopic analyses are shown in Table 2 and Fig. 8. Two of the zircon fractions are slightly discordant and the third almost concordant. Both monazite fractions are concordant and yield identical age. The discordia drawn in the diagram is calculated on all five points and has an upper intercept age of 1874±3 Ma and a lower intercept close to zero. Zircon fraction 3 indicates a somewhat younger age, which nevertheless is within the error limits of the upper-intercept age. The U content varies substantially between the three fractions. It is notable that despite the high U content of fractions 1 and 3, the discordance is small.

The good linear fit, the agreement between the zircon and monazite data and the

TABLE 1. Chemical analyses: Sample HCA930062 (dated sample): Trondhjemite, which cross-cuts the planar fabric of the Pultarliden conglomerate at Pultarliden. Sample FRS960031A: Tonalitic clast in Valliden conglomerate at Valliden. These two analyses were performed by Svensk Grundämnesanalys AB, Luleå, using a combination of ICP-AES and ICP-MS. Sample GI-2: Jörn granitoid of GI-type from the Jörn area (Wilson et al. 1987).

	HCA930062	FRS960031A	GI-2
N-coord.	722350	723804	722526
E-coord.	171582	170778	168606
SiO_2 (wt-%)	70.7	61.2	63.1
TiO_2	0.236	0.487	0.4
Al_2O_3	15.6	16.3	15.1
Fe_2O_3	1.97	6.75	1.2
FeO			4.8
MnO			0.11
MnO_2	0.0429	0.117	
MgO	0.74	2.79	1.18
CaO	2.35	6.22	5.3
Na_2O	4.98	3.39	2.7
K_2O	2.29	1	1.7
P_2O_5	0.0998	0.113	0.05
CO_2			1
H_2O^+			1.9
LOI	0.2	0.5	
Total	99	98.4	98.59
Ba (ppm)	883	385	315
Be	1.21	0.25	
Co	51.5	15.5	
Cr	23.4	29.4	
Cu	30.9	15.1	29
Ga	13.7	6	16
Hf	4.54	2.68	
Mo	1.92	1.05	
Nb	3.02	2.93	4.8
Ni	11.3	13.1	
Pb			9
Rb	45.1	21.5	42
Sc	2.98	17.5	
Sn	0.896	0.543	
Sr	652	399	188
Ta	0.479	0.6	
Th	2.49	3.69	4
U	1.25	1.51	5.1
V	21.5	101	
W	373	0.285	
Y	4.65	12	23
Zn	142	88.3	57
Zr	72.3	65.7	89
La	9.21	12.3	15.3
Ce	16.1	23	38.1
Pr	1.97	2.88	
Nd	7.26	12.1	14.4
Sm	1.14	1.98	3.1
Eu	0.693	0.441	0.69
Gd	1.01	1.97	3.46
Tb	0.197	0.391	
Dy	0.82	2.19	3.61
Ho	0.196	0.489	
Er	0.451	1.5	2.2
Tm	0.109	0.197	
Yb	0.567	1.68	2.52
Lu	0.232	0.213	0.41
Lab.	SGAB97388-9	SGAB97580-1	

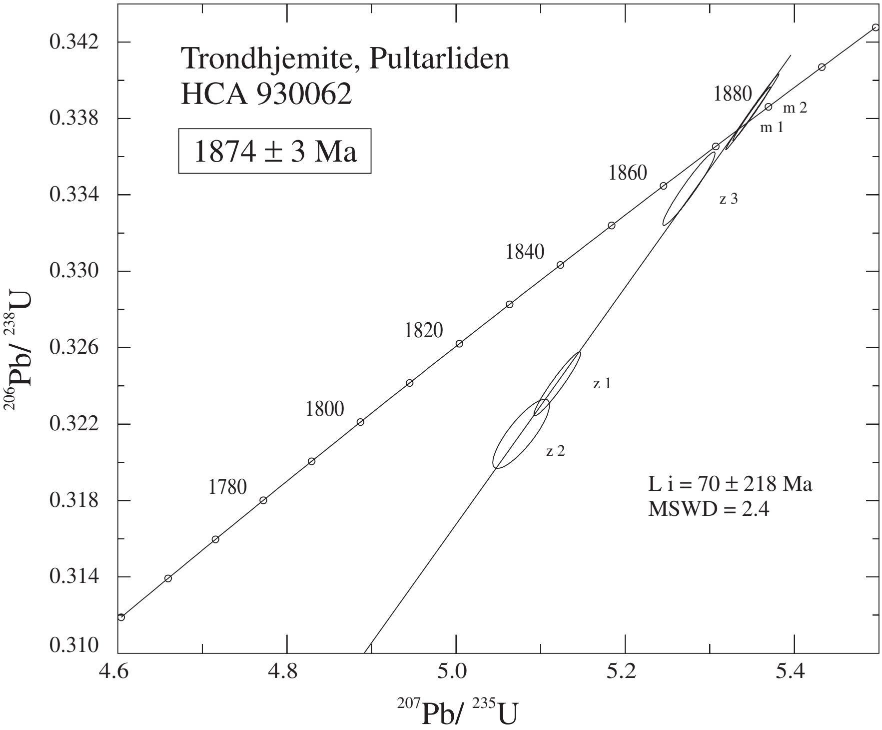


Fig. 8. Concordia plot for the Pultarliden zircons and monazites.

small or zero discordance all favour an interpretation of the upper intercept age as the crystallization age of the tonalitic trondhjemite.

It therefore seems that a penetrative foliation was imprinted on the host rocks of the Stavaträsk diorite and Pultarliden trondhjemite more than 1871 Ma ago.

DISCUSSION

The observations described above indicate ductile deformation along discrete shear zones, thorough, static recrystallization and intrusion of fine-grained, probably shallow dykes in and erosion of the Jörn GI granitoid before 1.86–1.87 Ga ago. Temporally (see Fig. 2), these processes could coincide with the pre-Stavaträsk–Pultarliden deformations described above, which, however, imprinted a much more penetrative fabric at a higher metamorphic grade than is found in the Jörn granitoids. This could indicate that the Jörn GI was deformed at shallower, cooler levels than the Stavaträsk–Pultarliden host rocks. The fine-grained, probably shallowly emplaced, subvolcanic dykes in the GI as well as the conglomerate clasts of this granitoid also

TABLE 2. U-Pb isotopic data for the Pultarliden trondhjemite (HCA930062).

Mineral and analysis No.	No. of crystals	Weight (µg)	U (ppm)	Pb. tot. (ppm)	Common Pb (ppm)	$\frac{^{206}Pb^{a}}{^{204}Pb}$	^{206}Pb-^{207}Pb-^{208}Pb Radiog. (atom%)[b]	$\frac{^{206}Pb^{b}}{^{238}U}$	$\frac{^{207}Pb^{b}}{^{235}U}$	$^{207}Pb/^{206}Pb$ age (Ma)
Zircon 1	3	4	1192	398	1.17	5539	83.8 - 9.6 - 6.6	0.3241±14	5.120±23	1873±2
Zircon 2	7	4	413	135	0.49	2168	84.7 - 9.7 - 5.6	0.3215±18	5.077±27	1873±5
Zircon 3	4	2	1918	647	0.24	7211	85.3 - 9.7 - 5.0	0.3343±16	5.275±25	1871±2
Monazite 1	3	37	3151	3126	0.55	70193	29.5 - 3.4 - 67.1	0.3383±12	5.349±18	1875±1
Monazite 2	10	38	2550	3014	0.83	43911	24.8 - 2.8 - 72.4	0.3384±16	5.350±26	1875±1

a) corrected for mass fractionation (0.1% per a.m.u).
b) corrected for mass fractionation, blank and common Pb.

Fig. 9. Granite clast in the Pultarliden conglomerate. (Coordinates 722434/171434.)

indicate that the Jörn GI in this area had reached a shallow crustal level at about 1.87 Ga, cf. Billström & Weihed (1996).

The events affecting the Jörn GI granitoid must have occurred after 1908 Ma, which is the upper age limit of the GI (see Fig. 2). The Brännbergsliden gneiss (Lundström & Persson 1998, this volume) was deformed more recently than 1879 Ma ago and is situated quite adjacent to the ductile shear zone described above (see map Fig. 1). It is therefore tempting to believe that this is the maximum age also for the deformation of the GI. The gneiss, however, is both structurally and metamorphically so different from the rocks immediately surrounding it, that it is doubtful what relevance the age of its deformation may have for its present surroundings.

A maximum age for the deformation of the Stavaträsk–Pultarliden host rocks cannot be estimated at present, but could be easily obtained if the clasts in the conglomerate were dated. A granitoid clast (Fig. 9) found in the Pultarliden conglomerate was sampled for age determination and will hopefully shed some light on this problem.

CONCLUSIONS

Numerous observations indicate that deformation was active in the Stavaträsk–Klintån area before 1860–1875 Ma, thereby indicating an earlier start of deformation than hitherto recognised. The Sikträsk gneiss dome, described by Weihed & Vaasjoki (1993) and Billström & Weihed (1996) to be deformed after 1862 Ma, is situated well on the southern margin of the Skellefte District, c. 50 km southwest of the area considered here. The dome and the Stavaträsk–Klintån area are therefore remote enough from each other to warrant separate structural histories. However, the time separation between the 'post-Sikträsk' and 'pre-Stavaträsk' deformations (see Fig. 2), support the multistage deformational history in the intervening area, demonstrated by Weihed et al. (1992), albeit with an earlier start than conceived by them.

The deformation suggested to predate the intrusion of the Stavaträsk plutonic rocks, would fit well temporally with the numerous events, described above, that occurred between the emplacement of the Jörn GI and GIII granitoids. However, regardless of this possible correlation in time, these intervening events show that the GI and GIII granitoids intruded independently of each other. As suggested by Billström & Weihed (1996), they should therefore most probably be understood as unrelated intrusive rocks, despite their close geographic connection.

Kautsky (1959) observed that both the Valliden conglomerate ("das konglomerat bei Snipp und Snapp" of Kautsky) and the conglomerates at Åselet contained granitoid clasts. Based on this evidence, Kautsky (1959) suggested that the metasedimentary rocks north of Stavaträsk should belong to the "Elvaberg Series" (Kautsky 1957) and thus be younger than the metavolcanic rocks. This is also the impression gained by many younging observations further south (see Fig. 1b). The granitoid conglomerate clasts also prompted Lindström et al. (1991) to propose that the metasedimentary rocks around Åselet belonged to the "upper Svecofennian". However, the Åselet conglomerate is situated along strike from and very similar to the Pultarliden conglomerate. As mentioned above, this conglomerate seems to have been deformed before c. 1871 Ma, i.e. possibly even before the deposition of the Valliden conglomerate. The Åselet–Pultarliden conglomerates are furthermore much more deformed and more metamorphosed than the Valliden conglomerate (cf. Figs. 5a, c with Figs. 7 and 9) and do not contain any recognizable Jörn GI granitoid clasts, typical of the Valliden conglomerate. They may thus even predate the Jörn GI granitoid. The stratigraphic position of the Stavaträsk metasedimentary rocks therefore remains enigmatic. However, shear zones abound along the metasediment/Arvidsjaur metavolcanite contact, and therefore a tectonic instead of a depositional contact is plausible.

