Rapporter och meddelanden 141

Geology of the Northern Norrbotten ore province, northern Sweden

Paper 11 (13)

Editor: Stefan Bergman

SGU
Sveriges geologiska undersökning
Geological Survey of Sweden

Rapporter och meddelanden 141

Geology of the Northern Norrbotten ore province, northern Sweden

Editor: Stefan Bergman

Sveriges geologiska undersökning
2018

ISSN 0349-2176
ISBN 978-91-7403-393-9

Cover photos:
Upper left: View of Torneälven, looking north from Sakkaravaara, northeast of Kiruna. ***Photographer:*** Stefan Bergman.
Upper right: View (looking north-northwest) of the open pit at the Aitik Cu-Au-Ag mine, close to Gällivare. The Nautanen area is seen in the background. ***Photographer:*** Edward Lynch.
Lower left: Iron oxide-apatite mineralisation occurring close to the Malmberget Fe-mine. ***Photographer:*** Edward Lynch.
Lower right: View towards the town of Kiruna and Mt. Luossavaara, standing on the footwall of the Kiruna apatite iron ore on Mt. Kiirunavaara, looking north. ***Photographer:*** Stefan Bergman.

Head of department, Mineral Resources: Kaj Lax
Editor: Stefan Bergman

Layout: Tone Gellerstedt och Johan Sporrong, SGU
Print: Elanders Sverige AB

Geological Survey of Sweden
Box 670, 751 28 Uppsala
phone: 018-17 90 00
fax: 018-17 92 10
e-mail: sgu@sgu.se
www.sgu.se

Table of Contents

Introduktion

Stefan Bergman & Ildikó Antal Lundin

Den här rapporten presenterar de samlade resultaten från ett delprojekt inom det omfattande tvärvetenskapliga Barentsprojektet i norra Sverige. Projektet initierades av Sveriges geologiska undersökning (SGU) som ett första led i den svenska mineralstrategin. SGU fick ytterligare medel av Näringsdepartementet för att under en fyraårsperiod (2012–2015) samla in nya geologiska, geofysiska och geokemiska data samt för att förbättra de geologiska kunskaperna om Sveriges nordligaste län. Det statligt ägda gruvbolaget LKAB bidrog också till finansieringen. Projektets strategiska mål var att, genom att tillhandahålla uppdaterad och utförlig geovetenskaplig information, stödja prospekterings- och gruvindustrin för att förbättra Sveriges konkurrenskraft inom mineralnäringen. Ny och allmänt tillgänglig geovetenskaplig information från den aktuella regionen kan hjälpa prospekterings- och gruvföretag att minska sina risker och prospekteringskostnader och främjar därigenom ekonomisk utveckling. Dessutom bidrar utökad geologisk kunskap till en effektiv, miljövänlig och långsiktigt hållbar resursanvändning. All data som har samlats in i projektet lagras i SGUs databaser och är tillgängliga via SGU.

Syftet med det här delprojektet var att få en djupare förståelse för den stratigrafiska uppbyggnaden och utvecklingen av de mineraliserade ytbergarterna i nordligaste Sverige. Resultaten, som är en kombination av ny geologisk kunskap och stora mängder nya data, kommer att gynna prospekterings- och gruvindustrin i regionen i många år framöver.

Norra Norrbottens malmprovins står för en stor del av Sveriges järn- och kopparmalmsproduktion. Här finns fyra aktiva metallgruvor (mars 2018) och mer än 500 dokumenterade mineraliseringar. Fyndigheterna är av många olika slag, där de viktigaste typerna är stratiforma kopparmineraliseringar, järnformationer, apatitjärnmalm av Kirunatyp och epigenetiska koppar-guldmineraliseringar. En vanlig egenskap hos de flesta malmer och mineraliseringar i Norr- och Västerbotten är att de har paleoproterozoiska vulkaniska och sedimentära bergarter som värdbergart. För undersökningarna valdes ett antal nyckelområden med bästa tillgängliga blottningsgrad. De utvalda områdena representerar tillsammans en nästan komplett stratigrafi i ytbergarter inom åldersintervallet 2,5–1,8 miljarder år.

Rapporten består av tretton kapitel och inleds med en översikt över de geologiska förhållandena, som beskriver huvuddragen i de senaste resultaten. Översikten följs av fyra kapitel (2–5) som huvudsakligen handlar om litostratigrafi och åldersbestämningar av ytbergarterna. Huvudämnet för de därpå följande fem kapitlen (6–10) är 3D-geometri och strukturell utveckling. Därefter kommer två kapitel (11–12) som fokuserar på U-Pb-datering av en metamorf respektive intrusiv händelse. Rapporten avslutas med en studie av geokemin hos morän i Norra Norrbottens malmprovins (kapitel 13).

Introduction

Stefan Bergman & Ildikó Antal Lundin

This volume reports the results from a subproject within the Barents Project, a major programme in northern Sweden. The multidisciplinary Barents Project was initiated by SGU as the first step in implementing the Swedish National Mineral Strategy. SGU obtained additional funding from the Ministry of Enterprise and Innovation to gather new geological, geophysical and till geochemistry data, and generally enhance geological knowledge of northern Sweden over a four-year period (2012–2015). The state-owned iron mining company LKAB also helped to fund the project. The strategic goal of the project was to support the exploration and mining industry, so as to improve Sweden's competitiveness in the mineral industry by providing modern geoscientific information. Geological knowledge facilitates sustainable, efficient and environmentally friendly use of resources. New publicly available geoscientific information from this region will help exploration and mining companies to reduce their risks and exploration costs, thus promoting economic development. All data collected within the project are stored in databases and are available at SGU.

This subproject within the Barents Project aims to provide a deeper understanding of the stratigraphy and depositional evolution of mineralised supracrustal sequences in northernmost Sweden. The combined results in the form of new geological knowledge and plentiful new data will benefit the exploration and mining industry in the region for many years to come.

The Northern Norrbotten ore province is a major supplier of iron and copper ore in Sweden. There are four active metal mines (March 2018) and more than 500 documented mineralisations. A wide range of deposits occur, the most important types being stratiform copper deposits, iron formations, Kiruna-type apatite iron ores and epigenetic copper-gold deposits. A common feature of most deposits is that they are hosted by Palaeoproterozoic metavolcanic or metasedimentary rocks. A number of key areas were selected across parts of the supracrustal sequences with the best available exposure. The areas selected combine to represent an almost complete stratigraphic sequence.

This volume starts with a brief overview of the geological setting, outlining some of the main recent achievements. This is followed by four papers (2–5) dealing mainly with lithostratigraphy and age constraints on the supracrustal sequences. 3D geometry and structural evolution are the main topics of the next set of five papers (6–10). The following two contributions (11–12) focus on U-Pb dating of a metamorphic event and an intrusive event, respectively. The volume concludes with a study of the geochemical signature of till in the Northern Norrbotten ore province (13).

Author, paper 11:
Fredrik A. Hellström
Geological Survey of Sweden
Department of Mineral Resources,
Uppsala, Sweden

11. Early Svecokarelian migmatisation west of the Pajala deformation belt, northeastern Norrbotten province, northern Sweden

Fredrik A. Hellström

ABSTRACT

An older phase of deformation and high-grade metamorphism is preserved in the Masugnsbyn area, west of the Pajala deformation belt, in the northeastern Norrbotten province. The Pajala deformation belt is a major high-strain belt characterised by NNE–SSW to NNW–SSE-oriented zones with high-grade metamorphic alterations, while the area west of the Pajala deformation belt is structurally heterogeneous, displaying both medium- and high-grade metamorphic alterations. High-grade metamorphism in the Pajala deformation belt was previously dated in the 1.83–1.78 Ga interval. In contrast, U-Pb SIMS analyses of metamorphic, low-Th/U zircon rims from a migmatitic, sillimanite-cordierite-bearing paragneiss in the western domain are dated here at 1878 ±3 Ma (2σ). This age is interpreted to date migmatisation and constrains the maximum age of folding of supracrustal rocks. There were possibly also later metamorphic/hydrothermal events in the Masugnsbyn area, as previously recorded by a U-Pb monazite age of approximately 1.86 Ga and by U-Pb titanite ages of 1.80–1.76 Ga. 1.88 Ga migmatisation was contemporaneous with large volumes of early orogenic intrusions, and it is suggested that heat from these intrusions caused high-grade metamorphism and partial melting in the southern part of the Masugnsbyn area. Metamorphic alteration of supracrustal rocks at 1.88 Ga has implications for the timing of skarn iron ore formation and base-metal sulphide mineralisations. Despite the limited amount of SIMS data on zircon core domains, the maximum depositional age of sediments in the Kalixälv group may be constrained by the youngest zircon core age of 1882 ±25 Ma (2σ), but must have occurred before migmatisation at 1878 ±3 Ma. 50% of the recorded zircon core ages fall in the range 2.02–1.92 Ga, suggesting that rocks of this age interval were the main source of the Kalixälv group, together with debris from 2.97–2.75 Ga Archaean rocks (29%). This suggests that 2.02–1.92 Ga felsic to intermediate rocks can be expected to be present to a greater extent than is known from available age determination of the rocks in the Svecokarelian orogen.

