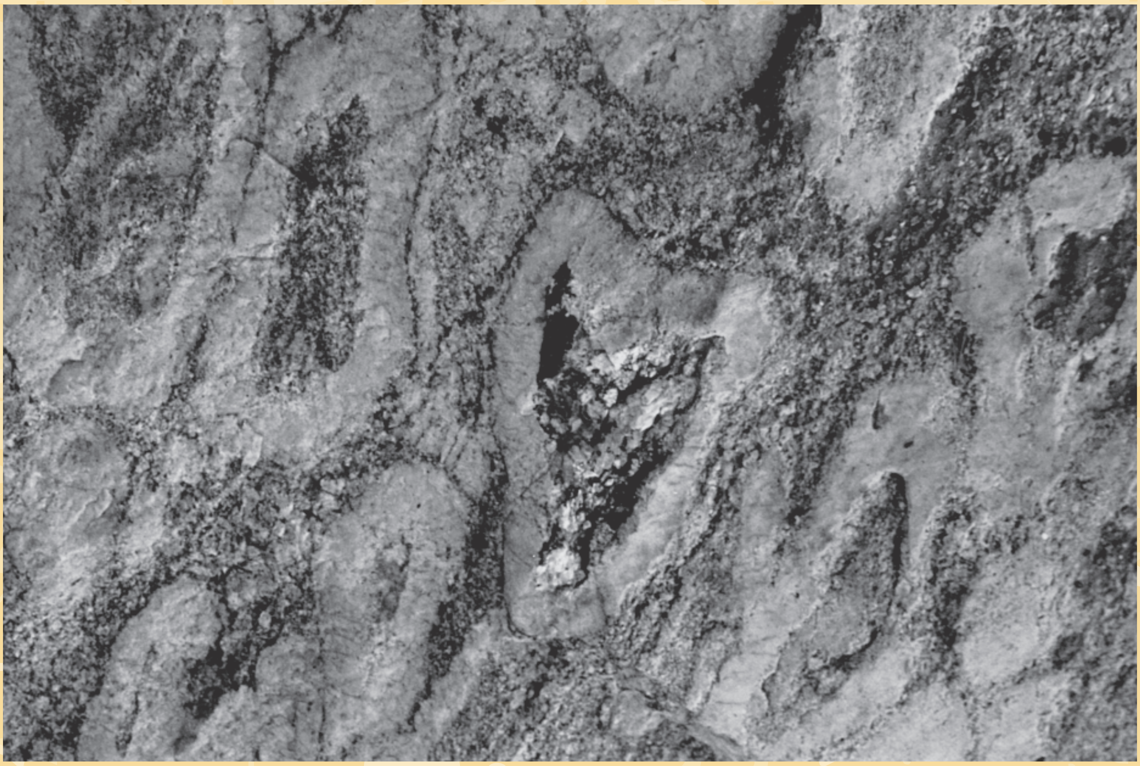
Research Paper C 834

Radiometric dating results 5

Stefan Bergman, editor



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Sveriges Geologiska Undersökning
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Radiometric dating results 5

Stefan Bergman (ed.)

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Cover: Orbicular granite from an outcrop c. 1.3 km north-east of the trading centre of Orminge.
See paper by Persson et al. (pp. 50–57).

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CONTENTS

Editor's preface

This volume is the fifth 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 eight papers in this volume present data from different geological provinces of the Swedish Precambrian bedrock, from the Kiruna region in the north to the Norrköping area in the south (see Fig. 1).

The fruitful co-operation with the Laboratory for Isotope Geology of the Swedish Museum of Natural History in Stockholm (director, Dr Per Andersson, former director Prof. Stefan Claesson) is gratefully acknowledged. The analytical methods for the U-Pb datings can be summarised 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–$^{233-235}U$ tracer was added to the ID-aliquots. Some of the smaller samples were spiked with a mixed ^{205}Pb–$^{233-235}U$ 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 using Ludwig's (1991b) ISOPLOT program. The total Pb blank was 4–10 pg and the U blank less than 2 pg. The assigned composition of common Pb was calculated according to the Pb evolution model of Stacey & Kramers (1975), which is a sufficient approximation for analyses with high $^{206}Pb/^{204}Pb$ (>~1000). For samples with low $^{206}Pb/^{204}Pb$ the uncertainty in the common Pb correction will result in large error ellipses. The mass fractionation for Pb is 0.10±0.04 % per a.m.u. U mass fractionation was monitored and corrected for by means of the $^{233-235}U$ 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 for the ion exchange procedure by which a HBr step was added for better purification of lead and a second HCl-HNO_3 cycle for purification of uranium.

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Uppsala, 2001-11-12

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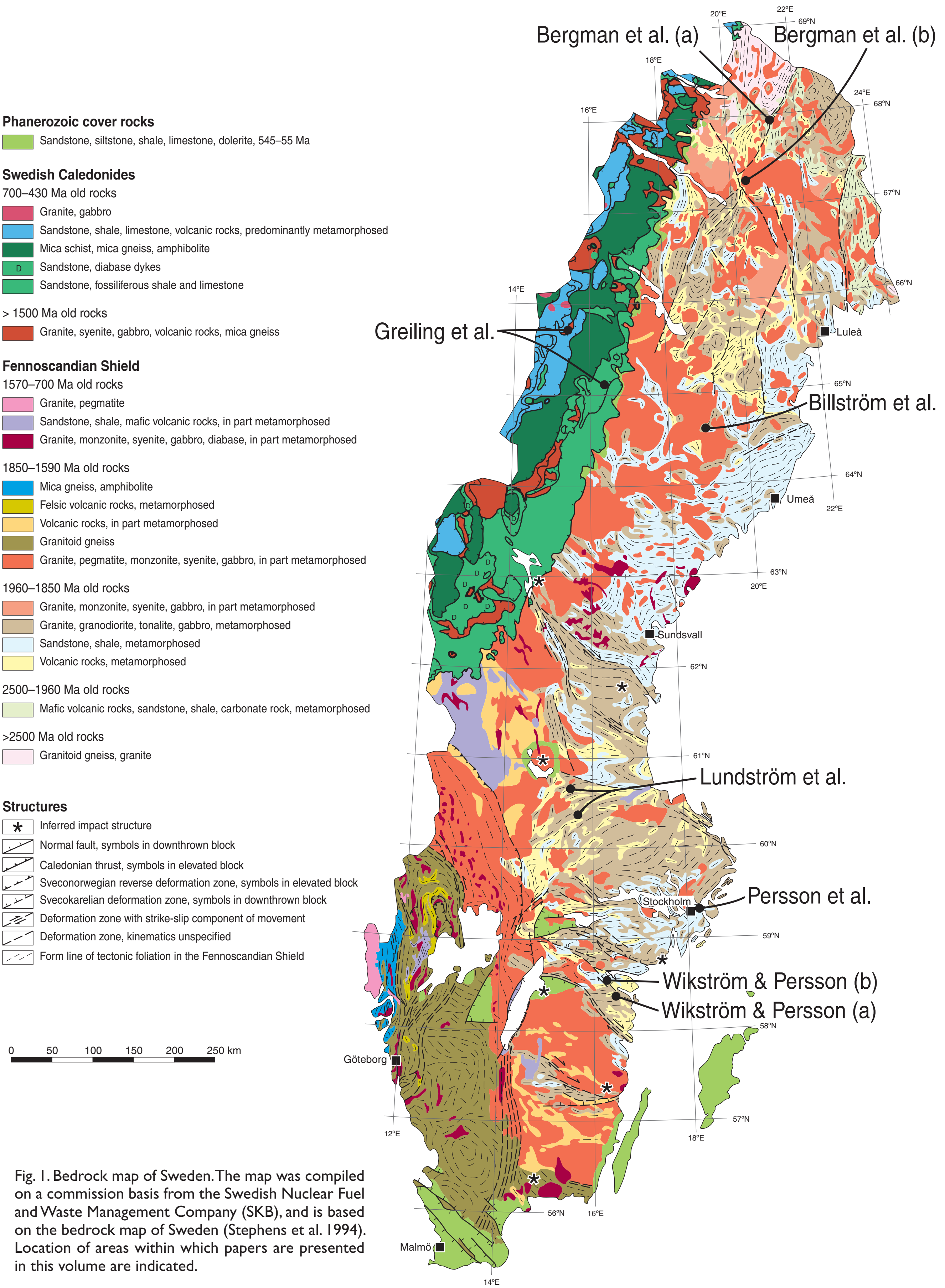

Fig. 1. Bedrock map of Sweden. The map was compiled on a commission basis from the Swedish Nuclear Fuel and Waste Management Company (SKB), and is based on the bedrock map of Sweden (Stephens et al. 1994). Location of areas within which papers are presented in this volume are indicated.

U-Pb zircon age of a metadiorite of the Haparanda suite, northern Sweden

Stefan Bergman, Olof Martinsson & Per-Olof Persson

Bergman, S., Martinsson, O. & Persson, P.-O., 2002: U-Pb zircon age of a metadiorite of the Haparanda suite, northern Sweden. *In* S. Bergman (ed.): *Radiometric dating results 5*. Uppsala 2002. *Sveriges geologiska undersökning C 834*, pp. 6–11. ISBN 91-7158-668-7.

A U-Pb zircon age of 1881±7 Ma has been obtained from a metadiorite of the Haparanda suite from the Esrange area, northern Sweden, and is interpreted as a crystallisation age. The age is within the analytical uncertainty of previously published ages in northernmost Sweden, and tentatively suggests that the magmatism started 10–20 Ma later there than in the Skellefte area and further to the south. The age of the diorite gives a maximum age of deposition of the unconformably overlying Younger Svecofennian clastic metasedimentary rocks. A regional deformation event c. 1.88 Ga ago was probably responsible for the uplift and exposure to erosion of the then newly crystallised diorite.

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Introduction

The age constraints on Precambrian metasedimentary rock units are generally poor in northern Sweden. A locality described by Ödman (1939) provides a unique opportunity to define the maximum age of the Vakko formation, a Younger Svecofennian metasedimentary unit. At this locality, which is situated ENE of Kiruna in northern Sweden (Fig. 1), a metadiorite of the Haparanda suite is unconformably overlain by a clastic sequence with a basal, diorite-pebble conglomerate. The aim of this paper is to present the U-Pb zircon age of the metadiorite, which is more precise than previously published ages of rocks of the Haparanda suite, and which indicates the maximum age of the overlying clastic sequence.

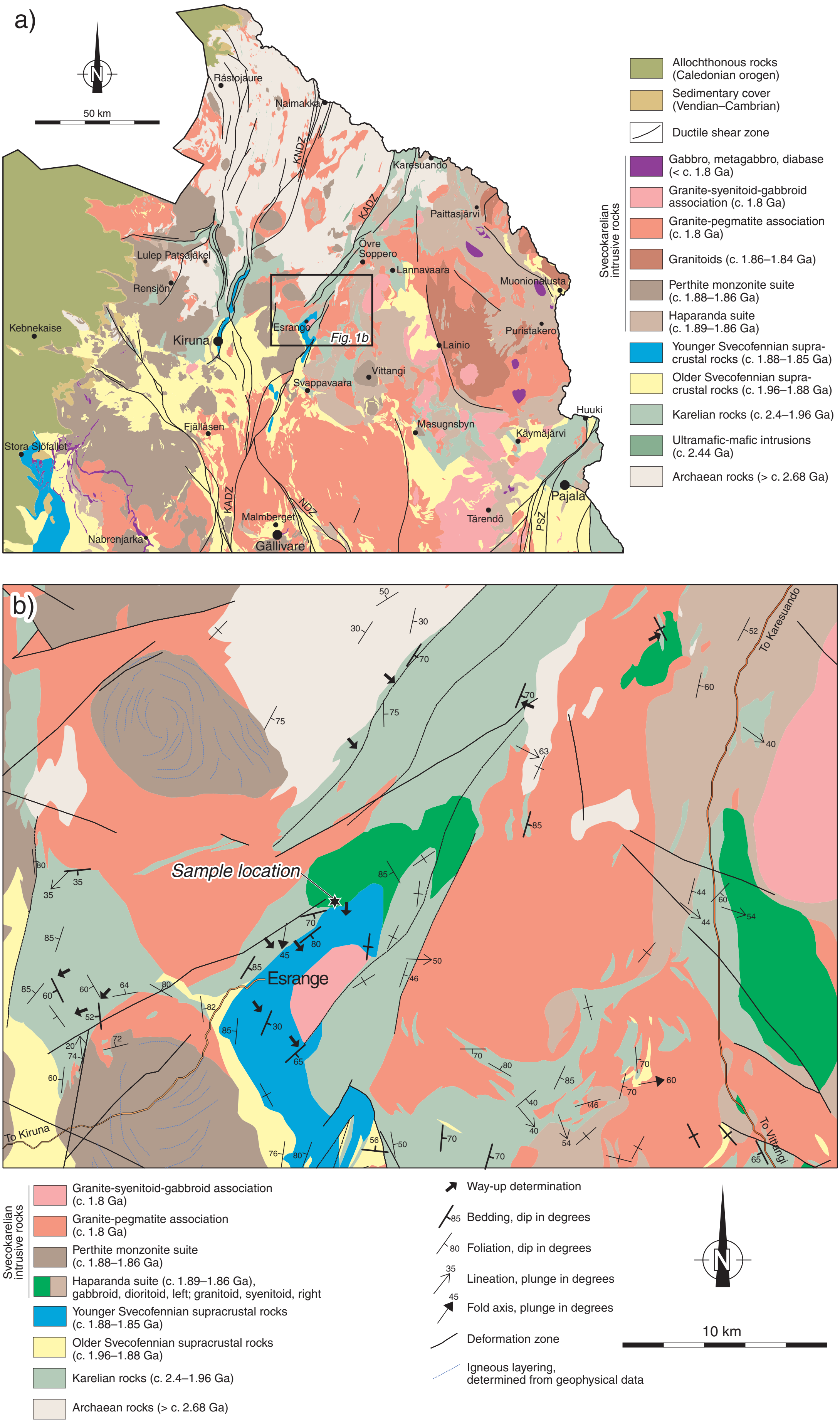
Geological setting

The bedrock of northernmost Sweden consists mainly of Archaean and Proterozoic plutonic and supracrustal rocks (Fig. 1). To the west these more or less deformed and metamorphosed older rocks are unconformably overlain by a thin cover of Vendian to Cambrian clastic sedimentary units, which are overthrust by nappes of the Caledonian orogen. The geology of the northern part of Norrbotten county has recently been described by Bergman et al. (2001).

Archaean rocks (c. 2.8–2.68 Ga) occupy the northernmost part and are dominated by metagranitoids, with minor supracrustal units. They are unconformably overlain by clastic metasedimentary and intermediate–mafic metavolcanic rocks (Kovo Group). The overlying Greenstone group consists mainly of metabasalt. Other important components are metaultramafic rocks, graphite schists, iron formations, and crystalline carbonate rocks. Swarms of mafic dykes cut the Archaean rocks, and the overlying units contain numerous mafic sills. The Kovo Group and Greenstone group are collectively called Karelian rocks. The overlying Svecofennian supracrustal rocks (c. 1.96–1.85 Ga) consist predominantly of calc-alkaline metaandesite (Porphyrite group), a bimodal group of mafic and felsic metavolcanic rocks (Porphyry group) and two units of clastic metasedimentary rocks. The clastic rocks discussed in this paper belong to the Younger Svecofennian supracrustal sequence. Six suites of intrusions were formed after c. 1.9 Ga ago. The Haparanda suite (1.89–1.86 Ga) contains deformed and metamorphosed gabbroids, dioritoids, syenitoids, and granitoids. The almost coeval Perthite monzonite suite (c. 1.88–1.86 Ga) consists of little deformed gabbroids, dioritoids, syenitoids, and granites. In the northeast there are in part deformed and metamorphosed granitoids with ages of c. 1.85 Ga. Two c. 1.8 Ga old intrusive suites have been recognised: the Granite-pegmatite association and the Granite-syenitoid-gabbroid association. The youngest intrusive suite consists of gabbro and diabase of uncertain age.

Northernmost Sweden is characterised by an approximately NNE–SSW to NNW–SSE structural grain. The degree of deformation is highly variable. High-strain zones alternate with zones of little deformation, and some intru-

Fig. 1. a) Bedrock map of northern Norrbotten county, modified from Bergman et al. (2000). KADZ = Karesuando–Arjeplog deformation zone, KNDZ = Kiruna–Naimakka deformation zone, NDZ = Nautanen deformation zone, PSZ = Pajala shear zone. b) Detailed bedrock map of the Esrange area, with indication of the sample location.


a)
N
50 km
Råstojaure
Naimakka
KNDZ
Karesuando
KADZ
Paittasjärvi
Övre Soppero
Lannavaara
Lulep Patsajäkel
Rensjön
Muonionalusta
Kebnekaise
Kiruna
Esrange
Fig. 1b
Puristakero
Lainio
Vittangi
Svappavaara
Huuki
Masugnsbyn
Käymäjärvi
Fjällåsen
Stora Sjöfallet
KADZ
NDZ
Pajala
Tärendö
PSZ
Malmberget
Gällivare
Nabrenjarka
Allochthonous rocks (Caledonian orogen)
Sedimentary cover (Vendian–Cambrian)
Ductile shear zone
Svecokarelian intrusive rocks
Gabbro, metagabbro, diabase (< c. 1.8 Ga)
Granite-syenitoid-gabbroid association (c. 1.8 Ga)
Granite-pegmatite association (c. 1.8 Ga)
Granitoids (c. 1.86–1.84 Ga)
Perthite monzonite suite (c. 1.88–1.86 Ga)
Haparanda suite (c. 1.89–1.86 Ga)
Younger Svecofennian supra-crustal rocks (c. 1.88–1.85 Ga)
Older Svecofennian supra-crustal rocks (c. 1.96–1.88 Ga)
Karelian rocks (c. 2.4–1.96 Ga)
Ultramafic-mafic intrusions (c. 2.44 Ga)
Archaean rocks (> c. 2.68 Ga)
b)
Sample location
Esrange
To Karesuando
To Kiruna
To Vittangi
Svecokarelian intrusive rocks
Granite-syenitoid-gabbroid association (c. 1.8 Ga)
Granite-pegmatite association (c. 1.8 Ga)
Perthite monzonite suite (c. 1.88–1.86 Ga)
Haparanda suite (c. 1.89–1.86 Ga), gabbroid, dioritoid, left; granitoid, syenitoid, right
Younger Svecofennian supracrustal rocks (c. 1.88–1.85 Ga)
Older Svecofennian supracrustal rocks (c. 1.96–1.88 Ga)
Karelian rocks (c. 2.4–1.96 Ga)
Archaean rocks (> c. 2.68 Ga)
Way-up determination
Bedding, dip in degrees
Foliation, dip in degrees
Lineation, plunge in degrees
Fold axis, plunge in degrees
Deformation zone
Igneous layering, determined from geophysical data
N
10 km

sive rocks lack evidence of ductile deformation. Intense deformation and high-grade metamorphism is found in the eastern part of the area, e.g. in the Pajala shear zone (Fig. 1). Another important regional zone is the Karesuando–Arjeplog deformation zone, which transects the central part of the area, near Esrange.

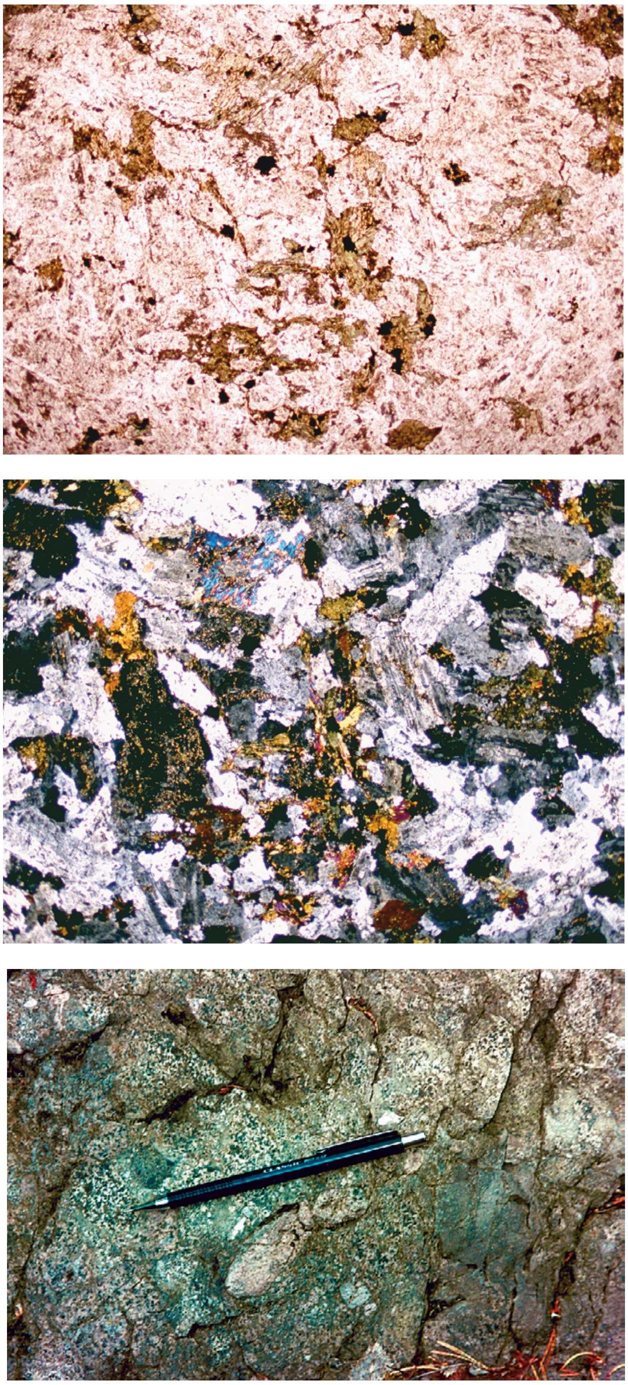
Description of the sample locality

In the Esrange area (Fig. 1) most of the major geological units are represented. The Archaean rocks to the north are overlain by Karelian rocks, which to the south are overlain by Svecofennian rocks. The upper part of the latter (Younger Svecofennian metasedimentary sequence) consists of clastic metasedimentary rocks, which were called the Vakko formation by Ödman (1939) and the Maattavaara quartzite group by Eriksson & Hallgren (1975). Intrusions of the Haparanda suite, the Perthite monzonite suite, the Granite-pegmatite association, and the Granite-syenitoid-gabbroid association are also present. The area is transected by several branches of the Karesuando-Arjeplog deformation zone but in domains between these branches the rocks may show only minor signs of deformation, such as at the sample locality.

The metadiorite is dark grey, medium-grained and isotropic. In some outcrops it is altered and contains epidote veins; for sampling, these outcrops were avoided. Fracture surfaces coated with sheet silicates are common. The magnetic susceptibility measured on outcrop varies between 2 000 and 5 000 x 10^{-5} SI units, with a median value of 4 000 x 10^{-5} SI units. The metadiorite sample STB951050 (Figs. 2a, b) was taken from an outcrop close to a small bog, between the Viesserova and Skaitevaara hills, 4 kilometres NNE of Esrange (Fig. 1, co-ordinates in the Swedish National Grid RT 90: 7546300/1724200).

The basal conglomerate (Fig. 2c) approximately 200 metres east of the sample locality is described by Ödman (1939, locality II) and is summarised as follows: The normal diorite grades into a somewhat irregular variety with diorite fragments in a matrix of diorite gravel or, in places, more normal sandy material. The fragments are up to 0.4 metres large and some are well rounded. Subordinate fragments of a sandy sedimentary rock were recorded. Stratigraphically upwards the amount of matrix increases and the rock grades into quartzite. The total thickness of the conglomerate is approximately 10–12 metres.

Less than 100 metres south of the sample locality there is a tectonic contact between metadiorite and quartzite. To the south-west the quartzite overlies metabasalt of the Greenstone group.



a) b) c)

Fig. 2. a) Photomicrograph of the 1881±7 Ma old metadiorite. Note magmatic texture and lack of ductile deformation. The long dimension of the photograph is 10 mm. b) Same as (a) but with crossed nicols. c) Basal metaconglomerate that was deposited on the metadiorite. The clasts mainly consist of metadiorite.

Petrographic description and analytical results

In thin section the following minerals have been observed: plagioclase, green hornblende, brown biotite, and magnetite, with quartz and zircon as accessory minerals. Sericitisation and saussuritisation of plagioclase are common, but the primary magmatic texture is still well-preserved (Figs. 2a, b). The only sign of ductile deformation is undulose extinction of the very few quartz grains present. Ödman (1939) reported anorthite contents of plagioclase of between 5 % and 40 %. The chemical composition of the sample is presented in Table 1.

The diorite sample yielded plenty of zircons, which constitute a fairly heterogeneous population. The colour varies from colourless to yellow, the yellow material sometimes being localised to patches within otherwise colourless grains. The morphological variation is large. A minority is euhedral and has low-order crystal faces. Many grains are fragmented and some have high-order crystal faces. The length/width ratios vary from 2 to >5. The high-index crystals are primarily short, with length/width ratios of 1–2. A large number of grains are anhedral or rounded. Cores, generally of rounded outline, are fairly common. Four fractions were handpicked for analysis. All analysed zircons were thoroughly abraded.

The analyses were made at the Laboratory for Isotope Geology in Stockholm. The analytical procedures are described in the Editor's Preface to this volume. The isotopic results are shown in Table 2 and Figure 3. Fraction 2 comprises zircons with a larger grain size than the others (sieve fraction >106 µm and 74–106 µm, respectively). Fractions 1–3 consist of euhedral zircons with low-index faces whereas fraction 4 consists of rounded grains with irregular surfaces. The data points are relatively weakly

TABLE 1. Chemical analysis of the dated metadiorite sample STB951050. The analysis was performed by Svensk Grundämnesanalys AB, Luleå. All elements were analysed by ICP-AES, except Ga, Hf, Mo, Nb, Rb, Sn, Ta, Th, U, W, Y and the rare earth elements which were analysed by ICP-MS. LOI = loss on ignition.

	(wt %)		(ppm)		(ppm)
SiO_2	56.2	Ba	348	La	33.4
TiO_2	0.824	Be	1.33	Ce	64
Al_2O_3	17.9	Co	14.4	Pr	7.68
Fe_2O_3	7.29	Cr	21.4	Nd	31.6
MnO_2	0.0706	Cu	<5.92	Sm	4.74
MgO	4.11	Ga	16.5	Eu	1.07
CaO	5.43	Hf	2.52	Gd	4.32
Na_2O	6.53	Mo	1.85	Tb	0.576
K_2O	0.775	Nb	4.47	Dy	2.82
P_2O_5	0.338	Ni	19.2	Ho	0.584
Total	99.5	Rb	17.8	Er	1.67
LOI	0.6	Sc	14.3	Tm	0.216
		Sn	4.92	Yb	1.67
		Sr	731	Lu	0.226
		Ta	0.442		
		Th	1.97		
		U	0.87		
		V	172		
		W	0.426		
		Y	13.7		
		Zn	21.4		
		Zr	95.5		

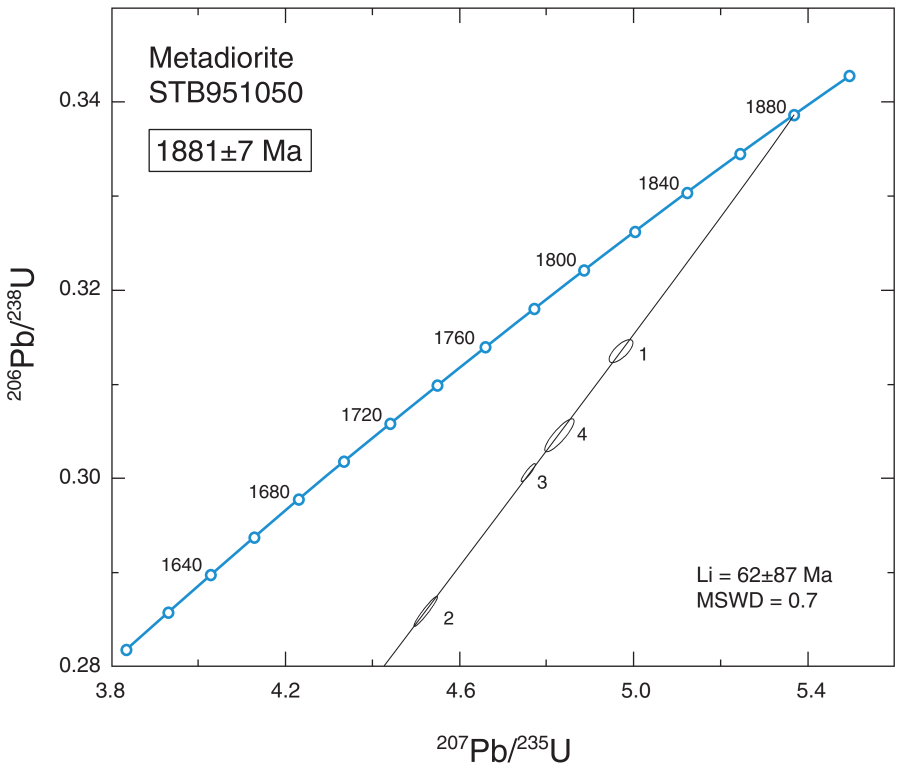


Fig. 3. Concordia diagram for analysed zircon fractions from the metadiorite sample STB951050.

TABLE 2. U-Pb isotopic data for sample STB951050.

Analysis No.	Weight (µg)	No. of crystals	U (ppm)	Pb tot. (ppm)	Common Pb (ppm)	$^{206}Pb^{a}/^{204}Pb$	^{206}Pb – ^{207}Pb – ^{208}Pb Radiog. (atom %)[b]	$^{206}Pb^{b}/^{238}U$	$^{207}Pb^{b}/^{235}U$	$^{207}Pb/^{206}Pb$ age (Ma)
1	27	10	224.1	83.0	0.30	6543	73.1–8.4–18.5	0.3135±10	4.971±22	1880±6
2	17	3	288.4	97.5	0.10	7665	72.9–8.4–18.7	0.2858±13	4.522±22	1876±3
3	27	11	237.5	85.3	0.06	9417	72.1–8.3–19.6	0.3006±8	4.758±13	1877±2
4	19	12	118.5	41.2	0.07	3624	75.6–8.7–15.7	0.3046±14	4.829±28	1880±5

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

discordant and define a discordia with intercept ages of 1881±7 and 62±87 Ma and an MSWD of 0.7. The rounded zircons have less U and ^{208}Pb than the euhedral ones but are chronologically identical with the others. The upper intercept age is interpreted as the crystallisation age of the diorite.

Discussion

Previous age determinations of rocks of the Haparanda suite in northernmost Sweden have yielded the following results: 1886±14 Ma from three localities in the Svappavaara–Vittangi area (Skiöld 1988), 1880±28 Ma from Paittasjärvi (Skiöld 1979), 1880 Ma (Lindroos & Henkel 1978) and 1873±23 (Skiöld 1981) from Puristakero, and 1877±14 Ma (Martinsson et al. 1999) from Lulep Patsajäkel (Fig. 1). Although these ages cluster around c. 1880 Ma, the indicated errors do not rule out the possibility that these rocks have crystallisation ages of 1910–1890 Ma, which appear to be common for comparable rocks in the Skellefte and Bergslagen areas to the south (e.g. 1902±2, Björk & Kero 1996; 1907±13 Ma, Bergström et al. 1999; 1890±3 Ma, Persson 1993; 1889±19 Ma, Persson & Persson 1999; 1891±6 Ma, Ripa & Persson 1997). The age of 1881±7 Ma obtained here is within the analytical uncertainty of the previously published ages in northernmost Sweden, and tentatively suggests that the magmatism started 10–20 Ma later there than in the Skellefte area and further to the south. The cause for this may have been the presence of Archaean crust which delayed the formation and ascent of magmas.

After the diorite had crystallised 1881±7 Ma ago, it was uplifted and exposed to erosion before deposition of the Younger Svecofennian clastic metasedimentary rocks. The evidence for an early Svecokarelian regional event of deformation and metamorphism c. 1.88 Ga ago in northernmost Sweden is discussed in Bergman et al. (2001). This event was probably responsible for the uplift which led to exposure of the then newly crystallised diorite. Whether the diorite was also metamorphosed during this event is still uncertain. The metamorphic hornblende and biotite in the metadiorite may have formed during this event or the late Svecokarelian event about 80 Ma later.