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U-Pb zircon ages of Archaean to Palaeoproterozoic granitoids in the Torneträsk–Råstojaure area, northern Sweden

By

Olof Martinsson, Matti Vaasjoki and Per-Olof Persson

INTRODUCTION

The eastern and northern parts of the Baltic Shield include large areas of Archaean rocks with ages between 2.65 and 3.2 Ga (e.g. Skiöld 1979a, Jahn et al. 1984, Luukkonen 1992, Lobach-Zhuchenko et al. 1993, Kärki et al. 1995). These are dominated by tonalite–granodiorite, while mafic to felsic volcanic rocks, metasedimentary rocks and undeformed red granites are minor constituents (Ward & Nurmi 1989, Luukkonen 1992, Lobach-Zhuchenko et al. 1993).

The most extensive area of Archaean rocks in Sweden lies north of Kiruna, whereas only small isolated areas have been found further to the south in Norrbotten. Archaean granitoids give ages from 2.64 to 2.71 Ga in the Luleå area (Lundqvist et al. 1996, Wikström et al. 1996), 2.67 Ga at Kukkola (Öhlander et al. 1987) and 2.71–2.83 Ga in the Kiruna area (Welin et al. 1971, Skiöld 1979a, Skiöld & Page 1998). The deformed and metamorphosed Archaean rocks are unconformably overlain by Palaeoproterozoic volcanic and sedimentary successions.

The Archaean basement and the Palaeoproterozoic volcanic and sedimentary cover have been intruded by four major groups of igneous rocks. The ages of early orogenic intrusions vary from 1.87 to 1.89 Ga (Skiöld et al. 1988). These intrusions have been subdivided into two types. The Haparanda Suite, ranging from gabbro to granite but dominated by diorite–granodiorite, was originally assigned to intrusions in southeastern Norrbotten (Ödman et al. 1949). Later it was extended to comprise petrographically similar intrusions in northern Norrbotten (Ödman 1957), and in northern Finland (Hiltunen 1982). The Perthite Suite, comprising monzogabbro, monzonite, syenite and granite, is restricted mainly to the northwestern and northern parts of Norrbotten (Geijer 1931, Witschard 1984). Intrusions of the Perthite Suite are generally undeformed and have therefore been considered somewhat younger than the Haparanda Suite, which is dominated by more or less deformed rocks. Characteristic of the Perthite Suite is the occurrence of phenocrysts of perthite–antiperthite, or plagioclase rimmed by perthite (Geijer 1931). Quartz-rich granites, pegmatites and aplites of the Lina Suite are extensively developed in northern Norrbotten. The granites are typically porphyritic with 4 to 15 mm large microcline phenocrysts, and they may exhibit a weak to rather strong foliation (Holmqvist 1906, Geijer 1931). Age determinations demonstrate an emplacement at 1.78 to 1.79 Ga for the Lina Suite (Skiöld et al. 1988, Wikström & Persson 1997a), which is similar to reported ages for syenitic to granitic intrusions, similar in character to the Transscandinavian Igneous Belt (TIB) at Kiruna and in the Narvik area (Romer et al. 1992, 1994).

GEOLOGY OF THE TORNETRÄSK–RÅSTOJAURE AREA

Late Archaean, and early Palaeoproterozoic, rock units are partly well exposed in the Torneträsk–Råstojaure area north of Kiruna. The Archaean rocks are mainly found in the northern part. Towards the south, they give way to Palaeoproterozoic cover successions and several suites of Svecofennian intrusions (Fig. 1). This basement area north of Kiruna has not been described in detail, but is known to consist of mainly tonalitic to granodioritic rocks (Ödman 1957, Öhlander et al. 1987, Kathol & Martinsson in press). Red, undeformed granites are less abundant (Ödman 1957, Offerberg 1967), but form characteristic clasts in the discordantly overlying basal conglomerate north of Kiruna (Geijer 1931, Martinsson 1997). Strongly recrystallized mafic to felsic volcanic rocks, quartzite, and gneiss of arkosic to pelitic origin are generally of minor importance (Kathol & Martinsson in press). Similar associations of plutonic, volcanic and sedimentary rocks are found further north in northwestern Finland (Lehtovaara 1995).

Chemically, the Archaean tonalites clearly differ from the Archaean granodiorites and granites in the Kiruna–Torneträsk–Råstojaure area (Fig. 2), which suggests differing magmatic origins for these rocks. Compared with the tonalites, the granodiorites are generally less deformed and may have a porphyritic texture (Kathol & Martinsson in press). The granitoids are locally strongly infiltrated by granitic material (Ödman 1957), and especially along shear zones the formation of secondary microcline may be extensive.

The Palaeoproterozoic cover, comprising the Kovo Group, the Kiruna Greenstone Group, the Kurravaara Conglomerate, the Kiruna Porphyries, and the Hauki Quartzite (Fig. 3), is preserved in several synclinal belts in the southern part of the Torneträsk–Råstojaure area. The Kovo Group include a basal clastic unit of conglomerate and quartzite, which is overlain by andesite, volcanogenic greywacke and tholeiitic basalt (Martinsson 1997). Mafic sills, intruding the lower part of the sequence, have a zircon age of c. 2200 Ma (Skiöld 1986), giving a minimum depositional age for this group. Tholeiitic basaltic lava, with intercalation of komatiites, mafic to felsic volcaniclastic rocks, black schist and carbonate rocks, constitutes the Kiruna Greenstone Group. Dyke swarms with a mainly tholeiitic composition intruding the Archaean basement in a NNE direction are probably related to the greenstone volcanism (Martinsson 1997).

Early orogenic intrusions of the Haparanda Suite are of minor importance in the Torneträsk–Råstojaure area. They are represented by gabbro, diorite and minor felsic intrusions. Generally these intrusions are to some extent affected by ductile deformation, resulting in a more or less pronounced mineral orientation. The Perthite Suite form large intrusions in the southwestern part of the area. Monzonite is a major component (Fig. 4), occurring together with varying amounts of gabbro, monzogabbro, monzodiorite, quartz monzonite and Perthite granite, partly in the form of zoned composite intrusions. Perthitic feldspar is a characteristic mineral in the intermediate and felsic intrusions, usually occurring as 1–2 cm large phenocrysts. Gradual contacts and hybrid rocks are commonly found between gabbro and monzonite, indicating coexist-

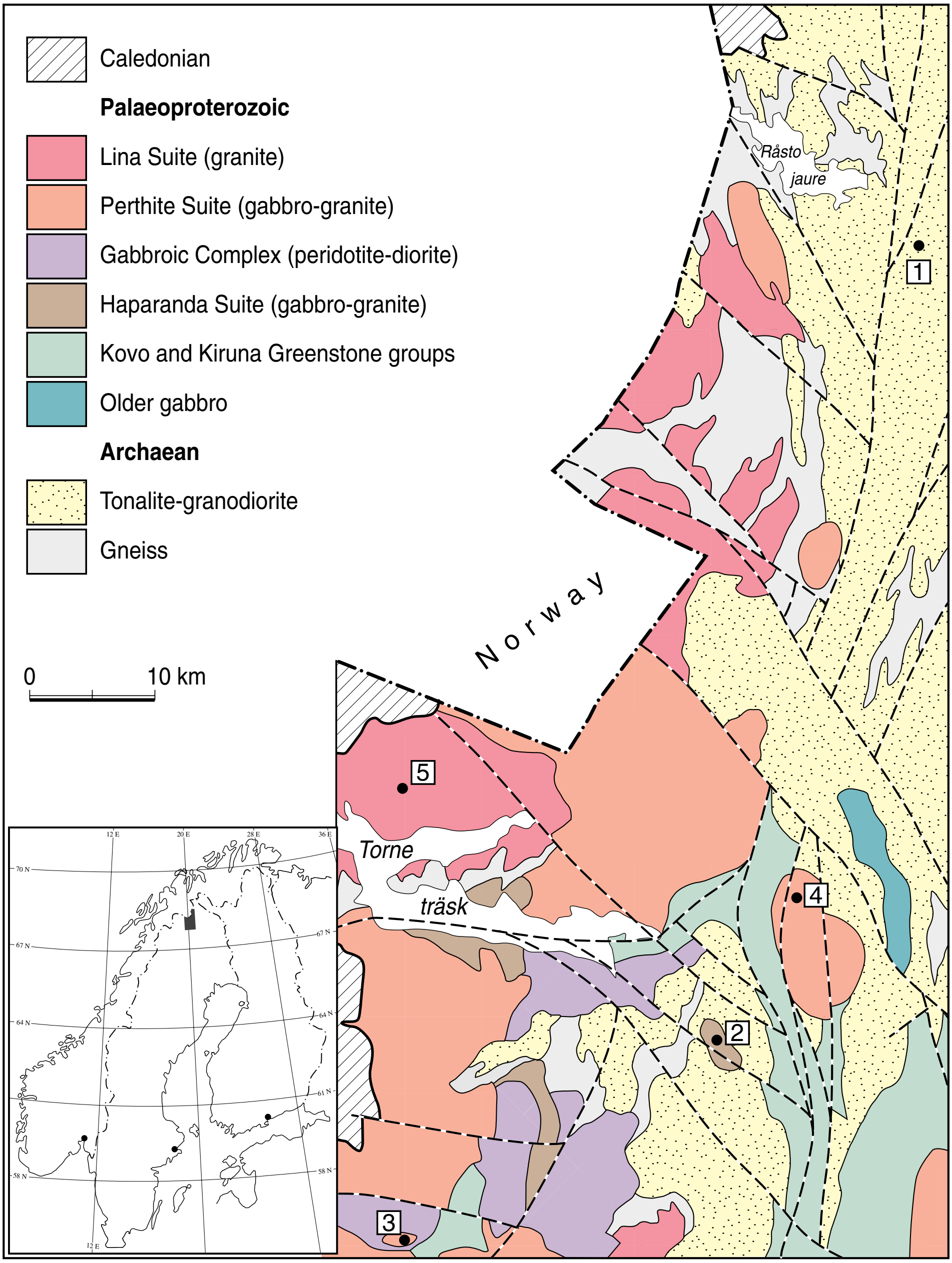

Fig. 1. Simplified geological map of the Torneträsk–Råstojaure area, map sheets 30J and 31J, with location of analysed samples: 1, tonalite at Råstojaure (BOM950401); 2, granite at Lulep Patsajäkel (BOM940243); 3, monzonite at Runkanjunnje (BOM940635); 4, granite at Rakisvare (BOM940362); 5, granite at Ripasjaure (BOM940758).