INTRODUCTION

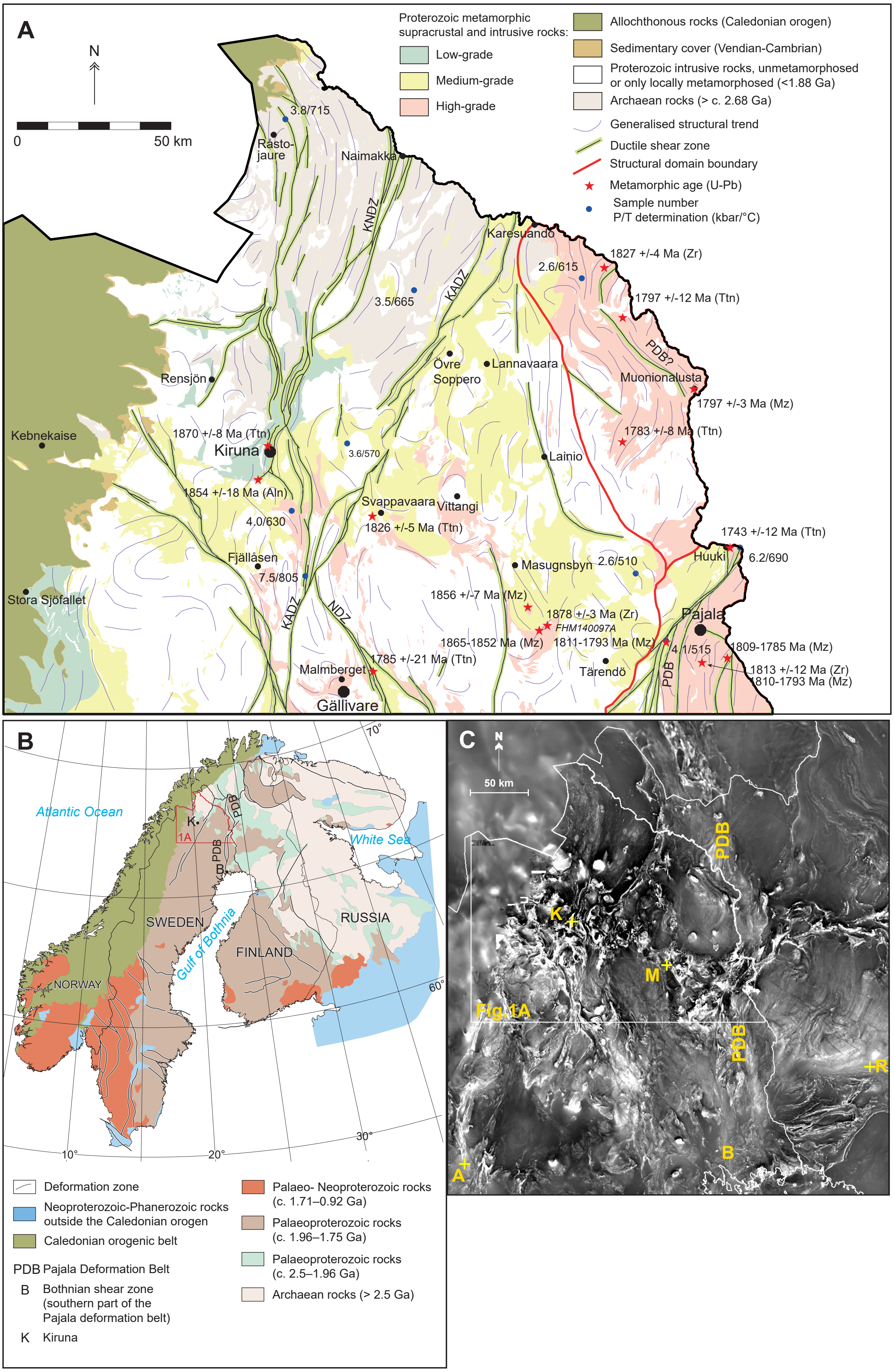
Bergman et al. (2006) recognised two different structural domains in northeastern Norrbotten separated roughly along a N–S-trending structural boundary defined by the western margin of the Pajala deformation belt (Fig. 1; see Luth et al. 2018). The eastern domain occurs within the Pajala deformation belt, and is characterised by N-NE to N-NW high-strain zones with high-grade metamorphic alterations. The area west of the Pajala deformation belt is structurally heterogeneous, with both medium- and high-grade metamorphic areas and is here referred to as the Masugnsbyn structural domain (Fig. 1; Bergman et al. 2001). The latter domain is located between the N-NE-oriented Karesuando–Arjeplog deformation zone in the northwest, the N-NE to NE-oriented Pajala deformation belt in the east, and the NW-trending Nautanen deformation zone in the southwest (Fig. 1). Metamorphic monazite and titanite as well as zircon overgrowths in the Pajala deformation belt verify deformation and high-grade metamorphism in the 1.83–1.78 Ga interval, while metamorphic monazite in rocks of the Masugnsbyn structural domain records a 1.86–1.85 Ga metamorphic event (Bergman et al. 2006, Hellström & Bergman 2016).

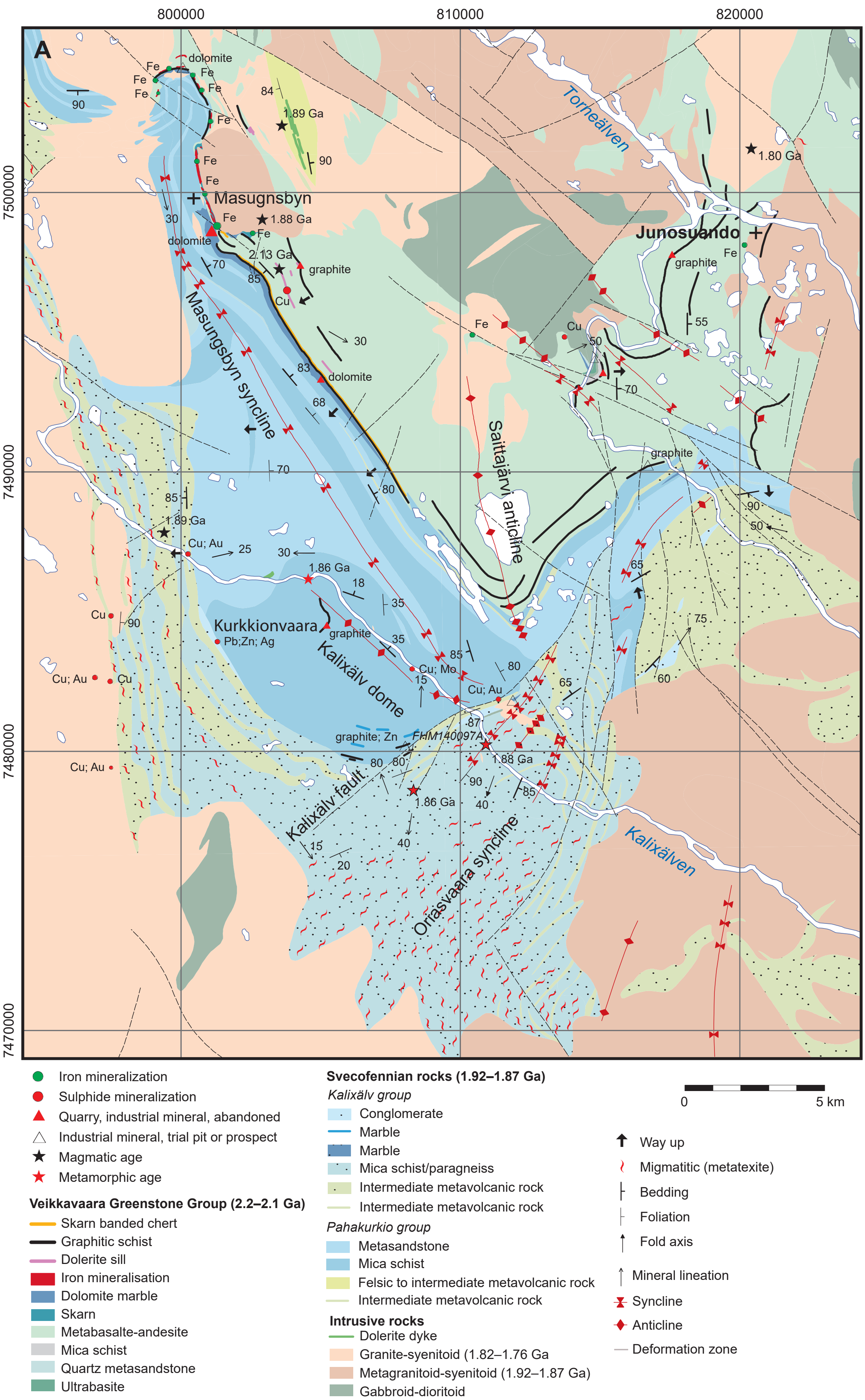
Monazite was dated from two localities south of Masugnsbyn (Fig. 1–2), interpreted to date metamorphism at approximately 1.86 Ga (Bergman et al. 2006). One sample was taken from an andalusite-bearing meta-argillite at Pahakurkio and the other sample from a weakly migmatitic, sillimanite-bearing paragneiss at Takanenvaara, i.e. in the higher-grade area southeast of Pahakurkio (Figs. 1–2; Bergman et al. 2006). The single discordant monazite analysis from the Pahakurkio sample has an upper intercept age of 1 856 ±7 Ma, whereas the two Takanenvaara analyses record ages of 1 856 ±4 and 1 861 ±4 Ma, with regression forced through a lower intercept at 300 ±300 Ma. Based on analysis of only 1–2 monazite fractions, the calculated ages are uncertain, however. A strongly migmatitic paragneiss was sampled close to the Takanenvaara locality in order to perform U-Pb SIMS dating of possible, secondary zircon domains to improve the poorly constrained approximately 1.86 Ga metamorphic age. It has recently been suggested that the Pajala deformation belt marks an old suture zone between the continents of Norrbotten and Karelia (Lahtinen et al. 2015). One of the significant questions addressed here is: is there a preserved older metamorphic event in the Masugnsbyn domain than within the Pajala deformation belt?