The clastic rocks in the Esrange area occupy a similar stratigraphic position as comparable units in the Kiruna and Stora Sjöfallet areas (Fig. 1). In the Kiruna area the Upper Hauki complex (Offerberg 1967) overlies the Porphyry group. The age of the Luossavaara iron ore, within the Porphyry group, is 1888±6 Ma (Romer et al. 1994). In the Stora Sjöfallet area the Snavva-Sjöfallet group (Zachrisson & Witschard 1995) overlies a metarhyolite in the Porphyry group, which has yielded an age of 1909^{+17}_{-16} Ma (Skiöld & Cliff 1984). These maximum ages for the Younger Svecofennian metasedimentary rocks are in agreement with the 1881±7 Ma age obtained here.

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U-Pb titanite and zircon ages of the Lina granite at the type locality NW of Gällivare, northern Sweden

Stefan Bergman, Per-Olof Persson & Lutz Kübler

Bergman, S., Persson, P.-O., & Kübler, L., 2002: U-Pb titanite and zircon ages of the Lina granite at the type locality NW of Gällivare, northern Sweden. *In* S. Bergman (ed.): *Radiometric dating results 5*. Uppsala 2002. *Sveriges geologiska undersökning C 834*, pp. 12–17. ISBN 91-7158-668-7.

The Lina granite in northern Sweden has been dated at the type locality, 26 km NW of Gällivare. The age of the granite is important because it constrains: 1) when the waning stages of the last regional ductile deformation occurred in the region, 2) timing of activity along the Karesuando–Arjeplog deformation zone, and, 3) the maximum age of a large flat-lying diabase intrusion. Four zircon fractions and one titanite fraction were analysed. Three of the zircon fractions define a discordia with an upper intercept age of 1811±6 Ma, but it is considered likely that the analysed zircons are affected by inheritance. The titanite age 1771^{+7}_{-5} Ma is interpreted as the magmatic age of the rock. However, since the cooling history of the granite pluton is not known, the age must be treated as a minimum age.

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Introduction

The Lina granite was originally described by Holmqvist (1905); the type area was chosen at the railway bridge at Linaälven River, 26 km NW of Gällivare (Fig. 1). The term Lina granite has subsequently been widely used for reddish, leucocratic granites in northernmost Sweden. In this paper the term is used in a more restrictive sense, from a geographical point of view, for a granite situated in the Gällivare–Fjällåsen–Svappavaara–Masugnsbyn area (Fig. 1). The type locality is situated in the western part of this area. On the bedrock map of northern Norrbotten county (Bergman et al. 2000) the Lina granite is included in the 1.81–1.78 Ga old Granite-pegmatite association. Intrusive suites, which can be correlated with the Granite-pegmatite association, are regionally widespread. Granites of similar composition and age are found in e.g. north-central Sweden (Skellefte granite, Härnö granite, Lundqvist et al. 1996), south-central Sweden (e.g. Fellingsbro granite, Patchett et al. 1987, Stockholm granite, Ivarsson & Johansson 1995) and northern Finland (Central Lapland granite, Silvennoinen et al. 1987). An age determination of Lina granite from Vettasjärvi yielded a U-Pb zircon age of c. 1795 Ma (Skiöld 1981). These zircon data were recalculated and combined with new data from the Tjårvetjarram granite, yielding an age of 1794±24 Ma (Skiöld 1988). The aim of this study was to present a more precise U-Pb age of the Lina granite. This would have implications for the tectonic evolution of northernmost Sweden and would allow more refined comparisons with other parts of the Fennoscandian Shield.

Geological setting

The bedrock of northernmost Sweden consists mainly of Archaean and Proterozoic plutonic and supracrustal rocks. To the west these more or less deformed and metamorphosed older rocks are unconformably overlain by a thin cover of Vendian to Cambrian clastic sedimentary rocks, which are overthrust by nappes of the Caledonian orogen. The geology of the northern part of Norrbotten county has recently been described by Bergman et al. (2001), and the brief summary that follows is based on that work.

Archaean rocks (c. 2.8–2.7 Ga) occupy the northernmost part and are dominated by metagranitoids, with minor supracrustal rocks. They are unconformably overlain by clastic metasedimentary and intermediate–mafic metavolcanic rocks (Kovo Group, c. 2.4–2.3 Ga). The overlying Greenstone group (c. 2.3–2.0 Ga) consists mainly of metabasalt. Other important components are metaultramafic rocks, graphite schists, iron formations, and crystalline carbonate rocks. Swarms of mafic dykes exist in the Archaean rocks, and the overlying rocks contain numerous mafic sills. The overlying Svecofennian supracrustal rocks (c. 1.96–1.85 Ga) predominantly consist of calc-alkaline metaandesite (Porphyrite group), a bimodal group of mafic and felsic metavolcanic (Porphyry group) and clastic metasedimentary rocks. Six suites of intrusions were formed after c. 1.9 Ga ago. The Haparanda suite (1.89–1.86 Ga) contains deformed and metamorphosed gabbroids, dioritoids, syenitoids, and granitoids. The almost coeval Perthite monzonite suite (c. 1.88–1.86) consists of little deformed gabbroids, dioritoids, syenitoids, and granites. In the north-east there are partly deformed and metamorphosed granitoids with ages of c. 1.85 Ga. Two intrusive suites with ages of c. 1.8 Ga have been recognised. This paper focuses on the Granite-pegmatite

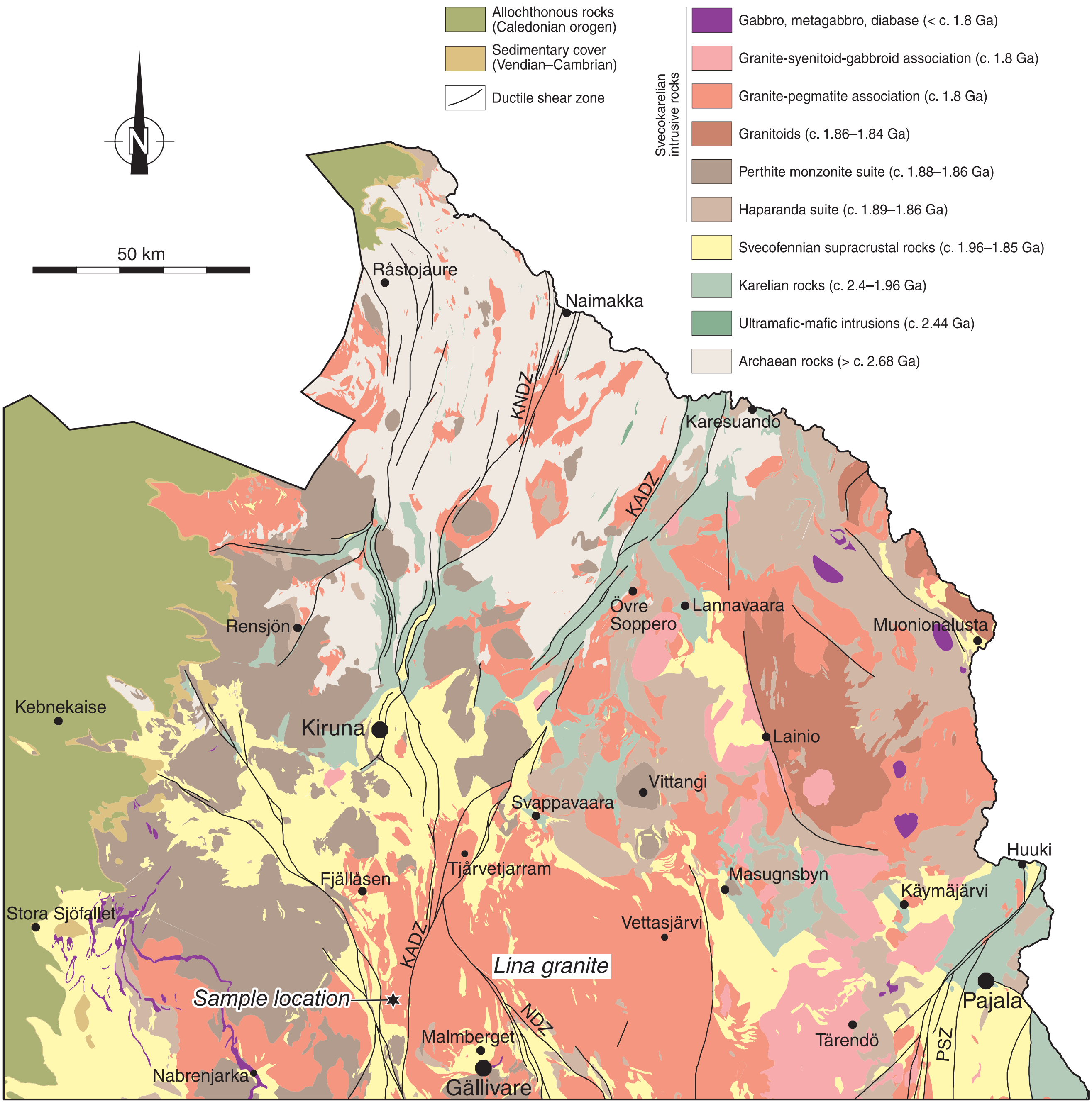


Fig. 1. Bedrock map of northern Norrbotten county, modified from Bergman et al. (2000), with indication of the sample location. KADZ = Karesuando-Arjeplog deformation zone, KNDZ = Kiruna-Naimakka deformation zone, NDZ = Nautanen deformation zone, PSZ = Pajala shear zone.

association. It is intruded by a gabbro-diabase suite of uncertain age.

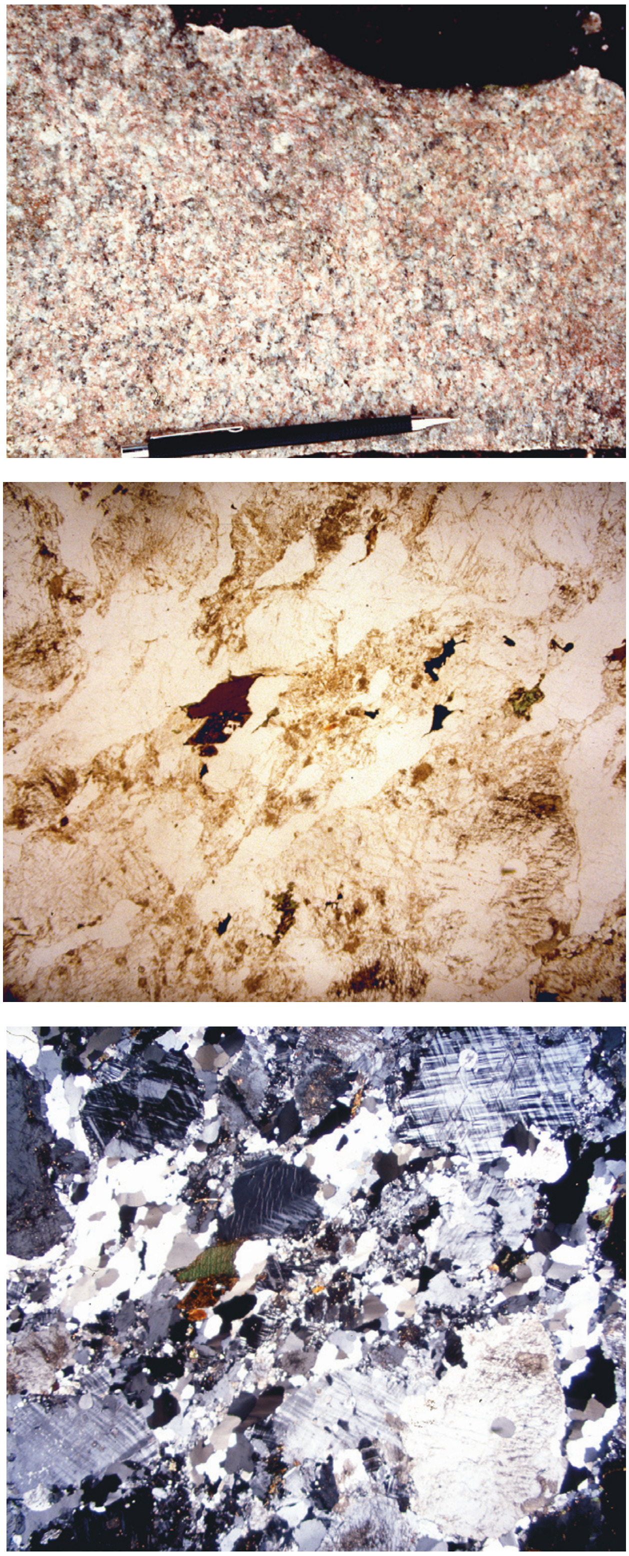
Northernmost Sweden is characterised by an approximately NNE–SSW to NNW–SSE structural grain. High-strain zones alternate with zones of little deformation, which makes the degree of deformation highly variable. Intense deformation and high-grade metamorphism are found in the eastern part of the area, e.g. in the Pajala shear zone. Another important regional zone is the Karesuando–Arjeplog deformation zone, which transects the central part of the area, including the Lina granite.

The rocks of the Granite-pegmatite association have a mean density of about 2 620 kg/m^3. The area occupied by Lina granite coincides with a positive long-wave gravity anomaly, which suggests that the granite is underlain by mafic rocks. Results from inversion modelling suggest different solutions which all, however, point to the occurrence of an extensive rock mass with densities of more than 2 750 kg/m^3 (width approx. 30 kilometres from east to west) at a depth of 8 kilometres to more than 2 850 kg/m^3 at a depth of 12 kilometres (Bergman et al. 2001). This implies that the overall geometry of the granite is a flat-lying sheet.

The Lina granite in the considered area is commonly greyish red, medium grained and weakly porphyritic (Fig. 2a). Red, finely grained and evenly grained varieties are also common. The content of mafic minerals is low with biotite as the common phase; muscovite is rare. The granite is usually associated with pegmatite, which in some areas forms large massifs. Fragments of assimilated country rock are common as well as diffuse bands with a higher biotite content than in the normal granite. Dykes and veins of granite, pegmatite or aplite belonging to this suite are common in older rocks.

Öhlander et al. (1987) studied the chemical characteristics of the Lina granite, which was called the Vettasjärvi granite in that paper. They found e.g. a restricted range in the SiO_2 content of 71.4–76.6 % and low contents of niobium, yttrium, tin, and fluorine. From the mineralogy and major and trace element geochemistry they concluded that the granite has a minimum-melt character and is undifferentiated. Negative initial ε_{Nd} values gave evidence for crustal anatexis with a major Archaean component as source material. Major element and oxygen isotope compositions suggested that the sources contained little or no pelitic material. Anomalous thorium contents (up to 75 ppm) of the Lina granite were reported by Bergman et al. (2001). A chemical analysis of the dated sample is presented in Table 1.

The Lina granite is isotropic in places, but normally a weak foliation can be seen. When observed in contact with more strongly foliated rocks of the Haparanda suite the foliations in both rocks are parallel, which suggests that the granite intruded while regional deformation was still active. The intensity of the foliation increases towards the Karesuando–Arjeplog deformation zone in the west, where Lina granite mylonites are present.



a) b) c)

Fig. 2. a) Greyish red, medium-grained, slightly porphyritic and foliated Lina granite from the type locality. b) Photomicrograph of the Lina granite. Note euhedral titanite crystal in contact with biotite grain. The height of the photograph equals 9.3 millimetres. c) Same as b) but with crossed nicols. Note aggregates of recrystallised quartz around feldspar grains.

Description of the sample locality

The granite sample STB971037 (Fig. 2a) was taken from an outcrop at the type locality in the map area 28J Fjällåsen SO. The co-ordinates in the Swedish National Grid RT 90 are 7472100/1689180. The outcrop consists of a greyish red, medium-grained, slightly porphyritic granite. The phenocrysts are up to 10 millimetres in size and consist of plagioclase and microcline. Millimetre-wide biotite-rich bands and lenses of quartz are found locally. The granite also contains pockets of pegmatite and is cross-cut by aplite dykes. The magnetic susceptibility measured on the outcrop varies between 2 000 and 5 000 x 10^{-5} SI units, with a median value of 2 500. A weak foli-

TABLE 1. Chemical analysis of the dated granite sample STB971037. The analysis was performed by Svensk Grundämnesanalys AB, Luleå. All elements were analysed by ICP-AES, except Ga, Hf, Mo, Nb, Rb, Sn, Ta, Th, U, W, Y and the rare earth elements which were analysed by ICP-MS.

	(wt %)		(ppm)		(ppm)
SiO_2	72.9	Ba	919	La	56
TiO_2	0.209	Be	1.57	Ce	100
Al_2O_3	14.1	Co	<5.24	Pr	10.7
Fe_2O_3	1.92	Cr	21.9	Nd	35.7
MnO_2	0.0218	Cu	<5.24	Sm	4.77
MgO	0.284	Ga	13.3	Eu	0.746
CaO	1.24	Hf	6.28	Gd	4.29
Na_2O	3.99	Mo	1.46	Tb	0.812
K_2O	4.62	Nb	9.01	Dy	3.29
P_2O_5	0.0893	Ni	24.2	Ho	0.812
Oxide sum	99.4	Rb	132	Er	2.08
LOI	0.2	Sc	<1.05	Tm	0.449
		Sn	5.09	Yb	1.86
		Sr	174	Lu	0.289
		Ta	1.75		
		Th	32.5		
		U	1.22		
		V	10.4		
		W	0.353		
		Y	16.3		
		Zn	31		
		Zr	214		

ation is defined by a preferred orientation of feldspar crystals and quartz aggregates. It varies in strike between north and north-west, and dips steeply to the west or south-west. The outcrop is flat due to gently dipping fractures, which is a characteristic feature of the Lina granite. The granite has been quarried to a minor extent.

Petrographic description and analytical results

In thin section (Fig. 2b, c) the following minerals have been observed: quartz, microcline, plagioclase, sericite, biotite, chlorite, magnetite, titanite, and zircon. The quartz is recrystallised and consists of elongated aggregates, with individual grains showing undulose extinction. Plagioclase grains are zoned with strongly sericitised internal parts and less altered rims. Microcline crystals are largely unaltered. Reddish brown biotite is a minor constituent showing local alteration to chlorite. Large euhedral grains of titanite are most likely of igneous origin. Titanite is also found as small grains in irregular aggregates between larger feldspar crystals. The foliation referred to above can also be seen in thin section.

The analyses were made at the Laboratory for Isotope Geology in Stockholm. The analytical procedures are described in the Editor's Preface to this volume. Analytical results from four zircon fractions and one titanite fraction are presented in Table 2. The zircons are mostly white to yellowish grey but brown grains are also found. Almost all are turbid and contain numerous cracks. Separate, clear, colourless crystals, however, are also present. Most zircons are euhedral with low-order crystallographic faces. The length/width ratio is 2–4. Cores are visible in some grains but the turbid nature generally makes it difficult to distinguish any internal structures. Fractions 1 and 2 are clear and euhedral with sharp edges and terminations but some turbid domains are present. Fractions 3 and 4 are brownish and more metamict. The zircons of fraction 4 have a multitude of longitudinal fractures. All fractions were strongly abraded.

The titanites are generally dark or reddish brown but light brown and yellowish brown grains are also present. One titanite fraction of large, dark brown crystals was selected and analysed. The grains were moderately abraded.

Three of the four analysed zircon fractions define a discordia with intercept ages of 1811±6 and 402±28 Ma and an MSWD of 0.2 (Fig. 3). Fraction 2 plots to the right of the discordia and indicates an older age. Fractions 3 and 4 are strongly discordant and are more uranium-rich than the others. Fraction 4, moreover, has a deviating ^{208}Pb content.

The titanite plots just slightly discordantly. A discordia through zero with a conservative error of ±400 Ma yields an upper intercept age of 1771^{+7}_{-5} Ma (Fig. 3).

Discussion

The titanite age is interpreted as the magmatic age of the rock. This is based on that the euhedral, large titanite grains that were observed in thin section are most likely igneous, and that no major metamorphic event has affected the Lina granite. The weak ductile deformation of the

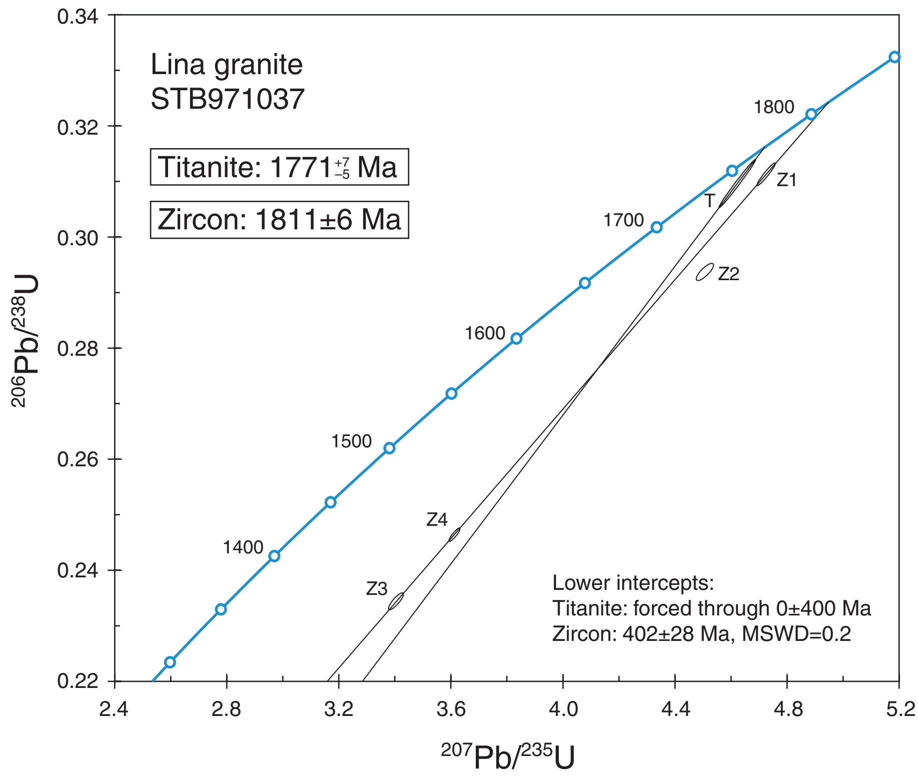


Fig. 3. Concordia diagram for analysed zircon and titanite fractions from the Lina granite sample STB971037.

granite was accomodated by recrystallisation of quartz, and did not visually affect the titanite grains. The closure temperature of the U-Pb system in titanite at slow cooling rates is estimated to be 630–730 °C, depending on e.g. grain size (Möller et al. 2000 and references therein). Examples from the Precambrian of the Fennoscandian Shield have been reported in which igneous titanite in granitoids has yielded identical ages as for zircon (e.g. Kornfält et al. 1997, Lundström & Persson 1999, Söderlund et al. 1999). However, since the cooling history of the granite pluton is not known, the age must be treated as a minimum age.

Due to the strong discordance of the zircons and the fact that one fraction plots outside the discordia, the zircon result must be treated with caution. It is likely that the analysed zircons are affected by inheritance, although no cores could be detected under the stereo microscope. No signs of assimilated older rocks (e.g. biotite-rich bands) were evident in the granite sample, but it is still possible that such components were present. Inheritance is a common feature among other rocks of this generation (see e.g. Wikström & Persson 1997).

The observation of a strong foliation in rocks of the Haparanda suite, while the Lina granite only shows a weak foliation, suggests that the regional deformation was in a waning stage at 1771 Ma ago. The Karesuando-Arjeplog deformation zone is an expression of the heterogeneous deformation during the Svecokarelian orogeny.

TABLE 2. U-Pb isotopic data for sample STB971037.

Analysis No.	Weight (µg)	No. of crystals	U (ppm)	Pb tot. (ppm)	Common Pb (ppm)	$^{206}Pb^{a}/^{204}Pb$	$^{206}Pb - ^{207}Pb - ^{208}Pb$ Radiog. (atom %)[b]	$^{206}Pb^{b}/^{238}U$	$^{207}Pb^{b}/^{235}U$	$^{207}Pb/^{206}Pb$ age (Ma)
Zircon 1	21	14	193.3	68.9	0.11	13551	75.3–8.3–16.4	0.3113±17	4.725±27	1801±3
Zircon 2	10	12	226.9	76.9	0.32	6020	74.9–8.4–16.7	0.2937±13	4.507±25	1821±6
Zircon 3	18	35	424.3	116.0	2.77	1866	75.6–8.1–16.4	0.2344±12	3.404±22	1720±6
Zircon 4	14	7	537.4	145.8	0.75	6358	78.6–8.3–13.1	0.2464±10	3.613±16	1738±4
Titanite	89	11	88.8	77.3	0.50	2828	31.0–3.3–65.7	0.3096±36	4.622±54	1771±3

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

The results presented here imply that this zone was still active after 1771 Ma ago.

Spatially related to the margins of the large Lina granite intrusion, there is a zone of high-grade metamorphic rocks (approximately 10 km wide in the present erosional surface). This spatial relationship suggests that the metamorphism is related to the formation and/or emplacement of the granite. This is in accordance with results from migmatitic rocks in the area south of Pajala, where metamorphic U-Pb ages in the range c. 1810–1774 Ma have been reported (Bergman & Skiöld 1998).

West of the sample locality the bedrock is intruded by a large flat-lying dolerite intrusion (Nabrenjarka gabbro diabase, Witschard 1975). The precise age of the diabase in not known, but some parts of the diabase and some satellite intrusions cross-cut a granite which is similar to the Lina granite. This indicates that the diabase has a maximum age of 1.77 Ga.

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Age, geochemistry and crustal contamination of the Hemberget mafic–ultramafic layered intrusion in the Knaften area, northern Sweden

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Billström K., Wasström, A., Bergström, U. & Stigh, J., 2002: Age, geochemistry and crustal contamination of the Hemberget mafic–ultramafic layered intrusion in the Knaften area, northern Sweden. *In* S. Bergman (ed.): *Radiometric dating results 5*. Uppsala 2002. *Sveriges geologiska undersökning C 834*, pp. 18–30. ISBN 91-7158-668-7.

The Hemberget gabbroic–ultramafic intrusion is located in the northern part of the Knaften area, south of the Skellefte district in northern Sweden. This layered intrusion intruded conformably as a sill along the contact between a mafic–intermediate volcanic sequence and an overlying felsic, reworked tuffitic sediment. During a late stage of solidification of the gabbroic–ultramafic intrusion, more intermediate differentiates intruded which now comprise dykes and sills of varying grain size. This intrusion event took place during an extensional stage at c. 1870 Ma ago, as suggested by U-Pb isotope (ion microprobe) data for zircons collected from one of these dykes. The outlined process is temporally connected with crustal extension, incipient rifting and magmatism in the Skellefte and Arvidsjaur districts. The gabbro–ultramafic intrusion has the chemical characteristics of a contaminated mantle-derived rock, and from Sm-Nd isotope evidence (ε_{Nd} values ranging between approximately –1.2 and +1.4) it could be advocated that some crustal material was admixed with the mantle-derived magma at relatively shallow crustal levels. Most likely this contamination is due to the incorporation of pre-1.95 Ga greywackes, which in turn contain minor amounts of an Archaean component. The greywackes are also likely to have contributed an Archaean zircon found in the investigated dyke sample. Apparently, the Sm and Nd concentrations vary considerably within the gabbroic–ultramafic intrusion, whereas the Sm/Nd ratios remain fairly constant. It is suggested that the former feature is only partly explained by the effect of different degrees of crustal assimilation. Also the variable mineralogy, which is a consequence of the layered structure, must be considered in this context.

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Introduction

The early Proterozoic bedrock of northern Sweden comprises a variety of rock types that formed c. 2.0 to 1.8 Ga ago. These rocks were formed during the Svecokarelian orogeny, which generally is assumed to have been characterised by a series of events including the formation of volcanic arc complexes, sedimentation, extensional tectonics, amalgamation of discrete arcs, regional metamorphism, intrusions of granitoids, and deformation.

A less well understood topic is the geologic history and general stratigraphy of the Proterozoic rocks within the marine Bothnian basin (cf. Lundqvist et al. 1998). The rocks of this basin define the Bothnian Group (Kousa & Lundqvist 2000) and they are dominated by turbiditic metagreywackes with local metaargillitic and intermediate–mafic metavolcanic intercalations. Felsic metavolcanic rocks are subordinate. Detrital zircons in the metagreywackes have yielded U-Pb ages between 2.1 and 1.9 Ga, but there is also a significant Archaean population present (Claesson et al. 1993).

Within the Bothnian basin (Fig. 1) there are several minor supracrustal-dominated areas which are more or less totally enclosed by large massifs of 1.8 Ga old post-orogenic granites, making correlations with adjoining areas difficult. The Knaften area, situated some 50 km south of the Skellefte District, is one such isolated area. It contains a 1954 Ma old metagranitoid that has intrusive contacts with surrounding metavolcanic and metasedimentary rocks (Wasström 1993). The discovery of this intrusion changed the prevailing view that sedimentary units in the Svecofennian part of Sweden always were overlying c. 1.9 Ga volcanic arc sequences. A 1940 Ma age for a metarhyolitic porphyry dyke (Wasström 1996) in the Knaften area, and later a 1959 Ma age for a metadacite in the Stensele area west of the Skellefte district (Eliasson & Sträng 1998), added further support to the existence of pre-1.9 Ga sediments. Also, intrusive granitoids in the southern part of the Bothnian basin have been dated at about 1.93 Ga (Lundqvist et al. 1998). In addition, intrusive metagranitoids with U-Pb zircon ages slightly above 1900 Ma have been identified at the edges of the Skellefte district, at Blåviksjön, approximately 45 km NW of the Knaften area (Björk & Kero 1996), at Björkdal in the easternmost part (Billström & Weihed 1996), and at Kristineberg (Bergström & Sträng 1999) in the westernmost

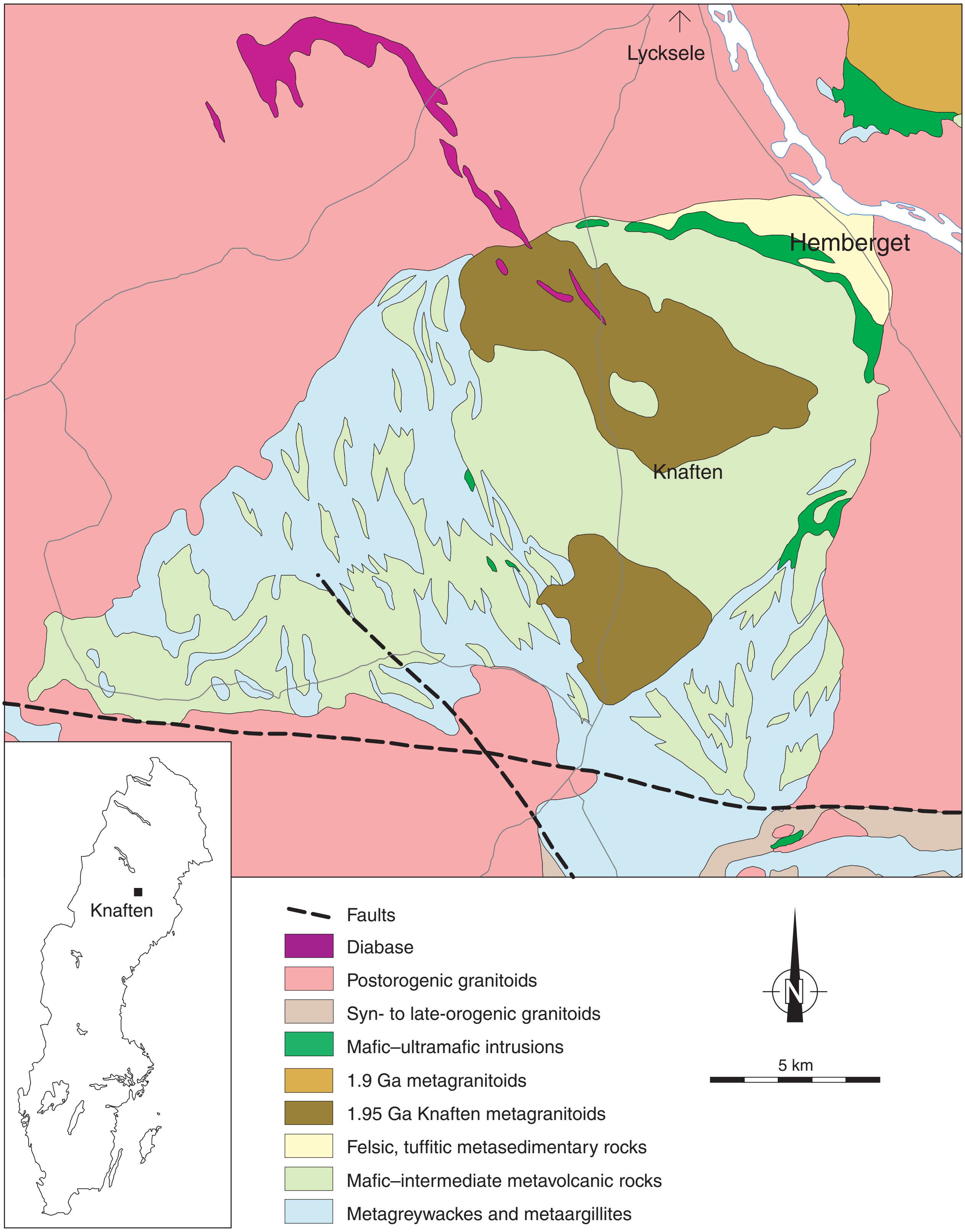

Fig. 1. Regional geology of the Knaften area (modified from Wasström 1990).

part of the Skellefte district.