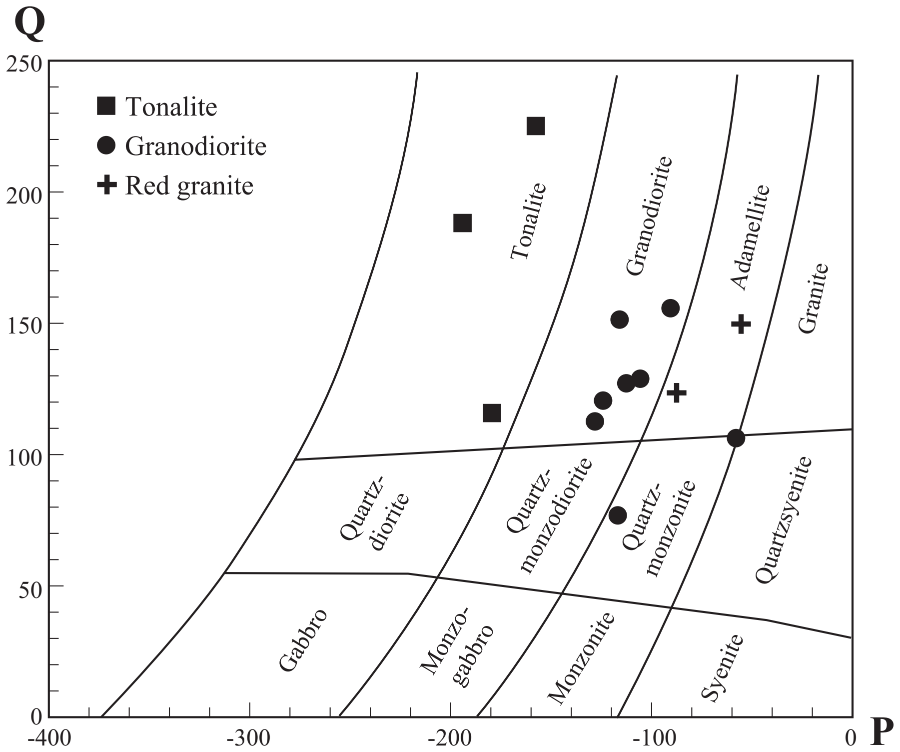

Fig. 2. Chemical classification of Archaean granitoids from the Torneträsk–Råstojaure area. P–Q diagram in molar proportions (Debon & LeFort 1983), unpublished data from SGU.

ing magmas. Minor dykes of aplite and fine-grained quartz monzonite occur locally in monzonite and gabbro. Intrusions of the Perthite Suite are generally undeformed, although magmatic foliation may occur at the contacts. However, south of Torneträsk they are affected by a strong ductile deformation along a E–W-trending shear zone.

Several gabbroic complexes occur in the southwestern part of the area in close association to monzonite of the Perthite Suite (Fig. 1). They are mafic to ultramafic in composition and exhibit in part a well developed igneous layering. Parallel-oriented plagioclase, pyroxene and olivine are the major minerals in the mafic parts. Peridotite occurs as layered units in the lower parts and as late intrusions. Diorite is an important component in the upper part of some complexes. Due to the well-preserved character of the complexes, and the spatial association with monzonite, they are suggested to belong to the Perthite Suite (Kathol & Martinsson in press).

Reddish and quartz-rich granites of Lina-type are found north of Torneträsk and along the Norwegian border towards Råstojaure. They are generally undeformed but, especially south of Råstojaure, foliated granites exist. At Torneträsk the granite is medium- to coarse-grained and the texture is partly porphyritic with c. 10 mm large mi-

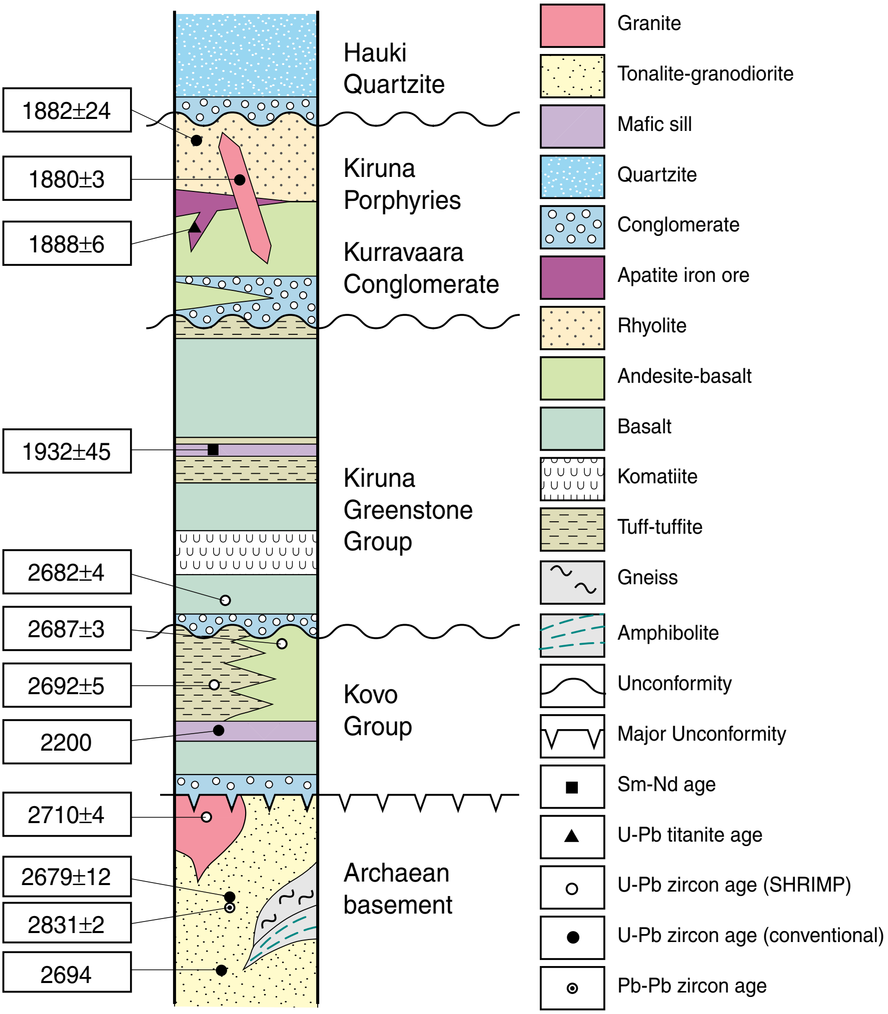

Fig. 3. Stratigraphy and geochronology of the Kiruna area, modified from Martinsson (1997). Chronological data from Skiöld (1979a, 1986), Skiöld & Cliff (1984), Welin (1987), Cliff et al. (1990), Romer et al. (1994), Skiöld & Page (1998) and this study.

crocline phenocrysts. Xenoliths of andesite and diorite are locally abundant (Kathol & Martinsson in press). Further northwards, intrusions of medium-grained granite are surrounded by migmatitic Archaean gneiss of arkosic to pelitic origin. Dykes of aplite and pegmatite occur within the granites, but they are most extensively developed in the surrounding rocks.

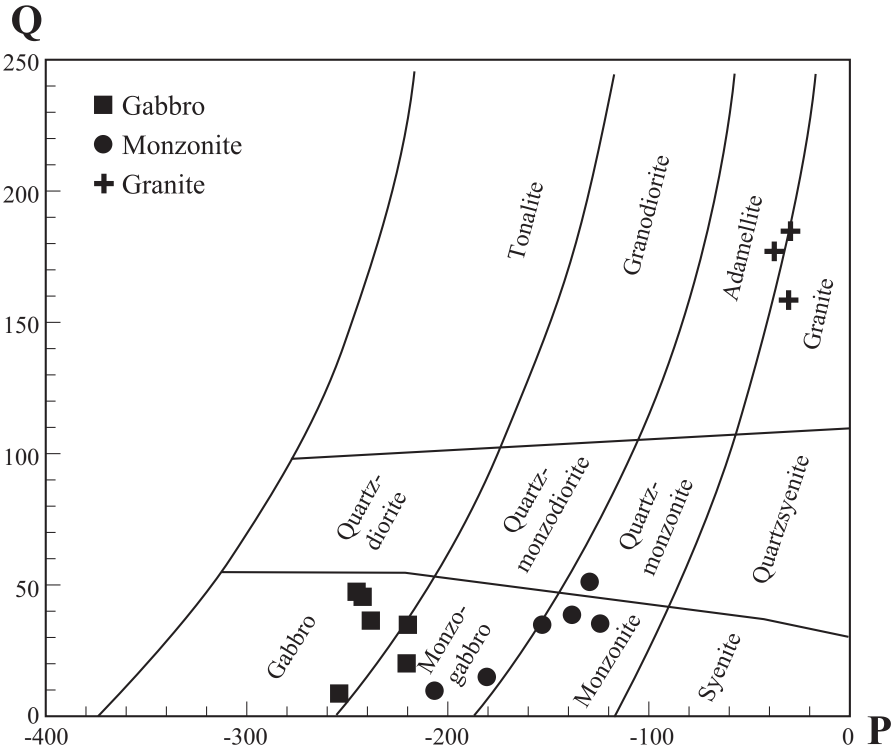

Fig. 4. Chemical classification of Perthite Suite intrusions from the Torneträsk–Råstojaure area. P–Q diagram in molar proportions (Debon & LeFort 1983), unpublished data from SGU.

SAMPLE DESCRIPTION AND RESULTS

Five samples of granitoid rocks were taken in the Torneträsk–Råstojaure area (Fig. 1). Two of them, a deformed tonalite (BOM950401) and an undeformed reddish granite (BOM940243), are from the Archaean domain. The Perthite Suite is represented by a granite (BOM940362) and a monzonite (BOM940635). The latter intrudes the Runkanjunnje gabbro complex, and was selected to give the minimum age of this intrusion as well as the age of the monzonite. The fifth sample is from a Lina-type granite (BOM940758).

All samples, except the tonalite, were analysed at the Unit for Isotope Geology, Geological Survey of Finland. Based on the specific gravity of the separated zircons, they have been split into three density fractions for each sample. One additional fraction consists of abraded zircons from the heaviest fraction in three of the samples. The tonalite sample was analysed at the Laboratory for Isotope Geology, Swedish Museum of Natural History in Stockholm. In this sample, the splitting into fractions of the separated zircons was based on morphology and quality of the crystals. See the Editor's Preface to this volume for information about the analytical procedure. Analytical data are given in Tables 1 and 2.

TABLE 1. U-Pb zircon data from the Råstojaure tonalite.

Sample	Weight (μm)	U (ppm)	Pb tot. (ppm)	Common Pb (ppm)	206/204[a]	206-207-208 Radiog. (atom%)[b]	206/238[b]	207/235[b]	207/206 age (Ma)
1	44	120.4	71.6	0.07	11316	70.4 - 12.8 - 16.8	0.4855±17	12.214±46	2675±3
2	51	121.5	71.7	0.13	10941	70.7 - 12.9 - 16.4	0.4830±13	12.182±34	2680±2
3	33	130.3	76.7	0.31	6153	70.3 - 12.8 - 16.9	0.4791±14	12.056±40	2676±2
4	23	130.4	74.2	0.27	5431	72.9 - 14.6 - 12.5	0.4804±20	13.288±56	2831±2

a) corrected for mass fractionation (0.1 % per a.m.u).
b) corrected for mass fractionation, blank and common Pb.