GEOLOGY OF THE MASUGNSBYN AREA

The Masugnsbyn area shows variable foliations and complexly-folded supracrustal rocks (Bergman et al. 2001). Metamorphism in the Masugnsbyn key area reaches medium- to high-grade, and generally increases towards the south and west, where migmatitic paragneiss occurs next to adjacent granitic intrusions (Fig. 2). In the central part of the area, the clastic metasedimentary rocks of the Pahakurkio

► Figure 1. **A.** Metamorphic map of northern Norrbotten showing high-grade rocks in the eastern and south-central parts of the area and low-grade rocks in the Kiruna and Stora Sjöfallet areas in the west. The study area at Masugnsbyn is of medium metamorphic grade, but the southern part contains high-grade, sillimanite-bearing, migmatitic paragneisses. KADZ – the Karesuando–Arjeplog deformation zone, KNDZ – the Kiruna–Naimakka deformation zone, NDZ – the Nautanen deformation zone, PDB – the Pajala deformation belt (modified after Bergman et al. 2001). Selected metamorphic ages (U-Pb) are from: Bergman et al. (2006), Storey et al. (2007), Smith et al. (2009), Hellström & Bergman (2016), and this study (FHM140097A). **B.** Simplified map of the Fennoscandian Shield, modified from Koistinen et al. (2001) & Bergman et al. (2006). The area of northern Norrbotten County is marked with a red polygon. **C.** Magnetic anomaly map of northern Sweden, including adjacent areas of Norway and Finland. White = high magnetisation, dark grey = low magnetisation. Data from adjacent areas have been supplied by the geological surveys of Norway (ngu.no), and Finland (gtk.fi). The Pajala deformation belt is seen as an approximately north–south-trending zone along the Swedish-Finnish border, with a continuation into Norway. M – Masugnsbyn, B – Bothnian shear zone (southern part of the Pajala deformation belt), K – Kiruna, R – Rovaniemi.


A
N
0
50 km
Proterozoic metamorphic supracrustal and intrusive rocks:
Low-grade
Medium-grade
High-grade
Allochthonous rocks (Caledonian orogen)
Sedimentary cover (Vendian-Cambrian)
Proterozoic intrusive rocks, unmetamorphosed or only locally metamorphosed (<1.88 Ga)
Archaean rocks (> c. 2.68 Ga)
Generalised structural trend
Ductile shear zone
Structural domain boundary
Metamorphic age (U-Pb)
Sample number
P/T determination (kbar/°C)
3.8/715
Rásto-jaure
Naimakka
KNDZ
Karesuando
2.6/615
1827 +/-4 Ma (Zr)
1797 +/-12 Ma (Ttn)
3.5/665
KADZ
PDB?
Övre Soppero
Lannavaara
Muonionalusta
1797 +/-3 Ma (Mz)
Rensjön
1783 +/-8 Ma (Ttn)
Kebnekaise
1870 +/-8 Ma (Ttn)
Kiruna
3.6/570
Lainio
1854 +/-18 Ma (Aln)
Svappavaara
Vittangi
4.0/630
1826 +/-5 Ma (Ttn)
1743 +/-12 Ma (Ttn)
Huuki
6.2/690
Fjällåsen
Masugnsbyn
2.6/510
7.5/805
Stora Sjöfallet
1856 +/-7 Ma (Mz)
1878 +/-3 Ma (Zr)
FHM140097A
Pajala
KADZ
NDZ
1865-1852 Ma (Mz)
1811-1793 Ma (Mz)
4.1/515
1809-1785 Ma (Mz)
1785 +/-21 Ma (Ttn)
Malmberget
Tärendö
PDB
1813 +/-12 Ma (Zr)
1810-1793 Ma (Mz)
Gällivare
B
70°
Atlantic Ocean
K.
1A
PDB
PDB
B
White Sea
SWEDEN
RUSSIA
Gulf of Bothnia
FINLAND
NORWAY
60°
30°
10°
20°
Deformation zone
Neoproterozoic-Phanerozoic rocks outside the Caledonian orogen
Caledonian orogenic belt
PDB Pajala Deformation Belt
B Bothnian shear zone (southern part of the Pajala deformation belt)
K Kiruna
Palaeo- Neoproterozoic rocks (c. 1.71–0.92 Ga)
Palaeoproterozoic rocks (c. 1.96–1.75 Ga)
Palaeoproterozoic rocks (c. 2.5–1.96 Ga)
Archaean rocks (> 2.5 Ga)
C
N
50 km
PDB
K
M
Fig.1A
PDB
R
A
B



800000
810000
820000
7500000
7490000
7480000
7470000
A
Masugnsbyn
Junosuando
Torneälven
Kalixälven
Masungsbyn syncline
Saittajärvi anticline
Kurkkionvaara
Kalixälv dome
Kalixälv fault
Oriasvaara syncline
1.89 Ga
1.88 Ga
2.13 Ga
1.80 Ga
1.86 Ga
FHM140097A
Iron mineralization
Sulphide mineralization
Quarry, industrial mineral, abandoned
Industrial mineral, trial pit or prospect
Magmatic age
Metamorphic age
Veikkavaara Greenstone Group (2.2–2.1 Ga)
Skarn banded chert
Graphitic schist
Dolerite sill
Iron mineralisation
Dolomite marble
Skarn
Metabasalte-andesite
Mica schist
Quartz metasandstone
Ultrabasite
Svecofennian rocks (1.92–1.87 Ga)
Kalixälv group
Conglomerate
Marble
Marble
Mica schist/paragneiss
Intermediate metavolcanic rock
Intermediate metavolcanic rock
Pahakurkio group
Metasandstone
Mica schist
Felsic to intermediate metavolcanic rock
Intermediate metavolcanic rock
Intrusive rocks
Dolerite dyke
Granite-syenitoid (1.82–1.76 Ga
Metagranitoid-syenitoid (1.92–1.87 Ga)
Gabbroid-dioritoid
0
5 km
Way up
Migmatitic (metatexite)
Bedding
Foliation
Fold axis
Mineral lineation
Syncline
Anticline
Deformation zone

◀ Figure 2. **A.** Bedrock geological map of the Masugnsbyn area. Age determinations are from Bergman et al. (2001, 2006) Hellström et al. (2018), Lynch et al. (2018) and this study (FHM140097A).