This paper describes a layered gabbroic–ultramafic intrusion (hereafter referred to as a *gabbro*) at Hemberget in the northern Knaften area. Several other gabbroic rocks occur in the northern part of the Bothnian basin, including Ni-bearing varieties in the so called Ni-zone situated east of the Knaften area and in the Risliden area north of the Knaften area (Nilsson 1985), but only limited geological information about these rocks has been published. Radiometric isotopic (U-Pb and Sm-Nd) and geochemical data, together with field observations, have been obtained for the Hemberget intrusion. These results will be discussed in the context of the timing and nature of emplacement of the gabbro intrusion. The rocks discussed from the Hemberget area are generally affected by a regional metamorphism, but for reasons of simplicity, the prefix *meta-* will be dropped below.

Geology of the Knaften area

The Knaften area (Fig. 1) is dominated by MORB- to island arc-type mafic–intermediate, pillowed and massive volcanic rocks, as well as both mono- and polymict volcaniclastic rocks (Wasström 1990). The volcanic sequence has been named the Knaften Group in the literature (Kousa & Lundqvist 2000), and the volcanic rocks are intercalated with turbiditic greywacke and graphite-bearing argillitic sedimentary rocks (Wasström 1990), which belong to the Bothnian Group. The entire sequence has been intruded, as previously mentioned, by the Knaften granitoids (1954±6 Ma, Wasström 1993) and by quartz-feldspar porphyritic dykes (1940±14 Ma, Wasström 1996). The granitoids and dykes are chemically similar to the calc-alkaline, felsic reworked tuffitic sedimentary rocks which are found in contact with the Hemberget gabbro.

Mafic–ultramafic sills have locally intruded along the contact between mafic–intermediate volcanic and volcaniclastic rocks and the overlying calc-alkaline felsic, reworked tuffitic sedimentary rocks. Similar sills elsewhere in the Knaften area have intruded into the volcanic and volcaniclastic rocks. These intrusions have a high magnetic susceptibility and their shapes were constrained using magnetic anomaly maps. Small Ni occurrences are known from some of these intrusions (Nilsson 1985).

The regional Svecokarelian deformation and metamorphism (upper greenschist to amphibolite facies conditions) in this part of Sweden occurred between 1865 and 1820 Ma (Kousa & Lundqvist 2000). Other observations, however, made close to Burträsk, about 50 km SE of the Skellefte district (Rutland et al. 1997), and in the eastern Skellefte district (Lundström et al. 1999), show an earlier pre-1.88 Ga deformation that has affected the bedrock, suggesting that a deformation of that age may also have affected the Knaften area.

At c. 1.81–1.78 Ga (Claesson & Lundqvist 1995, Kousa & Lundqvist 2000) large areas in this region were intruded by late to post-orogenic granitoid intrusions belonging to the Revsund suite. Even later, at 1.25–1.20 Ga, anorogenic dolerite dykes intruded (e.g. Lundqvist et al. 1990).

The Hemberget layered intrusion

The Hemberget intrusion constitutes an approximately 13 km long and at least 400 m thick arc-shaped body (Figs. 1 & 2). North of Lake Storbacksjön, the rock is exposed in outcrops allowing samples to be taken along a profile across the sill (Fig. 2).

This layered gabbro intruded semi-conformably at the contact between the mafic–intermediate volcanic rocks and felsic, tuffitic, reworked sedimentary rocks in the northern Knaften area (Fig. 2). The volcanic rocks include units of basaltic and andesitic compositions and are of the same type as those intruded by 1.95–1.94 Ga Knaften granitoids, suggesting that this age range sets a minimum emplacement age for the local supracrustal succession. At Lill-Tannträsket, the 1.81–1.78 Ga Revsund type granite has brecciated an ultramafic part of the Hemberget intrusion, and the lower limit for the emplacement of the gabbro is thus about 1.8 Ga.

The gabbro intrusion is mainly massive and medium-grained (6–7 mm), although both more fine-grained and coarse-grained (2–5 cm) varieties occur. In some outcrops stratigraphic younging directions have been possible to determine (up towards N05E–N10W/75N). The lower (southern) part seems to be somewhat more coarsely grained than the upper (northern) part. The magnetic susceptibility of the intrusion is in the range 35 to 5500 µSI, with the higher values in the more ultramafic parts.

At Hemberget, rhythmic layering (cumulate) occurs in some of the outcrops but at most places the gabbroic rock is massive without visual layering. The layering is normally from 0.5 dm up to some dm thick and can locally be traced in the strike direction (Fig. 3) for a maximum of tens of metres. At the lower part of the intrusion, the layers are dark melanocratic and pyroxene-rich (now amphibole), changing towards more light, leucocratic, and plagioclase-rich in the upper parts. Detailed magnetic surveys reveal magnetite concentration in some layers. The layering is subparallel to the strike of the intrusion and coincides rather well with the direction of the way-up determinations within the felsic tuffitic sedimentary rocks north of the intrusion. This indicates that the gabbroic body intruded as a sill during extension.

The intrusion is foliated in N70–85W/60–90N and thin ductile and brittle deformation zones are common. Due to the regional metamorphism and related alterations, the mineralogy corresponds to an upper greenschist facies metamorphic assemblage. Amphibole is the most common mineral (>70 %), comprising variable amounts

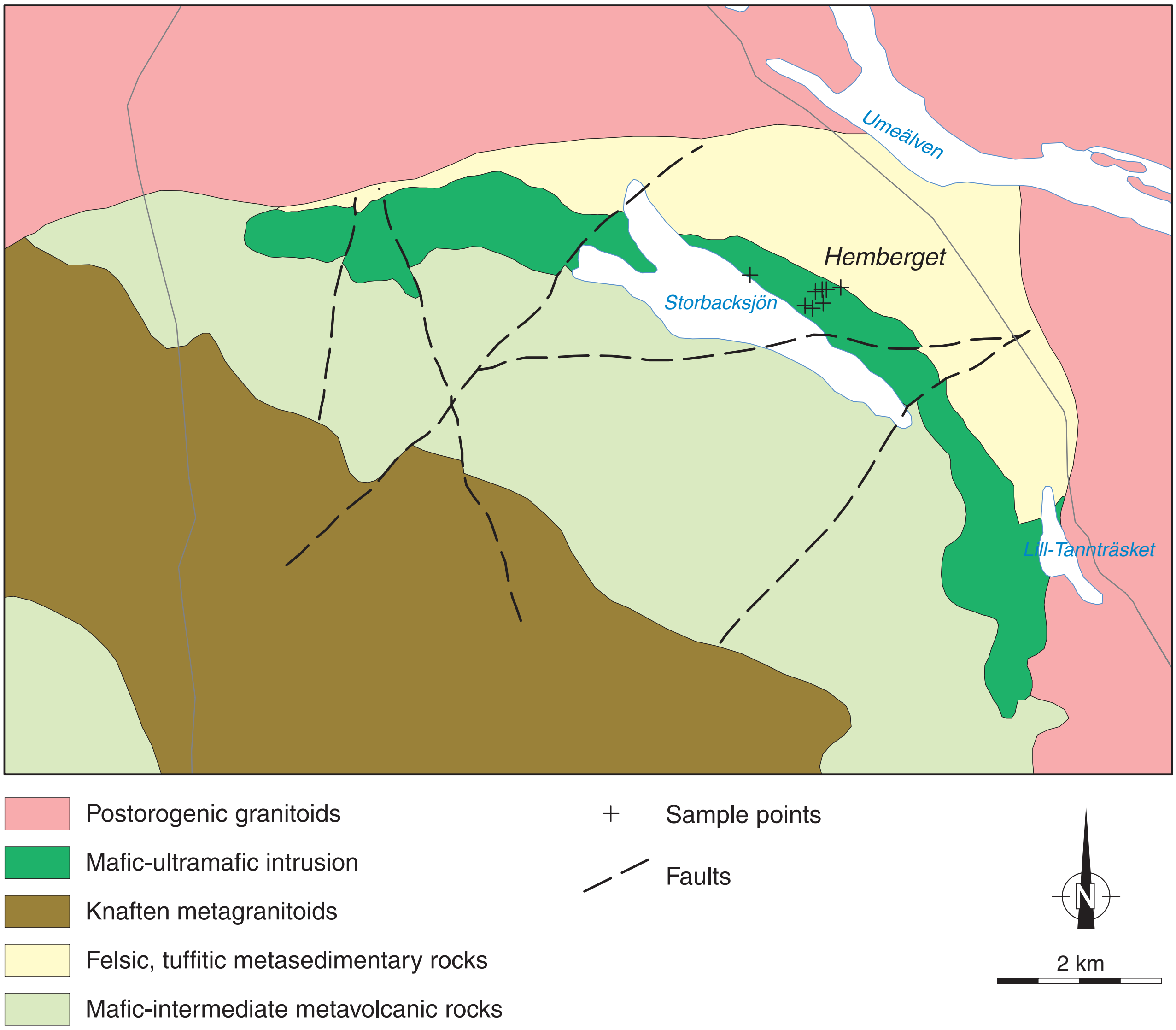

Fig. 2. Geological map of the Hemberget gabbro–ultramafic intrusion, based on a detailed interpretation of the magnetic anomaly map, also showing localities for geochemical/isotopic sampling.

of actinolite-tremolite, cummingtonite, and hornblende. Some amphiboles form rosettes or porphyroblasts, and others are pseudomorphs after pyroxene phenocrysts. Olivine has turned into iddingsite, bowlingite, and serpentine. The plagioclase is normally completely altered into muscovite-sericite, although some plagioclase (up to 9 %) may have survived in less altered parts. Accessory minerals include chlorite group minerals, calcite, biotite (locally up to 11 %), opaque minerals such as Fe oxides, epidote, apatite, zircon, titanite, and quartz (secondary).

Highly assimilated inclusions are common in some parts of the intrusion. Their origin is difficult to determine since the primary features are destroyed due to the assimilation processes. They may consist either of pieces of the roof wall-rock (the felsic tuffitic sediment) or the conduit crust (mainly greywackes and mafic–intermediate rocks), or they may originate from deeper levels in the crust.

Late residual phases

Minor aplitic and coarse-grained intermediate sills, dykes and pods, mainly <1 m wide, were found in the Hemberget gabbro intrusion during mapping. These were interpreted as late residual melts differentiated from the same magma that formed the host gabbro intrusion. These intermediate rocks must not be confused with the 1.94 Ga rhyolitic porphyritic dykes, which are related to the Knaften granitoids and which cross-cut the supracrustal rocks (Wasström 1990, 1996). The intermediate intrusions occur in a number of emplacement modes, comprising both sills parallel with the general stratification and cross-cut-

Fig. 3. Photo showing an outcrop with a typical layered sequence of the gabbro at Hemberget. Photo A. Wasström.

ting dykes. In the southern part of the exposed gabbro sill, the dykes are straight with a north-east trending direction, crossing the inferred layering of the sill at high angles. Further to the north, the dykes show a somewhat more wavy appearance with orientations trending more north–south and cross-cutting the layering at 30–60 degrees. In the northernmost part, the dykes are parallel to the contact with the tuffitic sediments.

The dykes are typically dark gray and even-grained, but the grain size varies considerably, giving the impression in the field of rocks ranging texturally from aplite to coarse-grained, almost pegmatitic types. The difference in grain size probably reflects a variable fluid content in the magma. Some of the dykes/sills are affected by alteration, as indicated by local sericitisation.

The mineralogy of the dykes is dominated by plagioclase and an actinolitic amphibole. The plagioclase, occurring as larger sericitised grains, has an oligoclase to andesine composition but smaller interstitial crystals also occur. Actinolite, related to small opaque grains of mainly magnetite, occurs as clusters. Quartz forms relatively small, interstitial crystals of a partly hexagonal shape. The quartz content is low, and with regard to this feature, it is justified to refer to these dykes as diorites. Potassium feldspar is totally absent. Accessories are apatite and zircon; in altered samples also carbonates, malachite, and chalcopyrite.

Geochemistry

Geochemical samples were taken along a profile from the exposed bottom to the top of the gabbro sill, and include two ultramafic samples (Kn-2 and Kn-5a), four gabbroic samples (Kn-1 and Kn-6 to Kn-8), and two intermediate samples: One dyke with an aplitic texture (Kn-4b) and one intermediate dyke/sill with a pegmatitic texture (Kn-5b) were also sampled. The locations are shown in Figure 2. The geochemical analyses were made by SGAB in Luleå (Sweden), applying the ICP-AES and ICP-MS methods. The dissolution step comprises a powdered sample of 125 mg, which was digested with 0.375 g of $LiBO_2$ and subsequently dissolved in nitric acid. Representative data from different parts of the intrusion are presented in Table 1, and data are given as mean values based on 3–4 measurements of each element.

The cumulate rocks of the Hemberget intrusion can geochemically be divided into ultramafic and mafic cumulates (Table 1).

The pegmatitic and aplitic dyke/sill phases are gabbro–diorites according to the criteria of De la Roche et al. (1980), whereas they are gabbros and diorites, respectively, when applying the criteria of Debon & Le Fort (1982) and Cox et al. (1981).

The gabbro intrusion is partly ultramafic, with high MgO (13.5–23.5 %), low TiO_2 (0.390–0.606 %), and low CaO (7.17–10.9 %). The alkalies are generally low, but increasing K (and LOI) occurs in the upper parts of the intrusion, probably due to assimilation processes. High Cr, Ni and Cu are related to samples with high MgO and these samples are found mainly in the upper parts of the sill. Elements such as Na, Zr, Y, and Sc are more enriched in the lower levels. This suggests more than one generation of magma influx, as the most primitive olivine-rich samples are found in the upper levels.

The samples taken from the late residual phases (aplitic and pegmatitic) represent geochemically more fractionated rocks, characterised by a high Na/K ratio and strong enrichment in trace elements like Sr and high field-strength elements as compared to the gabbro (Table 1). The aplitic sample does not seem to be particularly enriched in elements that could indicate assimilation, but the coarse-grained sample has elevated levels in elements like K, Rb and Ba. When comparing the geochemistry between the gabbroic intrusion and the late residual phases, most of the differences can be explained by fractional crystallisation and perhaps minor contamination. The geochemical similarities are striking, however, which strongly suggests that the two magma types emanated from a common source.

The gabbro samples show weakly fractionated REE patterns (Fig. 4a) with no major discrimination between the lower and upper parts of the intrusion. The samples from the late residual phases show rather flat REE curves with distinct Eu anomalies (Fig. 4b). In a spidergram these phases display a positive Sr anomaly, but no negative Nb anomaly is present, which is typical for volcanic arc magmas (Fig. 4c).

Sm and Nd concentrations are higher for the late residual phases as compared to the gabbroic ones (see Table 1 and Fig. 5), which is consistent with the expected

TABLE 1. Geochemistry of selected rock types of the Hemberget intrusion.

	MAFIC CUMULATES			ULTRAMAFIC CUMULATES			INTERMEDIATE SILLS/DYKES	
SAMPLE	Kn-1	Kn-8	Kn-7	Kn-2	Kn-5a	Kn-6	Kn-4b	Kn-5b
SiO_2 (wt %)	48.1	47.7	47.9	45.1	45.3	46.0	58.2	57.5
TiO_2	0.606	0.478	0.425	0.391	0.39	0.416	1.4	1.06
Al_2O_3	12.5	11.4	9.97	7.57	7.92	8.88	18.2	13.7
Fe_2O_3	12.4	11.2	11.1	11.3	11.3	10.6	5.88	7.25
MnO	0.188	0.187	0.186	0.176	0.181	0.17	0.112	0.183
MgO	13.5	15.5	17.2	23.5	23	20	3.13	6.95
CaO	8.9	10.9	9.62	7.17	8.21	9.75	7.4	6.08
Na_2O	2.19	2.02	1.94	0.363	0.63	0.868	5.55	5.7
K_2O	0.611	0.357	0.799	0.0859	0.107	1.2	0.308	0.661
P_2O_5	0.118	0.119	0.109	0.115	0.116	0.117	0.418	0.326
LOI	1.5	0.8	1.4	4.6	3.1	2.5	0.5	1.4
SUM	100.6	100.7	100.6	100.4	100.3	100.5	101.1	100.8
Ba (ppm)	141	99.7	170	15.5	3.59	142	161	519
Co	59.2	58.6	64.1	78.4	88.4	73.1	18.7	22.4
Cr	1020	1510	1500	2270	2240	2320	61.4	417
Cu	56.6	33.9	24	38.6	50.5	72.2	84.5	364
Ga	29.1	22.5	25.6	14.3	14.9	22	32.1	32.2
Hf	1.43	1.38	0.953	1.14	0.881	0.688	4.58	4.01
Mo	1.11	0.97	0.775	1.06	0.826	0.944	1.07	7.44
Nb	2.46	2.53	2.7	2.24	1.77	1.56	11.7	11.1
Ni	215	361	465	746	771	572	22.5	79.6
Rb	37	13	35.3	7.3	8.08	53.4	12.7	33.8
Sc	32.9	29.1	25.7	22.5	21.7	27.5	10.3	20.9
Sn	2.72	2.05	3.13	1.79	1.01	2.43	0.915	2.12
Sr	372	203	149	107	77.9	196	603	1200
Ta	0.173	0.219	0.227	0.137	0.132	0.108	0.716	0.918
Th	1.92	1.97	2.13	2.07	2.03	1.59	4.53	8.06
U	0.985	0.955	1.21	1.14	1.21	1.02	2.58	2.99
V	211	195	166	146	143	160	126	262
W	0.434	0.264	0.441	0.537	0.354	0.77	0.299	0.438
Y	14.7	9.25	9.02	10.7	5.46	5.29	24.7	27.4
Zn	102	89.6	88.3	72.3	70.6	78.1	34	59.7
Zr	34.4	35.2	35.8	26.8	25.2	19.7	176	135
La	5.95	7.62	8.3	6.48	5.42	6.29	9.55	22.3
Ce	14.1	17.6	17.4	14.5	12.6	13.3	28.8	50.3
Pr	1.75	2.25	2.07	1.72	1.63	1.57	3.54	6.18
Nd	8.79	10.5	9.32	8.19	7.61	6.71	17.6	26
Sm	1.81	1.95	2.1	1.53	1.32	1.2	3.97	5.24
Eu	0.502	0.702	0.602	0.406	0.185	0.443	0.765	0.675
Gd	2.61	2.89	2.76	2.43	1.9	1.93	5.79	7.74
Tb	0.425	0.415	0.37	0.303	0.248	0.228	0.817	0.958
Dy	1.96	2.29	2	1.54	1.17	1.33	4.83	5.96
Ho	0.476	0.517	0.464	0.342	0.278	0.298	0.97	1.21
Eb	1.28	1.21	1.26	0.817	0.722	0.712	2.86	3.43
Tm	0.191	0.227	0.186	0.186	0.111	0.144	0.434	0.506
Yb	1.07	1.17	1.05	0.632	0.544	0.574	2.34	2.83
Lu	0.161	0.185	0.186	0.107	0.112	0.105	0.387	0.359
	Low intr.	Low intr.	Low intr.	Up intr.	Up intr.	Contact	dyke	sill
Coordi-nates	164100E 715943N	164046E 715974N	164111E 715949N	164109E 715958N	164116E 715960N	164134E 715962N	164106E 715942N	164116E 715960N

pattern (Faure 1986) for a set of co-magmatic samples involving late differentiates as well as more primitive mafic specimens. A tendency for decreasing Sm and Nd concentrations towards the top of the intrusion is also noted (Fig. 5). Sm/Nd ratios, on the other hand, are fairly constant, irrespective of sample type or the location within the intrusion.

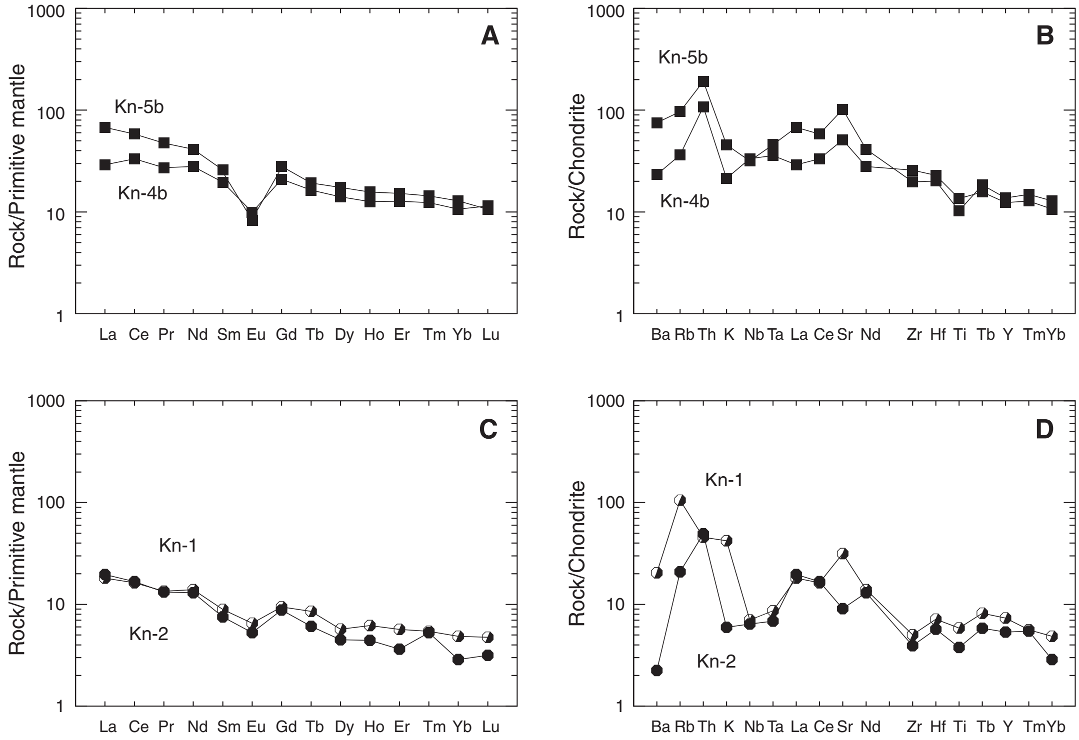

Fig. 4. Geochemical diagrams for samples from the Hemberget intrusion. a) REE plot for intermediate dykes/sills, normalised to primitive mantle (Sun 1982), b) Spidergram plot for intermediate dykes/sills, normalised to chondrite (Thompson 1982), c) REE plot for one mafic cumulate sample and one ultramafic cumulate sample, normalised to Primitive mantle (Sun 1982), d) Spidergram plot for one mafic cumulate sample and one ultramafic cumulate sample, normalised to chondrite (Thompson 1982).

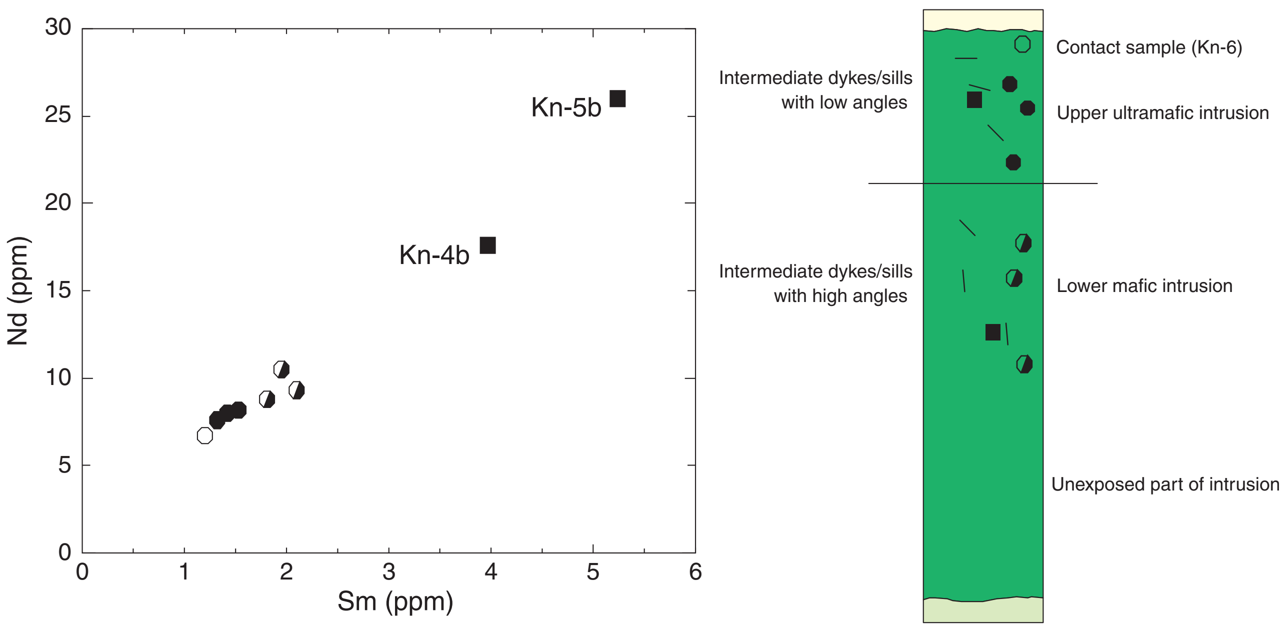

Fig. 5. Co-variation of Sm and Nd concentrations with a stratigraphic column for the Hemberget intrusion including sample points. High and low angles refer to the strike of the dyke/sills in relation to the observed layering in the intrusion.

Isotope analytical procedures and sample description

Zircon is a useful mineral for constraining magmatic crystallisation ages, and a minor amount of zircon was extractable from the intermediate sample (Kn-5b). Zircons are variably well crystallised, but the majority of the grains have a prismatic shape and are metamict. Dark inclusions are common and biotite and amphibole often forms minor overgrowths on zircon grains. In the cathodoluminescence (CL) pictures, cores were seen in crystals 1 and 5 (Table 2), and a zonation in U concentration was noted for a few grains.

U-Pb analyses on single zircon crystals were performed using the ion microprobe (NORDSIM facility) at the Laboratory for Isotope Geology (LIG) of the Swedish Museum of Natural History. The SIMS analyses at LIG followed routines described in Whitehouse et al. (1999). Errors on ratios and ages in Table 2 are 1σ and include propagated errors on the standard analyses (Geostandards 91500; 1065 Ma, Wiedebeck et al. 1995). All results of regression calculations are presented at the 95 % confidence level.

Sm-Nd data were obtained for five of the specimens that were sampled for geochemical analysis (Table 3). It should be noted, however, that the whole-rock powder analysed with the isotope dilution technique is not identical with the powder used for geochemical work. That is, one set of rock chips was taken in the field for isotope work and another for geochemistry work. This point is further outlined below in the discussion of the significance of concentration data obtained by different methods. The Sm-Nd analytical work followed routine procedures used at LIG (Billström & Weihed 1996).

Isotope results

U-Pb data

Only relatively few U-Pb zircon data are available. Data have been collected from altogether nine spots from six discrete grains (Table 2). The analytical errors are considerable, but three spots generate almost concordant ages as defined by a mean ^{207}Pb/^{206}Pb age at 1865 Ma (Fig. 6). Five of the remaining spots show a variably discordant behaviour, and if these are linearly regressed together with the concordant points they define an age of 1866±11 Ma (MSWD = 6.9). The corresponding lower intercept age is 184±52 Ma age, which is in agreement with data for other Svecofennian rocks, and suggests that the regression is justified. The n12a data spot is very discordant and may even be Archaean in age, and if this point is left out of the regression, the upper intercept age changes to 1868±11 Ma (Li = 225±79 Ma) with a MSDW value of 4.4. These two regressions include both inner and outer parts of grains, and the samples involved in the regression are thus seemingly simple grains with no core-overgrowth complexities. We therefore choose to consider 1.87 Ga as the magmatic emplacement age for the intrusion. The lack of any sign of 1.80–1.82 Ga aged spots also indicates that the regional metamorphism did not lead to any new growth of zircon. In addition, an old Archaean 2.84 Ga age was obtained for a core (n01a in Table 2) that was recognised in the CL image. This age clearly suggests an inherited component in the magma. Some of the sample spots in the zircons from the coarse-grained dyke/sill, n10a and n17a (Table 2), showed a high content of common Pb. This feature is most likely related to the presence of chalcopyrite in this rock, suggesting that metal-bearing solutions were part of the fluid activity at the time of dyke emplacement.

TABLE 2. Ion-microprobe U-Th-Pb data for zircons from the Hemberget intrusion (sample Kn-5b).

Grain/ spot	Character	^{207}Pb/^{206}Pb	Error	^{206}Pb/^{238}U	Error	^{206}Pb/^{204}Pb measured	f_{206}(%)[a]	Discord.[b] (%)	^{207}Pb/^{206}Pb age (Ma)	^{206}Pb/^{238}U age (Ma)	U ppm	Pb ppm	Th/U_{calc}[c]
n259-01a	Core	0.2022	±05	0.5628	±149	7446	0.25	–1.5	2844	2878	298	211	0.208
n259-01b	Rim	0.1143	±02	0.3380	±89	207943	0.01	–0.5	1869	187	1898	742	0.147
n259-05a	Core	0.1142	±03	0.3431	±91	5071	0.37	–2.1	1868	1901	549	222	0.231
n259-05b	Rim	0.1109	±13	0.2236	±59	1076	1.74	31.2	1814	1301	817	208	0.071
n259-06a	Centre	0.1136	±06	0.3381	±90	2294	0.82	–1.2	1858	1878	277	111	0.233
n259-12a	Centre	0.1035	±10	0.1108	±30	1026	1.82	62.9	1687	678	478	68	0.238
n259-17a	Centre	0.1128	±15	0.2760	±74	677	2.76	16.7	1845	1571	186	64	0.390
n259-17b	Rim	0.1127	±02	0.2915	±105	157257	0.01	11.9	1844	1649	2739	932	0.165
n259-18a	Centre	0.1151	±05	0.3282	±88	8606	0.22	3.2	1882	1829	286	115	0.372
n259-10a	Centre	0.1090	±12	0.2043	±22	280	6.68	35.9	1782	1198	761	182	0.136

All errors are 1σ

a) percentage of common Pb detected. Calculated from measured ^{204}Pb assuming t = 0 Ma in the Stacey & Kramers (1975) model

b) degree of discordance in percent

c) calculated from measured ThO intensity

TABLE 3. Sm-Nd isotope data for samples from the Hemberget mafic intrusion.