TABLE 2. U-Pb zircon data from the Torneträsk-Råstojaure area.

	Fraction	U ppm	Pb ppm	206/204 meas.	206-207-208 Radiog. (atom %)[a]	206/238[a]	207/235[a]	207/206 age (Ma)
BOM940243-Lulep Patsajäkel								
A	+4.5 abr	163.3	56.61	1128	75.12 - 8.56 - 16.32	0.2905±17	4.541±26	1854±2
B	+4.5	215.6	67.13	641	75.48 - 8.53 - 15.99	0.2533±15	3.929±23	1840±3
C	4.3-4.5	505.1	111.30	337	77.42 - 8.31 - 14.27	0.1709±10	2.518±15	1746±5
D	4.2-4.3	1336.4	201.84	117.5	78.25 - 7.26 - 14.49	0.0905±5	1.152±7	1474±16
BOM940635-Runkanjunnje								
A	+4.5 abr	341.3	100.92	1970	77.49 - 8.61 - 13.90	0.2601±15	3.967±23	1809±1
B	+4.5	344.7	104.63	1479	77.50 - 8.59 - 13.91	0.2646±15	4.026±24	1805±2
C	4.3-4.5	707.8	163.27	1069	77.92 - 7.88 - 14.20	0.1804±11	2.502±15	1634±8
D	4.2-4.3	1667.6	294.22	351	74.67 - 7.12 - 18.21	0.1333±8	1.744±10	1525±8
BOM940362-Rakisvare								
A	+4.5 abr	108.4	36.10	2140	68.81 - 7.75 - 23.44	0.2617±15	4.046±23	1834±2
B	+4.5	159.5	44.48	1569	70.58 - 7.85 - 21.57	0.2228±13	3.399±20	1810±2
C	4.3-4.5	497.1	84.91	1362	72.64 - 7.54 - 19.82	0.1395±8	1.986±12	1683±2
D	4.2-4.3	1030.3	117.47	1121	73.46 - 6.89 - 19.65	0.0934±5	1.202±7	1495±3
BOM940758-Ripasjaure								
A	4.3-4.5 abr	863.4	147.60	478.3	78.73 - 7.81 - 13.46	0.1407±8	1.916±11	1600±7
B	4.3-4.5	972.4	155.92	476.5	79.65 - 7.81 - 12.54	0.1332±8	1.792±11	1577±1
C	4.2-4.3	1284.4	139.70	414.2	79.73 - 7.35 - 12.92	0.0890±5	1.126±7	1463±3
D	red	902.2	159.31	270.6	79.38 - 7.70 - 12.91	0.1353±8	1.801±12	1558±8

a) Correction for mass fractionation, blank and common Pb, common Pb: ^{206}Pb/^{204}Pb: 15.7; ^{207}Pb/^{204}Pb: 15.4; ^{208}Pb/^{204}Pb: 35.2.

Råstojaure tonalite (sample BOM950401)

Tonalite is a major component of the Archaean bedrock in the northeastern part of the Torneträsk–Råstojaure area. Minor belts of paragneiss and amphibolite, representing older crust, occur in the tonalite and amphibolite xenoliths are locally abundant. Small xenoliths are generally strongly absorbed and appear as clots of biotite. Secondary microcline may occur in veinlets, as replacement of plagioclase or porphyroblasts, and in irregular patches with diffuse outlines. Extensive microcline infiltration may end up in a strongly recrystallized granitic product. Sample BOM950401 is from a small outcrop 7 km southwest of Råstojaure at the eastern side of Njárgajárvi (topographic map sheet 31J NO, coordinates in the National Grid 7631020/1697840). The tonalite is grey, medium grained and exhibits a well-developed foliation. It contains 25–30 % bluish quartz and 5–10 % biotite. Minor xenoliths of amphibolite exist in the outcrop, but secondary microcline is almost non-existing.

Most of the separated zircon crystals are euhedral, but their edges are generally more or less rounded. High-index faces occur occasionally. Several crystals have also rugged or corroded faces. The length–breadth ratio of the crystals varies from 1 to 4. Most of the zircons are metamict and turbid, and are pale yellow to pink or colourless. Cores were found in approx. 10 % of strongly rounded zircons, while euhedral crystals rarely contained any detectable older material. The cores are generally small, metamict and located close to the margins of the grains. In one grain however, the core constituted approx. 90 % of the total grain volume.

Four fractions of zircons without detectable cores or overgrowths have been handpicked. All fractions were strongly abraded before analysis.

1) Sixteen euhedral to slightly rounded crystals of good quality. They are transparent and have a pink colour. Small high-index faces occur in some crystals. Fractures are rare.

2) Fifteen euhedral to slightly rounded crystals. Similar to fraction 1, but of slightly poorer quality with more abundant fractures in outer parts.

3) Fourteen euhedral to slightly rounded crystals. Similar to fractions 1 and 2, but of poorer quality.

4) Ten strongly rounded crystals with some fractures. They are colourless, or pink to pale yellow.

The three euhedral zircon fractions give an upper intercept age of 2679±12 Ma (Fig. 5), with a MSWD of 11. This rather high MSWD value may indicate the existence of optically undetectable heterogeneities in the crystals. The rounded zircons are significantly different. Their ^{207}Pb/^{206}Pb age is 2.83 Ga, which represents a minimum age. They contain a smaller portion of ^{208}Pb, indicating a higher U/Th-ratio in the rounded zircons when compared with the euhedral crystals, suggesting crystalliza-

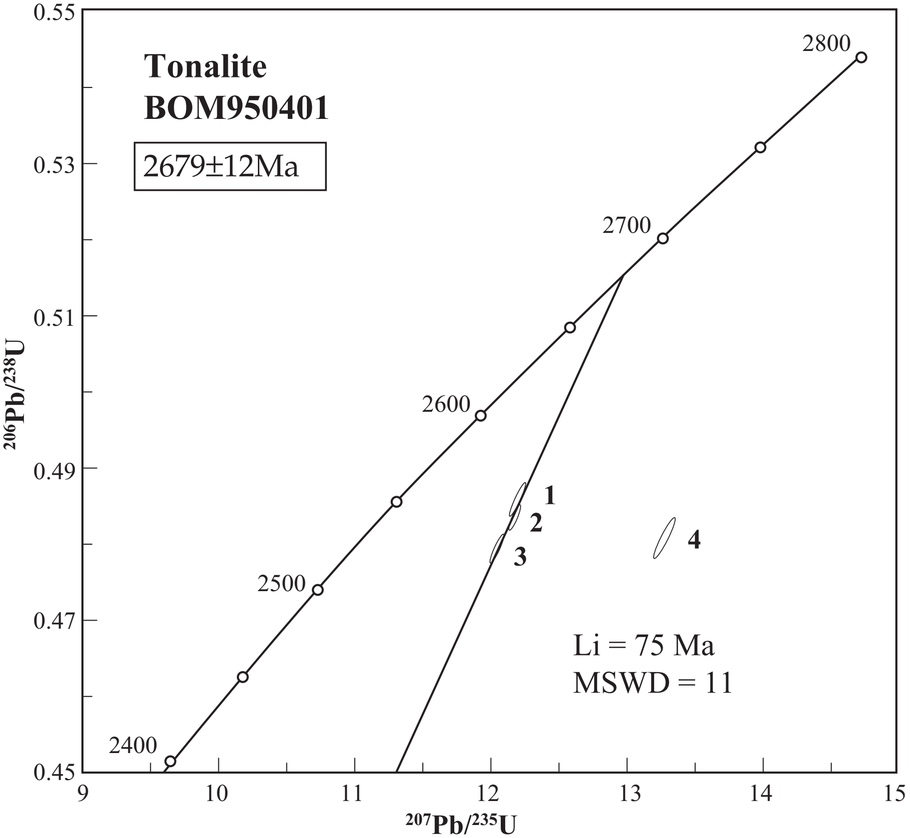

Fig. 5. U-Pb concordia diagram for zircons in sample BOM 950401, a deformed grey tonalite from Råstojaure.

tion in magmas of different composition for these two zircon populations. It is also possible that the rounded zircons represent a mixed population, although no cores were visible in alcohol.

Granite at Lulep Patsajäkel (sample BOM940243)

The sample BOM940243 is from an outcrop on the southeastern side of Lulep Patsajäkel (topographic map sheet 30J SO, coordinates in the National Grid 7567640/ 1681640). The granite forms a 4 x 2 km large intrusion in Archaean granitoids and gneiss. The contacts of the granite are not exposed, but aplite and pegmatite dykes are found locally in the surrounding rocks. Several metadiabases with chilled margins intrude the granite along a northwest-trending fault. The granite is pale red, undeformed and medium-grained. It contains 25–30 % quartz, 5 % biotite and accessory titanite.

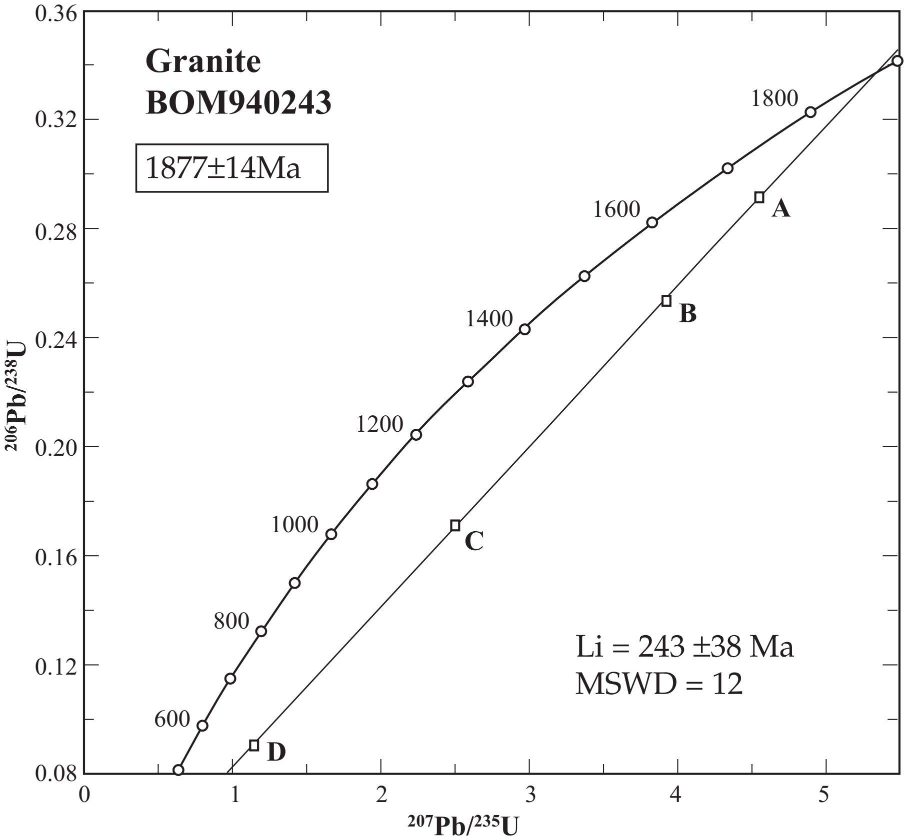

Fig. 6. U-Pb concordia diagram for zircons in sample BOM 940243, an undeformed red granite from Lulep Patsajäkel.