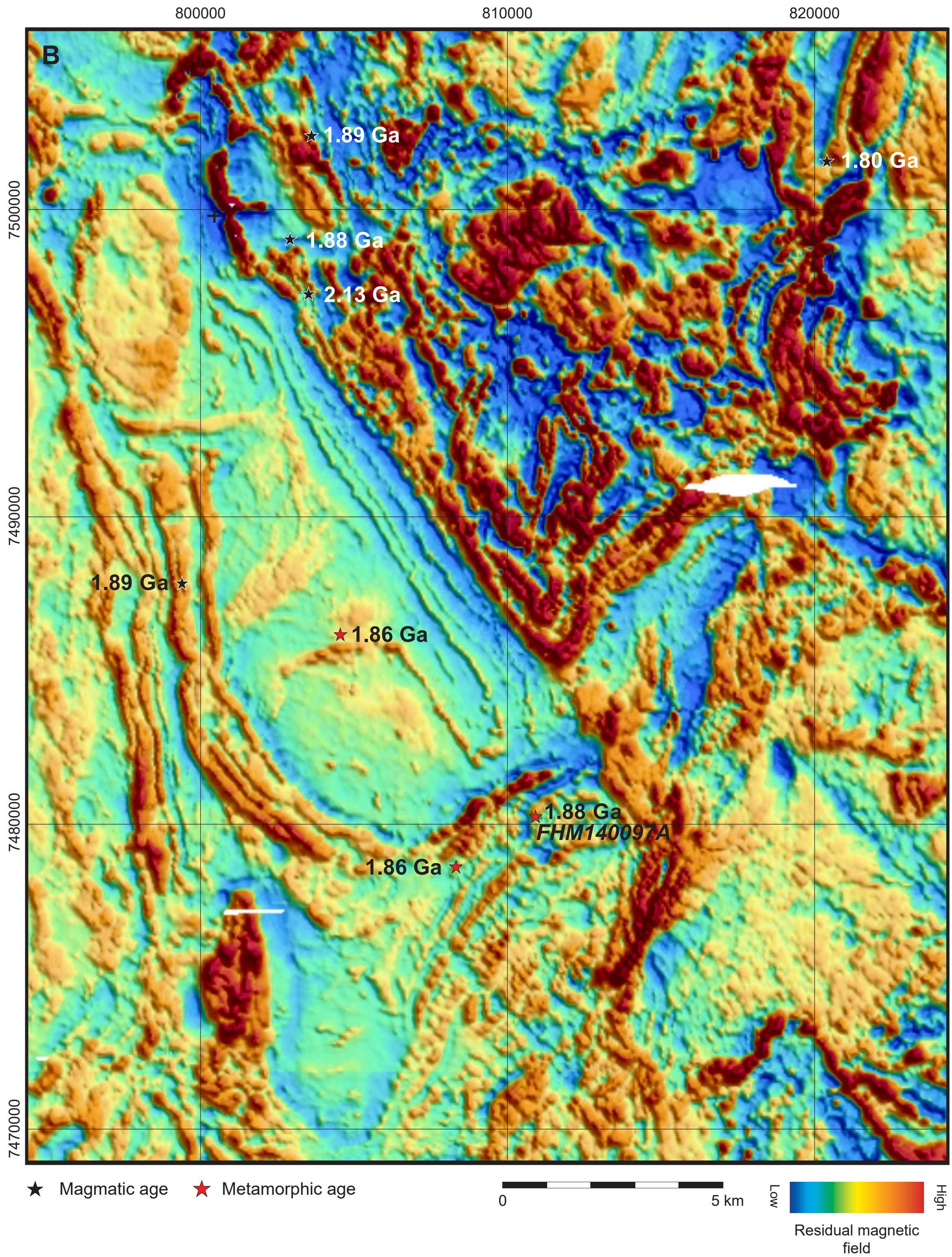


Figure 2. **B.** Magnetic anomaly map with same extent as in figure A. Map gridded from SGU data.

group still show primary sedimentary structures such as cross-bedding (Padget 1970). The sampled migmatitic paragneiss is part of the Kalixälv group, which forms the upper part of the supracrustal sequence in Masugnsbyn (Figs. 2, 3).

Karelian greenstones of the Veikkavaara greenstone group are overlain by Svecofennian metasedimentary pelitic to arenitic rocks of the Middle sediment group (Witschard 1984), which include the Pahakurkio and Kalixälv groups (Padget 1970). The latter group also contains intermediate metavolcanic rocks. Of economic interest in the Masugnsbyn area are layers of iron mineralisations and dolomite between the greenstones and metasedimentary rocks, as well as graphite schist layers and base-metal, sulphide mineralisations within the volcaniclastic greenstones and in the Svecofennian supracrustal rocks (Geijer 1929, Padget 1970, Witschard et al. 1972, Grip & Frietsch 1973, Niiniskorpi 1986, Frietsch 1997, Martinsson et al. 2013, 2016, Hellström & Jönsson 2014, Bergman et al. 2015).

The supracrustal sequence in the Masugnsbyn area is deformed into large-scale fold structures and cut by faults. The structures have NE or NW trends, thus intersecting at high angles. According to Padget (1970), the main tectonic features include the Kalixälv dome, the Masugnsbyn syncline, the Saittajärvi anticline and the Oriasvaara syncline with the associated Kalixälv fault (Fig. 2, Padget 1970). The fold structures in Masugnsbyn have recently been evaluated by Grigull et al. (2018), with the Saittajärvi fold structure now interpreted as a synform structure, supported by geophysical modelling. The fold axial planes are oriented in a northwesterly direction, except for the Oriasvaara syncline, which has a northeasterly trend, parallel to the Kalixälv fault, and the Saittajärvi synform, which has a N–NW orientation.

The Oriasvaara syncline is bounded to the NW by the northeasterly-oriented Kalixälv fault. Movements along that fault have down-thrown the southeastern block, creating a tectonic contact between the Pahakurkio and Kalixälv groups. For a description of the structural geology of the Masugnsbyn area, see Grigull et al. (2018).

The original shales of the Pahakurkio group have been metamorphosed to andalusite +/- sillimanite-bearing mica schists (Fig. 4A, C, D), and the sandstones have been recrystallised to quartzites with metamorphic biotite (Padget 1970, Kumpulainen 2000, Hellström et al. 2018). Other secondary minerals include muscovite, epidote, amphibole and scapolite, the last-named mineral showing a characteristic white spotted appearance in basic to intermediate rocks (Fig. 4B). The higher-grade gneisses in

Superunit	Unit	Subunit	Rock units
Svecofennian supracrustal rocks	Rissavaara quartzite	4	Quartz arenite
	Kalixälv grp	3b	Semipelitic,-pelitic-, basic schists, migmatitic paragneiss
		3a	Conglomerate, meta-arenite, intermediate metavolcanic rocks
	Sakarinpalo suite		Intermediate metavolcanic rocks
	Pahakurkio grp	2d	Meta-arenite
		2c	Pelitic schist, graphite schist, carbonate rocks
		2b	Meta-arenite, greenshist
		2a	Pelitic schist
Karelian supracrustal rocks	Veikkavaara greenstone grp	Masugnsbyn fm (1c)	Graphite schist, skarnbanded chert (BIF), carbonate rock
		Nokkokorvanrova greenstone fm (1c)	Basaltic tuff, graphite schist, dolerite sills
		Suinavaara fm (1b)	Pelitic schist and meta-arenite (Suinavaara quartzite)
		Tuorevaara greenstone fm (1a)	Basaltic greenstone

Figure 3. Schematic stratigraphy of the Masugnsbyn area. grp = group, fm = formation, modified from Padget (1970). The names used in Padget (1970) have been modified, and new names have been added, here used as informal names (see Lynch et al. and Hellström et al., both 2018).

the south of the area contain bundles of fibrolitic sillimanite, growing at the expense of biotite, and locally cordierite and andalusite. The rocks have been altered to migmatitic paragneisses in places (Fig. 4E). The migmatitic gneiss is interlayered with quartzitic bands, interpreted to represent a primary variation from pelitic to arenitic layers, where the former composition is more susceptible to melting during high-grade, amphibolite-facies metamorphic conditions (4F). The primary mafic minerals in the Veikkavaara greenstones have been altered to amphibole, giving the rocks their dark green colour. The amphibole is commonly a green pleochroic hornblende, but non-pleochroic, pale-coloured amphibole is also quite common (Padget 1970). Garnet porphyroblasts occur together with amphibole in certain, distinct layers in the basaltic tuffs (Fig. 4G) and seem to be late-kinematic, overgrowing the foliation in the rock (Fig. 4H). The composition of the plagioclase ($An_{10–50}$) and the presence of hornblende together with almandine suggest the rocks are in the garnet amphibolite facies of regional metamorphism (Padget 1970). The metamorphic mineral association in the mica schists with andalusite, sillimanite and cordierite, and the absence of kyanite also indicate amphibolite facies conditions of relatively high temperature and low to moderate pressure. Partial melting in the migmatitic paragneisses in the south suggests this area has even reached an upper amphibolite facies grade of metamorphism.

Sample description

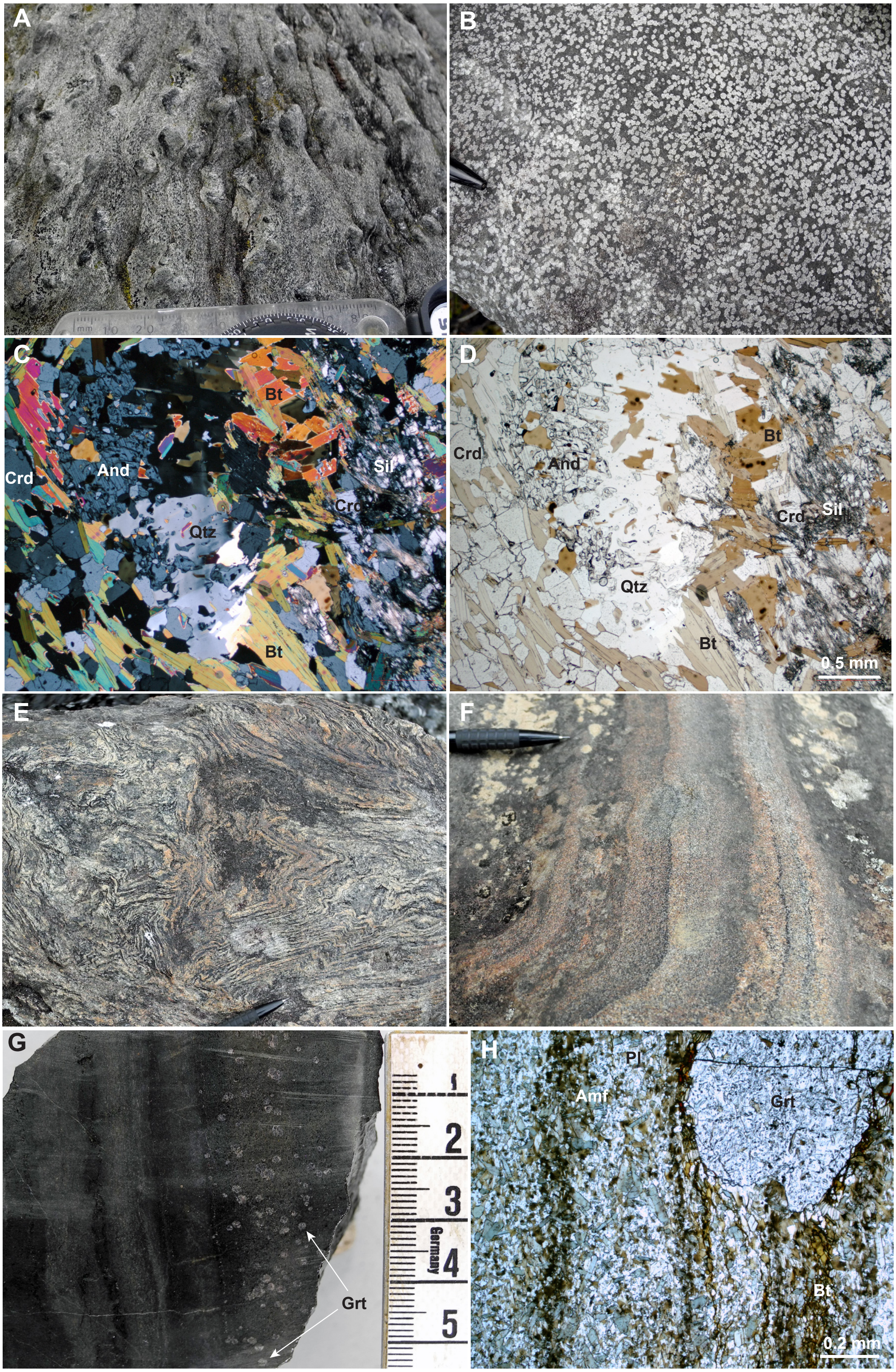
The sampled rock for U-Pb SIMS geochronology is a sillimanite-cordierite-biotite-muscovite-bearing migmatitic paragneiss from the Kalixälv group in the southern part of the Masugnsbyn area (Fig. 4E, 5A–B, Table 1). The gneiss is rich in medium- to coarse-grained, granitic leucosome, interlayered with quartzitic bands showing less partial melting (Fig. 4F). The veining is complexly and polyphase folded, in part asymmetric with both S and Z folds. Needles of fibrolitic sillimanite have grown at the expense of biotite and cordierite, and seem to crosscut post-kinematic muscovite (Fig. 5B), suggesting that sillimanite is a late phase. Accessory mineral phases are monazite, zircon, sulphides and tourmaline.