Sample	Type	$^{143}Nd/^{144}Nd^a$	$2\sigma_m^b$	Sm (ppm)	Nd (ppm)	$^{147}Sm/^{144}Nd^c$	$\varepsilon_{Nd(t)}^d$	T_{DM}^e
Kn-2	gabbro	0.511985	±14	1.85	8.13	0.1378	1.41	2.13
Kn-4a	gabbro	0.512154	±10	4.74	18.52	0.1548	0.62	2.31
Kn-4a dup	d:o	0.512138	±8	4.82	18.34	0.1589	–0.68	2.54
Kn-5b	anorthosite	0.511926	±9	5.87	25.95	0.1368	0.48	2.22
Kn-7	gabbro	0.512014	±9	2.25	9.01	0.1509	–1.19	2.52
Kn-8	gabbro	0.512142	±13	1.49	5.92	0.1512	1.24	2.20

a) ratios were corrected for Sm interference and normalised to $^{146}Nd/^{144}Nd$ =0.7219, and further corrected for mass discrimination on basis of repeated measurements of the La Jolla Nd standard.
b) errors are two standard deviations of the mean.
c) errors in the $^{147}Sm/^{144}Nd$ ratio are estimated to ± 0.7 %.
d) eNd values were calculated for a common emplacement age (t) of 1870 Ma, typical errors in eNd values are ±0.5 units.
e) depleted mantle (DM) model ages were calculated according to DePaolo (1981).

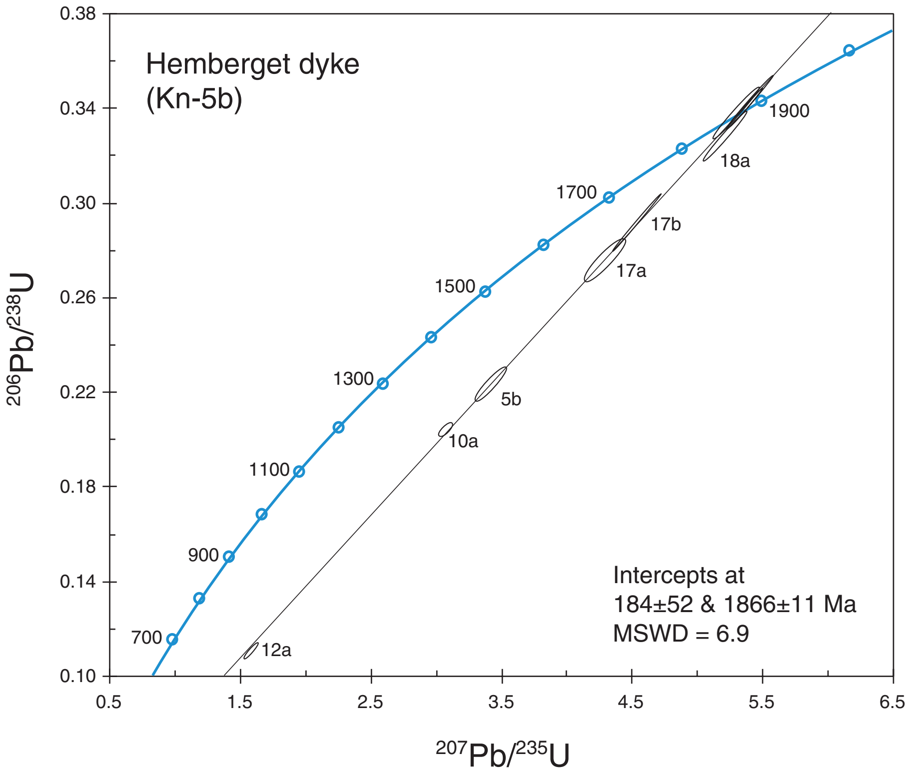

Fig. 6. U-Pb ion micro-probe data (NORDSIM) for zircons from one coarse-grained dyke/sill (Kn-5b) from Hemberget.

Sm-Nd data

Five whole-rock samples were analysed, including the coarse-grained dyke/sill sample (Kn-5b) used for zircon analysis. It became evident that the concentrations, determined by the isotope dilution (ID) technique given in Table 3, were not fully consistent with data for corresponding samples tabulated in Table 1. The latter were derived from ICP-MS measurements and the discrepancy, especially for Kn-8 (gabbro specimen), is much too large to be explained by just standard errors in the respective method. However, for the remaining samples, the agreement is satisfying. Two duplicate ID analyses of the Kn-4a gabbro sample (which was not analysed by SGAB) gave reproducible concentration data, and thus it seems that both the ICP-MS and ID techniques generate accurate results. The reason for the discrepancy may be sought in the sample strategy (two sets of samples taken from one location), which occasionally leads to significantly deviating whole-rock chemistry data. Although the discrepancy noted for sample Kn-8 is undesirable it gives us an opportunity to discuss the possible effect of sample mineralogy on Sm-Nd isotope systematics. It may be that the small-scale differences on a cm to dm scale with respect to the mineralogy, in particular the proportions between plagioclase and pyroxene, are responsible for the noted discrepancy in element concentrations between the two analytical approaches. For instance, pyroxene would tend to concentrate Nd (and Sm) by a factor of about 4 relative to plagioclase (Faure 1986), and differences in the relative proportions of plagioclase and pyroxene could thus cause drastic effects on a whole-rock scale for a certain element concentration. Besides, it is known that the content of magnetite may vary over short distances at Hemberget. As magnetite is a phase that tends to concentrate REE, an erratic distribution of magnetite would give the same effect on REE concentrations as variable proportions of plagioclase and pyroxene.

Much more data and careful new sampling would be needed to understand the role of sample mineralogy in the interpretation of element concentrations, and this aspect was not fully appreciated at the time of sampling. However, the objective of the present contribution is to discuss some general features and we prefer to consider the achieved Sm-Nd concentrations (ID technique) and related isotope ratios as trustworthy for the samples that were sampled for that purpose. Calculated ε_{Nd} (t = 1870 Ma) values show a moderate spread between –1.2 and +1.4, and depleted mantle (DM) model ages are between 2.1 and 2.5 Ga. The coarse-grained dyke/sill (Kn-5b) sample shares the same general Sm-Nd isotopic features as displayed for the gabbroic samples.

Discussion

The age of the Hemberget layered intrusion is constrained to around 1.87 Ga from U-Pb data obtained for zircons from a texturally pegmatitic intermediate dyke/sill cutting the gabbro intrusion. Field relationships indicate that the intermediate dykes and sills are late residual melt differentiates that emanated from the same source as the mafic to ultramafic magma. Thus the given zircon age should be a good approximation of the age of the emplacement of the intrusion. Similarities in geochemistry support a co-genetic relationship between the gabbroic part and the intruding dykes/sills, as do coherent Sm-Nd isotope systematics. The 1.87 Ga age for the Hemberget intrusion is in good agreement with ages reported for volcanic rocks further to the south in the Bothnian basin, for example the 1870±2 Ma age at Sollefteå (Lundqvist et al. 1998) and the 1874±6 Ma age at Rocksjö (Welin 1987). Additionally, this age fits well with the timing of the magmatism in the 1.88–1.87 Ga Vargfors and Arvidsjaur Groups (Billström & Weihed 1996) to the north (including the c. 1.88–1.87 Ga Gallejaur monzonite and gabbro) (Skiöld et al. 1993, Kousa & Lundqvist 2000). Moreover, ages for tonalitic–dioritic intrusions in the eastern part of the Skellefte district also fall within this time interval (for example Lundström et al. 1999, Lundström & Persson 1999). A number of gabbroic intrusions occur also in the western Skellefte district but these have poorly constrained ages (Bergström & Sträng 1999). One of them, the Lainijaur Ni-bearing intrusion, was interpreted by Martinsson (1996) to have intruded at the end of the time interval 1.89–1.87 Ga. The 1875–1870 Ma interval has been interpreted (Allen et al. 1996) as a stage with crustal extension incipient rifting resulting in the tapping of primitive mafic magma, continued subsidence in the area of the Skellefte arc, and renewed but more continental arc volcanism to the north. It may thus be concluded that the Hemberget intrusion is a sill emplaced during extension in the Bothnian basin and its age further stresses that the 1.87 Ga old extensional event was a widespread phenomenon in northern Sweden.

Factors controlling ε_{Nd} values and Nd concentrations

The mafic–ultramafic composition of the Hemberget intrusion is consistent with a mantle-derived origin, but the geochemical characteristics (no MORB signature is indicated) and the ε_{Nd} values clustering around zero (deviant from a depleted mantle signature of around +4) contradict a pure mantle origin. Instead, it is suggested that an old crustal component (with negative ε_{Nd} values at 1.87 Ga) has been admixed with a mantle-derived magma. Both the identification of the 2.84 Ga zircon in the coarse-grained dyke/sill and the presence of partly dissolved xenoliths strongly suggest that assimilation processes were important. The local rock types include pre-1.95 Ga mafic–intermediate volcanic rocks with a primitive chemistry, greywackes and subordinate felsic volcanic rocks. The greywackes appear to be a good source candidate for the crustal contaminant, as Sm-Nd data from Svecofennian sedimentary rocks clearly suggest that Archaean detritus constitute part of the incorporated erosional material (Welin et al. 1993, Claesson et al. 1993).

The variable ε_{Nd} signatures and element concentrations may be explained by a combination of different factors. It is important to distinguish between cumulate processes and fractional crystallisation processes. These processes can both be looked upon as internal features occurring within the magma chamber, but the former process is more or less instantaneous and leads to differences in mineralogical composition in different gabbroic parts of the intrusion. Fractional crystallisation, on the other hand, will tend to increase the concentration of REE with time (i.e. with increasing silica content). Neither of these processes will discriminate Nd isotopes, i.e. cause changes in the Nd isotope ratios which characterise a crystallising rock or substantially change the Sm/Nd ratio, but both of them will affect the ultimate Nd concentration in the studied rock samples. Thus, the change from a typical mantle-ε_{Nd} value of around +4 to variable values close to zero must be due to an external type of process, most likely incorporation of older crustal material. The observed difference in ε_{Nd} values of around 2–3 units calls for a partial homogenisation between an isotopically evolved contaminant and a primitive mafic magma. The inferred partial homogenisation process must have occurred at some stage prior to the onset of magma crystallisation in order to smooth out most of the contrast in isotopic signatures between the two end-members. The felsic tuffitic sediment, which forms the roof wall rock of the gabbro intrusion, may possibly have contributed to a late-stage, in-situ assimilation process. The geochemical evidence for more than one magmatic pulse adds further complexities to this picture and this may have played a role in generating somewhat diversified Nd isotope ratios. It is interesting to note that the intermediate dyke/sill, which apparently crystallised at a later stage than the gabbroic samples, has an ε_{Nd} value similar to the gabbroic samples. This further suggests that this intermediate rock is co-magmatic with the gabbros, and also that the inferred assimilation processes must have preceded fractional crystallisation processes within the magma chamber.

The variable Nd (and Sm) concentrations, however, may be explained in a different way. Although few data exist, it is suggested that the ε_{Nd} values are not directly linked with Nd concentrations. For instance, if assimilation processes would be important in the control of Nd concentrations, then Nd-rich sedimentary components added to a magma would lead to a crystallised hybrid rock with high Nd content and a distinct negative ε_{Nd} value. But this is not the case since sample Kn-4 for example has 18 ppm Nd and an ε_{Nd} value of +0.6. This observation strengthens the hypothesis that sample mineralogy, i.e. the pyroxene/plagioclase ratio and/or the magnetite content, is important to the resulting Nd concentration of a sample. The effect of such a process can also provide a reasonable explanation for the highly deviating Nd and Sm concentrations obtained for different rock chips from this locality. If, for instance, a more plagioclase-rich layer, which would tend to be low in Sm and Nd, was sampled and analysed with the ICP-MS technique, while a more pyroxene-enriched layer was analysed with the ID technique, then a pattern of the observed type would be expected. Possibly, this hypothesis could be tested if a very careful additional sampling was carried out, which also included more homogeneous, strictly non-layered samples, which ideally should yield Nd concentration data resembling that of the magma. However, the probable erratic presence of more or less totally digested xenoliths would still pose a problem in identifying the "undisturbed" magmatic composition prior to rock crystallisation. Another explanation that should be considered in this context is how a "nugget" effect would affect element concentrations. It may be that the modal abundance of accessory minerals, rich in REE, is biased if a small sample size is used in the analytical techniques and the REE-rich phases are coarse-grained.

Assimilation processes

The presence of an Archaean zircon core in the dyke/sill from Hemberget is noteworthy. Although it has long been known that Archaean zircon populations occur in Svecofennian sedimentary rocks, the Archaean core at Hemberget, to our knowledge, is the first identified Archaean component in a magmatic rock emplaced during the Svecofennian crustal-forming stage. Most likely the Archaean zircon at Hemberget did not originate by a direct contribution from a lower crustal Archaean segment situated beneath the intrusion. Such a hypothesis was advocated for e.g. 1.52 Ga mafic and felsic rocks, situated close to Sundsvall, with highly negative ε_{Nd} values (Andersson 1997). However, if a similar process had operated at Hemberget, a zircon phase inherited at lower crustal depths would not have been likely to survive transport in a high-T, mafic–ultramafic magma to shallower levels. Instead, in analogy with the process responsible for the lowered ε_{Nd} signature for the Hemberget gabbro magma, it is suggested that the ascending magma, which crystallised as the anorthosite-like (Kn-5b) sample, may have picked up zircons by interaction with greywacke country rocks at shallower depths. The trace element chemistry of the dated sample does not contradict the hypothesis of an active assimilation event.

Several authors dealing with 1.9 Ga magma-mixing processes have attempted to model achieved ε_{Nd} values for granitoids, assumed to have been contaminated with older crustal material, by using a simple two-component mixing model (e.g. Öhlander et al. 1999). This approach assumes that the Nd isotope characteristics (ε_{Nd} values and Nd concentrations) are known for the end-member components, and the measured ε_{Nd} values for the granitic rocks considered are used to calculate the proportions between a juvenile mantle component and a hypothetical crustal component. This approach is questionable for several reasons, one being the likelihood that a two-component mixing model is an oversimplification of the actual process, another being the uncertainty in particular of the Nd concentration for the mantle component. Calculations involving 5, 10 and 15 ppm for this end-member have been presented, and clearly only the 5 ppm estimate may be adopted in the case of the Hemberget gabbro samples, since the concentration of Nd in these specimens normally is less than 10 ppm. Mineralogical effects, such as the internal cumulate processes, are also likely to affect the Nd concentration in a specific gabbro sample, and it is impossible to quantitatively evaluate the extent to which assimilation and mineralogy, respectively, contribute to the Nd isotope characteristics. However it may be of interest to give an example of how a simple two-component model may work for the Hemberget gabbro samples. Let us first make the assumption that the original primitive mantle component had a Nd isotope concentration of 5 ppm and an ε_{Nd} value of +4 at t = 1.87 Ga. Secondly, it is assumed that the mafic-ultramafic magma in fact had a rather uniform mean Nd concentration of approx. 8 ppm (cf. Table 1) just before the crystallisation process was initiated, and that the change from 5 to 8 ppm was caused by assimilation of Archaean sediments with a Nd concentration of 31 ppm and an ε_{Nd} value of –11.5. Then, the isotope characteristics of an "average" gabbroic sample at Hemberget with an ε_{Nd} value close to +0.3 can be explained by a 5 % assimilation of a pure Archaean component. It is probably more likely that the contamination occurred as an assimilation of a 1.96 Ga greywacke component (ε_{Nd} value is hypothetically –2.5 and a Nd concentration of 29 ppm; cf. Welin et al. 1993), and for that situation approximately 22 % assimilation is assumed. Although it is a crude approximation, this suggests a substantial assimilation of local country rocks during the evolution of the mafic magma. However, the gabbroic whole-rock chemistry is not consistent with such a large assimilation, calling for a need to change one or several of the assumptions made in the calculations. A plausible explanation is that the primary mafic magma, rather than having a typical depleted mantle chemistry before assimilation processes started, had a more enriched mantle melt composition and thus was characterised by a less positive ε_{Nd} value.

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Crystalline basement rocks in the Lower and Middle Allochthons, Västerbotten, Sweden: Palaeoproterozoic U-Pb zircon ages from the north-central Swedish Caledonides

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Three crystalline basement rocks from the Lower and Middle Allochthons in the Caledonides of Västerbotten, Sweden have been dated using the U-Pb multiple zircon technique. A quartz monzodiorite from the antiformal stack in the Bångonåive window near Tärnaby (Lower Allochthon) and a quartz syenite in the Lower Allochthon at Mörrösjöbäcken, south of Dikanäs yielded ages of 1805^{+18}_{-12} (MSWD=6.9) and 1798±6 Ma (MSWD=0.07), respectively. A foliated meta-quartz syenite in the Middle Allochthon near Harrvik, northeast of Dikanäs, yielded an age of 1766^{+15}_{-12} Ma (MSWD =3.8). These ages are interpreted to represent the timing of intrusion of the rocks. The U-Pb zircon age-dating results, in combination with geochemical data, indicate a close relationship of the crystalline basement rocks in the Lower and Middle Allochthons, in this segment of the Caledonides to the c. 1810–1760 Ma suite of igneous rocks in the Transscandinavian Igneous Belt, in the south-western part of the Fennoscandian Shield. Furthermore, a lower intercept age (1026±79 Ma) in the sample from the Middle Allochthon indicates a Sveconorwegian disturbance of the U-Pb system.

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Introduction

Crystalline basement rocks have long been recognised in the lower tectonic units of the Scandinavian Caledonides (see Asklund 1962, Kulling 1972 for reviews). In relatively weakly deformed units of the Lower Allochthon (Fig. 1), these basement rocks can be demonstrated to lie with a primary, discordant contact beneath mostly clastic cover sequences (e.g. Zachrisson & Greiling 1993, Greiling et al. 1999a) which, where fossiliferous, can be biostratigraphically dated as probably Early and certainly Middle Cambrian in age (e.g. Kulling 1955, Greiling et al. 1999b). Therefore, it is clear that the basement rocks must be Precambrian in age. However, apart from geochronological data from the Rombak window in the northern part (Romer 1992), and the Grong-Olden area in the central part of the Caledonides (see review by Roberts & Stephens 2000), further direct age evidence is not yet available from the Lower Allochthon along the eastern, external part of the Caledonian orogenic belt. Radiometric work in the overlying Middle Allochthon (Fig. 1) in Sweden is restricted to the Tännäs area in Jämtland (Claesson 1980) and to the Sarek area in Norrbotten (Page 1992). However, both these studies were primarily concerned with dating Caledonian metamorphism and deformation and provided only one late Palaeoproterozoic protolith age (Claesson 1980).

In the course of the recent mapping programme at the Geological Survey of Sweden, representative crystalline basement rocks from the Lower and Middle Allochthons in Västerbotten, Sweden, were sampled, analysed and dated with the U-Pb multiple zircon grain technique.

Regional geological context

Most Caledonian rocks in Scandinavia are allochthonous and have been thrust towards the east or south-east on top of a thin, autochthonous sequence of Vendian–Cambrian sedimentary rocks, which form part of the Baltoscandian platform. The Caledonian thrust rocks are divided in ascending order into the Lower, Middle, Upper (Seve and Köli Nappe Complexes), and Uppermost Allochthons (Kulling 1972, Gee et al. 1985, Stephens et al. 1985; Fig. 1). The units up to and including the Seve units are interpreted as parts of the imbricated and shortened margin of the continent Baltica. These units are composed of both clastic cover sequences and units of Precambrian crystalline basement rocks. All units have a complex structural and metamorphic history. The Middle Allochthon and the Seve Nappe Complex were probably affected, at least partly, by a Late Cambrian–Early Ordovician event, which produced greenschist-facies and higher grade metamorphic mineral assemblages. Deformation and metamorphism continued, and the various complexes were successively brought together along a suture zone formed during the collision of the continents Baltica and Laurentia. After nappe emplacement onto the Baltoscandian platform and establishment of the Lower Allochthon in the Silurian–Early Devonian, the Caledonian activity faded out.

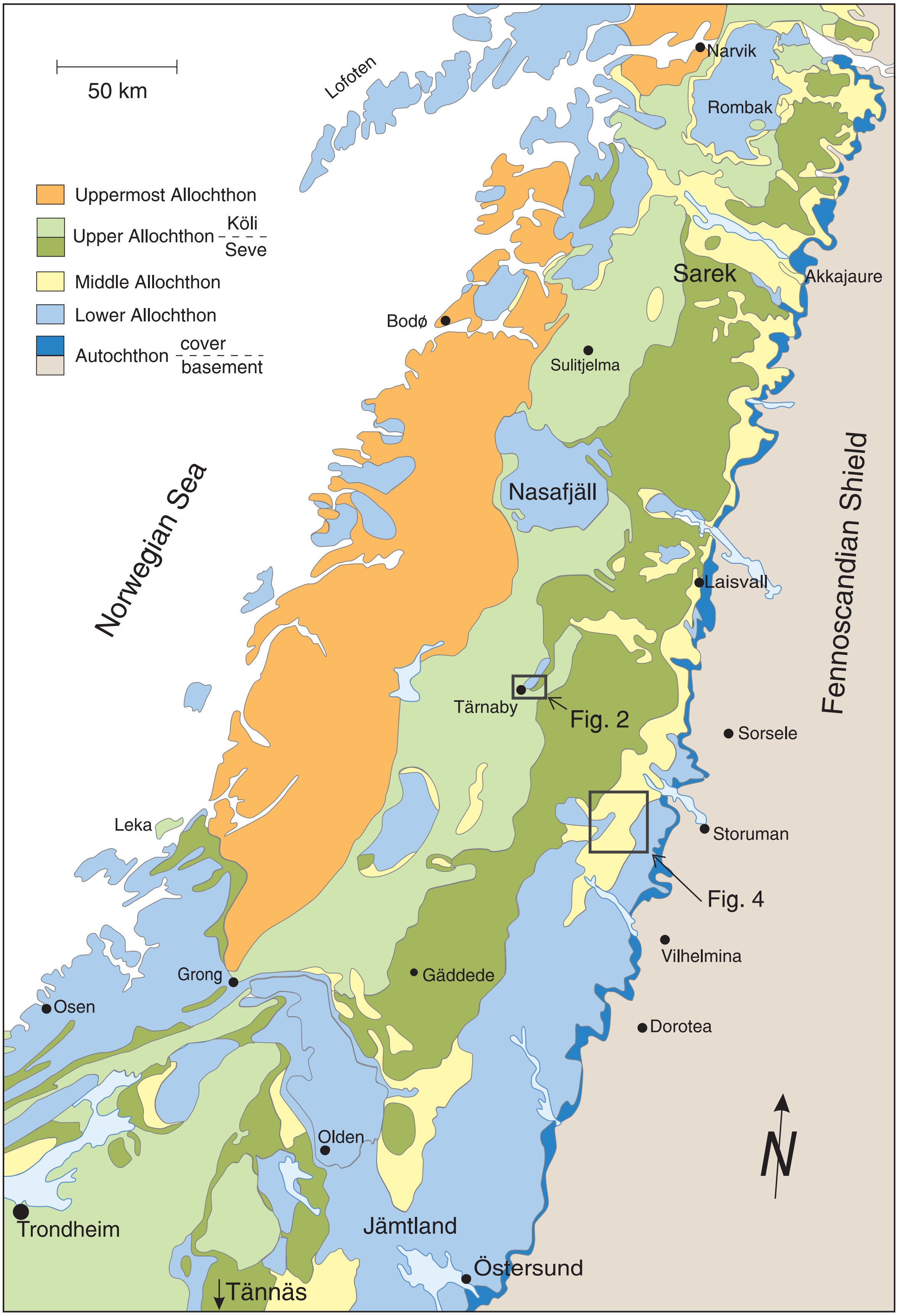

Fig. 1. Sketch map of the north-central Scandinavian Caledonides showing major thrust nappe units (modified from Zachrisson 1986) and the location of detailed maps (Figs. 2 and 4). Except for the basement/cover contact in the Autochthon, all other contacts are tectonic in character.

Lower Allochthon

The Lower Allochthon along the eastern margin of the Caledonian orogenic belt is predominantly composed of structural slices or horses of sedimentary (cover) sequences and subordinate older crystalline basement rocks. The latter are mostly represented by coarse-grained felsic intrusive rocks, which are comparable, at least in part, with the Revsund granite exposed in the autochthonous basement to the east (e.g. Greiling 1982, Greiling & Zachrisson 1999). Mafic crystalline rocks and doleritic dykes form a minor component in the basement complexes. Comparable basement rocks also occur in tectonic windows beneath higher Caledonian thrust units to the west. They have locally been dated using Rb-Sr techniques, yielding imprecise Palaeoproterozoic ages (e.g. Gustavson 1973, Stephens 1977).

Middle Allochthon

The Middle Allochthon in the Västerbotten part of the Caledonides is dominated by the Stalon Nappe (Kulling 1942, 1955). Other units, including the Särv and Fjällfjäll Nappes, are subordinate and not relevant here (see Stephens et al. 1985, Greiling 1989, for reviews). The Stalon Nappe includes crystalline, pre-Caledonian, basement-derived rocks and metasedimentary, generally psammitic rocks. The different lithological units are separated by shear zones.

The crystalline basement rocks are represented by abundant greenish mylonites, metagabbro and subordinate felsic meta-igneous rocks (Greiling 1985, Zachrisson & Greiling 1996, Roos 1997). The lower part of the metasedimentary sequence is dominated by coarse, mostly polymictic conglomerates in a psammitic matrix. The upper part of the sequence consists of thick-bedded, homogeneous, coarse meta-arkoses with rare pelitic beds as thin (mm-cm) dark grey interlayers or locally as angular fragments within the psammites. Lithological similarities suggest a correlation of the sedimentary sequence of the Stalon Nappe with the Risbäck Group of the Lower Allochthon (Greiling & Zachrisson 1999).

It is remarkable that all of the crystalline rocks are strongly sheared and primary textures are only preserved in rare, low strain lenses. In contrast, the metasedimentary rocks are mostly well preserved.

Upper Allochthon, Seve Nappe Complex

The higher-grade rocks in the structurally lower part of the Upper Allochthon are included in the Seve Nappe Complex. Within the Västerbotten part of the Caledonides, they are represented by a sequence of mica schist, mica gneiss, amphibolite, and minor marble, with bodies of ultramafic rocks. A well-preserved to highly deformed orthogneiss (Nuortenjuone Gneiss) forms a recognisable unit that can be traced over a considerable distance. This unit has been shown to represent a pre-Caledonian continental basement rock. Radiometric age and geochemical characteristics suggest a correlation of this orthogneiss with the intrusive rocks of the Transscandinavian Igneous Belt (TIB) in the southwestern part of the Fennoscandian Shield (Zachrisson et al. 1996).

Field relationships, lithology and geochemistry of the dated rocks

Lower Allochthon: Bångonåive

Syenitoids represent the major part of the Lower Allochthon in the Bångonåive window, northeast of Tärnaby, Västerbotten. These rocks are exposed in the core of an antiformal structure beneath minor, discontinuous Middle Allochthon units and major thrust nappes of the Upper Allochthon (Stephens 1977, 2001, Greiling et al. 1993). The Lower Allochthon core of the antiformal structure has been shown to be an antiformal stack with several basement-cover horses. In one of these horses, a quarry for road construction aggregates exposes the Bångonåive syenitoids and associated mafic rocks (Fig. 2). Figure 3a shows the relationships betweeen mafic and felsic varieties within these igneous rocks. Although there is a clear intrusive contact of the felsic rock into the more mafic one, it is assumed that the sequence originated broadly at the same time, during a single, major intrusive event. A mafic variety with a quartz monzodioritic composition (Figs. 3b, c) has been dated here (sample number MBS 950166, coordinates in national grid 7292600/1479800).

Lower Allochthon: Mörrösjöbäcken

The quartz syenite in the Lower Allochthon at Mörrösjöbäcken, Västerbotten (sample BFRG 97002, coordinates 7217850/1504290) forms the core of a minor, E–W-trending and doubly plunging anticline beneath sedimentary cover rocks (Fig. 4). A primary, unconformable contact between the quartz syenite and cover rocks is exposed at both ends of the anticline. Towards the west, these cover rocks belong to the Upper Riphean Risbäck Group (Fig. 3d), whereas towards the east the Risbäck Group is missing and the quartz syenites are overlain by quartzites and shales of the Gärdsjön Formation (Vendian–Early Cambrian). The Risbäck Group at Mörrösjöbäcken consists of continental red beds (conglomerate, arkose, subordinate shale). Beneath the Risbäck Group sedimentary rocks, the quartz syenite has a dark red colour, prob-

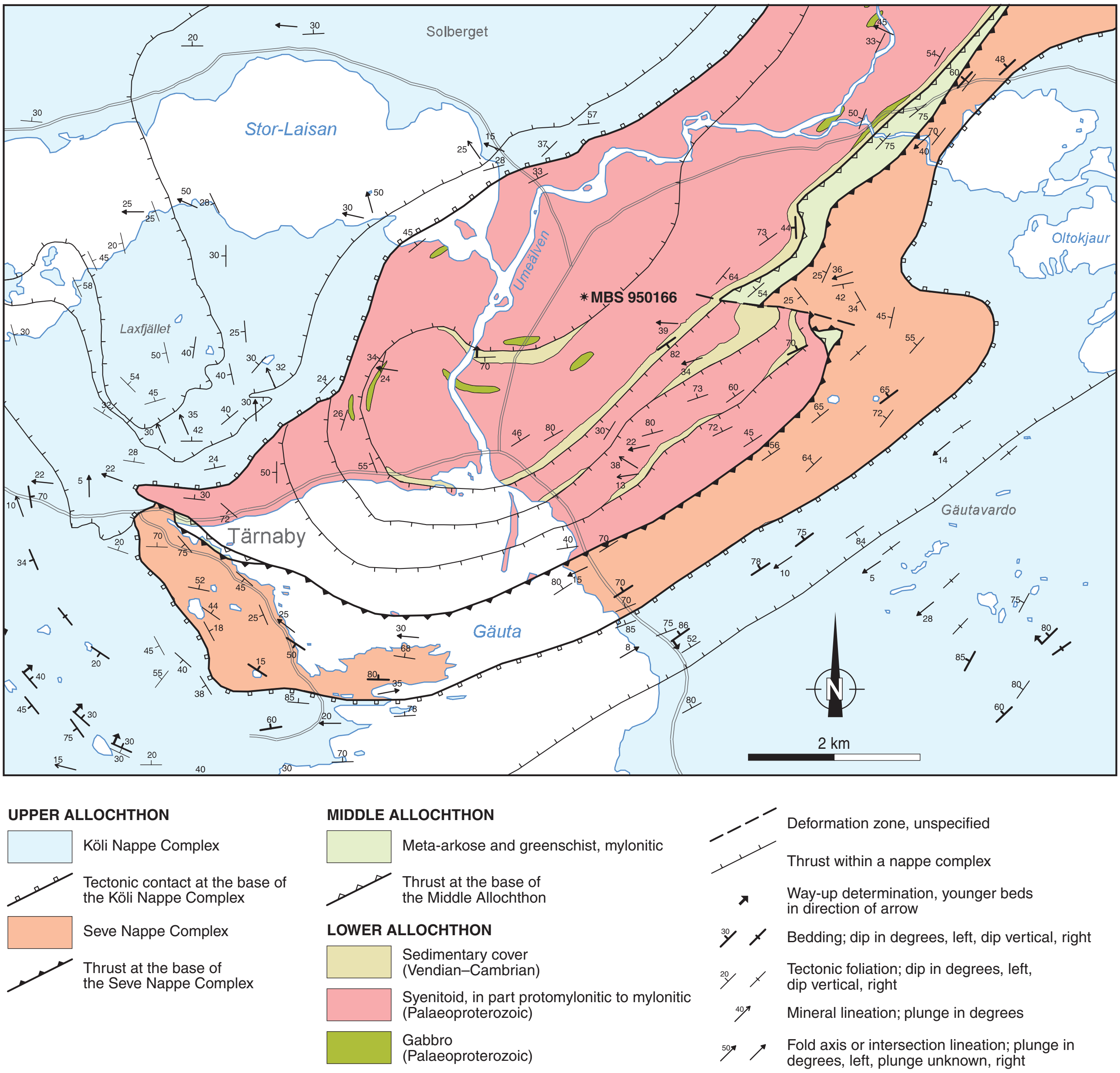

Fig. 2. Map of the southern part of the Bångonåive antiform with the major thrust nappe units and the location of the quarry, where the studied samples were taken. Modified from Stephens (2001).

ably due to continental weathering prior to sedimentation of the cover rocks (Figs. 3d, e). The quartz syenite is characterised by a porphyritic texture of cm-sized microcline phenocrysts in a mm-size groundmass of plagioclase, orthoclase, and quartz, with some primary biotite (Fig. 3f). Although the primary texture is mostly well-preserved, quartz shows undulatory extinction and some grains are broken or bent. Some feldspar grains also show traces of brittle deformation.