The texture is partly porphyritic, with 4–8 mm large phenocrysts of microcline. Petrologically, the granite at Lulep Patsajäkel is similar to red granites, occurring as pebbles at the base of the Kovo Group, and it was selected as a possible late Archaean granite.

Based on colour and morphology, two zircon populations are distinguished. About 90 % of the material consists of translucent pale-brown or brown subhedral crystals with a length/breadth ratio of 1.2 to 2.5. The remaining 10 % are reddish, translucent, and subhedral to anhedral crystals. Under oil immersion it appears that about 20 % of the crystals in the heavy (+4.5) fraction are turbid and anhedral, while the rest are either fragments of, or complete euhedral, transparent crystals. The number of turbid crystals increases in the lighter zircon fractions. No zoning or inclusions were detected in the transparent population. During hand-picking, the red crystals were removed and analyses were made on the brown zircons only.

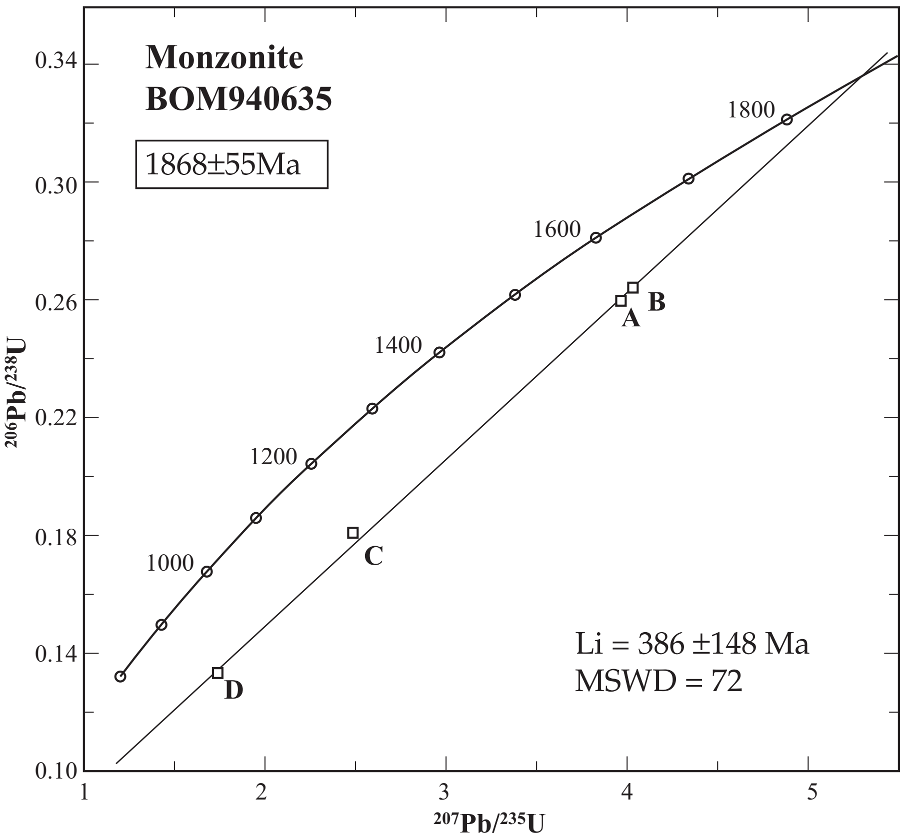

Fig. 7. U-Pb concordia diagram for zircons in sample BOM 940635, an undeformed brownish monzonite intruding the Runkanjunnje gabbroic complex.

The degree of discordancy and the uranium content increase with decreasing density of the zircons, which is the normal pattern for igneous rocks. However, the variation in both uranium and common lead contents is unusually large. The four analysed fractions give an upper intercept age of 1877±14 Ma and a lower intercept age of 243±38 Ma, with a MSWD of 12 (Fig. 6). As the abraded fraction (A) exhibits only 76 % of the uranium observed in the corresponding unabraded fraction (B) and has a $^{206}Pb/^{204}Pb$ ratio almost twice as high, it may be argued that much of the uranium and the common lead resides in the turbid and probably softer crystals.

Monzonite at Runkanjunnje (sample BOM940635)

At Runkanjunnje there is a 10 x 5 km large gabbroic complex with a well-developed layered structure in its middle part. It is surrounded by monzonite, which also forms intrusions in the complex. The sample BOM940635 is from a 3 x 1 km large monzonite intrusion in the southeastern part of the Runkanjunnje complex (topographic map sheet 30J SV, coordinates in the National Grid 7551460/1655920). It is undeformed and has a reddish to brownish grey colour. The texture is porphyritic with 6–10 mm large phenocrysts of perthite occurring in a medium-grained matrix of feldspar, 10–15 % amphibole and approx. 5 % biotite. Petrologically it is similar to the much larger monzonite intrusions of the Perthite Suite occurring in the southeastern part of the Råstojaure–Torneträsk area.

More than 60 % of the separated zircons do not pass the 70 μm sieve. The colour varies from translucent clear, to brown. Hardly any pyramidal faces are developed and crystal forms range from subhedral (prismatic faces) to anhedral. Faint zoning occurs occasionally, and no obvious cores were detected. The most heavy zircon fraction (A), seems to be rather homogeneous as air abrasion has practically no effect on either uranium or lead concentrations or isotopic ratios. All fractions are highly discordant and there may be some source heterogeneity, as the MSWD is very high at 72. Consequently, the upper intercept is rather imprecise and the age based on four fractions is 1868±55 Ma (Fig. 7).

Perthite granite at Rakisvare (sample BOM940362)

The granite at Rakisvare constitutes the dominant part of a 12 x 7 km large composite Perthite Suite intrusion. The southern and eastern parts consist of quartz monzonite, while perthite granite occupies the central and northern parts. A fine-grained and porphyritic rim is developed at the northwestern side of the intrusion and a gabbroic dyke runs along the wallrock contact in this area. The sample BOM940362 is from an outcrop on the west slope of Rakisvare (topographic map sheet 30J NO, coordinates in the National Grid 7579440/1687260). The granite is red, medium- to coarse-grained, and undeformed. The texture is porphyritic, with 6–10 mm large phenocrysts of perthite. It contains 25–30 % quartz, 1–5 % biotite, and accessory amounts of titanite and fluorite.

Separated zircons are generally less than 70 μm in size. Morphologically, they are characterized by short prismatic surfaces. More than 90 % are clear and translucent, the rest being yellowish-reddish in colour. No inherited cores were detected under oil immersion, but oscillatory zoning may be seen. The analyses show a distribution typical of magmatic rocks: the uranium contents and the discordance increase as density decreases. However, even the abraded fraction is distinctly discordant. Four zircon fractions give an age of 1874±12 Ma, with a MSWD of 9.7. The corresponding lower intercept age is 241±15 Ma (Fig. 8).

Granite at Ripasjaure (sample BOM940758)

A large area of Lina-type granite exists north of Torneträsk. The approx. 20 x 13 km large granite intrusion is bordered towards the south by a 2 to 4 km wide zone intensely injected by pegmatite and aplite dykes. Xenoliths of andesite and diorite up to 3 km

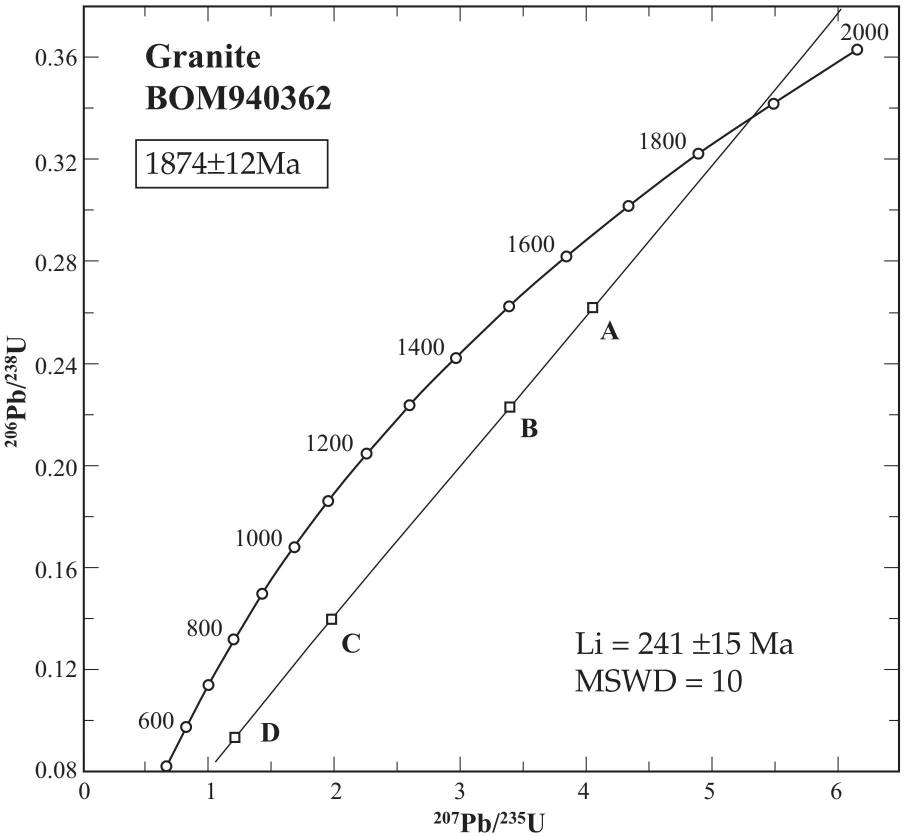

Fig. 8. U-Pb concordia diagram for zircons in sample BOM 940362, an undeformed red Perthite granite from Rakisvare.

in size are locally abundant in the granite. Minor pegmatite and aplite dykes are common late phases. Porphyrite dykes locally cut the granite in a northwesterly direction. The sample BOM940758 is from an outcrop southwest of Ripasjaure (topographic map sheet 30J NV, coordinates in the National Grid 7588460/1656010), close to the Caledonian front. The granite is pale red, medium grained and undeformed. The texture is heterogranular or porphyritic with 5–8 mm large microcline phenocrysts. It contains 25–30 % quartz, and approx. 5 % biotite.