Analytical results and interpretation of geochronological data

Zircons were obtained from a density separate of a crushed rock sample using a Wilfley water table. Magnetic minerals were removed with a hand magnet. Handpicked crystals were mounted in transparent epoxy resin together with chips of the reference zircon 91 500. Zircon mounts were polished and after gold coating examined with Back Scattered Electron (BSE) and Cathodoluminescence (CL) imaging using electron microscopy at EBC, Uppsala University and the Swedish Museum of Natural History in Stockholm. High-spatial resolution secondary ion masspectrometer (SIMS) analysis was carried out in November and December 2014 using a Cameca IMS 1280 at the Nordsim facility at the Swedish

Table 1. Summary of the sample data.

Rock type	Migmatitic paragneiss
Tectonic domain	Svecokarelian orogen
Tectonic sub-domain	Norrbotten lithotectonic unit
Stratigraphic unit	Kalixälv group
Sample number	FHM140097A
Lab ID	n5161 (Nordsim)
Coordinates	7480256 / 810923 (SWEREF 99TM)
Map sheet	28L NO (RT90)
Locality	Tiankijoki
Project	Barents


A
B
C
Bt
Crd
And
Sil
Crd
Qtz
Bt
D
Crd
And
Bt
Crd
Sil
Qtz
Bt
0.5 mm
E
F
G
Grt
1
2
3
4
5
Germany
H
Pl
Amf
Grt
Bt
0.2 mm

◀ Figure 4. **A.** Mica schist with porphyroblasts of andalusite (Pahakurkio group, unit 2b 7483486/807939. **B.** Strongly scapolite-altered meta-andesite, with characteristic whitespotted appearance of the scapolite (Pahakurkio group, unit 2c, greenschist, 7489838 / 806809). **C.** Photomicrograph in cross-polarised light of andalusite-sillimanite mica schist (same rock as in Fig. 4 A). **D.** Photomicrograph in plane-polarised light of andalusite-sillimanite mica schist (same extent as in Fig. 4C). **E.** Complexly poly-phase-folded, migmatitic paragneiss at Tiankijoki. North is to the left in the photograph (Kalixälv group, 7480253/810919). **F.** The migmatitic gneiss is interlayered with quartzitic bands, interpreted to represent a primary variation from pelitic to arenitic layers, where the pelitic layers are more susceptible to melting during the high-grade, amphibolite facies metamorphic conditions. **G.** Certain layers within the Veikkavaara greenstones contain abundant garnet porphyroblasts (7497316 / 804044). **H.** The garnet in the basaltic tuffs appears late-kinematic, overgrowing the lamination and foliation in the rock (7494442 / 805044). Coordinates are in SWEREF 99TM. All photographs by Fredrik Hellström.

Museum of Natural History. Detailed descriptions of the analytical procedures are given in Whitehouse et al. (1997, 1999), and Whitehouse & Kamber (2005). An approximately 6 nA O^{2-} primary ion beam was used, yielding spot sizes of 10–15 µm. U/Pb ratios, elemental concentrations and Th/U ratios were calibrated relative to the Geostandards zircon 91 500 reference, which has an age of approximately 1 065 Ma (Wiedenbeck et al. 1995, 2004). Common Pb-corrected isotope values were calculated using modern common Pb composition (Stacey & Kramers 1975) and measured ^{204}Pb, in cases of a ^{204}Pb count rate above the detection limit. Decay constants follow the recommendations of Steiger & Jäger (1977). Diagrams and age calculations of isotopic data were made using Isoplot 4.15 software (Ludwig 2012). BSE imaging of the dated zircons was performed using electron microscopy at the Department of Geology, Uppsala University.

The heavy mineral concentrate contains subhedral zircon with rounded edges; most are turbid. Many rounded grains of yellowish monazite are also present in the sample. BSE images of the zircon reveal oscillatory zoned cores and texturally younger, homogenous, BSE-bright rims (Fig. 5C). Two analyses (4c, 6a) show high values for common lead (f_{206}% = 4.99, 0.51), and are excluded in the description and diagrams below (see Table 2). Rims are rich in uranium (807–1 303 ppm) and are very low in Th (2.7–16.3 ppm), resulting in very low Th/U ratios, 0.00–0.01 (Fig. 5D, Table 2). In contrast, the oscillatory zoned cores have distinctly higher Th/U ratios (0.33–1.78), with 49–372 ppm uranium and 26.1–301 ppm Th. Examination of the post-analysis BSE images show that some rim analyses include some core domain material (analyses no 02, 03b, 04, 09, Fig. 5C) and these analyses record slightly higher Th/U ratios (0.03–0.06), and somewhat older (mixed) ages (Fig. 5E, Table 2).

Two rim analyses are excluded from the age calculations; analysis no 6b hits a fracture, and plots discordantly, and analysis no 01 records a rather high value for common lead (f_{206}% = 0.35), probably because the spot was placed too close to, and partly outside the margin of the grain. It also seems to include BSE-dark inclusions. The remaining seven rim analyses record a concordia age of 1880 ±5 Ma. High MSWD of concordance at 24 and zero probability of concordance, result from analyses being slightly reversely discordant, although all but two plot concordantly at the two sigma confidence level. The weighted average ^{207}Pb/^{206}Pb age is calculated at 1 878 ±3 Ma (Fig. 5, MSWD = 0.94, probability = 0.47, n = 7) and is chosen as the best age estimate, interpreted to date migmatisation at approximately 1.88 Ga.

The oscillatory zoned core analyses plot concordant or weakly reversely discordant, and show a spread in ^{207}Pb/^{206}Pb apparent ages from 2 972 ±23 Ma to 1 882 ±25 Ma (2σ). The age distribution is: 2.97 Ga (n = 1), 2.87–2.86 Ga (n = 2), 2.75 (n = 1) 2.35–2.34 Ga (n = 2), 2.02 Ga (n = 1), 1.99–1.98 Ga (n = 2), 1.96 Ga (n = 1), 1.93–1.92 (n = 3) and 1.88 Ga (n = 1). The youngest core analysis (5C) records a similar age to the BSE-bright rim (no 5) in the same grain (Table 2).