Middle Allochthon: Harrvik

The meta-quartz syenite to the east of Harrvik in the Middle Allochthon of Västerbotten (sample BFRG 97003, coordinates 7242220/1594030) is exposed on both sides of the road from Harrvik to Ullisjaur (Greiling & Zachrisson 1999; Fig. 4). It is an apparently lens-shaped ”pod” of relatively low strain, enclosed in a larger thrust unit composed predominantly of highly deformed mylonitic rocks and further lower strain lenses of crystalline, meta-igneous rocks. Whereas in the surrounding mylonites, the character of a protolith is not easily recognisable, the meta-quartz syenite in the lower strain lens still retains at least

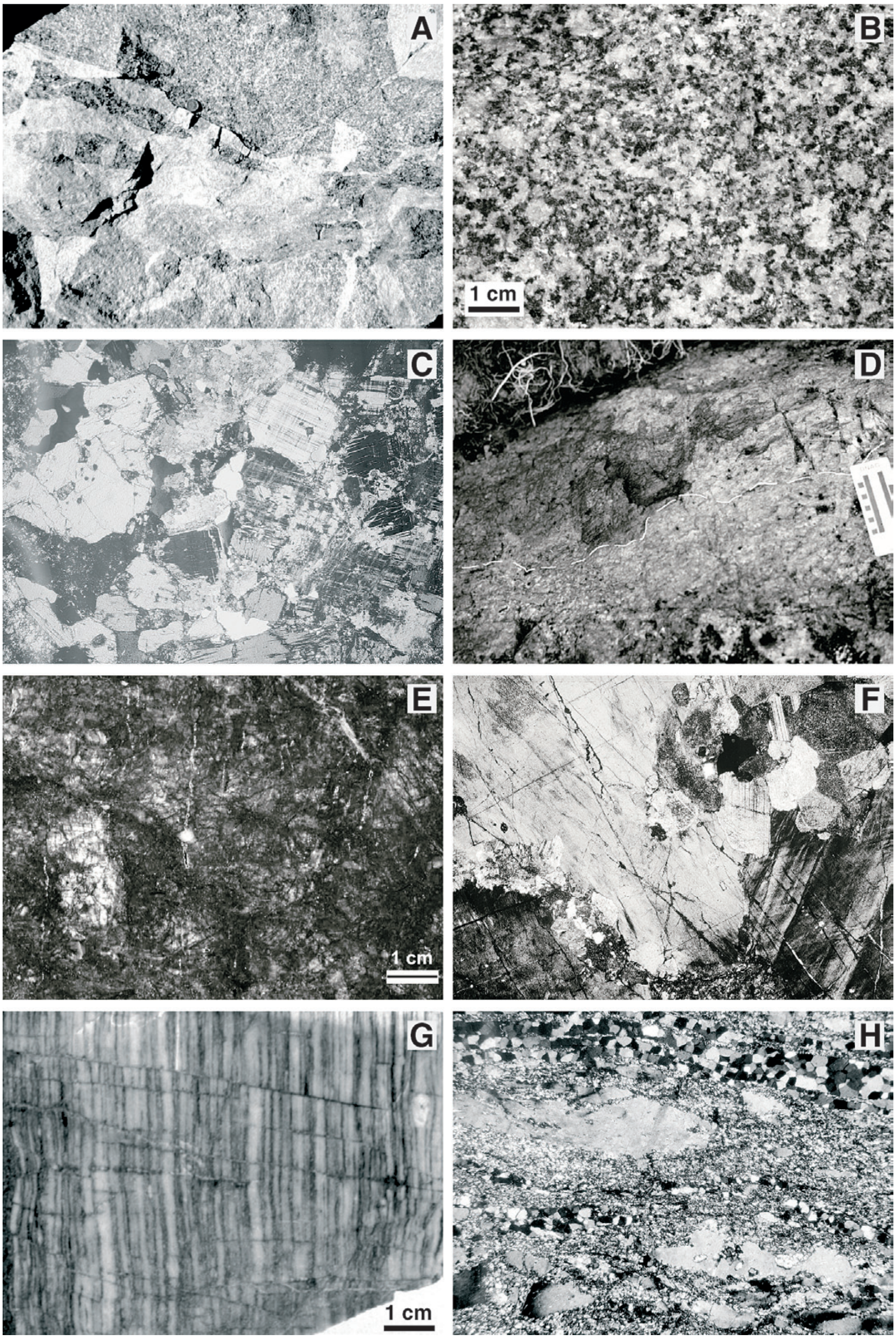

Fig. 3. Photographs and photomicrographs of the studied samples. Coordinates of sample locations are provided in the text. a) relationship between mafic and felsic parts of the Bångonåive intrusive suite; boulder in quarry, 4 km northeast of Tärnaby. See Figure 2 for location. 10 SEK coin for scale (15 mm). b) hand specimen of a more mafic variety in the Bångonåive intrusive suite. Location as in a). c) photomicrograph of the sample (G 99:11) shown in b). The width of the photomicrograph is 4 mm. d) Mörrösjöbäcken quartz syenite with irregular, unconformable contact (marked by dashed line) with overlying Risbäck Group sedimentary rocks. White patches are due to kaolinisation in the quartz syenite and arkosic cover rocks, respectively. For location see Fig. 4. Scale in cm and inches. e) hand specimen of Mörrösjöbäcken quartz syenite. Location as in d). f) photomicrograph of Mörrösjöbäcken quartz syenite, sample G 80:M10. The width of the photomicrograph is 4 mm. g) hand specimen of strongly foliated meta-quartz syenite from Harrvik. For location see Fig. 4. h) photomicrograph of the sample (G 97:3) shown in g). The width of the photomicrograph is 2 mm.

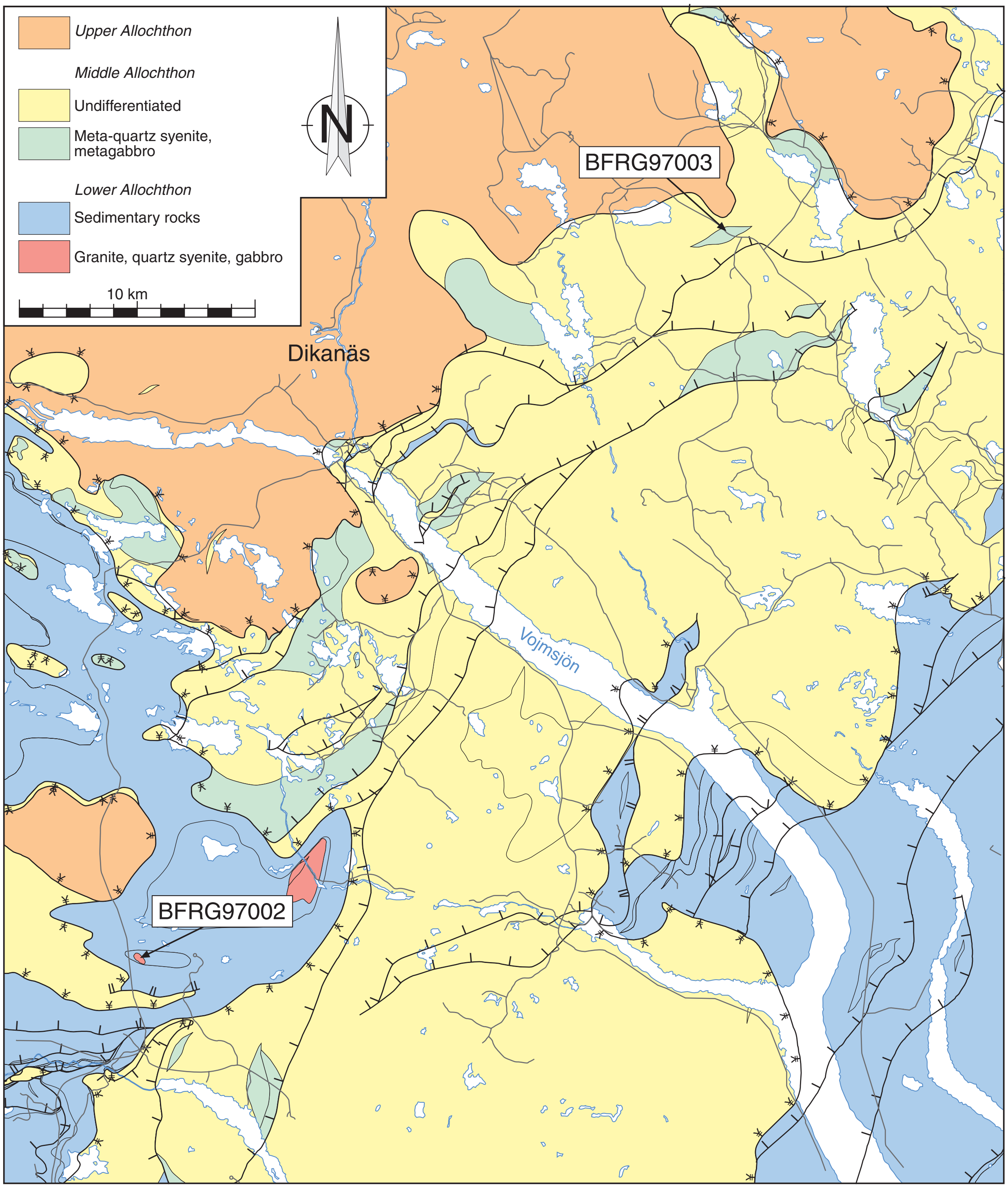

Fig. 4. Map of the Caledonian margin in Västerbotten, showing the two sample locations in the Lower and Middle Allochthons, respectively. Simplified from Greiling & Zachrisson (1999).

parts of its primary mineralogy and texture and, for this reason, it was selected for radiometric dating. In the field, the rock is very brittle and glassy. Figure 3g shows a hand-specimen of the meta-quartz syenite, which is strongly foliated. It contains porphyroclasts of orthoclase in a fine-grained, sheared matrix. In thin section, the mineralogy is characterised by orthoclase, plagioclase and quartz, with secondary mafic minerals such as epidote and clinozoisite (Fig. 3h).

Geochemical data

The dated samples were analysed for major, trace, and REE elements using the ICP-AES and ICP-MS methods at SGAB Analytica, Luleå, Sweden. The results are shown in Tables 1 and 2. The plots in Figures 5 and 6 have been used to document the chemical characteristics of the analysed samples and to permit some comparison with samples from the Fennoscandian Shield. Figure 5a shows that samples MBS 950166 and BFRG 97003 lie along the trend defined by the rocks belonging to the Transscandinavian Igneous Belt in the Bergslagen area (and surroundings), central Sweden. They display monzogabbroic and quartz syenitic chemical compositions, respectively. Sample BFRG 97002 displays a quartz syenitic composition with higher K_2O content, but lies outside the trend defined by the rocks in the Transscandinavian Igneous Belt. The REE-pattern (Fig. 5b) displays a moderate slope with

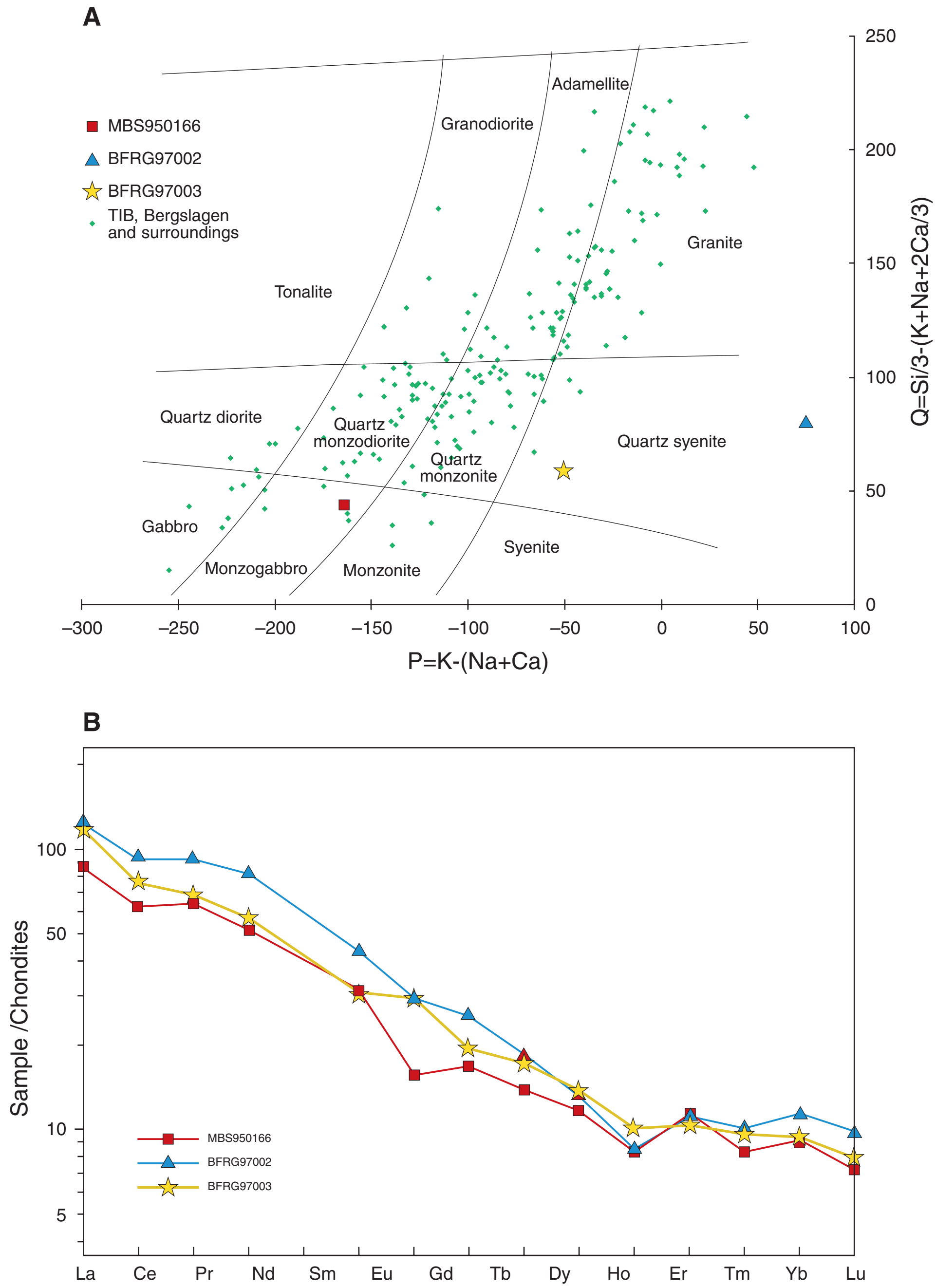

Fig. 5. a) Classification diagram using major element geochemical data (after Debon & Lefort 1983). Larger symbols represent samples of the present study. For comparison purposes, intrusive rocks belonging to the Transscandinavian Igneous Belt in the Bergslagen area and surroundings (SGU geochemical database) are shown with small green diamonds. b) REE pattern for the dated rocks.

TABLE 1. Major and trace element analyses of rocks dated by the U-Pb zircon technique.

Sample		MBS950166	BFRG 97002	BFRG 97003
SiO_2	(wt %)	54.5	61.4	62.9
Al_2O_3		16.6	17.0	17.4
CaO		6.4	0.6	2.6
Fe_2O_3		7.8	5.6	3.8
K_2O		3.1	8.0	6.0
MgO		4.6	1.2	1.0
MnO_2		0.2	0.1	0.1
Na_2O		3.9	2.6	4.1
P_2O_5		0.4	0.1	0.2
TiO_2		0.8	0.7	0.5
LOI		1.5	1.4	0.8
Total		99.8	98.7	99.4
Ba	(ppm)	901	1310	2550
Be		1.5	0.6	<0.6
Co		25.9	<5.5	<5.7
Cr		62	27.8	19.4
Cu		54.2	7.6	17
Ga		22.8	26.6	24.3
Hf		8.9	15.4	12.2
Mo		2.5	3.5	1.0
Nb		7.4	17.2	10.5
Ni		35.2	<11	<11.4
Rb		78.5	167	63.9
Sc		17.4	9.5	4.04
Sn		0.7	0.8	1.4
Sr		895	187	418
Ta		0.7	1.4	0.6
Th		9.0	2.3	0.5
U		4.3	1.0	0.4
V		132	25	28.9
W		0.5	0.7	<0.1
Y		14.8	20.1	17.1
Zn		88.2	81.2	66.6
Zr		356	648	552

TABLE 2. REE data of rocks dated by the U-Pb zircon technique.

Sample		MBS950166	BFRG 97002	BFRG 97003
La	(ppm)	29.5	42.8	40.3
Ce		57.9	86.1	70.3
Pr		7.9	11.3	8.4
Nd		29.7	47.9	33.2
Sm		6.1	8.5	6.0
Eu		1.1	2.2	2.2
Gd		4.3	6.5	5.0
Tb		0.6	0.9	0.8
Dy		3.3	3.8	3.9
Ho		0.6	0.6	0.8
Er		2.2	2.1	2.0
Tm		0.3	0.3	0.3
Yb		1.8	2.2	1.8
Lu		0.2	0.3	0.3
La/Yb		16.39	19.45	22.39

La_N/Yb_N ratios of 16, 19, and 22, and with both positive and negative Eu-anomalies. The analysed samples plot in the field of A-type ”granites” after Whalen et al. (1987) but show distinctly lower FeO*/MgO ratios on the Fe0*/MgO versus Zr+Nb+Ce+Y plot compared with the Rapakivi granites of Finland (Rämö & Haapala 1990). This feature is once again similar to that described for the felsic intrusive rocks of the Transscandinavian Igneous Belt in central Sweden (Andersson 1997).

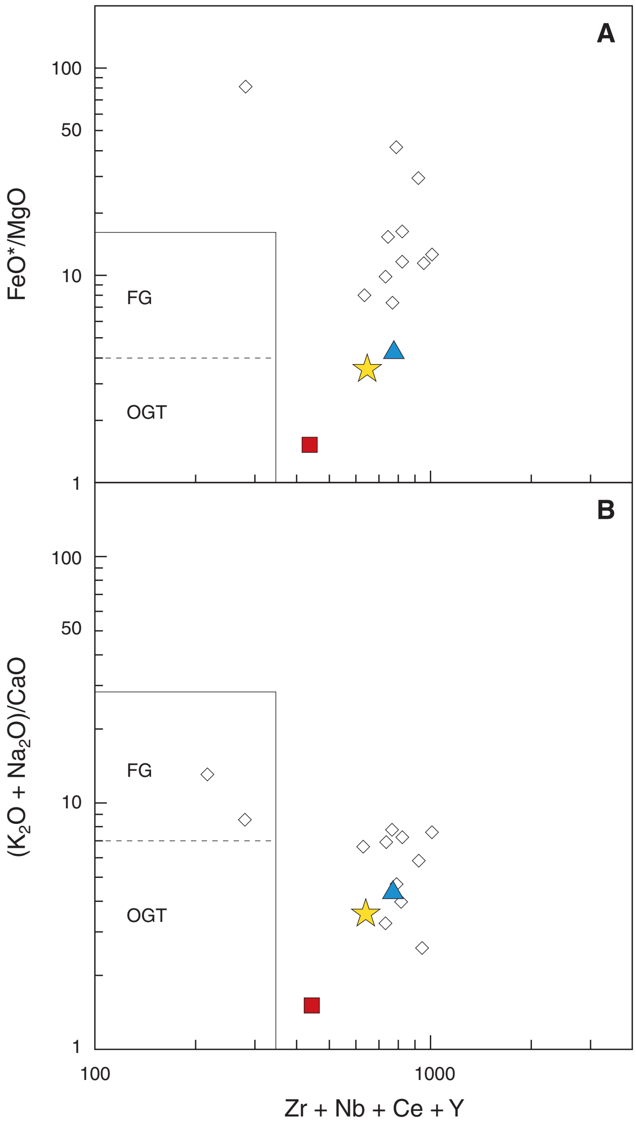

Fig. 6. Discrimination diagram for fractionated granite (FG), unfractionated M-, I-, and S-type granites (OGT) and A-type granite (unmarked; Whalen et al. 1987). Symbols for analysed samples as in Figure 5a. Open diamonds represent Rapakivi granite and syenite from Rämö and Haapala (1990).

Character of zircons and age-dating results

Analytical procedures are described in the Editor’s Preface in this volume. The analytical results are presented in Table 3.

MBS 950166. Quartz monzodiorite at Bångonåive, Lower Allochthon

The zircons are brown to reddish brown and turbid. Only a small number are transparent and such grains were selected for isotopic analysis. The majority of the grains are anhedral or fragmented. Both low-index and high-in-

TABLE 3: U-Pb isotopic data.

Analysis No.	Weight (µg)	No. of crystals	U (ppm)	Pb tot. (ppm)	Common Pb (ppm)	$^{206}Pb^{a}/^{204}Pb$	$^{206}Pb - ^{207}Pb - ^{208}Pb$ Radiog. (atom %)[b]	$^{206}Pb^{b}/^{238}U$	$^{207}Pb^{b}/^{235}U$	$^{207}Pb/^{206}Pb$ age (Ma)
MBS950166. Quartz monzodiorite, Bångonåive, Lower Allochthon.										
1	42	17	231.1	71.9	0.15	10979	81.2 - 8.9 - 9.9	0.2929±8	4.408±15	1785±3
2	25	5	234.7	75.9	0.18	7830	81.2 - 8.9 - 9.9	0.3042±7	4.598±12	1793±2
3	24	15	216.0	67.7	0.39	4870	81.3 - 8.9 - 9.8	0.2945±9	4.441±16	1789±4
4	42	12	292.7	95.1	0.13	18225	81.7 - 9.0 - 9.3	0.3084±7	4.658±12	1792±1
5	4	1	281.0	92.3	0.32	6371	82.3 - 9.1 - 8.6	0.3133±14	4.759±24	1802±4
BFRG 97002. Quartz syenite, Mörrösjöbäcken, Lower Allochthon.										
1	28	5	137.2	45.1	0.24	4561	83.0 - 9.1 - 7.9	0.3157±19	4.779±29	1796±3
2	20	10	195.3	62.8	0.23	5207	83.3 - 9.1 - 7.6	0.3104±10	4.696±18	1795±4
3	27	14	141.2	45.1	0.16	7746	83.5 - 9.2 - 7.4	0.3087±21	4.666±33	1794±4
4	28	14	231.1	74.4	0.09	17317	83.4 - 9.2 - 7.4	0.3117±13	4.715±21	1794±2
BFRG 97003. Meta-quartz syenite, Harrvik, Middle Allochthon.										
1	32	6	208.0	66.7	0.01	46327	80.5 - 8.5 - 11.0	0.3000±11	4.386±16	1733±2
2	9	1	167.1	44.9	0.01	9625	84.5 - 8.4 - 7.1	0.2637±17	3.627±26	1619±5
3	27	5	107.8	34.4	0.58	2501	81.4 - 8.6 - 10.0	0.2965±9	4.314±16	1724±4
4	51	13	77.6	24.6	0.04	15857	81.2 - 8.6 - 10.2	0.2993±14	4.351±21	1722±2
5	20	14	139.3	44.4	0.01	19457	81.5 - 8.6 - 9.9	0.3018±8	4.423±13	1737±3
6	20	8	108.0	34.1	0.09	9251	81.3 - 8.6 - 10.1	0.2978±9	4.325±14	1721±3
7	11	4	83.3	22.8	0.03	6425	82.3 - 8.3 - 9.4	0.2609±12	3.634±21	1643±6
8	13	6	190.4	51.1	0.04	15045	82.1 - 8.7 - 9.2	0.2561±12	3.730±19	1725±3
9	15	6	134.5	40.2	0.39	4311	81.0 - 8.3 - 10.7	0.2788±16	3.950±24	1674±3

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

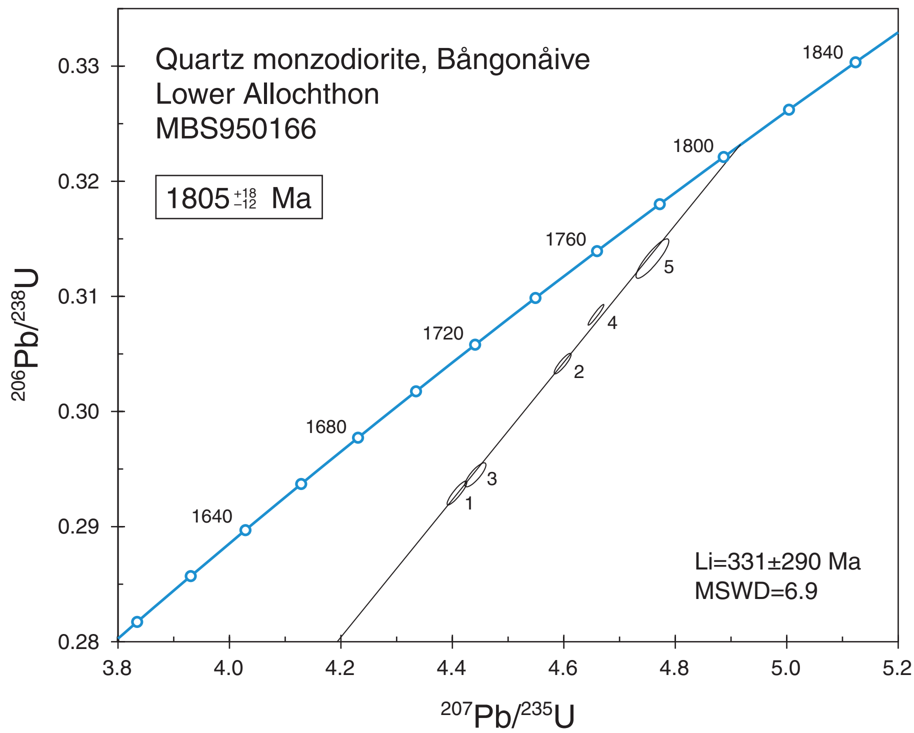

Fig. 7. Concordia diagram from analysed zircon fractions from the Bångonåive quartz monzodiorite.

dex faces are seen on zircons with developed crystal faces. Most of the larger grains contain light-coloured (white, grey or light green) material in addition to the brown material, occurring either as cores or irregularly distributed domains. The analysed crystals consist of brown material alone. A large number of grains have dark brown, rounded cores and light brown mantles. No signs of inherited cores or secondary overgrowths can be seen in the analysed crystals. The latter are of good quality, i.e. transparent and devoid of cracks and metamict domains, and were strongly abraded. Despite the good quality and thorough abrasion of the analysed zircon grains, the data points are 5–10 % discordant (Fig. 7). The linear fit is not perfect, as evidenced by the MSWD of 6.9 and the large uncertainty of the upper intercept age, 1805^{+18}_{-12} Ma. Thus, it is likely that the zircons have an age heterogeneity that is not visible when examined under the stereo microscope. The age is tentatively interpreted as the intrusion age of the quartz monzodiorite.

BFRG 97002. Quartz syenite at Mörrösjöbäcken, Lower Allochthon

The zircons display different shades of brown but some are more or less colourless. Most are severely metamict but a few grains of good quality are also present. Most crystals are short, with length/width ratios of 1–3; only few are longer. Crystals with low index faces predominate, but among the analysed crystals some grains with high indices are present. Cores or overgrowths were only seen in a few crystals. All analysed zircons were strongly abraded. Fraction 1 consists of large but fragmented crystals (sieve fraction >106 µm) whereas the other fractions consist of middle-size crystals (sieve fraction 74–106 µm). Some inclusions and magmatic zonation can be seen in the zircons of fractions 3 and 4 but the remainder lack internal structures.

In the concordia diagram (Fig. 8), the data points are slightly discordant, plotting closely together but on a straight line (MSWD = 0.07). The upper intercept age is 1798±6 Ma, which is interpreted as the intrusion age of the quartz syenite.

BFRG 97003. Meta-quartz syenite at Harrvik, Middle Allochthon

Most of the zircons are brown, some are colourless. All have a more or less rounded outline and many are almost spherical, due to numerous, small high-index surfaces. The rounding is probably a result of the strong deformation in the sample. Many grains are fragmented. Magmatic zonation is common. In some grains, this zonation is sometimes confined to the outer part whereas the central part is homogeneous. Some grains display cores which generally are either very small and euhedral or large and rounded. The analysed crystals lacked visible signs of cores or overgrowths. All analysed zircons were strongly abraded.

Fraction 2 diverges chemically slightly from the others by being richer in ^{208}Pb (thorogenic Pb). As seen on the concordia diagram, the zircons have experienced variable degrees of disturbance of the U-Pb isotope system follow-

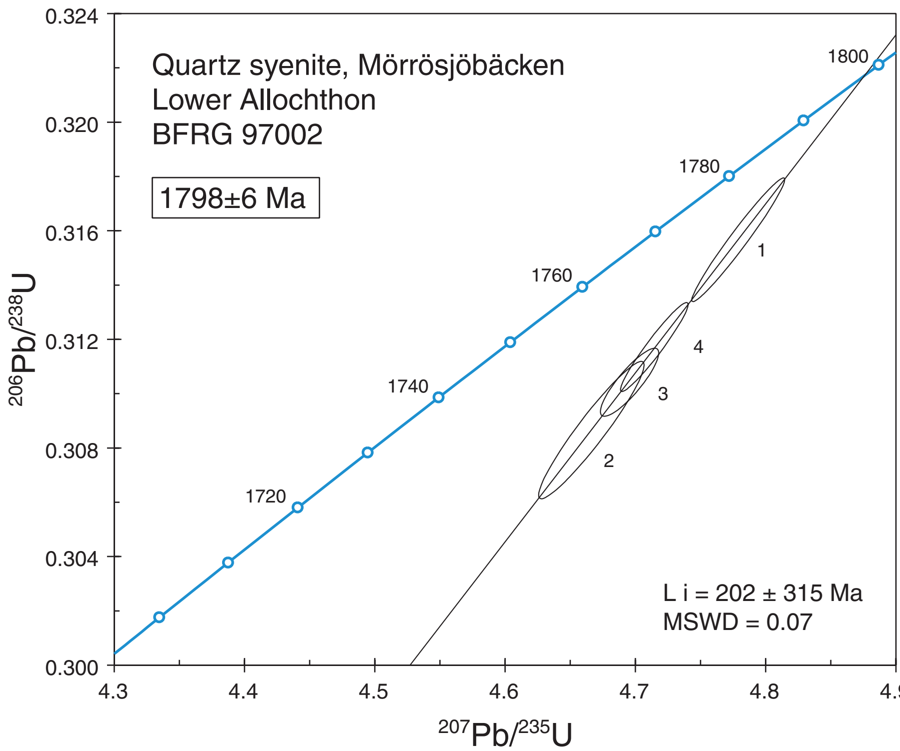

Fig. 8. Concordia diagram from analysed zircon fractions from the Mörrösjöbäcken quartz syenite.