Most separated zircons are small (90 % < 70 µm), and exhibit simple prismatic and pyramidal crystal forms. The length/breadth ratio ranges from 1.5 to 3. Two colour varieties are distinguished: a dominating (approx. 80 %) pale brown population and subordinate reddish crystals. Both types vary from translucent to turbid. Under oil immersion, a pronounced oscillatory zoning is observed. No significant inclusions or older cores exist. Sample A represents an air abraded portion of the heavi-

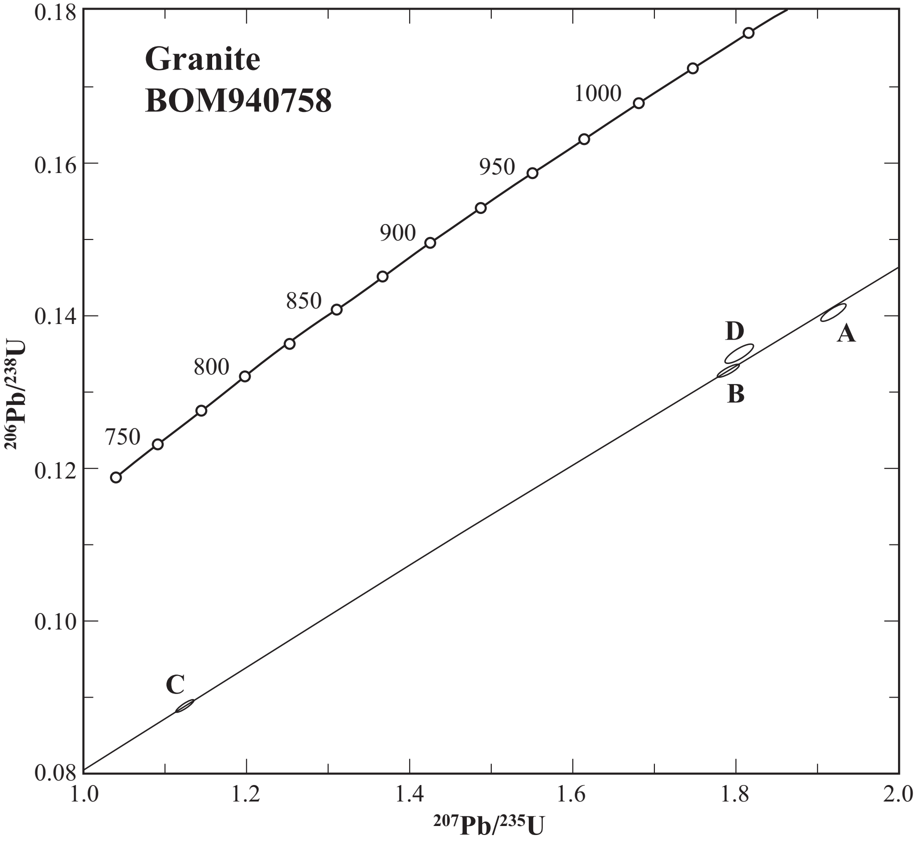

Fig. 9. U-Pb concordia diagram for zircons in sample BOM 940758, an undeformed red granite from Ripasjaure.

est fraction (4.3–4.5 g/cm^3), while samples B and C are unabraded. The reddish crystals were hand-picked, apart from these three zircon populations, combined and analysed separately as sample D.

All samples have a rather high uranium and common lead content. They are also extremely discordant (Fig. 9), and consequently the calculated intercept ages, 1696±65 and 164±55 Ma, are not well constrained and should not be used as geochronologic data. Excluding the red zircons from the calculation does not significantly affect the result. It may be argued that the highly discordant pattern is the result of a three-stage lead loss history: 1) lead loss by continuous diffusion from the initial emplacement to the Caledonian event, 2) episodic lead loss during the Caledonian, and 3) continuous loss by diffusion from the Caledonian to the present time.

DISCUSSION

The analysed sample of Råstojaure tonalite is dominated by euhedral zircon crystals with no detected cores, but there are also corroded euhedral crystals and rounded zircon grains. Based on three fractions, the euhedral crystals give an upper intercept age of 2679±12 Ma. Although the calculated error is rather low, the 2679 Ma age might be less precise due to the close spacing of the data points, in combination with their discordant character and the large MSWD (Fig. 5). The $^{207}Pb/^{206}Pb$ age for one fraction of rounded zircon grains is approx. 2.83 Ga. At least two alternative interpretations have to be considered: 1) the younger age represents the magmatic emplacement of the tonalite, while the older age is given by inherited zircons from the melt source, and 2) the older age is the emplacement of the tonalite and the younger age represents a later metamorphic overprint.

The euhedral zircon crystals giving the age of c. 2.68 Ga lack detectable cores, and have a length–breadth ratio between 1 and 4. The morphology of these zircons and their higher ^{208}Pb-content suggest them to be of magmatic origin, and consequently this age should represent the emplacement of the tonalite. Zircon crystals giving the $^{207}Pb/^{206}Pb$ age of c. 2.83 Ga are distinctly different in character and their markedly rounded shape suggests a xenocrystic origin.

However, this interpretation may be in conflict with existing geological and geochronological data from Archaean rocks in northern Sweden. The deformation of the Archaean granitoids north of Kiruna is generally strongest in the tonalites, while granodiorites are less affected and the red granites are almost undeformed. These red granites are a major constituent of the basal conglomerate in the unconformally overlying Kovo Group north of Kiruna. If the late Archaean deformation event was of regional importance in northern Sweden, the existence of undeformed red granites with an age of 2710±4 Ma in the Kiruna area (Skiöld & Page 1998), must imply an age in excess of 2.7 Ga for the deformed tonalites at Råstojaure. Thus, the 2.68 Ga age of the deformed Råstojaure tonalite may alternatively be interpreted as a metamorphic age, and 2.83 Ga its age of emplacement. This is consistent with existing geochronological data from Archaean tonalitic to granodioritic intrusions north of Kiruna. Two poorly defined ages indicate an emplacement at c. 2.8 Ga (Welin et al. 1971, Skiöld 1979a), while a 2.69 Ga age, given for euhedral to subhedral zircons in the granodiorite, is suggested to represent a metamorphic event (Skiöld 1979a).

At the present state of knowledge, neither of these two alternative interpretations for the Råstojaure tonalite can be rejected. However, the existence of markedly rounded zircon crystals with older cores clearly demonstrates a complex history of the Archaean granitoids in northern Sweden. To decipher the late Archaean magmatic–metamorphic chronology in this area, the ion probe technique might be more successful than conventional zircon dating.

Irrespective of whether the 2.68 Ga age for the Råstojaure tonalite represents the emplacement or a later metamorphic event, this must be the maximum age of the discordantly overlying Kovo Group (Fig. 3). Volcanic and volcaniclastic rocks of andesitic composition from the Kovo Group, and a basaltic lava from the lower part of the

Kiruna Greenstone Group, give zircon ages in the range 2682±4 to 2692±5 Ma (Skiöld & Page 1998). By using the outer limits of the age errors, this might not be a chronostratigraphic contradiction, but an extensive erosion of the Archaean crust and the following deposition of the Kovo Group had to occur within a few million years (Fig. 10). The existence of a major unconformity at c. 2.7 Ga is not supported by the presence of 2638 to 2655 Ma old Archaean granites in southeastern Norrbotten (Lundqvist et al. 1996, Wikström et al. 1996); a more likely explanation is the occurrence of inherited Archaean zircons in these volcanic rocks. A similar interpretation was made for the c. 2.7 Ga zircon ages recorded for intermediate to felsic volcanic rocks in the Palaeoproterozoic greenstone successions in northern Finland (Lehtonen et al. 1992), and for 2693 Ma zircons in a c. 1980 Ma basalt from Karelia (Puchtel et al. 1998). Based on petrographic and stratigraphic criteria, the Kovo Group has been correlated with Sumi–Sariolan units in Karelia, implying a depositional age between 2.5 and 2.3 Ga (Martinsson 1997).

The granite at Lulep Patsajäkel was selected as a possible late Archaean intrusion. However, the zircon age of 1877±14 Ma for this granite demonstrates a relation to the early orogenic Haparanda or Perthite suites, both exhibiting ages around 1.88 Ga (Fig. 11). Red granites are important components of the Perthite Suite. The Perthite granites are generally undeformed and contain bluish quartz and perthite as major minerals, the latter partly in the form of 10–20 mm large phenocrysts (Geijer 1931, Ödman 1957). Fine-grained and porphyritic borders may exist and they often occur in distinctly outlined composite intrusions ranging from gabbro to granite (Ödman 1957, Kathol & Martinsson in press). The granite at Lulep Patsajäkel does not exhibit these characteristics of Perthite granites. Although the Haparanda Suite is dominated by diorite–granodiorite, it may include minor amounts of reddish and mainly undeformed granites (Ödman et al. 1949, Eriksson & Hallgren 1975, Witschard 1984). The granite at Lulep Patsajäkel probably belongs to this suite, which ranges in age from c. 1870 to 1890 Ma (Fig. 11). However, intrusions assigned to the Haparanda suite outside the type area are chemically, and to some extent petrographically, not easily distinguished from plutons of the Perthite Suite. As these two suites also have overlapping ages, this highlights a problem with classification of early orogenic intrusions in northern Norrbotten.

A genetic relation between the Perthite Suite and the Kiruna Porphyries was suggested by Witschard (1984), based on similarities in chemistry. This is supported by the 1879±7 Ma age for a syenite from this suite (Skiöld & Öhlander 1989). However, gradations between Perthite granite and Lina granite occur locally, indicating the possible existence of two generations of Perthite granite (Ödman 1957). The new results from the Perthite granite at Rakisvare (1874±12 Ma) and the monzonite at Runkanjunnje (1868±55 Ma) confirm an age of c. 1850–1880 Ma for the Perthite Suite (Fig. 11). This is also the minimum age of the gabbroic complexes south of Torneträsk, which are intruded by monzonite and quartz monzonite. Based on their undeformed character and the well-preserved mineralogy, these complexes are regarded as representing early intrusions of the Perthite Suite.

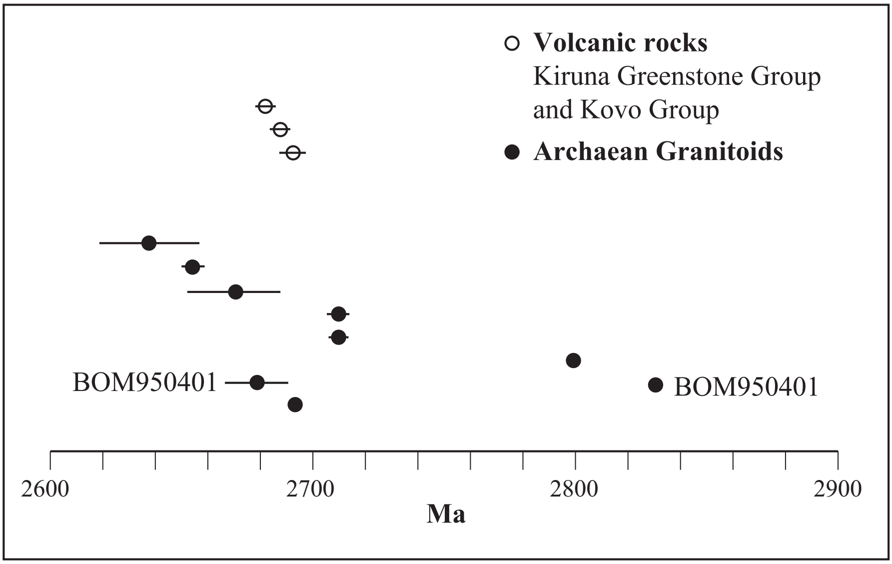

Fig. 10. Chronology of Archaean granitoids in northern and eastern Norrbotten, and volcanic rocks from the Kovo Group and the lower part of the Kiruna Greenstone Group. Data points with error bars. Data from Welin et al. (1971), Skiöld (1979a), Öhlander et al. (1987), Lundqvist et al. (1996), Wikström et al. (1996), Skiöld & Page (1998) and this study (BOM950401).