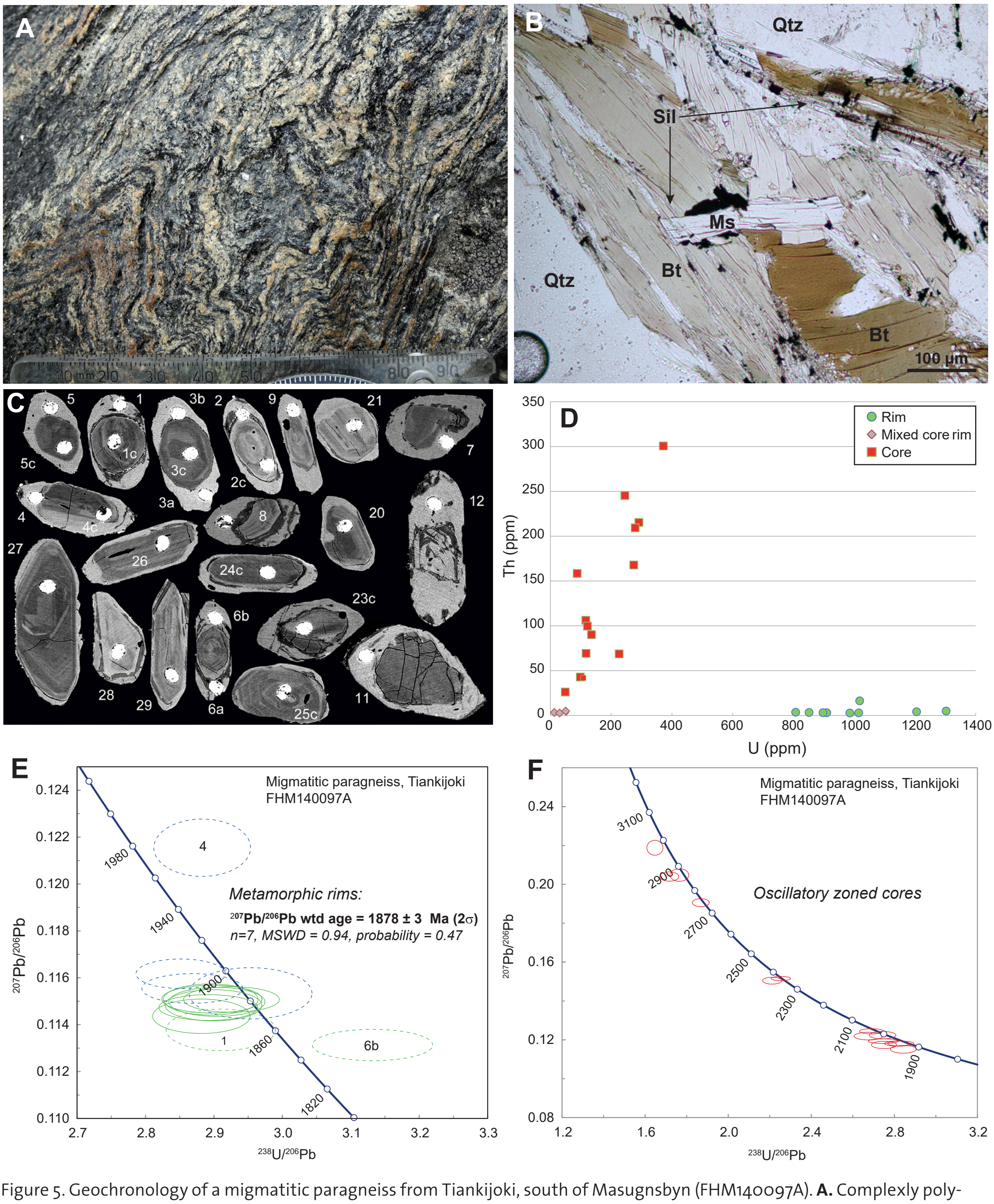


Figure 5. Geochronology of a migmatitic paragneiss from Tiankijoki, south of Masugnsbyn (FHM140097A). **A.** Complexly polyfolded migmatitic paragneiss at the sampling locality (7480253 / 810919 SWEREF 99TM). North is to the left in the photograph. **B.** Needles of fibrolitic sillimanite growing at the expense of biotite, but also crosscutting post-kinematic (?) muscovite. **C.** Back-scattered electron (BSE) images of analysed zircon grains. White spots (c. 10µm) mark the locations of analyses. Numbers refer to analytical spot numbers in Table 2. **D.** Th versus U content of zircon analyses. **E.** Tera Wasserburg diagram with U-Pb SIMS data on the migmatitic paragneiss. Rim analyses are marked in green. Rim analyses partly mixed with core domain material are marked in blue. Analyses shown with broken lines are excluded from age calculation (see text for explanation). **F.** Tera Wasserburg diagram showing U-Pb SIMS data of core analyses (red). All photographs by Fredrik Hellström.

Table 2. SIMS U-Pb-Th zircon data (FHM140097A, Lab-id: n5161).

Sample/ spot #	Comment	U ppm	Th ppm	Pb ppm	Th/U calc[1]	$^{207}Pb/^{235}U$	±σ %	$^{208}Pb/^{232}Th$	±σ %	$^{238}U/^{206}Pb$	±σ %	$^{207}Pb/^{206}Pb$	±σ %	ρ [2]	Disc. % conv. [3]	Disc. % 2σ lim. [4]	$^{207}Pb/^{206}Pb$	±σ Ma	$^{206}Pb/^{238}U$	±σ Ma	$^{206}Pb/^{204}Pb$ measured	f_{206}% [5]
n5161-01	BSE-bright rim, close to margin	807	4	[310]	no data	5.391	1.17	no data	no data	2.910	1.12	0.1138	0.32	0.96	2.7		1861	6	1904	19	5375	0.35
n5161-01c	Osc zon core	88	158	85	1.78	16.389	1.19	0.1500	2.89	1.716	1.08	0.2040	0.48	0.91	4.4	1.4	2859	8	2960	26	120444	{0.02}
n5161-02	Metamict rim mixed with core	1503	51	572	0.03	5.384	1.30	0.0888	6.61	2.954	1.24	0.1153	0.39	0.95	-0.3		1885	7	1880	20	15114	0.12
n5161-02c	Osc zon core	226	69	100	0.33	6.152	1.15	0.1115	2.42	2.743	0.96	0.1224	0.63	0.84	0.7		1991	11	2004	17	29211	{0.06}
n5161-03a	BSE-bright rim, close to margin	899	3	348	0.00	5.472	1.04	0.0409	82.55	2.882	1.01	0.1144	0.26	0.97	3.1	0.7	1870	5	1920	17	15326	0.12
n5161-03b	BSE-bright rim, close to core, mix?	939	13	370	0.03	5.617	0.96	0.2058	4.89	2.851	0.94	0.1162	0.22	0.97	2.4	0.3	1898	4	1938	16	119155	{0.02}
n5161-03c	Osc zon core	98	43	80	0.45	18.320	1.20	0.1652	2.39	1.647	0.97	0.2188	0.72	0.80	3.7	0.2	2972	12	3059	24	122403	{0.02}
n5161-04	BSE-bright rim partly mixed with core	761	30	300	0.06	5.813	1.08	0.1495	5.46	2.883	1.00	0.1215	0.41	0.93	-3.5	-0.8	1979	7	1920	17	55402	0.03
n5161-04c	Osc zon core	111	78	78	0.65	12.639	10.26	0.1274	29.09	1.920	1.74	0.1760	10.11	0.17	4.1		2615	159	2703	38	375	4.99
n5161-05	BSE-bright rim	851	3	328	0.00	5.480	1.01	0.0940	4.59	2.895	0.98	0.1151	0.24	0.97	1.9		1881	4	1913	16	110883	{0.02}
n5161-05c	Osc zon core	108	42	47	0.40	5.584	1.14	0.1008	2.51	2.843	0.90	0.1151	0.70	0.79	3.7		1882	13	1943	15	24164	{0.08}
n5161-06a	Metamict-BSE-bright rim	1910	8	671	0.00	4.888	0.99	0.0757	56.31	3.172	0.96	0.1124	0.25	0.97	-4.5	-2.3	1839	4	1767	15	3670	0.51
n5161-06b	BSE-bright rim, with fracture	1018	16	363	0.01	4.981	1.17	0.0543	11.24	3.132	1.15	0.1131	0.24	0.98	-4.0	-1.5	1850	4	1786	18	15497	0.12
n5161-07	BSE-bright rim	1015	3	391	0.00	5.477	1.05	0.0462	32.51	2.897	1.03	0.1151	0.21	0.98	1.9		1881	4	1912	17	49649	0.04
n5161-08	BSE-bright rim	986	3	379	0.00	5.458	1.01	0.0809	16.55	2.904	0.99	0.1150	0.22	0.98	1.7		1879	4	1907	16	86506	0.02
n5161-09	BSE-bright rim partly mixed with core	1074	50	423	0.05	5.554	1.07	0.0995	2.58	2.868	1.05	0.1155	0.22	0.98	2.4	0.0	1888	4	1928	18	96225	0.02
n5161-10	Rim	1302	5	497	0.00	5.423	1.00	0.0730	8.89	2.926	0.98	0.1151	0.19	0.98	0.9		1881	3	1895	16	111274	0.02
n5161-11	BSE-bright rim	908	3	349	0.00	5.460	1.02	0.0645	17.73	2.899	1.00	0.1148	0.24	0.97	2.0		1877	4	1910	16	62360	0.03
n5161-12	BSE-bright rim	1205	4	465	0.00	5.470	1.04	0.0751	9.12	2.892	1.02	0.1147	0.20	0.98	2.4	0.1	1876	4	1915	17	134586	0.01
n5161-20c	Osc zon core	122	100	62	0.84	6.283	1.25	0.1055	2.36	2.675	1.06	0.1219	0.66	0.85	3.7		1985	12	2047	19	44901	{0.04}
n5161-21c	Osc zon core	291	215	141	0.76	5.990	1.14	0.1042	2.59	2.746	1.07	0.1193	0.41	0.93	3.4	0.5	1946	7	2002	18	>1e6	{0.00}
n5161-22c	Osc zon core	245	245	129	1.04	6.375	0.98	0.1093	2.46	2.690	0.88	0.1244	0.44	0.89	1.0		2020	8	2038	15	315381	{0.01}
n5161-23c	Osc zon core	372	301	228	0.83	9.272	0.90	0.1280	2.22	2.254	0.84	0.1515	0.30	0.94	0.2		2363	5	2367	17	39852	0.05
n5161-24c	Osc zon core	135	90	82	0.70	9.380	0.99	0.1290	2.24	2.211	0.86	0.1504	0.49	0.87	2.8	0.0	2351	8	2405	17	>1e6	{0.00}
n5161-25c	Osc zon core	116	106	90	0.93	14.068	1.00	0.1484	2.23	1.868	0.90	0.1906	0.44	0.90	0.8		2747	7	2764	20	44800	{0.04}
n5161-26c	Osc zon core	117	69	55	0.60	5.886	1.11	0.1012	2.35	2.750	0.90	0.1174	0.65	0.81	5.0	1.5	1917	12	2000	16	16515	{0.11}
n5161-27c	Osc zon core	49	26	37	0.51	16.001	1.23	0.1455	2.57	1.765	1.04	0.2048	0.64	0.85	1.3		2865	10	2894	24	18118	{0.10}
n5161-28c	Osc zon core	279	209	132	0.74	5.788	0.98	0.0989	2.62	2.813	0.87	0.1181	0.44	0.89	2.0		1927	8	1961	15	57629	{0.03}
n5161-29c	Osc zon core	274	168	126	0.64	5.753	1.01	0.1043	2.22	2.831	0.91	0.1181	0.44	0.90	1.3		1928	8	1950	15	420974	{0.00}