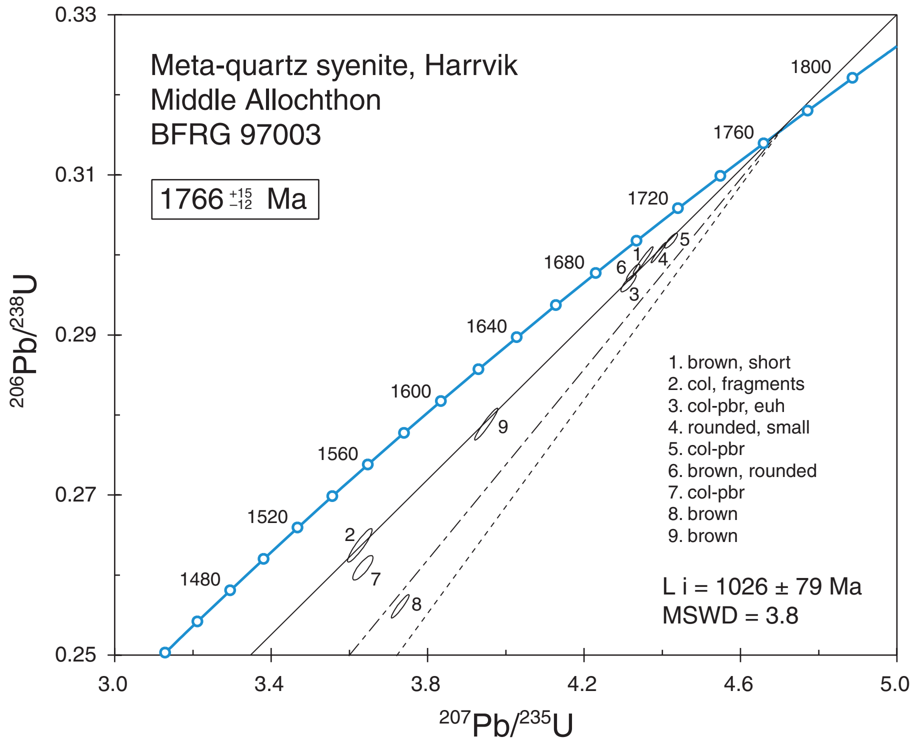

Fig. 9. Concordia diagram from analysed zircon fractions from the Harrvik foliated meta-quartz syenite. col = colourless, pbr = pale brown, euh = euhedral. The upper dashed line has a lower intercept age of 400 Ma (Caledonian). The lower dashed line has a lower intercept of zero.

ing crystallisation of the intrusion. This disturbance probably occurred at different times. All points except 7 and 8 fall on a discordia with intercept ages of 1766^{+15}_{-12} and 1026±79 Ma and an MSWD of 3.8. The zircons in fractions 7 and 8 have also been affected by younger events. A line through fraction 8 has a lower intercept of 308 Ma, if an upper intercept of 1766 Ma is assumed. Hence, if a Caledonian tectonothermal event affected these zircons, its imprint is obscured by an even later (recent?) event. The intrusion age provided on the printed geological map (1768±21 Ma; Greiling & Zachrisson 1999) was based on preliminary results.

Conclusions

Both the U-Pb zircon dating results and the geochemical data suggest a close relationship of the studied samples to the c. 1810–1760 Ma suite of intrusive rocks in the Transscandinavian Igneous Belt. Similar rocks and ages have been reported from the Fennoscandian Shield immediately to the east of the Caledonian front, e.g. the Sorsele granite (Lundqvist et al. 1995).

The zircon dating of the meta-quartz syenite at Harrvik suggests a Sveconorwegian disturbance of the U-Pb isotope system. Dating of an orthogneiss in the overlying Upper Allochthon did not show any Sveconorwegian influence (Zachrisson et al. 1996). Since this Upper Allochthon orthogneiss restores to a position west of the Middle Allochthon meta-quartz syenite, it may limit a Sveconorwegian domain to the west. Further work will be needed to show whether such a pre-Caledonian tectonometamorphic event may explain the strong deformation of the basement rocks in the Middle Allochthon, where the (post-Sveconorwegian) sedimentary cover sequences are mostly relatively less deformed (e.g. Greiling 1989).

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Ages of post-tectonic dyke porphyries and breccias in Bergslagen, south-central Sweden

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Lundström, I., Persson, P.-O. & Ahl, M., 2002: Ages of post-tectonic dyke porphyries and breccias in Bergslagen, south-central Sweden. *In* S. Bergman (ed.): *Radiometric dating results 5.* Uppsala 2002. *Sveriges geologiska undersökning C 834,* pp. 43–49. ISBN 91-7158-668-7.

In order to obtain minimum emplacement ages for post-orogenic breccias, which are cross-cut by and at places intermingled with post-orogenic porphyries, attempts have been made to date these porphyries with the U-Pb method on zircons.

The Gustafs porphyry forms regional, north-east trending dyke swarms and is an isotropic, quartz-plagioclase-phyric rock with euhedral phenocrysts. It has a granitic composition and within plate granite geochemical characteristics. Like the nearby, post-orogenic Noran intrusion, it seems to be an evolved A-type rock, similar to the evolved types of the rapakivi rocks. It is poor in zircons, which yield discordant data points that define a discordia with an upper intercept of 1474±4 Ma, which is interpreted as the intrusion age.

The Bjursås porphyry is only known from a small horizontal dyke, distinctly cross-cutting the Bjursås breccia. It is an isotropic, plagioclase-phyric rock with euhedral plagioclase phenocrysts. The composition is granitic, but close to quartz-monzonitic and quartz-syenitic. It plots within the volcanic arc and post-collision granite fields and shows mixed S- and I-type characteristics. These features make the Bjursås porphyry difficult to assign to any rock suite known from the neighbourhood. It contains only few and heterogeneous zircons and therefore only single crystal analyses were performed. Four out of five data points define a discordia with an upper intercept of 1787±9 Ma. The remaining point plots to the left of the discordia. Inheritance may have affected the results, but the upper intercept age is suggested to be the most probable intrusion age.

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Introduction

The Bergslagen province is regionally dominated by rocks that are early- or syn-orogenic in relation to the Svecokarelian orogeny (Stephens et al. 2000). In addition, there are a number of rocks of limited regional extent that are post-tectonic in relation to Svecokarelian structures. The following contribution reports two attempts to date such rocks radiometrically, namely the Gustafs porphyry described e.g. by Geijer (1922), Hjelmqvist & Lundqvist (1953) and Hjelmqvist (1966), and a hitherto unknown, completely different plagioclase porphyry from Bjursås (Fig. 1). Both occur as straight dykes that clearly cross-cut and post-date any Svecokarelian fabric. As the porphyries also cross-cut some strange breccias, the porphyry ages would furthermore yield the minimum emplacement ages for the breccias, which was one of the main reasons for undertaking these dating attempts. The geologic interrelations between the porphyries and the breccias are described by Lundström et al. (2000) and Lundström et al. (2002). In the latter work, the breccias are suggested to have formed as autoclastic flow breccias.

Geologic and radiometric data

The Gustafs porphyry

Field relations

NE-trending dyke swarms of Gustafs porphyry are frequent in a very restricted region in the southern part of the county of Dalecarlia (Dalarna) (Fig. 1). According to Törnebohm's (1878–82) map, the swarms seem to occur essentially between two major, NW–SE-trending morphological lineaments (Fig.1). According to Hjelmqvist & Lundqvist (1953), the dykes may be up to 20 metres wide and, locally, making up almost half of the bedrock. Hjelmqvist & Lundqvist (1953) and Hjelmqvist (1966) described complicated interrelationships with the Tuna dolerites, which have the same general strike and occur in the same, but somewhat wider, area. They are believed to be coeval with the Gustafs porphyries and have been dated by Patchett (1978) at 1371±50 Ma with the Rb-Sr whole-rock method. A felsic, possibly related intrusion occurs at Noran and was dated at 1469±10 Ma with the U-Pb method on zircon by Claesson & Kresten (1997).

The site sampled for this work is located approximately 10 km NW of Säter at Pellesberget (Fig. 1), where the Gustafs porphyry intrudes and intermingles with the breccia in a spectacular way (see Lundström et al. 2000 and Lundström et al. 2002, Figs. 9, 14, and 16). The sample was taken from a vertical, approx. 20 m wide and distinctly cross-cutting dyke, but locally the porphyry also forms a matrix in the breccia and occurs as breccia clasts, suggesting that the breccia and the Gustafs porphyry were emplaced coevally.

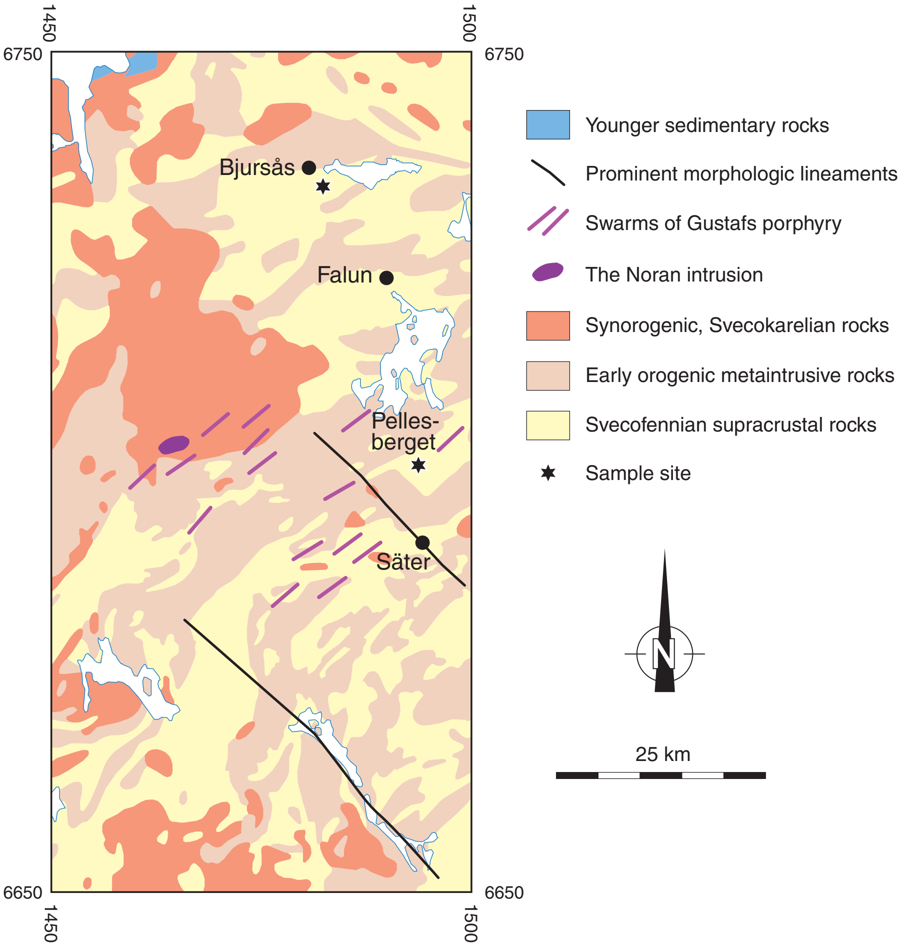

Fig. 1. Schematic bedrock map of the Säter-Falun area. Based on Törnebohm, (1879–82), Kulling & Hjelmqvist (1948), Hjelmqvist & Lundqvist (1953), Kresten (1987a, b), Lundqvist et al. (1994) and Strömberg (1996).

Sample description

The sampled Gustafs porphyry is an isotropic, fine-grained, quartz-plagioclase-phyric rock with euhedral phenocrysts. The quartz phenocrysts are rhomboidal and corroded in many places and the plagioclase phenocrysts are euhedral and glomerophyric and may be myrmekitic. The phenocrysts are less than 4 mm in size. The matrix is fairly even-grained, with an allotriomorphic-granular texture and a grain-size less than 0.02 mm (see Fig. 2 and Figs. 14 and 16 in Lundström et al. 2002). In addition to quartz and feldspar, the matrix also contains biotite and chlorite as main minerals and accessory fluorite.

The chemical composition of the Gustafs porphyry is shown in Table 1. The silica content is high and the rock is a granite s.s. according to the P-Q diagram (Fig. 3a) of Debon & LeFort (1983). It is slightly peraluminous (aluminium saturation index: AI 1.04), and has a rather evolved chemistry with a low K/Na ratio (0.90) as well as a low Mg # (0.11), and a FeO^{tot}/MgO ratio of 13.81. The Rb/Sr ratio is very high (35.0) and the sum of Zr+Rb+Ce+Y is 1593 ppm. In the tectonic setting discrimination diagram of Pearce (1996) the Gustafs porphyry plots distinctly in the within-plate granites field (Fig. 3b). The chondrite-normalised REE-diagram shows a pronounced negative Eu anomaly with a Sm/Eu_N ratio of 16.51, high $HREE_N$ values and a rather moderate slope (the La/Yb_N ratio is 2.30, Fig. 3c). In a normalised rock/primitive mantle spider diagram the pattern shows high contents of LIL (large ion lithophile) elements such as Rb, Th, and of HFS (high field strength) elements such as Nb, Zr, Hf and Ta, whereas Ba, Sr and P are low (Fig. 3d).

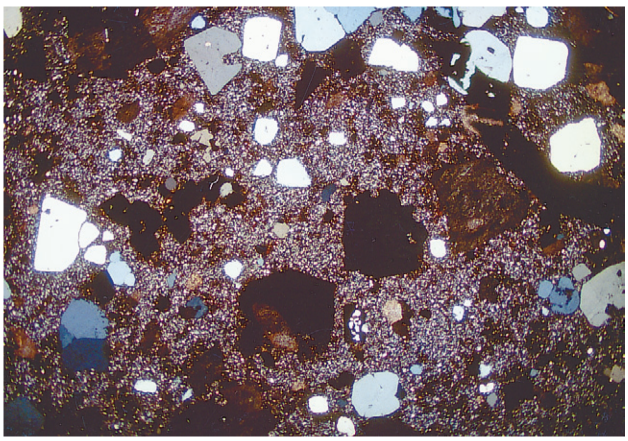

Fig. 2. Gustafs porphyry. Microphotograph, double nicols. Long side of photograph approximately 14 mm. Outcrop in power line at Pellesberget, 200 m northeast of the road. (6699889/1493058)

TABLE 1. Chemical analyses of Gustafs and Bjurså s porphyries. The analyses were made with the ICP-AES and ICP-QMS methods at Svensk Grundämnesanalys AB, Luleå.

	PB2C Gustafs porphyry Pellesberget	OIL980094D Plagioclase porphyry Bjurås		PB2C Gustafs porphyry Pellesberget	OIL980094D Plagioclase porphyry Bjurås
N-coord.	6699836	6733238			
E-coord	1493066	1482316			
SiO_2 (wt %)	76.5	61.5	La (ppm)	53.9	32.5
TiO_2	0.117	0.416	Ce	132.0	58.3
Al_2O_3	11.2	17.8	Pr	14.0	10.4
Fe_2O_3	2.41	5.17	Nd	60.7	39.0
MnO_2	0.038	0.107	Sm	15.90	8.41
MgO	0.16	1.73	Eu	0.36	1.98
CaO	0.13	1.21	Gd	18.40	7.31
Na_2O	3.36	3.65	Tb	3.46	1.01
K_2O	4.62	4.29	Dy	26.5	5.8
P_2O_5	0.03	0.33	Ho	5.91	1.19
Summa	98.6	96.2	Er	15.30	3.75
LOI	0.7	3.2	Tm	2.65	0.79
			Yb	15.80	4.49
Ba (ppm)	72	950	Lu	2.21	0.72
Be	4.99	1.03			
Co	66.7	<5.73			
Cr	<11.9	16.7			
Cu	37.8	<5.73			
Ga	31.5	40.1			
Hf	46.2	6.9			
Mo	<2.38	<2.29			
Nb	112	11			
Ni	<11.9	<11.5			
Rb	312	125			
Sc	2.04	6.97			
Sn	38.0	6.9			
Sr	9	475			
Ta	11.4	1.5			
Th	47.7	12.8			
U	24.60	6.54			
V	<2.38	50			
W	598	2			
Y	139	20			
Zn	134	90			
Zr	1210	176			

Results

The porphyry contains few zircons and the ones that exist constitute a heterogeneous population. The colour ranges from colourless to pink and yellowish brown. Most crystals are euhedral and have only faces with low crystallographic indices but anhedral grains are also present. Most crystals are severely metamict. The majority of the zircons have cores, generally of rounded outline, but the analysed crystals lacked visible cores or overgrowths. Magmatic zonation is present in most crystals. All analysed zircons were strongly abraded.

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 isotopic results are shown in Table 2 and Fig. 4. All data points are discordant and fraction 3 is markedly more discordant than the others and has a much larger uranium concentration. The discordia has intercept ages of 1474±4 Ma and 54±11 Ma and an MSWD of 0.16. The upper intercept age is interpreted as the intrusion age of the Gustafs porphyry.

The Bjurås plagioclase porphyry

Field relations

The Bjurås plagioclase porphyry was sampled from an approxmately 1 m thick, straight, almost horizontal dyke, in a small prospect, south of Lake Rappsmälingen, 12 kilometres NW of Falun (Fig. 1). The dyke clearly crosscuts a breccia, similar to the Pellesberget breccia. In contrast to the Gustafs porphyry, however, the Bjurås plagioclase porphyry is strictly confined to the dyke and does not intermingle with the breccia. Consequently, the breccia must have existed before the plagioclase porphyry intruded. Due to poor outcrops, however, the field relations of the plagioclase porphyry are poorly known outside the sample site. See Lundström et al. (2002, Figs. 2, 4 and 7).

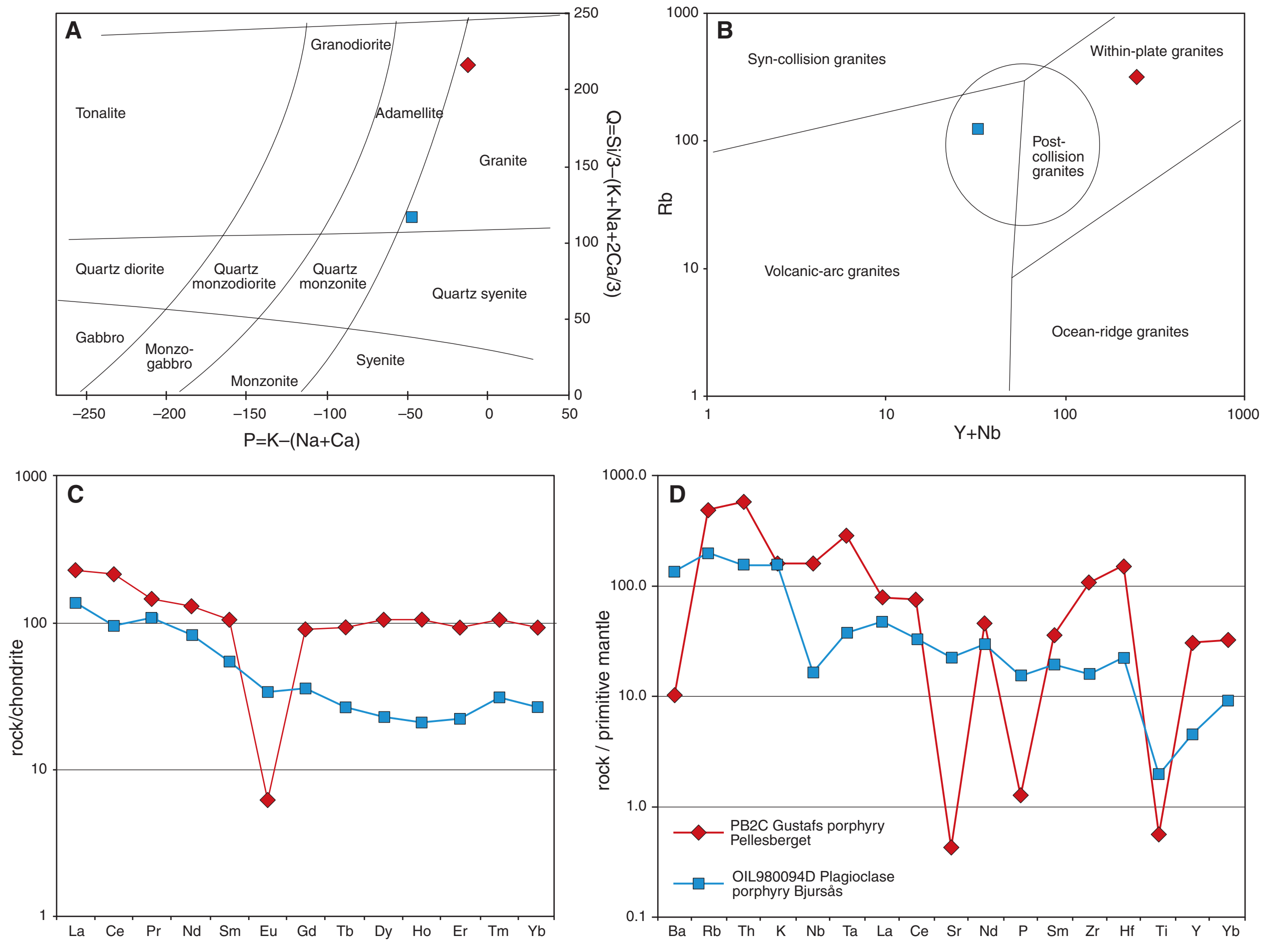

Fig. 3. Geochemical discrimination diagrams. Red diamonds: Gustafs porphyry. Blue squares: Bjurås plagioclase porphyry. a). P-Q classification diagram (Debon & LeFort 1983). b) Y+Nb versus Rb diagram, indicating different tectonic environment (Pearce 1996). c) Chondrite-normalised REE-diagram (Sun and Donough 1989). d) Primitive mantle-normalised trace element diagram (Sun and Donough 1989).

Sample description

The Bjurås plagioclase porphyry is an isotropic rock, consisting of plagioclase, sericite, and opaques as the main minerals. The groundmass is dominated by radiating, lath-shaped, and up to 0.3 mm large plagioclase grains and interstitial opaque minerals. The phenocrysts make up approximately 10 vol.-% of the rock and consist of mostly thoroughly sericitised, euhedral, zoned, somewhat glomerophyric, c. 0.5 mm large plagioclase grains, see Figure 5.

The chemical composition of the Bjurås plagioclase porphyry is shown in Table 1. In the Debon & LeFort (1983) nomenclature diagram the rock plots as a granite close to the fields for quartz monzonite and quartz syenite (Fig. 3a). It is strongly peraluminous (AI 1.36), the K/Na ratio is 0.77, and the Mg # is 0.40. The rock displays a FeO^{tot}/MgO ratio of 2.69. The Rb/Sr ratio is low (0.26) and the sum of Zr+Rb+Ce+Y is 266 ppm. In the Pearce (1996) diagram (Fig. 3b), the Bjurås plagioclase porphyry plots distinctly in the volcanic arc granite as well as in the post-collision granite field. The REE-pattern displays a Sm/Eu_N ratio of 1.60 and a rather flat slope with a La/Yb_N ratio of 4.88 (Fig. 3c). In the spider diagram (Fig. 3d) the pattern shows a moderate enrichment of LIL- and HFS-elements.

Results

The isotopic results are shown in Table 2 and Figure 6. The porphyry contains very few zircons, forming a heterogeneous population. Some are colourless, euhedral and clear. Others are colourless to beige, metamict and somewhat rounded. A large portion are yellowish brown and euhedral. Many crystals are fragmented. Due to the small number of zircons at hand and the heterogeneous population, only single crystal analyses were performed but no abrasion was carried out. No cores or overgrowths were detected in the analysed crystals.

TABLE 2. U-Pb isotopic data.

Analysis No.	Weight (μg)	No. of crystals	U (ppm)	Pb tot. (ppm)	Common Pb (ppm)	$^{206}Pb^{a}/^{204}Pb$	^{206}Pb – ^{207}Pb – ^{208}Pb Radiog. (atom %)^{b}	$^{206}Pb^{b}/^{238}U$	$^{207}Pb^{b}/^{235}U$	$^{207}Pb/^{206}Pb$ age (Ma)
PB 2C. Gustafs porphyry at Pellesberget.										
1	4	4	640.5	153.1	0.68	7546	81.0–7.5 –11.5	0.2242±8	2.847±12	1470±4
2	5	5	503.2	122.0	0.45	8367	81.8–7.5–10.7	0.2296±18	2.916±24	1470±4
3	6	6	1815.3	301.6	2.70	5394	78.7–7.2–14.1	0.1507±7	1.896±10	1452±3
4	2	2	627.3	156.9	4.52	1504	79.8–7.4–12.8	0.2309±11	2.937±18	1472±7
OIL 980094. Plagioclase porphyry at Bjursås.										
1	2	1	476.3	158.2	0.49	6434	75.2–8.2–16.6	0.2890±12	4.355±20	1787±3
2	3	1	170.6	48.1	0.86	1371	83.7– 9.2–7.1	0.2698±22	4.075±36	1792±6
3	2	1	599.9	184.2	3.62	1788	83.2– 9.1–7.7	0.2912±19	4.398±19	1792±5
4	2	1	229.3	65.7	0.44	3545	84.7–9.2– 6.1	0.2803±19	4.177±19	1768±5
5	1	1	323.6	90.5	0.99	2332	84.4–9.2–6.4	0.2716±14	4.093±29	1787±9

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

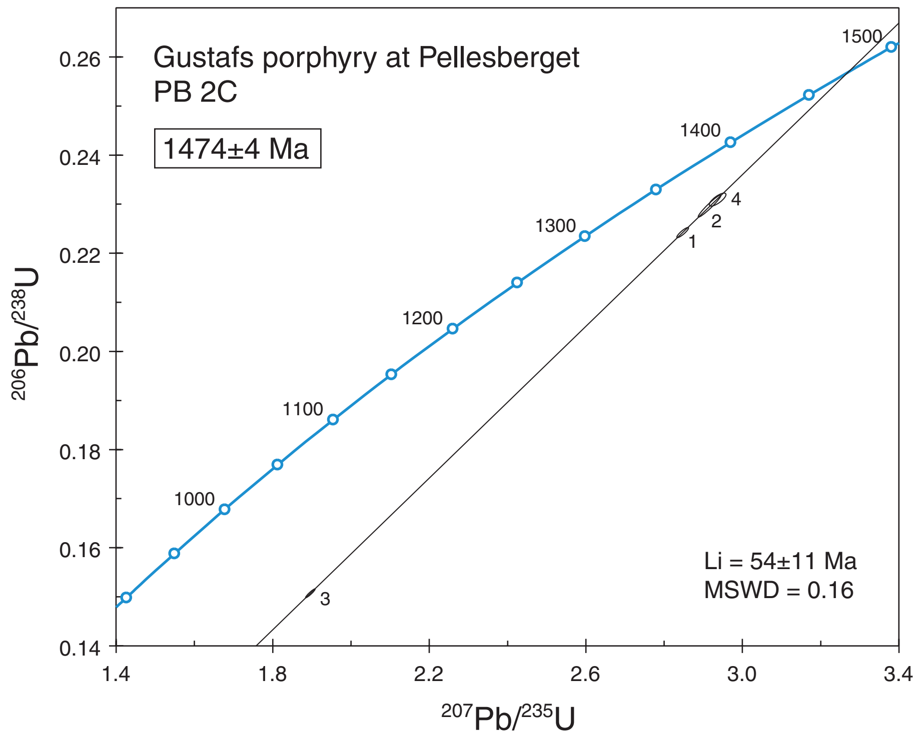

Fig. 4. Concordia plot for the Gustafs porphyry at Pellesberget.

Fraction 3 is a brown crystal whereas the other four are colourless. These are euhedral with sharp edges and pyramids but fragmented. Four of the five data points define a discordia with intercepts at 1787±9 and –38±140 Ma and an MSWD of 1.6. The remaining crystal (No. 4) plots to the left of the discordia and has, consequently, a younger ^{207}Pb–^{206}Pb age. There is, however, no distinct chemical difference between this zircon and the others.

Discussion

The crystallisation age of 1474±4 Ma obtained for the Gustafs porphyry is in good agreement with the 1469±10 Ma age obtained for the Noran intrusion by Claesson & Kresten (1997). Hence it can be concluded that the Gustafs porphyry and the Noran intrusion belong to the same magmatic generation and that the intruded breccia was emplaced at the same time.

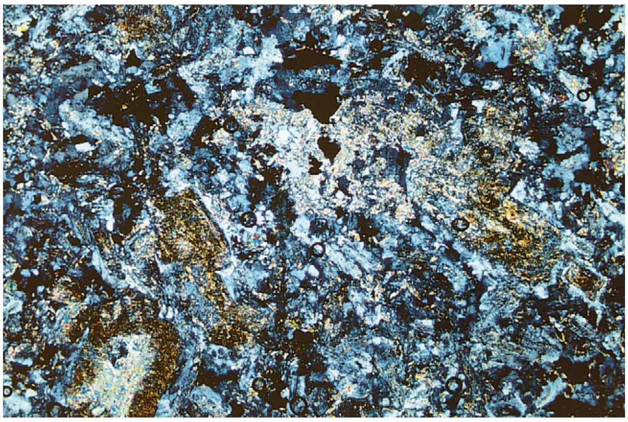

Fig. 5. Bjursås plagioclase porphyry. Microphotograph, double nicols. Long side of photograph approximately 3 mm. Small prospect south of Lake Rappsmälingen. (6733238/1482316)

Furthermore, the Gustafs porphyry and Noran intrusion seem to share many chemical characteristics (cf. Claesson & Kresten 1997). Features, such as the high contents of Si, Hf, Rb, Sn, Y, Zr, and REEs (except Eu) and depletion of Ba and Sr together with high ratios FeO^{tot}/MgO and Rb/Sr, suggest that the Gustafs porphyry is an evolved A-type rock similar to evolved types within the rapakivi complexes of the Fennoscandian shield (Rämö & Haapala 1995, Andersson 1997 and references therein).

The intercept age of the Bjursås porphyry may well reflect the intrusion age of the porphyry but the scarcity and heterogeneous appearance of the zircons render it necessary to also consider the possibility that the zircons are inherited from the protolith or the country rock. The euhedral shape and lack of cores or overgrowths, however, argue against inheritance. The fact that four out of five fractions define a discordia age also strengthens the probability that the discordia age is the age of the rock. No outcrops of 1.79 Ga intrusions are present in the immediate vicinity of the Bjursås porphyry and this argues against a country-rock origin of the zircons. Consequently, the Bjursås breccia most probably existed before 1.79 Ga.

The Bjursås porphyry displays mixed S- and I-type characteristics such as a high aluminium index, a high content of Sr, and a low Ca content as well as a low K_2O/Na_2O ratio. It is not possible to reliably assign it to the syn- to late-orogenic suite or to the suite of post- to anorogenic intrusive rocks.

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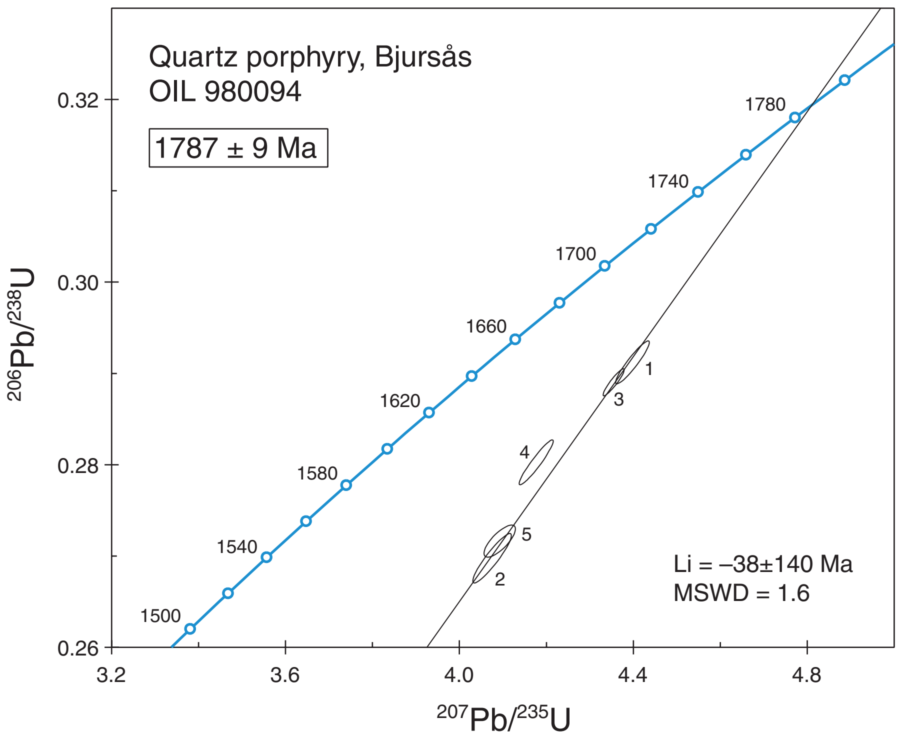

Fig. 6. Concordia plot for the plagioclase porphyry at Bjursås.