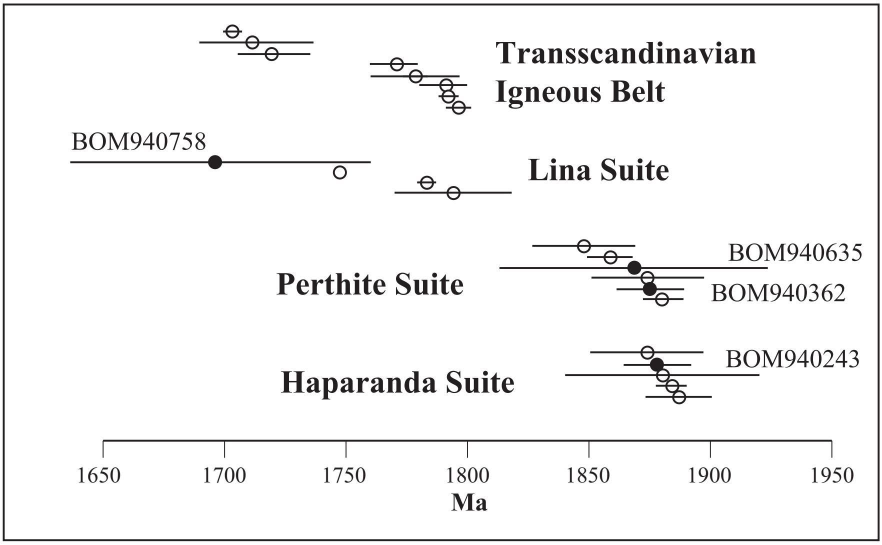

Fig. 11. Chronology of Svecofennian intrusions in northern and eastern Norrbotten. Data point with error bars. Data from Skiöld (1979b, 1981a, 1981b, 1988), Skiöld et al. (1988), Skiöld & Öhlander (1989), Romer et al. (1992, 1994), Witschard (1996), Wikström & Persson (1997a, b) and this study (filled symbols).

Due to the highly discordant character of the zircon results from the Ripasjaure granite, the calculated age of c. 1.7 Ga is very uncertain and is almost lacking in geochronological significance. Previous zircon dating of individual Lina granite intrusions in northern Norrbotten have suffered from similar problems. However, pooled data from two intrusions give an age of 1794±24 Ma (Skiöld 1988). A similar, and more precise, age of 1783±3 Ma was obtained for a Lina granite in southeastern Norrbotten (Wikström & Persson 1997a). Thus, considering the imprecise age of the Ripasjaure granite, it could be of Lina age (c. 1770–1790 Ma), although a relation to the c. 1710 Ma Transscandinavian Igneous Belt (TIB) granitoids in the Rombak–Tysfjord area (Romer et al. 1992) is also possible (Fig 11). The overlapping ages exhibited by the Lina Suite and the older generation of the TIB Suite may indicate a genetic relation, with the latter constituting the heat source for extensive crustal melting and generation of the Lina Suite minimum-melt granites.

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U-Pb zircon age of the Vätö granite, south central Sweden

By

Lars Persson and Per-Olof Persson

INTRODUCTION

The Vätö granite is a red to reddish grey rock occurring near the east coast of south central Sweden, about 70 km northeast of Stockholm (Fig. 1). It has been referred to the suite of early orogenic Svecokarelian granitoids which is c.1.9 Ga old (Persson 1993, Ripa & Persson 1997, Persson & Persson 1997). The largest intrusion of the Vätö granite, about 3 x 2 km in size, is situated on the middle eastern part of the island of Vätön, approximately 17 km ENE of Norrtälje. According to Lundegårdh (1954) other outcrops of Vätö granite can be found in the southern parts of the island of Björkön; west, south and east of a gabbro intrusion near Rådmansö, about 7 km to the south of the main intrusion of the Vätö granite; south of Grisslehamn (about 45 km NNE of Norrtälje); and near the church of Roslags-Kulla (about 38 km NE of Stockholm).

The Vätö granite is used as building and ornamental stone and was quarried at several places in the main intrusion (Lundegårdh 1971). Today only one quarry is in operation, at Karlsängen, where the sampling was made.

The granite has been investigated by Lundegårdh (1954) and Andréasson (1973). The basic and ultrabasic rocks of this region were described by Lundegårdh (1943, 1946, 1947, 1949) and Andréasson (1970).

GENERAL GEOLOGY

In a wide sense, south central Sweden belongs to the ore-bearing district of Bergslagen, forming part of the Svecokarelian orogen (2.0–1.7 Ga). The oldest constituents of the bedrock are metasedimentary and metavolcanic rocks (Fig. 1). The metasedimentary rocks are dominated by tuffitic arenites, greywackes, but intercalations of argillitic material occur. Both rhyolites and basalts (amphibolites) exist among the metavolcanic rocks which are about 1.9 Ga old (Welin 1987, Allen et al. 1996, Lundström et al.1998. The supracrustal rocks are generally altered to veined gneisses and raft migmatites (cf. Lundqvist 1979). The early orogenic granitoids have granitic to tonalitic compositions. The Vätö granite has been considered coeval with the Vänge and Sala granites situated to the west of Uppsala. It was considered as early orogenic by Stålhös (1972, cf. Persson & Stålhös 1991). The Sala granite is representative of granitic to granodioritic members of the suite. The Sala–Vänge granite (sampling point immediately to the east of the town of Sala, c.120 km NW of Stockholm) gave a U-Pb zircon age of 1891±6 Ma (Ripa & Persson 1997) which is practically identical with the U-Pb zircon age 1890±3 Ma obtained on the Sala granite, actually a grano-

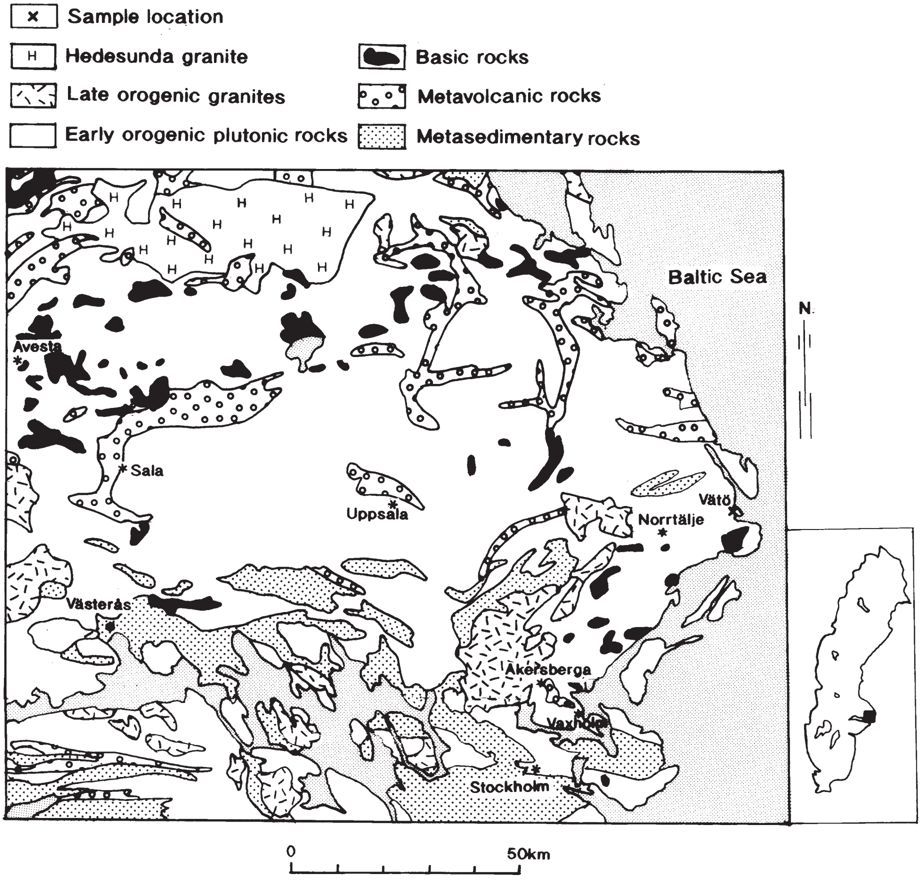

Fig. 1. Geological map of eastern south central Sweden, simplified from: Geology, National Atlas of Sweden, 1994.

diorite (Persson 1993). The granodiorite was sampled c.15 km northwest of Sala. A similar granite in Åkersberga (Fig. 1) has a U-Pb zircon age of 1875±6 Ma (Persson & Persson 1997) and thus represents a later intrusive phase.

SAMPLING

The Vätö granite has been sampled in the quarry at Karlsängen (Fig. 1; map sheet 11J Norrtälje NO, coordinates in the Swedish national grid: 6635780/1678350). Both red and grey varieties were sampled. The transition between the two is gradational, implying derivation from the same magma.

PETROGRAPHY AND CHEMISTRY

The predominant type of Vätö granite is pinkish red and coarsely medium-grained (Fig. 2). Pink feldspar crystals have a length between 5 and 15 mm, usually around 10–12 mm. The greyish red variety usually displays feldspar crystals with a length between 8 and 10 mm. Both granite types show a distinct lineation although the granites seem massive in surfaces perpendicular to the lineation.

According to Lundegårdh (1954), the granite at Karlsängen has the following modal composition: microcline 36 %, plagioclase 33 %, quartz 28 % and biotite, including chlorite, 3 %. Subordinate minerals are opaques, epidote, apatite, allanite and zircon. Thus, it is a monzogranite in the sense of Streckeisen (1967).

The chemical composition presented in Table 1 is a bulk analysis of both red and greyish red granite. Lundegårdh (1954, p.16) presented results from five and Andréasson (1973) four chemical analyses of the Vätö granite. Those from Karlsängen are shown in Table 2. The results from the older and the present investigation are fairly similar.