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

DISCUSSION

Overall, ages of metamorphism and deformational events in the Svecokarelian orogeny north of the Skellefte district are poorly constrained. Within the Pajala deformation belt in eastern Norrbotten County, deformation and high-grade metamorphism occurred in the 1.83–1.78 Ga interval (Bergman et al. 2006, Luth et al. 2016, Hellström & Bergman 2016), possibly overprinting earlier structures. In the southern part of the Pajala deformation belt, migmatisation and related emplacement of Lina granite is dated at 1 783 ±3 Ma (Wikström & Persson 1997). In the central and southwestern part of Norrbotten County, 1.88–1.87 Ga metagranitoid-metasyenitoid intrusions of the Perthite-monzonite suite show variable low to high degrees of deformation and metamorphic recrystallisation, suggesting heterogeneous, post-1.87 Ga age of deformation and metamorphism also in large areas west of the Pajala deformation belt domain (Hellström et al. 2012, 2015). Granites-pegmatites of the late-orogenic 1.81–1.78 Ga Lina suite are also usually weakly foliated in central Norrbotten County. In contrast, Bergman et al. (2001) suggested there was an early orogenic event at 1.89–1.87 Ga, based on the observation of markedly different degrees of deformation between rocks of the Haparanda and the Perthite monzonite suites in the northwestern part of the Norrbotten County, although radiometric age determinations show no significant age differences between the two intrusive suites. Evidence of an older phase of migmatisation and shearing was reported from the southeastern part of the Norrbotten County, where the 1 881 ±9 Ma Bläsberget felsic-mafic dykes cuts migmatites occurring immediately west of the Pajala deformation belt (at "B" in Fig. 1B; B – Baltic–Bothnian mega-shear; Wikström et al. 1996). In the northeastern part of the Skellefte ore district, 1.88 Ga old plutons also crosscut deformed metasedimentary rocks (Lundström et al. 1997, 1999).

The Masugnsbyn area, just west of the Pajala deformation belt, is an area with a preserved, older phase of early orogenic Svecokarelian migmatisation and deformation. U-Pb analyses of secondary BSE-bright rim domains are interpreted to date migmatisation in the Tiankijoki paragneiss at 1 878 ±3 Ma (2σ). The rim analyses have very low Th/U ratios in contrast to core analysis, which suggests a metamorphic origin of the rims and a contemporaneous crystallisation with the coexisting monazite. Bergman et al. (2006) dated monazite from a meta-argillite at Pahakurkio and a weakly migmatitic paragneiss at Takanenvaara, both located close to Tiankijoki dating locality (Fig. 2). A weighted average $^{207}Pb/^{206}Pb$ age of the two weakly discordant fractions of Takanenvaara monazites can be calculated at 1 857 ±3 Ma (2σ), suggesting an age of metamorphism of approximately 1.86 Ga. The 20 Ma age difference between the zircon rim age obtained in this study and the monazite age of Bergman et al. (2006), may reflect resetting of the U-Pb isotopic system in monazite during a later metamorphic event, i.e. 20 million years after the migmatisation event dated by U-Pb in zircon. Martinsson et al. (2016) reported single fraction, weakly discordant U-Pb titanite $^{207}Pb/^{206}Pb$ ages of 1.80–1.76 Ga, interpreted to date an even younger event of metamorphism or hydrothermal alteration in the Masugnsbyn area.

The 1.88 Ga age of migmatisation is contemporaneous with large volumes of early orogenic intrusions of the 1.88–1.86 Ga Perthite monzonite suite (Bergman et al. 2001, Hellström et al. 2015). The increase in metamorphic grade towards the adjacent intrusive rocks in the Masugnsbyn area suggests that heat from the intrusions was responsible for the metamorphic conditions. Thus, heat from these intrusions is inferred to have caused the high-grade metamorphism and partial melting. The area to the southeast of the migmatites is dominated by granites, syenites and gabbro. Padget (1970) placed the granites in the Lina suite, whereas Bergman et al. (2001) suggested that the rocks belong to the 1.8 Ga granite-syenitoid-gabbroid association. However, 30 km towards the southeast, in the Narken area, a nearly isotropic metagranite sample was dated at 1 872 ±4 Ma (MSWD = 1.4, n = 4, TIMS, U-Pb zircon, Hellström et al. 2012). That granite is co-magmatic with gabbroic rocks and was assigned to the Perthite monzonite suite, which is also suggested to have an affinity with the intrusive rocks southeast of the Masugnsbyn key area. The Tärendö gabbro occupies an area of 22 × 6 km, and several smaller gabbro intrusions surrounded by granite also occur. Input of large volumes of mafic magmas would increase the temperature of the crust, possibly causing partial melting and migmatisation in the pelitic rocks south of Masugnsbyn.

Implications for mineralisations

The metamorphic alteration of supracrustal rocks at 1.88 Ga has implications for the timing of skarn iron ore formation, and remobilisation of base metals in sulphide mineralisations. The Masugnsbyn iron mineralisations form a more or less regular sheet, concordant between the Veikkavaara greenstones and the overlying quartzitic and metapelitic metasedimentary rocks of the Pahakurkio group (Figs. 2–3, Frietsch 1997, Geijer 1929, Padget 1970, Witschard et al. 1972). The southern iron deposits are classified as skarn iron ores, whereas the mineralisations to the north have characteristics of sedimentary, millimetre- to centimetre-wide, quartz-magnetite banded iron ore of an exhalative origin. A significant difference between the mineralisations is that the southern area is characterised by the presence of a rather thick dolomitic marble unit and by a perthite granite, which borders the skarn iron ores. The close spatial connection between the skarn iron ores and the perthite granite suggests that the intrusion of the granite is responsible for skarn formation and remobilisation of iron, with a higher grade and coarser grain size of the magnetite ore in the footwall next to the granite. The perthite granite was dated at 1 858 ±9 Ma using discordant U-Pb TIMS zircon data (Skiöld & Öhlander 1989). However, recent U-Pb SIMS zircon data suggest an age of 1 881 ±5 Ma (Hellström et al. in prep.), thus contemporaneous with the age of migmatisation in the high-grade southern part of the Masugnsbyn area.

The Kurkkionvaara Zn-Pb-Cu mineralisation is located approximately 15 km south of Masugnsbyn at the contact between the metasedimentary rocks of the Pahakurkio group and the metasedimentary and intermediate metavolcanic rocks of the Kalixälv group (Fig. 2, Niiniskorpi 1986). The mineralisations occur as scattered sulphide veins or fracture fillings with sphalerite and galena, mainly in the metasedimentary rocks of the Pahakurkio groups, but also in the overlying quartz-rich conglomerate. Locally, richer mineralisations in some fracture zones, with total Zn-Pb content up to a few per cent over 0.4–2.0 m occur. Impregnations of pyrrhotite and pyrite occur in metre-wide zones, where the richest concentrations of Fe-sulphides occur in the 10–20 m wide conglomerate horizon above the Pahakurkio group as an impregnation in the matrix. Veins of pyrrhotite generally occur parallel to bedding in the sedimentary rocks, whereas the Pb-Zn-filled fractures usually dip steeply and crosscut bedding. Lithochemical analyses show a positive correlation between B and Zn + Pb content, suggesting a hydrothermal system with boron-rich fluids containing base metals (Niiniskorpi 1986). At Kurkkionvaara, tourmaline-rich layers (tourmalinites) occur in the pelitic sedimentary rocks, along with tourmaline-rich pegmatites. Boron-rich fluids probably have a source in the metapelites, originally deposited as marine sediments. Sulphide mineralisations may have resulted from boron-rich fluids formed during migmatisation of these pelitic sedimentary rocks, but the fracture-style Zn-Pb mineralisation suggests that this type of mineralisation post-dates migmatisation and ductile deformation. The migmatisation age obtained thus provides a maximum age of the fracture-type Pb-Zb mineralisation at Kurkkionvaara.