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A new occurrence of orbicular granite in Stockholm, Sweden

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Persson, L., Persson, P.-O. & Sträng, M., 2002: A new occurrence of orbicular granite in Stockholm, Sweden. *In* S. Bergman (ed.): *Radiometric dating results 5*. Uppsala 2002. *Sveriges geologiska undersökning C 834*, pp. 50–57. ISBN 91-7158-668-7.

Two outcrops with orbicular granites have been discovered south-east of Stockholm, 1.3 km south-east of the Orminge shopping centre. The orbicular rocks are hosted by a gneissic, early-orogenic granite, which has been affected by migmatisation. The orbicules are of a simple type, with one or two whitish granitic shells, most commonly with a core of the gneissic granite. They are rounded and elongated, ranging in size from 20 x 12 cm to 10 x 5 cm. The orbicules grade into the veins and schlieren of the gneissic granite. A late- to post-orogenic granite, similar to the Stockholm granite, apparently cuts the outcrop and is thus younger than the orbicular granite. The Stockholm granite is c. 1.8 Ga old. The orbicules were formed by magmatic crystallisation but were affected by later migmatisation. The intrusion age of the orbicular granite is 1.89 Ga. Two thermal events affected the granite, i.e. at 1824±3 and 1803±2 Ma. The latter age coincides with the age of the Stockholm granite. It is probable that the other orbicular rocks of the Stockholm region have a similar origin and age.

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Introduction

Orbicular rocks are conspicuous and rare features in the bedrock. Their mode of formation has been debated over the years and igneous as well as metamorphic and metasomatic processes have been suggested. Currently, there is rather wide agreement that they are of igneous origin (e.g. Enz et al. 1979, Menard et al. 1999). Although relatively rare, more than 100 outcrops and boulders containing orbicular rocks have been reported from the Precambrian of Sweden and Finland. Leveson (1966) gave a summary of orbicular granites in the world, of which 10 were from Sweden and 14 from Finland. Affholter (1979) wrote a thesis on orbicular granites from Sandia Mountains in New Mexico (cf. Affholter & Lambert 1982) in which she included a list of 146 other localities around the world, of which 16 were in Sweden. Sederholm (1928) gave a thorough description of orbicular granites/diorites in Finland. He compared the formation of the orbicules with the ovoids of Rapakivi granites. Grip & Russell (1971) have described orbicular granites in the Skellefte District. The same authors (1973) investigated two boulders from Nordsjövallen and Smålands Anneberg (10 km NE of Nässjö). Orbicular granites have also been found in Vasastaden in Stockholm (Brögger & Bäckström 1887), as boulders at Kortfors and Enviken (Bäckström 1894), and at Norr-Husby in the county of Västmanland (von Post 1872). Holst (1885) described the Slättemossa orbicular diorite in Småland. Erdmann (1848) originally mentioned this rock and further information is given in Holst & Eichstädt (1884). This rock is still beautifully exposed in two outcrops south of Järnforsen, map sheet 6F Vetlanda SO (Persson 1989). An occurrence of rudimentary orbicular granite has also been observed in Uppsala, near Kåbo gärde (Wiman 1930 p. 32). Boulders of orbicular granite have been discovered west of Edsele in the county of Västernorrland (Lundqvist et al. 1990).

A new occurrence of orbicular granite has been discovered at Orminge in the eastern part of Stockholm. It was sampled for U-Pb dating of zircon and monazite.

Orbicular rocks in Stockholm

Brögger & Bäckström (1887) described an orbicular rock found in five different places near Vanadisvägen Road and Hälsingegatan Street in Vasastaden, in north-central Stockholm. The orbicules occur lying in a fine-grained, grey granite of so-called Stockholm type. However, this granite is highly unequigranular and contains cm-large, white megacrysts, i.e. it is not a typical late- to post-orogenic Stockholm granite. Such unequigranular porphyritic granites are usually connected with the Svecokarelian migmatisation. The orbicules may attain a length of 40 cm but are usually smaller, with a slightly elongated, oval form. Normal sizes are: length 30 cm, width 14–17 cm and thickness 8–10 cm. The granitic core of the orbicules is often darker than the surrounding granite but the SiO_2 content has been reported to be higher. The orbicular parts of the outcrops have been cut by normal even-grained Stockholm granite, by light, mica-poor granite (which in turn intersects the normal Stockholm-type granites) and by pegmatites.

Boulders of orbicular rock have also been found at Artillerigatan Street in the Östermalm district of east-central Stockholm.

The new occurrence of orbicular rocks

Location

The new locality consists of two outcrops close to each other. They are situated about 1.3 km north-east of the Orminge shopping centre, 875 m and 975 m to the west of the church of Boo (co-ordinates in the Swedish National Grid 658207/164039 and 658212/164033) on topographic map sheet 10I Stockholm NO, 6i. All sampling was done at the first locality.

General geology

The orbicular rocks form part of a small, elongated massif of early-orogenic Svecokarelian gneissic granite, which is intrusive into the surrounding Svecofennian gneisses of mostly sedimentary origin (arenites and argillites; Fig. 1). The gneissic granites are grey, finely medium- to medium-grained, felsic, and slightly foliated with aggregated biotite in lenses and with pegmatitic schlieren. Amphibolitic and metasedimentary xenoliths occur sparsely. In some places the granite reveals more or less distinct, 1 to 2 cm large megacrysts of feldspar in a porphyritic texture. The rock type containing orbicules is mostly even-grained and does not contain feldspar megacrysts (Fig. 2). Deformation and migmatisation affected the supracrustal rocks and the early-orogenic Svecokarelian plutonic rocks. Migmatites in this region are of the veined-gneiss type. After these events anatectic, mostly isotropic, fine- to medium-grained, late- to post-orogenic granites of so-called Stockholm type, as well as pegmatites, intruded. A similar granite at Frescati, north-central Stockholm, has yielded a U-Pb zircon age of 1803^{+23}_{-19} Ma (Ivarsson & Johansson 1995). Öhlander & Romer (1996) presented ages between c. 1770 and 1780

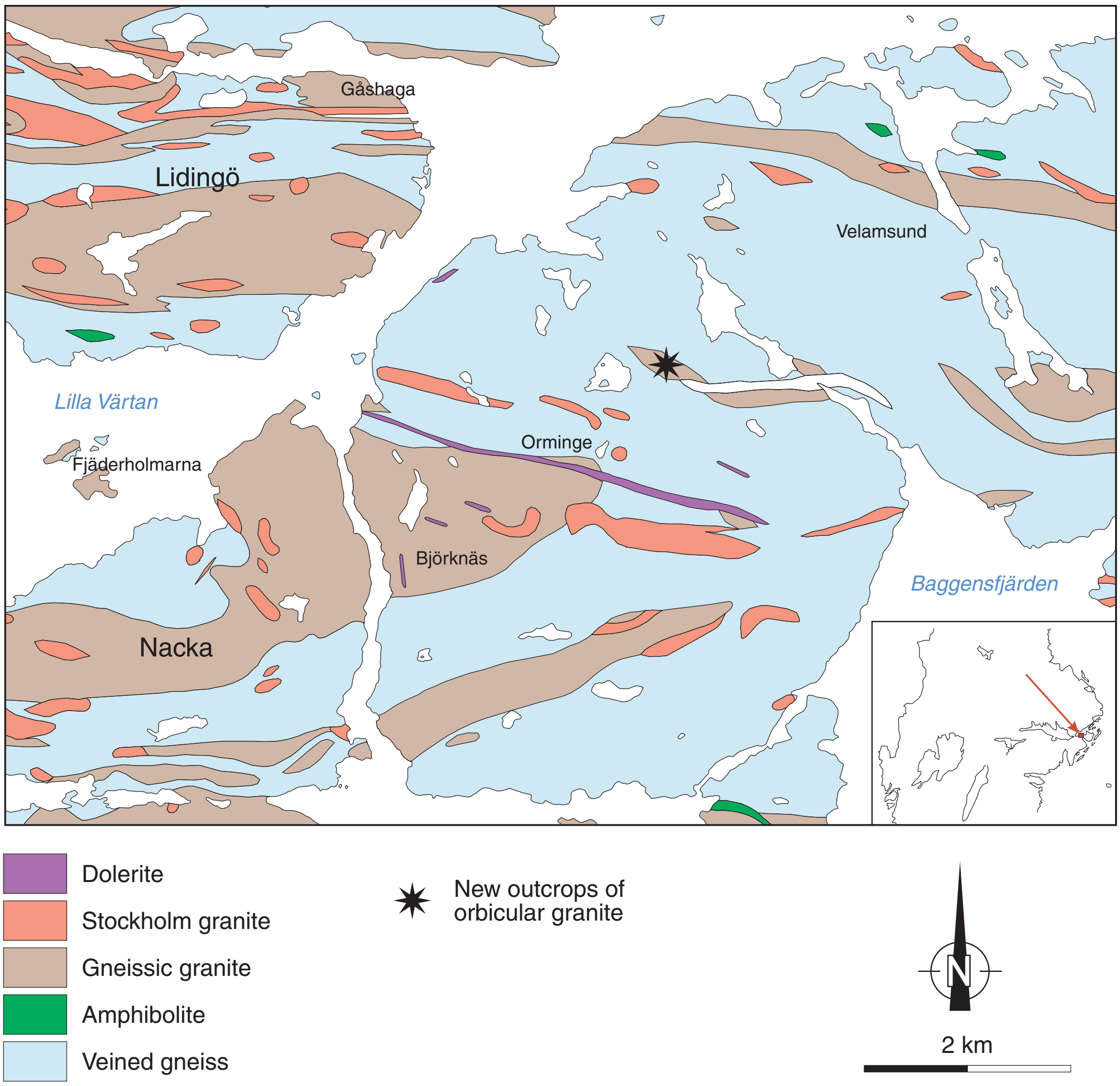

Fig. 1. General bedrock geology of the investigated area, east of Stockholm.

Ma (cf. Welin 1980, Welin & Blomqvist 1964). Ages of dated early-orogenic granites are 1880–1890 Ma. Thus, the Åkersberga granite-monzonite has an age of 1875±6 Ma (Persson & Persson 1997), the Sala granite an age of 1890±3 Ma (Persson 1993) strikes E–W and dips 80° and the Sala-Vänge granite an age of 1891±6 Ma (Ripa & Persson 1997). All are U-Pb ages.

Description of the host rock

The gneissic granite in the immediate neighbourhood of the orbicular rock has the same macroscopical appearance as described in the general geology section above, and is shown in Figure 2. The foliation strikes E–W and dips 80° to the north. A dyke of grey, medium-grained, massive granite (2 metres wide) cuts the orbicular parts of the gneissic granite. The vertical contact strikes N25°W. This granite probably belongs to the generation of late- to post-orogenic Stockholm granites, in turn intersected by pegmatites. Thin veinlets of pegmatite also intersect the orbicular rock. The veinlets strike N80°W and dip vertically (+10°).

The modal composition of the early-orogenic gneissic granite is monzogranitic transitional to granodioritic (Table 2). The granite contains brown, chloritised biotite and strongly sericitised plagioclase. The late- to post-orogenic granite, probably a dyke, is syenogranitic and has a similar content of brown, chloritised biotite as the older rock. The chemistry of the main rock types is reported in Table 1 and all three analyses plot in the granite field in the P-Q classification diagram of Debon & Le Fort (1982). The younger granite is typically enriched in U, Th, Y, and Zr.

TABLE 1. Chemical analyses of surrounding early- and late- to post-orogenic granite types.

Sample	LEP 94:29b Late- to post-orogenic granite Finely medium -grained, grey, partly foliated, veined	LEP 94:29c Early-orogenic, gneissic granite Medium-grained, grey, partly foliated	MP 94:01 Early-orogenic gneissic granite
SiO_2 (wt.%)	74.8	71.4	72.1
TiO_2	0.25	0.36	0.34
Al_2O_3	12.8	14.6	14.8
Fe_2O_3	2.39	2.30	2.18
MnO	0.02	0.02	0.02
MgO	0.42	0.56	0.65
CaO	1.40	1.94	1.55
Na_2O	2.29	2.80	2.77
K_2O	5.36	5.36	5.85
Ba (ppm)	1010	2630	2970
Co	<6.14	<6.11	<5.94
Cr	<12.3	14.8	<11.9
Ga	31.3	27.9	27.5
Hf	9.03	3.20	2.20
Mo	1.67	1.88	2.07
Nb	22.1	8.80	9.79
Ni	6.88	8.08	<5.94
Rb	198	170	202
Sn	1.64	1.43	1.71
Sr	148	226	235
U	2.92	0.27	0.37
Th	24.8	2.58	8.02
V	16.8	24.9	24.8
W	0.24	0.44	0.46
Zr	289	60	62
Zn	22.1	19.7	18.8
Y	32.4	7.18	6.38
Cu	40.7	22.1	23.2

Description of the orbicules

The cores of the orbicules are commonly made up of material similar to the gneissic granite (Figs. 4 and 6). They are surrounded by white, fine-grained, massive, felsic granitic to aplitic material. There is generally only one shell, but locally two shells can be seen. In some cases the whole orbicule may be white and felsic. The cores of the orbicules are 4–7 cm and the rims 2–4 cm in section. The orbicules are beautifully rounded, elongated and oval in form. Some of the larger objects can be very elongated, e.g. 30 x 6 cm, but more common sizes are 20 x 12 cm to 10 x 5 cm (Figs. 3 and 5). The contact zone with the surrounding gneissic granite is more or less diffuse.

Thin sections across some orbicules and adjacent host rock at two locations of the outcrop have been examined and the results are shown in Tables 2 and 3. The host rock 1 cm from one orbicule, approximately 8 cm across (LEP 94:29a, Table 2), is a monzogranite but has a higher content of K-feldspar (string and vein perthite) and a lower content of plagioclase than the surrounding gneissic granite. The biotite is strongly chloritised and the plagioclase completely sericitised. The rock shows a substantial spread in grain size, whereas the orbicules in general are more or less even-grained. The rims of the orbicules are enriched in K-feldspar and low in plagioclase and dark minerals. The centre of the aforementioned orbicule (LEP 94:29a) has a composition intermediate between that of the rim of the orbicule and the host rock just outside. The quartz in the orbicules is highly strained, showing undulose extinction. A thin section taken in the contact zone of the orbicule (LEP 94:29a, 5) displays the general features noted above, i.e. the host rock is non-equigranular and has a coarser grain size and a greater amount of dark minerals than the orbicule.

Table 3 shows modal compositions of orbicules and host rock in another sample. One of the investigated orbicules has two felsic shells (MP 94:3, 1–3). In this case, with two shells, the potassium content increases inwards, due to a K-feldspar content as high as 70 % in the central part. This rock type is of alkali feldspar granitic composition. In another case (MP 94:3, 4–5), where the orbicule has only one light shell, the difference between shell and central part of the orbicule is quite small, and the composition is almost identical to that of the light shell of anoth-

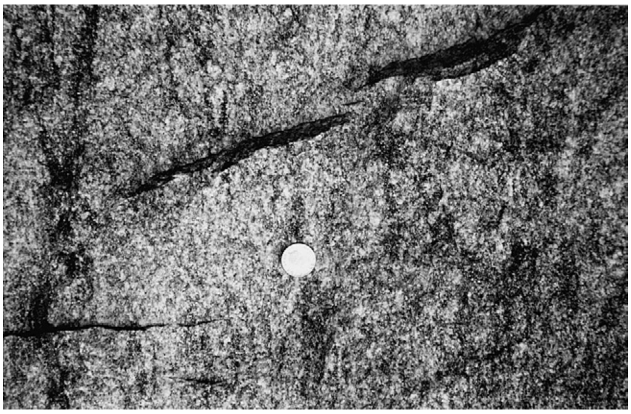

Fig. 2. Host rock, i.e. grey, finely medium- to medium-grained, felsic, slightly foliated gneissic granite, slightly migmatised with felsic granitic schlieren and veins.

Fig. 5. Weathered surface of orbicular granite.

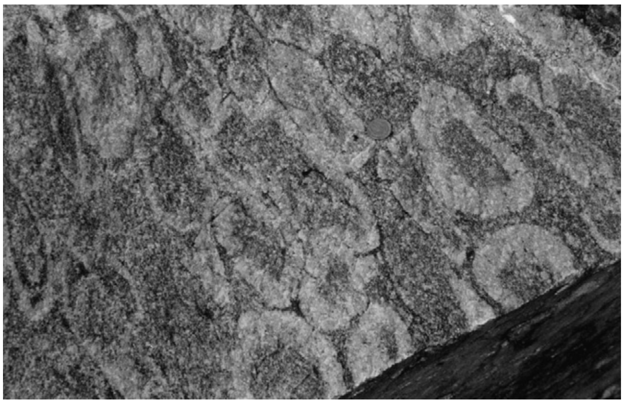

Fig. 3. Orbicular granite.

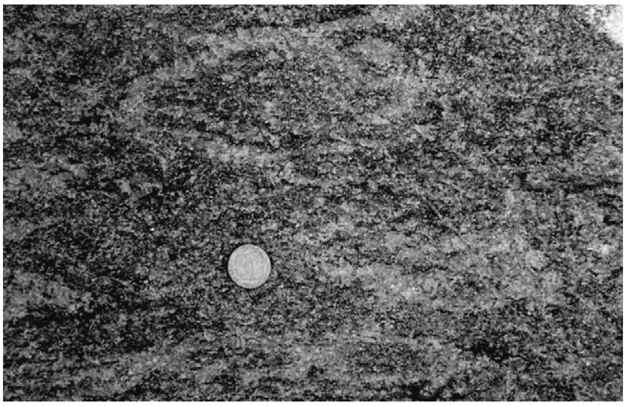

Fig. 6. Orbicules grading into host rock.

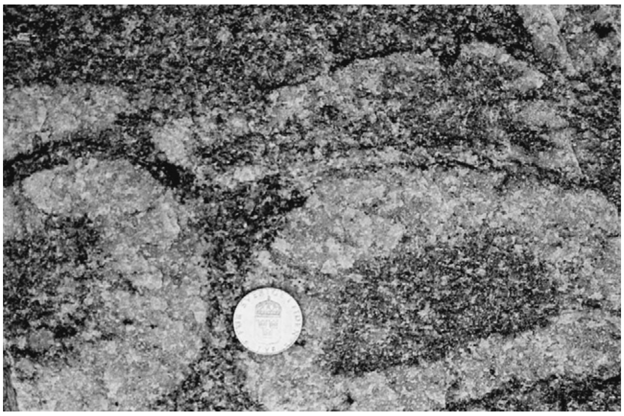

Fig. 4. Orbicular granite.

er orbicule. The grey, granitic host rock between two orbicules shows even higher K-feldspar values, but this section of the granite has many felsic veins. Some orbicules are ultra-felsic and white. Locally the mica content is raised in the centre of the orbicule. The central part of such an orbicule (MP 94:3, 9) displays a moderate K-feldspar content (approximately 40 %), similar to the orbiculitic rock type with one single shell.

U-Pb geochronology

Mineral description

The whole orbicular rock was sampled for U-Pb analysis. Two types of zircon were encountered. The first type has a normal size distribution, i.e. the majority falls in the 70–100 µm sieve fraction. These zircons are light brown to yellowish brown, but colourless grains are also present. They generally have rounded terminations. When examined in liquid with a high refractive index, many of the zircons of this type display thin rims. Weakly metamict domains as well as zonation and inclusions could not be completely avoided and are present in most of the analysed grains. All fractions were strongly abraded. Fraction 6 was more strongly abraded than the other; the diameter after abrasion was about one third of the original.

Zircon crystals of the second type are conspicuously large, generally falling in the >150 µm sieve fraction, and reach a size of 500 x 250 µm. The length/width ratio varies substantially and is generally between 1 and 5. Some of the elongate crystals (l/w = 4–5) are euhedral but most have rounded terminations and consist mainly of low-index faces. The shorter crystals display numerous high-

TABLE 2. Modal analyses (vol.%) of orbicules and surrounding early- and late- to post-orogenic granite types. + = < 1%.

Sample	LEP 94:29b	LEP 94:29c	LEP 94:29a (1)	LEP 94:29a (2)	LEP 94:29a (3)	LEP 94:29a (4)
Rock type/ Mineral	Late- to post-orogenic granite	Early-orogenic gneissic granite	Host rock 1 cm from orbicule	Rim of orbicule (8 cm across)	Centre of orbicule, 4 cm from contact	Rim of orbicule,
Quartz	26	36	29	24	25	20
K-feldspar	44	22	37	64	47	68
Plagioclase	21	35	25	10	22	11
Sericite/ muscovite	+	1	+	+	+	+
Biotite	7	4	4	1	+	
Chlorite	1	2	4	1	4	1
Epidote	+	+	+	+	1	+
Titanite	+		+	+	1	+
Apatite	+	+	+	+	+	+
Ore minerals	+	1	1	+	1	+
Calcite	+	+	+	+		
Prehnite	+	+	+	+	+	+
Nomen-clature	Syeno-granite	Monzo-granite	Monzo-granite	Syeno-granite	Syeno-granite	Syeno-granite

TABLE 3. Modal analyses (vol.%) of orbicules and surrounding granites. + = < 1%.

Sample	MP 94:3 (1)	MP 94:3 (2)	MP 94:3 (3)	MP 94:3 (4)	MP 94:3 (5)	MP 94:3 (7)	MP 94:3 (8)	MP 94:3 (9)
Rock type/ mineral	Orbicule with two light, felsic shells			Orbicule with one light shell		Host rock with felsic veins	Orbicule	Orbicule, completely felsic
	Central part	Inner shell	Outer shell	Shell	Central part	Between two orbicules	Light shell near contact to host rock	Central part with some mica
Quartz	23	19	34	24	24	28	27	28
K-feldspar	70	65	23	43	42	59	44	40
Plagioclase	6	12	35	19	26	10	23	23
Sericite/ muscovite	+	+	+	1	1	+	1	+
Biotite	+	2	3	9	1		1	4
Chlorite	1	1	5	2	3	1	3	3
Epidote	+		1	+	+		+	+
Titanite	+	+		+	+	+	+	+
Apatite	+			+	+	+		+
Ore minerals	+	+	+	1	1	+	+	1
Calcite	+	+	+	+	1	+	+	+
Prehnite	+	+					+	+
Amphibole					+			
Zircon				+				
Nomenclature IUGS (1973)	Alkali feldspar granite	Syeno-granite	Monzo-granite	Syeno-granite	Monzo-granite	Syeno-granite	Monzo-granite	Monzo-granite

index faces, which give the crystals an overall rounded or anhedral appearance. The colour is different shades of brown but some grains are colourless. Many crystals, especially among the largest, show cores which are mostly rounded, but euhedral cores are also found. Fractions 7, 8, and 9 consist mainly of fragments which were not abraded. Fraction 10 consists of a cut-off tip of a very large crystal and it was abraded. Fraction 11 consists of an abraded, cut-off euhedral core of a large, broken crystal. All the analysed crystals were transparent, non-metamict and with no or very few cracks.

The same sample of orbicular granite contained small amounts of monazite, which was also analysed for U-Pb isotopes. The selected grains were yellowish green and transparent.

Results

Results of the isotopic analyses are shown in Table 4 and Figure 7. A description of the analytical procedure is found in the Editor's Preface to this volume. The zircons of type 1 show a scatter in the concordia diagram. This was expected, considering the presence of rims in many of the zircons. Fraction 6, which was very strongly abraded, possibly removing most of the rims, yields the least discordant point and the oldest $^{207}Pb/^{206}Pb$ age. A regression line through the six points gives an upper intercept age of 1888±22 Ma and an MSWD of 21. This can be regarded as an approximation of the age of magmatic crystallisation of the granite.

Zircons of the second type yield a distinctly different age. The average U and Pb contents of the zircons of type 2 are lower than those of type 1. The ^{208}Pb proportion is also marginally higher. The discordia yields an upper intercept age of 1824±3 Ma. Despite the good quality of the analysed zircon crystals, the data points are discordant. Oddly, the grain in analysis 10, which is of excellent quality and has an extremely high $^{206}Pb/^{204}Pb$ ratio, is markedly more discordant than the others.

The two monazite fractions yield almost concordant data points with a $^{207}Pb/^{206}Pb$-age of 1803±2 Ma, which is interpreted as the crystallisation age of the monazite. A discordia forced through a lower intercept of zero with a conservative uncertainty of ±400 Ma has an upper intercept age of 1803±2 Ma.

Significance of the isotopic ages

As suggested above, the 1.89 Ga age of the small zircon crystals can be interpreted as the intrusion age of the granite. The rims are thin and the crystals abraded, which reduces the influence of the rims on the isotopic age of the zircons. The obtained age agrees with other ages on metamorphosed early Svecokarelian granites and volcanic rocks in south-central Sweden and southern Finland (e.g. Persson 1993, Persson & Persson 1997, Ripa & Persson 1997, Lundström et al. 1998).

The U-Pb ages of the monazite and the large zircon crystals indicate that at least two thermal events affected the granite, at 1824±3 and 1803±2 Ma. During the first episode, Zr-bearing minerals broke down and enabled the formation of new zircon. During the second episode, monazite was formed, possibly as a result of fluid migration. In the examined thin sections (Table 3) one large zircon crystal was found in an orbicule shell in section 94:3 (4). No other zircons were seen and it is thus not known whether the two different zircon types are confined to distinct parts of the rock. Similar ages as those of the large zircons have been reported for columbite in pegmatites at Utö, 40 km south of Orminge (Romer & Smeds 1994) and for strongly discordant monazite in a cordierite-sillimanite gneiss at Flen, 100 km to the south-west (Andersson 1997).

The age of the monazite coincides approximately with the ages reported for the Stockholm granite (Patchett et al. 1987, Ivarsson & Johansson 1995) as well as for columbite from a younger pegmatite group in the Stockholm area (Romer & Smeds 1994). It is also coeval with the monazite of a garnet-cordierite-sillimanite gneiss from Nyköping, 100 km SSW of Orminge (Andersson 1997). That age is interpreted as the age of the peak regional metamorphism. Since no monazite was observed in the examined thin sections it is not known whether it crystallised in the groundmass or in the orbicules.

TABLE 4. U-Pb isotopic data.

Analysis No. sieve fraction (µm) and characteristics[a]	Weight (µg)	No. of crystals	U (ppm)	Pb tot. (ppm)	Common Pb (ppm)	$^{206}Pb^{b}/^{204}Pb$	$^{206}Pb – ^{207}Pb – ^{208}Pb$ Radiog. (atom %)[c]	$^{206}Pb^{c}/^{238}U$	$^{207}Pb^{c}/^{235}U$	$^{207}Pb/^{206}Pb$ age (Ma)
1. 74–106, c–lb	11	6	533.6	176.8	0.62	7423	85.5–9.8–4.7	0.3285±10	5.196±18	1876±2
2. <74, c–lb	11	14	499.2	165.2	0.33	9495	85.5–9.8–4.7	0.3283±17	5.197±28	1877±1
3. <74, c–lb	17	17	293.1	95.2	0.03	11833	85.0–9.7–5.3	0.3208±12	5.036±20	1862±2
4. <74, c–lb	25	9	808.1	255.9	0.46	18262	86.1–9.8–4.1	0.3164±11	4.986±18	1869±1
5. <74, c–lb	18	23	577.8	190.8	1.29	6554	84.9–9.7–5.4	0.3236±10	5.128±18	1879±2
6. 74–106, c–lb	9	20	705.4	239.6	1.00	10367	84.4–9.7–5.9	0.3321±14	5.269±23	1881±2
7. 74–106, f,c	24	13	145.9	47.1	0.07	10431	84.1–9.4–6.5	0.3157±14	4.847±24	1822±4
8. 106–150, f,c	25	5	321.6	102.2	0.56	6225	83.2–9.3–7.5	0.3058±11	4.694±18	1821±2
9. 106–150, f,b	26	6	553.4	175.8	0.15	30891	82.6–9.2–8.2	0.3048±10	4.683±16	1822±2
10. >150, c	103	1	333.5	98.8	0.01	108145	82.1–9.1–8.8	0.2826±6	4.336±13	1820±1
11. >150, c	14	1	492.9	163.4	0.13	20090	82.1–9.1–8.8	0.3160±9	4.859±16	1825±3
M 1	56	4	541.5	1259.7	0.52	17291	12.0–1.3–86.7	0.3209±6	4.875±10	1803±1
M 2	15	2	452.1	1932.9	0.64	10256	6.5–0.7–92.8	0.3206±11	4.870±18	1803±2

a) f = fragments, c = colourless, b = brown, M = monazite.
b) corrected for mass fractionation (0.1 % per a.m.u).
c) corrected for mass fractionation, blank and common Pb.

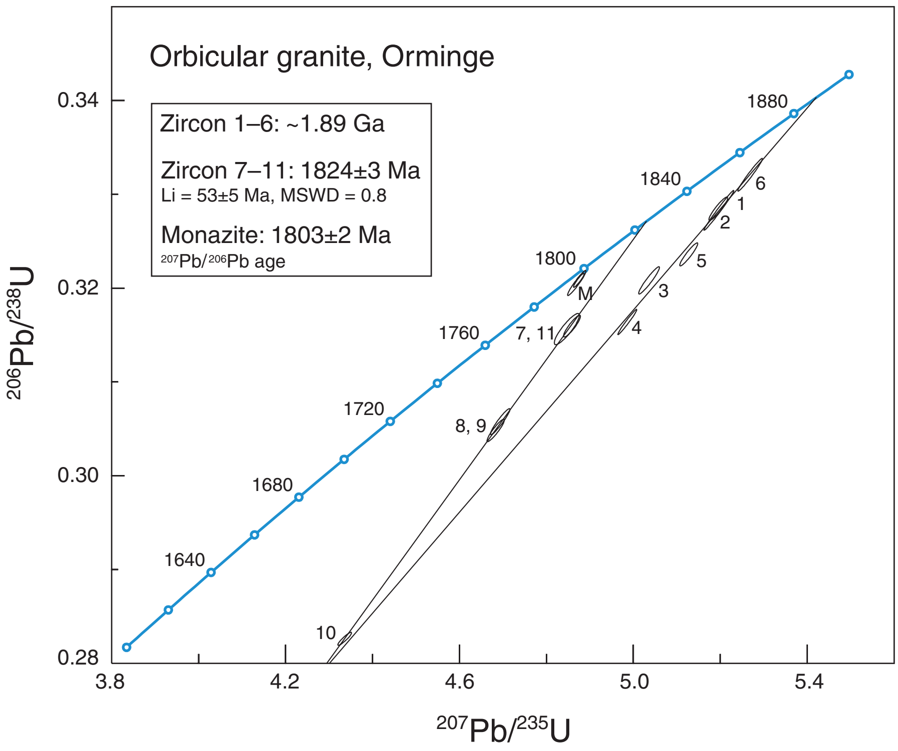

Fig. 7. Concordia diagram for zircon and monazite.

Conclusions

The orbicular rocks constitute small parts of the outcrops where the host rock is a Svecokarelian gneissic granite affected by migmatisation and displaying felsic granitic veins and schlieren. The orbicules are of a simple type with one or two whitish granitic shells, most commonly with a core of the same rock type as the host rock. Especially the light granitic shells, but also the granitic cores and the neighbouring host rock, have increased contents of K-feldspar and lower values of plagioclase compared with the composition of the host rock. Mica and chlorite contents are also low in the most felsic parts. The orbicules grade into the veins and schlieren of the gneissic granite. Thus, the process of orbicule formation seems to be magmatic, and the orbicules have later been affected by migmatisation. Younger granite seems to cut the outcrop, and thus the formation of the orbicules is older than this rock. This younger granite might be coeval with the Stockholm granite at Frescati, central Stockholm, which yielded a U-Pb zircon age of 1803^{+23}_{-19} Ma (Ivarsson & Johansson 1995). The intrusion age of the orbicular granite is 1.89 Ga. Two thermal events affected the granite: at 1824±3 and 1803±2 Ma. The latter age coincides with the age of the Stockholm granite. It seems probable that the other orbicular rocks of the Stockholm region have a similar origin and age.