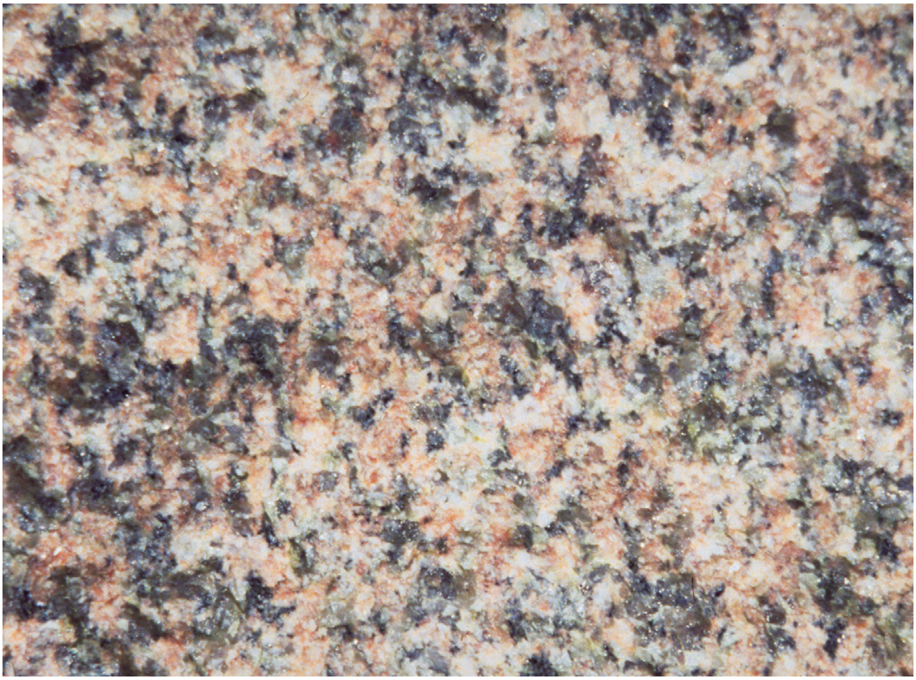

Fig. 2. Photograph of Vätö granite. The feldspar megacrysts are on average 12 mm long.

TABLE 1. Chemical composition of the Vätö granite from the Karlsängen quarry. The analysis was performed by Svensk Grundämnesanalys AB, Luleå, using a combination of ICP-AES and ICP-MS.

Sample, Vätö granite	**wt.-%**
SiO_2	74.3
TiO_2	0.173
Al_2O_3	13.6
Fe_2O_3	2.42
MnO	0.072
CaO	1.46
MgO	0.26
Na_2O	3.35
K_2O	5.07
P_2O_5	0.0853
LOI	0.2
Total	100.9

LOI=loss on ignition

Sample, Vätö granite	**ppm**
Ba	802
Be	2.02
Co	<5.90
Cr	30.4
Cu	<5.90
Ga	16.6
Hf	5.38
Mo	2.83
Nb	9.45
Ni	15
Rb	150
Sc	3.12
Sn	3.98
Sr	179
Ta	1.58
Th	16.9
U	12.9
V	4.41
W	0.588
Y	17.5
Zn	53.3
Zr	167
La	43.1
Ce	77.8
Pr	9.25
Nd	33.2
Sm	5.74
Eu	0.855
Gd	4.18
Tb	0.731
Dy	3.23
Ho	0.643
Er	1.9
Tm	0.336
Yb	1.93
Lu	0.317

TABLE 2. Chemical composition of the Vätö granite from the Karlsängen quarry according to Andréasson (1973) and Lundegårdh (1954).

Sample, Vätö granite	**wt.-%, Andréasson (1973)**	**wt.-%, Lundegårdh (1954)**
SiO_2	73.8	74.38
TiO_2	0.22	0.19
Al_2O_3	14.7	12.76
Fe_2O_3	0.7	0.74
FeO	1.39	1.15
MnO	0.05	0.03
CaO	1.9	0.86
MgO	0.51	0.21
Na_2O	2.9	3.51
K_2O	4.0	5.67
BaO	0.09	
SrO		0.07
P_2O_5		0.15
Total	100.3	99.7
	ppm	
Sr	270	
Zr	80	

ZIRCON DESCRIPTION AND ANALYTICAL RESULTS

The red and grey granite samples contain zircons of similar appearance. They vary from colourless to brown, with continuous gradations. Some grains are patchy brown. The quality is generally poor: only metamict or fractured crystals were detected and inclusions are common. About half the population consists of euhedral crystals with sharp edges and only displaying faces of low crystallographic indices. The other crystals are more or less anhedral or rounded, and show high-index faces. There is no correlation between colour and crystal habit. When examined in high-refractive liquid, almost all grains show magmatic zoning. About 20 % have rounded cores. Such grains are encountered primarily within the brown population. The crystals selected for isotopic analysis did not show any signs of cores or overgrowths when viewed in alcohol. All analysed crystals were thoroughly abraded.

Five fractions each from the red and grey granite varieties were selected and analysed at the Laboratory for Isotope Geology, Swedish Museum of Natural History, Stockholm. Mostly colourless grains were chosen but three fractions consisted of brown grains. The zircons from the red granite were not divided into size fractions. The analysed zircons from the red granite are short prismatic with length/width ratios of 1–2, except fraction 1:4 which has l/w = 3–5. The zircons from the grey granite have l/w ratio of 1–4. The analytical procedure is described in the Editor's Preface to this volume.

The analytical data are shown in Table 3 and Fig. 3. The brown zircons are richer

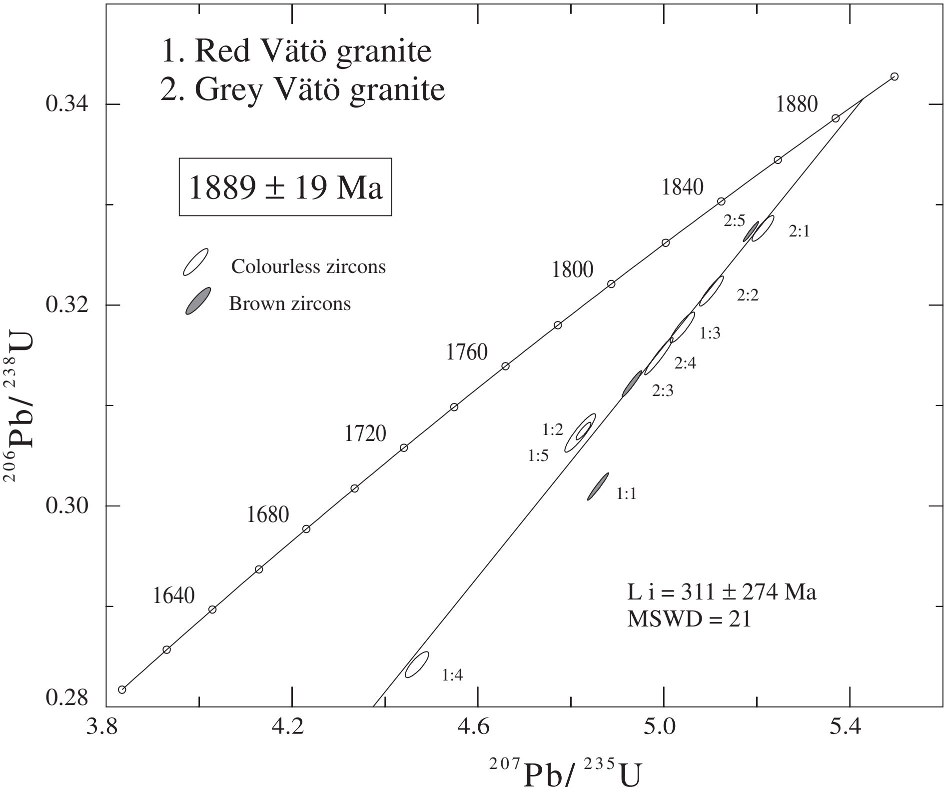

Fig. 3. Concordia diagram for zircons from the Vätö granite.

in uranium and poorer in ^{208}Pb (implying lower Th content) than the colourless. However, even among the colourless fractions, the variation in ^{208}Pb is conspicuously large. This might indicate a heterogeneous population where zircons crystallized under different magmatic conditions, incorporated inherited material, or were overgrown with new material. The data points do not define a perfect linear array in the concordia diagram (Fig. 3). A plausible explanation for this is that, although devoid of visible cores, some grains obviously contain inherited or added material. This applies particularly to the brown zircons of the red granite (fraction 1:1) which have a markedly older ^{207}Pb/^{206}Pb age. Since the two samples undoubtedly are comagmatic, the age calculation can be made on all fractions combined. However, since the brown zircons are more prone to show inheritance, the regression was made on the colourless fractions only (7 points). The obtained age is 1889±19 Ma with an MSWD of 21 due to the large scatter. A calculation using the four least discordant colourless fractions (2:1, 2:2, 1:3 and 2:4) results in an upper intercept age of 1894±7 Ma, a lower intercept age of 333±156 Ma and an MSWD of 0.03. However, it is hardly justi-

TABLE 3. U-Pb isotopic data for zircons from the Vätö granite.

Analysis No., size fraction (µm)	**No. of crystals**	**Weight (µg)**	**U (ppm)**	**Pb tot. (ppm)**	**Common Pb (ppm)**	$\frac{^{206}\mathrm{Pb}^{a}}{^{204}\mathrm{Pb}}$	**^{206}Pb-^{207}Pb-^{208}Pb radiog. (atom%)^{b}**	$\frac{^{206}\mathrm{Pb}^{b}}{^{238}\mathrm{U}}$	$\frac{^{207}\mathrm{Pb}^{b}}{^{235}\mathrm{U}}$	**^{207}Pb/^{206}Pb age (Ma)**
LP 97:1	**Red Vätö granite**									
1:1. br	9	11	1035.3	320.9	2.48	5906	84.4 -9.9 - 5.7	0.3019±11	4.858±18	1906±2
1:2. col	3	10	179.6	56.7	0.08	4518	83.8 - 9.5 - 6.7	0.3073±16	4.820±27	1860±4
1:3. col	7	9	299.2	101.9	0.34	5141	80.5 - 9.3 - 10.2	0.3178±12	5.040±22	1880±3
1:4. col, el	5	14	147.1	45.5	0.03	5087	79.2 - 9.0 - 11.8	0.2842±11	4.469±21	1865±5
1:5. col	7	11	410.2	133.6	1.31	3835	82.0 - 9.3 - 8.7	0.3075±7	4.828±13	1862±2
LP 97:2	**Grey Vätö granite**									
2:1. col, <74	12	7	614.3	210.5	1.26	5460	82.7 - 9.6- 7.7	0.3276±10	5.213±19	1886±3
2:2. col, <74	14	12	392.9	134.3	0.12	11102	81.0 - 9.3 - 9.7	0.3214±12	5.102±21	1882±3
2:3. br, <74	9	7	848.9	269.7	0.47	11163	84.7 - 9.7 - 5.6	0.3122±11	4.931±17	1873±2
2:4. col, >74	8	11	558.4	183.5	2.29	3527	83.5 - 9.6 - 6.9	0.3149±15	4.989±25	1878±3
2:5. br, >74	9	11	697.8	231.5	0.35	13993	85.0 - 9.8 - 5.2	0.3273±8	5.187±13	1879±1

a) corrected for mass fractionation (0.1% per a.m.u).
b) corrected for mass fractionation, blank and common Pb.
br = brown, col = colourless, el = elongate

fied to disregard so many of the data points merely because they diverge from the discordia, so we chose the conservative age figure displayed in the diagram.

CONCLUSIONS

The zircon age of the Vätö granite (1889±19 Ma) coincides with that of the Sala and Sala–Vänge granites and also lies within the error of the Åkersberga granite. We therefore conclude that the Vätö granite belongs to the group of early-orogenic, Svecokarelian granitoids in south central Sweden.

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