Acknowledgements

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A c. 1845 Ma ("Askersund") age of the Hälla augen gneiss in south-eastern Östergötland, south-east Sweden

Anders Wikström & Per-Olof Persson

Wikström, A. & Persson, P.-O., 2002: A c. 1845 Ma ("Askersund") age of the Hälla augen gneiss in south-eastern Östergötland, south-east Sweden. *In* S. Bergman (ed.): *Radiometric dating results 5*. Uppsala 2002. *Sveriges geologiska undersökning C 834*, pp. 58–61. ISBN 91-7158-668-7.

Minor massifs of augen gneiss are situated near the Baltic coast of Östergötland and Småland. It has been debated whether these gneisses are deformed equivalents of the Småland granites (belonging to the Transscandinavian Igneous Belt) or if they are older. The obtained age of 1845±8 Ma for the Hälla granite, south of the town of Söderköping, coincides with ages of similar augen gneisses further to the north and northwest in the transition zone towards Svecofennian rocks. It thus belongs to the older generation of TIB intrusions.

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Introduction

The bedrock of the county of Östergötland, SE Sweden consists primarily of Svecofennian (c. 1.9 Ga) supracrustal rocks and orthogneisses and c. 1.8 Ga old granites belonging to the Transscandinavian Igneous Belt (TIB). In the southeastern part (Fig. 1a) a number of augen gneiss bodies of hitherto uncertain age(s) are found. On the geological map sheets of Torönsborg (Asklund 1923), Gusum (Asklund 1928), and Valdemarsvik (Sundius 1928), located along the Baltic coast in the county of Östergötland, these augen gneisses were classified as "younger granites" and were referred to the Småland-Värmland granites in the descriptions (although Sundius stated in his map description that he mainly followed the practice on the adjacent map sheets). The same interpretation is encountered on the bedrock map of Sweden by Magnusson et al. (1958). Nowadays, the Småland-Värmland granites are described as parts of the TIB. Sundius (1927) criticised this classification and one of his arguments was that the regionally deformed (amphibolite facies) character contrasted with the "cross-cutting" appearance of the Småland-Värmland granites. This was also the main reason why the augen gneiss named Hälla granite (Asklund 1928) on the bedrock map of Norrköping NO (Wikström 1975) was regarded as belonging to the older plutonic rocks. It was noted, however, that the regional fold structures associated with this augen gneiss were younger ("F4") than the regionally important Svecokarelian fold structures ("F2" and "F3") further to the north. The older structures bend into the "F4" structures, which have a somewhat varying NNW to N–S trend. On the county map of Östergötland (Wikström 1992) these gneisses were labelled as having an uncertain stratigraphic position. To gain further information on this question a sample for U-Pb dating was collected at Hälla (co-ordinates in the Swedish National Grid 647590/153700).

The Hälla augen gneiss

The bedrock map of the County of Östergötland (Wikström 1992) is mainly a compilation of previously published maps. The geographical distribution of the augen gneisses in southeastern Östergötland was mainly outlined according to the previously mentioned maps from the 1920s (Fig. 1a). This distribution is also marked on the newly released magnetic anomaly map (Geological Survey of Sweden 1999, geophysical database) in Figure 1b. Parts of the Hälla augen gneiss are low-magnetic and easily distinguishable on the map. These parts are affected by younger "subjotnian" faults but the parallel, in general NNW, trend of these parts implies an older tectonic history as well. Other parts are more magnetic and difficult to distinguish from the surrounding rocks.

In general, the augen gneisses are porphyritic with rounded, perthitic microcline megacrysts, 2–3 cm in diameter (Fig. 2). The dark minerals are hornblende and biotite of various amounts and the quartz is white or locally bluish. The augen gneisses have a composition that varies between granite, granodiorite and quartz monzonite but syenitic varieties also occur and noritic gabbros are locally associated with the augen gneisses. These petrographical features have been used as the criteria for an association with the Småland-Värmland granites. However, although some contacts can be sharp towards the country rock gneisses, other contacts are diffuse and difficult to map, leading Sundius (1927) to claim that the augen gneisses belonged to the older gneiss complex. With regard to deformation style, both an older amphibolite facies foliation can be seen as well as a younger foliation where the matrix quartz has been reduced in grain size, whereas the feldspar megacrysts show very little evidence of deformation. The investigated sample from Hälla is somewhat affected by this later deformation.

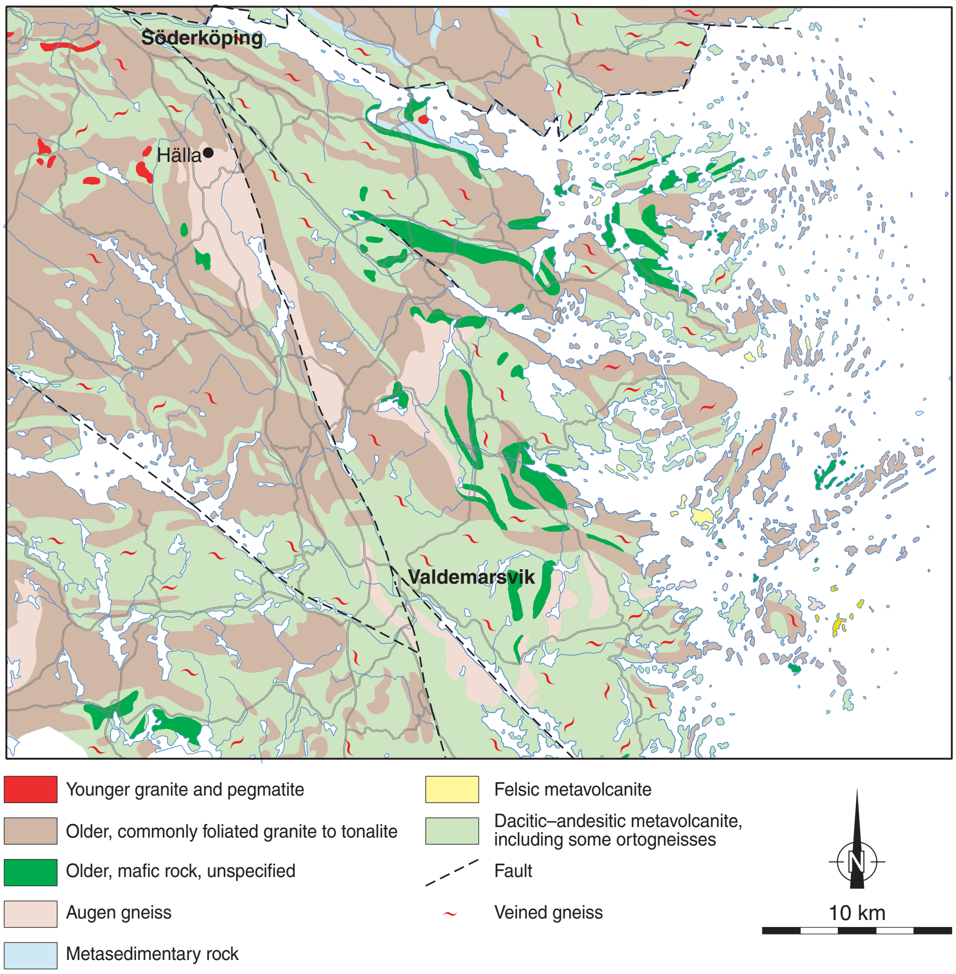

Fig. 1a. Excerpt from the bedrock map of the County of Östergötland (Wikström 1992) of an area in the southeastern part showing the geographical distribution of discussed augen gneisses.

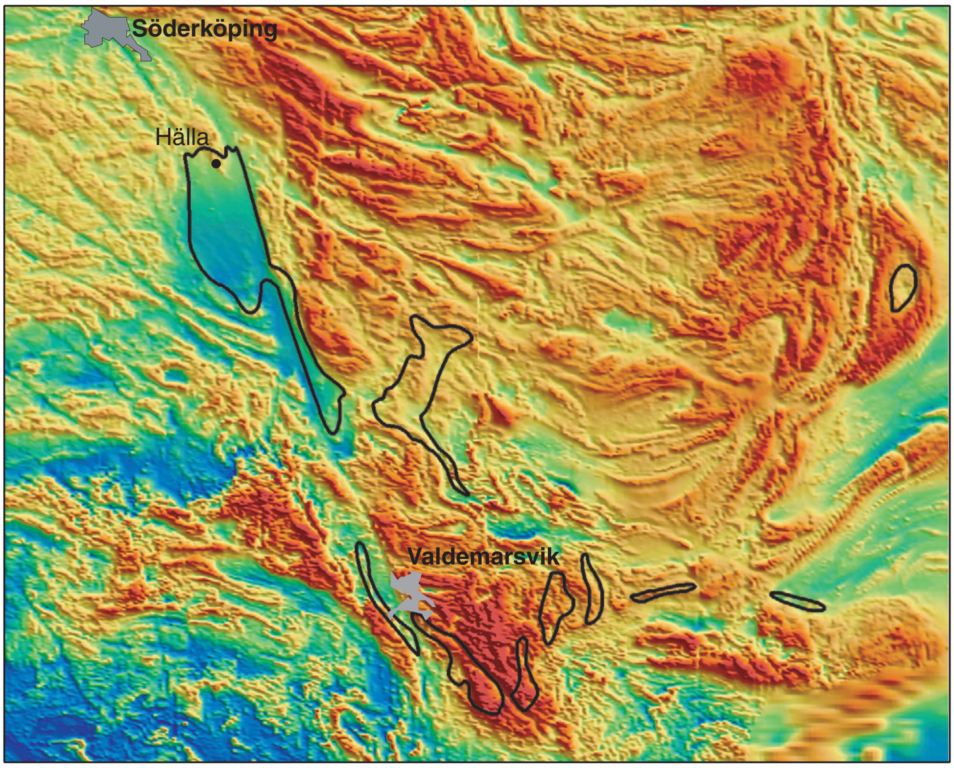

Fig. 1b. Magnetic anomaly map, produced by SGU in 1999, of the same area, with the distribution of the augen gneisses shown by black contours. These have mainly been drawn according to maps by Asklund (1923, 1928), Sundius (1928), and Wikström (1975).

Fig. 2. Hälla augen gneiss from the investigated locality.

Three chemical analyses of the Hälla augen gneiss can be found in Table 8 in Wikström (1975), of which sample number 256 comes from the locality of our investigation. In Figure 14 (Wikström 1975), the low Mg/Mg+Fe-ratio for these rocks was observed to be typical for TIB-rocks (with present nomenclature).

Zircon descriptions and analytical results

The zircon crystals are prismatic and show mainly faces with low crystallographic indices. They are euhedral with slightly rounded terminations and have length/width ratios between 1 and 4. They are colourless to reddish, commonly with the red colour confined to patches or zones. Magmatic zonation is common and euhedral cores are quite frequent but such crystals were avoided when selecting grains for analysis. Most grains are severely metamict but the analysed ones were of good quality, although grains with cracks and/or inclusions could not be completely avoided. All analysed crystals were strongly abraded. A description of the analytical procedure is found in the Editor's Preface to this volume.

The analytical results are presented in Table 1 and Figure 3. The four data points display a linear array with one almost concordant point, representing the smallest crystals. The upper-intercept age is 1845±8 Ma and the lower intercept is close to zero. The age is interpreted as the intrusion age of the granite.

Discussion

U-Pb zircon ages of c. 1.86–1.84 Ga on augen gneisses within the Svecokarelian province are not uncommon. Such ages have been obtained on granitoids from Loftahammar (Åberg 1978), Askersund, (Persson & Wikström 1993, Wikström 1996), Ljusdal (Delin 1993), and Revsund in Jämtland (Högdahl 2000). The important feature in the Askersund area is that this age period is not confined to the augen gneisses but also comprises parts that are visually isotropic. These have been classified on all previously published maps as TIB (or corresponding older names) and labelled "post-orogenic Svecokarelian". Since it is very difficult to separate this generation from the younger c. 1800 Ma old generation also in the field, the distribution of the c. 1845 Ma generation is essentially unknown within the visually isotropic TIB.

The existence of a c. 1845 Ma old augen gneiss in southeastern Östergötland with geochemical and petrographical TIB signatures that are involved in the later Svecokarelian deformation episodes, further strengthens the close connection with the late Svecokarelian development and the start of TIB magmatism (Andersson & Wikström 2001). The view of the TIB as a more or less north–south trending "belt" cross-cutting regional Svecokarelian structures is true on a mega-scale and concerning the 1800 Ma and younger TIB-generations, but it is misleading when it comes to the TIB generation as a whole. In plate reconstruction models (e.g. Park 1994, Åhäll & Larson 2000) delineating the tectonic evolution of the Baltic shield, this has led to the suggestion that the TIB-magmatism heralds a drastically new tectonic regime. As the onset of TIB magmatism took place during the Svecokarelian orogeny the shift in tectonic regime between c.1845 Ma and c. 1800 Ma appears to be a gradual process.

TABLE 1. U-Pb isotopic data for the Hälla augen gneiss.

Analysis No.	Weight (μg)	No. of crystals	U (ppm)	Pb tot. (ppm)	Common Pb (ppm)	$^{206}Pb^{a}/^{204}Pb$	$^{206}Pb - ^{207}Pb - ^{208}Pb$ Radiog. (atom %)[b]	$^{206}Pb^{b}/^{238}U$	$^{207}Pb^{b}/^{235}U$	$^{207}Pb/^{206}Pb$ age (Ma)
1	10	9	266.9	80.4	0.3	6272	84.1–9.4–6.5	0.2935±16	4.546±25	1838±3
2	28	40–50	120.1	40.7	0.3	5010	83.5–9.4–7.1	0.3264±19	5.076±36	1844±7
3	10	7	222.2	60.2	0.1	5794	84.1–9.4–6.5	0.2640±6	4.088±12	1836±3
4	5	3	245.9	78.9	0.4	5364	84.0–9.5–6.5	0.3115±12	4.844±21	1845±3

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

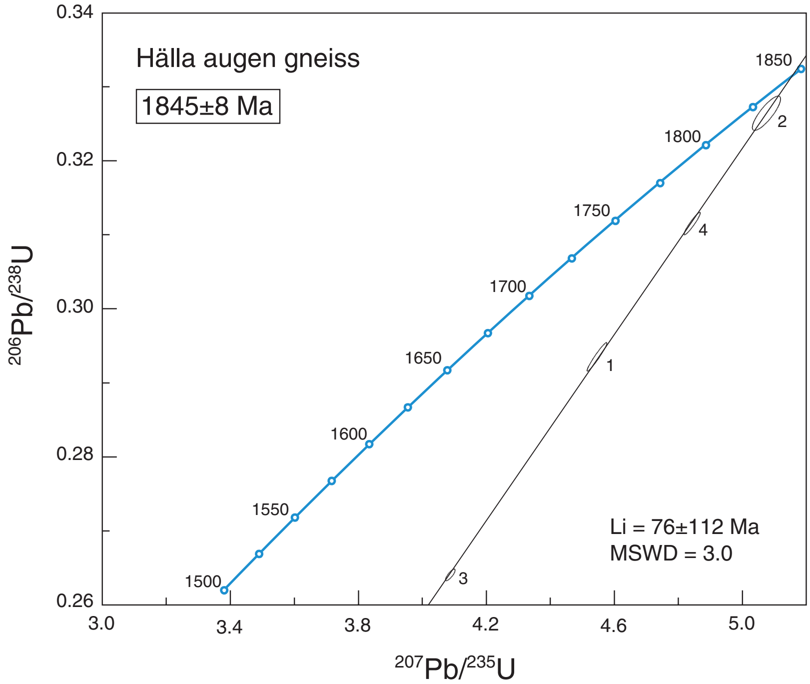

Fig. 3. Concordia diagram for the Hälla augen gneiss.

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A 1813 Ma old, probably shear-zone related granite near Norrköping, south-eastern Sweden

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Wikström, A. & Persson, P.-O., 2002: A 18135 Ma old, probably shear-zone related granite near Norrköping, south-eastern Sweden. *In* S. Bergman (ed.): *Radiometric dating results 5*. Uppsala 2002. *Sveriges geologiska undersökning C 834*, pp. 62–65. ISBN 91-7158-668-7.

The Fransberg granite is grey to reddish grey, medium-grained, more or less foliated and with a peraluminous chemical composition. It forms an irregular, about 20x3 km large, WNW-trending massif close to the town of Norrköping. It is dextrally faulted in a major deformation zone oriented NW–SE. The granite is suggested to have intruded in an active shear zone. The obtained zircon age of 1813±21 Ma would then also date the shearing.

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Introduction

The area of north-eastern Östergötland and southern Sörmland is dominated by Svecofennian supracrustal rocks and granitoids with ages around 1.9 Ga generally metamorphosed in amphibolite facies. Less voluminous are granitic, mostly S-type, late-orogenic intrusions, about 1.8 Ga old. Some of these are lineament-correlated. They were e.g. described as minor, east–west striking, lineament-correlated intrusions in the eastern Kolmården area by Lundström (1974), as bodies following the major, north–north-west striking Sillen lineament by Stålhös (1975), and as following the west–north-west lineaments south of Katrineholm (Wikström 1983). In several cases these granites are foliated.

The topic for this paper will be the Fransberg granite, which is located on the map sheets Norrköping NV (Kornfält 1975) and Norrköping NO (Wikström 1975) (described under this name in the latter publication). This granite is associated with the major Norrköping shear and fault zone, which has been active several times in geological history. Since the publication of the maps and descriptions mentioned above, increased knowledge has been gained on the formation and development of ductile shear zones and how they developed. As some of the lineaments in the area have been reinterpreted as parts of major shear zones (Stephens & Wahlgren 1993) there is now a renewed interest in investigating these late-orogenic intrusions and their age(s).

The Norrköping shear and fault zone

On the magnetic anomaly map released in 1999 (Geological Survey of Sweden, geophysical database) (Fig. 1b) the Norrköping shear and fault zone is visible as a prominent north-west-striking structure. It has been claimed (Stephens & Wahlgren 1993) to be a part of a major, dextral "Norrköping-Åsbro" shear zone extending northwestwards. Within the city of Norrköping, a fault in this zone separates high amphibolite facies rocks in the northeast from andalusite-mica schists in the south-west (Kornfält 1975) and cuts Lower Cambrian sandstone further to the north (Persson et al. 1975). No major horizontal component can be traced in these later movements. A NNE-trending dolerite dyke (undiscovered by Wikström 1975) probably belongs to the Blekinge-Dalarna dolerite group (age approximately 1000 Ma) and it seems to cross-cut the shear and fault structures seemingly undisturbed (Fig. 1b). Both ductile mylonites and giant quartz healed breccias (Kornfält 1975) are associated with the zone. In his work on brittle lineaments in the area, Asklund (1923) claimed a close connection between the development of these lineaments and the intrusion of the "subjotnian" dolerites (age 1550 Ma?) in the area. The Fransberg granite partly follows the Norrköping shear and fault zone and the age of the granite could put time constraints on the regional structures in the area.

The Fransberg granite

The Fransberg granite is a mostly even-grained, grey to reddish grey, muscovite bearing microcline granite with peraluminous affinity. Modal and chemical analyses have been presented by Kornfält (1975) and Wikström (1975). It is more or less strongly foliated with a steep foliation in general oriented parallel to the boundary of the massif. The intensity of deformation is highest in the north-western part of the massif. In Figures 1a and b its areal distribution has been somewhat modified compared with the maps by Kornfält (1975) and Wikström (1975). This especially concerns its boundary towards the older granites in the southern parts of the city of Norrköping which Kornfält (op. cit.) described as unclear, mainly related to the similar deformation style in both rocks. The southern boundary from Lake Glan to Klinga (bounded by mylonites) is anticipated here to continue east–south-eastwards to Lake Ensjön following the magnetic anomaly pattern as

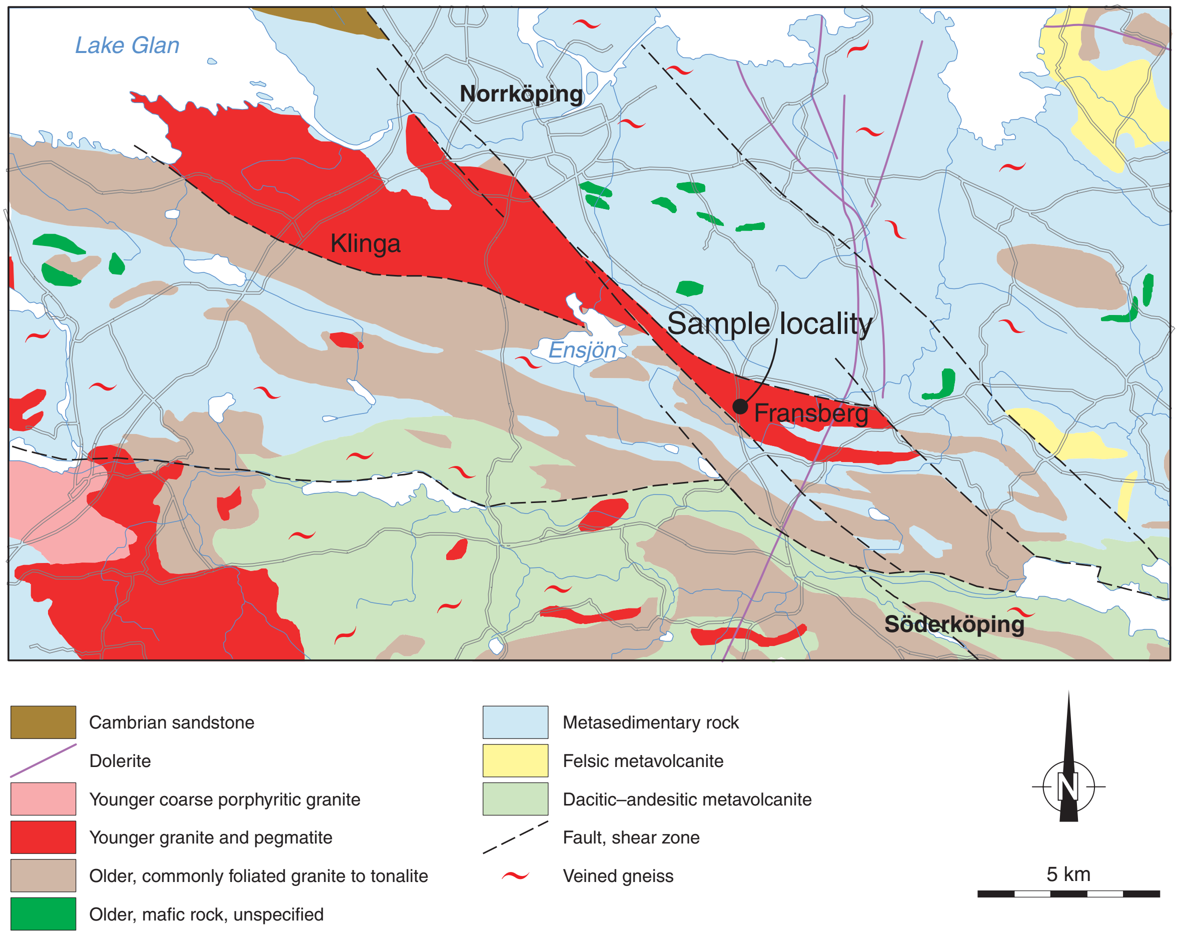

Fig. 1a. Bedrock map of the Norrköping area with the Fransberg granite shown in yellowish red.

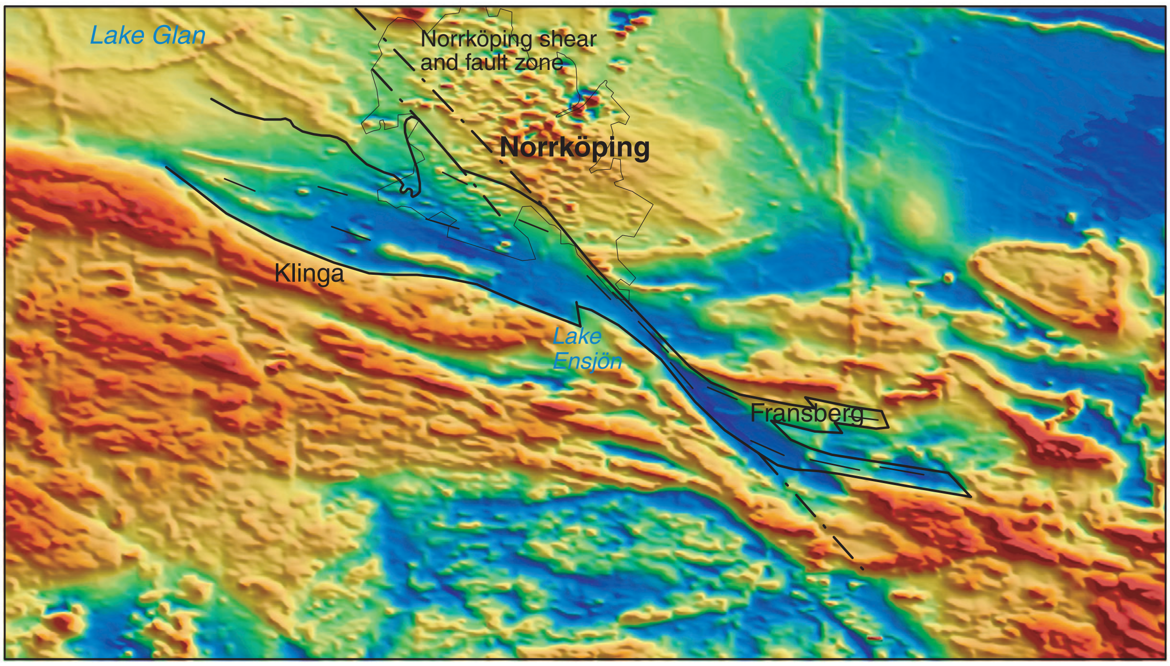

Fig. 1b. Excerpt from magnetic anomaly maps covering the same area (northern parts of the map sheets of Norrköping NV and NO). The areal extent of the Fransberg granite, shown with a black contour, is somewhat modified (according to this map) compared with Kornfält (1975) and Wikström (1975). The orientation of the steep foliation is schematically indicated together with some names mentioned in the text.

TABLE 1. U-Pb isotopic data for the Fransberg granite.

Analysis No.	Weight (µg)	No. of crystals	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)
1	15	5	328.1	106.6	2.67	1853	78.2–8.5–13.3	0.2877±11	4.336±19	1788±4
2	23	1	110.0	39.6	0.16	5322	71.2–7.9–20.9	0.2967±17	4.497±27	1798±3
3	8	10	171.1	62.6	0.20	6151	70.4–7.8–21.8	0.2981±20	4.508±32	1794±4
4	6	7	205.4	63.7	1.76	1303	77.1–8.4–14.5	0.2705±10	4.050±19	1776±5

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

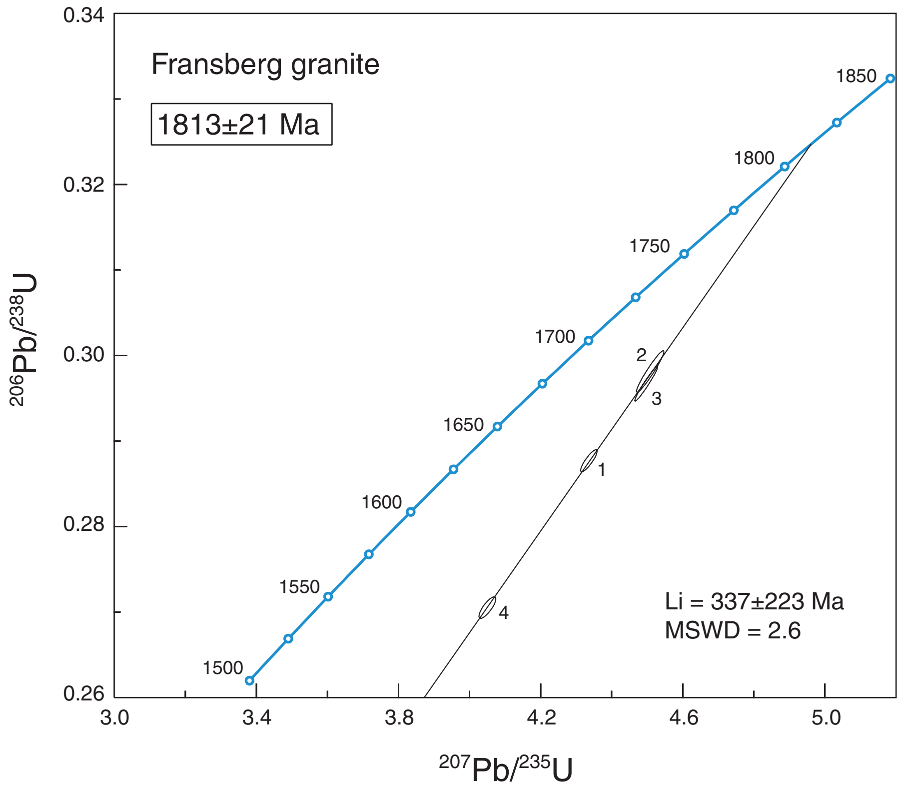

Fig. 2. Concordia diagram for the Fransberg granite.

seen in Figure 1b (no field work has been done to support this idea). The northern contact towards the andalusite-mica-schists is mainly intrusive. The other contacts, mainly against upper amphibolite facies country rocks, are tectonic. Flint-like, dense mylonites are present mainly along the Norrköping shear and fault zone but are also observed along the southern contact in the Klinga area in the western part. They range in thickness from some decimetres to approx. 50 metres and can locally have rather varying internal fabric orientation.

On the microscope scale, the granite is generally more affected by tectonic deformation than can be judged from a hand specimen. This applies especially to the parts within the Norrköping shear and fault zone where more brittle structures can be observed. The perthitic microcline has mostly survived whereas the quartz has been more or less crushed. The plagioclase has in many places been altered to white mica and epidote whereas biotite is more or less chloritised. Kink-folded megacrysts of muscovite have been observed (Wikström 1975, Fig. 20).

The co-ordinates for the sample taken for U-Pb dating is 648862/152808 (Swedish National Grid RT 90). A chemical analysis from this outcrop is presented in Wikström (1975), Table 10, sample 236.

U-Pb dating

The granite had a low zircon yield and the population is heterogeneous. Some grains are greyish brown, large, turbid and have high-index faces. Others are colourless to pinkish and clear, albeit often with cracks. These crystals are mostly elongate and display mainly low-index surfaces. The majority of the zircons, however, are small, colourless to yellowish brown and have length/width ≈3–5. The prism faces have low crystallographic indices whereas the pyramids also display high-index faces. Under the stereo microscope, cores are visible in some grains, primarily in the larger ones. All analysed crystals were strongly abraded, with the exception of fraction 3 which was only moderately abraded due to the large length/width ratio (3–8) of the crystals.

The analytical procedure is described in the Editor's Preface to this volume. The isotopic results are shown in Table 1 and Figure 2. All fractions are discordant and two of them plot together. Fractions 1 and 4 differ from the other two in their $^{206}Pb/^{204}Pb$ ratio and ^{208}Pb content. This might indicate a differing origin but they all plot on the same discordia. The intercept ages are 1813±21 Ma and 337±223 Ma and the MSWD=2.6. The upper intercept age is interpreted as dating the crystallisation of the granite.

Discussion and conclusion

The obtained age for the Fransberg granite is somewhat older than, although within the error limits well comparable with, other similar late-orogenic granites in south-eastern Sweden. The deformed nature of the granite also implies that deformation episodes younger than c. 1813 Ma have affected the area. The general shape of the intrusion is similar to structures described in several papers in recent years. A superficially almost identical structure has been described by Saint-Blanquat & Tikoff (1997) for the Mono Creek granite in Sierra Nevada. They argued for a close connection between an active shear zone and granite emplacement. A similar interpretation is near at hand for the Fransberg granite.

Although (mainly) brittle, dextral "subjotnian" faults in this part of the country are common (Asklund 1923, Wikström 1985) and distinctly displayed on magnetic anomaly maps, the north-west trending, dextral shearing in the Fransberg granite is older and may be associated with the ductile shear zone mentioned by Stephens & Wahlgren (1993).

These structures are younger than the complex fold pattern which has developed on Vikbolandet in the east and older than the brittle structures which seem to partly follow older zones of weakness.

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We thank Carl Ehlers and Ulf Söderlund for their critical reading of earlier versions of the manuscript.

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