Provenance

The large spread in zircon core ages suggests a detrital origin of the zircon, and therefore a sedimentary origin of the migmatitic gneiss. Despite the limited number of SIMS analyses on zircon core domains, the maximum depositional age can be constrained by the youngest core analysis (5c) at 1 882 ±25 Ma (2σ), but deposition must have occurred before migmatisation at 1 878 ±3 Ma (2σ). 50% of the recorded ages fall in the range 2.02–1.92 Ga, suggesting that rocks of this age interval were the main source, together with debris from Archaean rocks (29%). Archaean rocks are exposed in the

Råstojaure complex in northernmost Sweden (Martinsson et al. 1999, Lauri et al. 2016). Sm-Nd isotopic analyses of Proterozoic granitoids and metavolcanic rocks suggest a covered Archaean basement south of the Råstojaure Complex (Öhlander et al. 1987a, b, 1993, Skiöld et al. 1988, Lauri et al. 2016, Hellström et al., 2018).

The Archaean palaeoboundary zone between the reworked Archaean craton in the north and more juvenile Palaeoproterozoic domains to the south occurs along the Luleå–Jokkmokk zone in Sweden and along the Raahe–Ladoga zone in Finland (Öhlander et al. 1993, Mellqvist et al. 1999, Vaasjoki & Sakko 1988, Nironen 1997). To date, there are very few age determinations of igneous rocks in the interval 2.02–1.92 Ga, but some occur in the Savo schist belt within the Raahe–Ladoga zone in Finland, at Norvijaur in the Jokkmokk area and in the Rombak–Sjangeli basement window of the Caledonides, all of which lie along the Archaean–Palaeoproterozoic boundary (Helovuori 1979, Korsman et al. 1984, Vaasjoki & Sakko 1988, Kousa et al. 1994, Lahtinen & Huhma 1997, Vaasjoki et al. 2003, Kousa et al. 2013, Skiöld et al. 1993, Romer et al. 1992; Hellström 2015). In addition, 1.96–1.94 Ga calc-alkaline rocks with island arc affinity occur in the northern part of the Bothnian Basin, south of the Skellefte district (Wasström 1993, 1996, Lundqvist et al. 1998, Eliasson et al. 2001, Skiöld & Rutland 2006).

CONCLUSIONS

- Early Svecokarelian migmatisation is dated at 1 878 ±3 Ma in the Masugnsbyn structural domain, west of the Pajala deformation belt, which constrains the maximum age of folding of the supracrustal rocks.
- It is suggested that the 1.88 Ga migmatisation was caused by heat transfer from large volumes of contemporaneous early orogenic Svecokarelian intrusions.
- Intrusion of a 1.88 Ga perthite granite at Masugnsbyn caused contact metamorphic alterations of the upper part of the Veikkavaara greenstones, containing banded iron formations and carbonate rocks, resulting in skarn formation and remobilisation of iron to higher grades to form the Masugnsbyn skarn iron ores, contemporaneous with migmatisation in the higher-grade south of the Masugnsbyn area.
- The obtained migmatisation age provides a maximum age for the Kurkkionvaara fracture-type Pb-Zb mineralisation, which occurs in metapelites in the upper part of the Pahakurkio group, below the migmatitic paragneisses of the Kalixälv group.
- The maximum depositional age of the original sediments in the Kalixälv group is constrained by the youngest zircon core analysis at 1 882 ±25 Ma (2σ), but must have occurred before migmatisation at 1 878 ±3 Ma.
- The main source of the original sediments of the Kalixälv group is 2.02–1.92 Ga (50%) and 2.97–2.75 Ga rocks (29%). 2.02–1.92 Ga felsic to intermediate rocks can be expected to be present to a greater extent than is known from present age determination of rocks in the Svecokarelian orogeny.

ACKNOWLEDGEMENTS

Carl-Henric Wahlgren, George Morris and Stefan Bergman are gratefully acknowledged for their careful review, which significantly improved the manuscript. Cecilia Jönsson is much thanked for conducting ground geophysical measurements at Masugnsbyn, as well as for compilation, gridding and interpretation of geophysical data. Ildikó Antal Lundin is thanked for gridding the magnetic data on the map in Figure 1. U-Pb isotopic zircon data were obtained from beneficial cooperation with the Laboratory for Isotope Geology at the Swedish Museum of Natural History (NRM) in Stockholm. The Nordsim facility is operated under an agreement between the research funding agencies of Denmark, Norway and Sweden, the Geological Survey of Finland and the Swedish Museum of Natural History. We would like to express our gratitude to Martin Whitehouse, Lev Ilyinsky and Kerstin Lindén at the Nordsim analytical facility for their first-class analytical support with SIMS analyses. Martin Whitehouse reduced the zircon analytical data, Lev Ilyinsky assisted during ion probe analyses and Kerstin Lindén prepared the zircon mounts. Our sincere thanks also go to Milos Bartol at the Evolutionary Biology Centre and Jaroslaw Majka at the Department of Geology, Uppsala University, an also Kerstin Lindén at NRM for their support during BSE/CL imaging of zircons. Tone Gellerstedt and Maxwell Arding are much thanked for editing and proofreading.

REFERENCES

Bergman, S., Billström, K., Persson, P.-O., Skiöld, T. & Evins, P., 2006: U-Pb age evidence for repeated Palaeoproterozoic metamorphism and deformation near the Pajala shear zone in the northern Fennoscandian shield. *GFF 128*, 7–20.

Bergman, S., Kübler, L. & Martinsson, O., 2001: Description of Regional Geological and Geophysical Maps of Northern Norrbotten County (east of the Caledonian Orogen). *Sveriges geologiska undersökning Ba 56*, 110 pp.

Bergman, T., Hellström, F. & Ripa, M., 2015: Verksamhetsrapport 2014: Norrbottens malm och mineral. *Sveriges geologiska undersökning SGU-rapport 2015:08,* 20 pp.

Eliasson, T., Greiling, R., Sträng, T. & Triumf, C., 2001: Bedrock map 23H Stensele NV, scale 1:50 000. *Sveriges geologiska undersökning Ai 126*.

Frietsch, R., 1997: The iron ore inventory program 1963–1972 in Norrbotten County. *Rapporter och meddelanden 92*, Sveriges geologiska undersökning. 77 pp.

Geijer, P., 1929: Masugnsbyfältens geologi. *Sveriges geologiska undersökning C 351*, 39 pp.

Grigull, S., Berggren, R., Jönberger, J., Jönsson, C., Hellström, F.A. & Luth, S., 2018: Folding observed in Palaeoproterozoic supracrustal rocks in northern Sweden. *In:* Bergman, S. (ed): Geology of the Northern Norrbotten ore province, northern Sweden. *Rapporter och Meddelanden 141,* Sveriges geologiska undersökning. This volume pp 205–257.

Grip, E. & Frietsch, R., 1973: *Malm i Sverige 2. Norra Sverige*. Almqvist & Wiksell, 295 pp.

Hellström, F.A., 2015: SIMS geochronology of a 1.93 Ga basement metagranitoid at Norvijaur west of Jokkmokk, northern Sweden. *SGU-rapport 2015:01*, Sveriges geologiska undersökning. 18 pp.

Hellström, F. & Bergman, S., 2016: Is there a 1.85 Ga magmatic event in northern Norrbotten? − U-Pb SIMS zircon dating of the Pingisvaara metagranodiorite and the Jyryjoki granite, northern Sweden. *GFF 138, 526–532.*

Hellström, F. & Jönsson, C., 2014: Barents project 2014: Summary of geological and geophysical information of the Masugnsbyn key area. *SGU-rapport 2014:21*, Sveriges geologiska undersökning. 84 pp.

Hellström, F., Carlsäter Ekdahl, M. & Kero, L., 2012: Beskrivning till berggrundskartorna 27L Lansjärv NV, NO, SV & SO. *Sveriges geologiska undersökning K 387–390*, 27 pp.

Hellström, F., Kathol, B. & Larsson, D., 2015: Age and chemical character of the Perthite monzonite suite in south-western Norrbotten, northern Sweden. *SGU-rapport 2015:38*, Sveriges geologiska undersökning. 23 pp.

Hellström, F.A., Kumpulainen, R., Jönsson, C., Thomsen, T.B., Huhma, H. & Martinsson, O., 2018: Age and lithostratigraphy of Svecofennian volcanosedimentary rocks at Masugnsbyn, northernmost Sweden – host rocks to Zn-Pb-Cu- and Cu ±Au sulphide mineralisations. *In:* Bergman, S. (ed): Geology of the Northern Norrbotten ore province, northern Sweden. *Rapporter och Meddelanden 141,* Sveriges geologiska undersökning. This volume pp 151–203.

Helovuori, O., 1979: Geology of the Pyhäsalmi ore deposit, Finland. *Economic Geology 74*, 1084–1101.

Korsman, K., Hölttä, P., Hautala, T. & Wasenius, P., 1984: Metamorphism as indicator of evolution and structure of the crust in eastern Finland. *Geological Survey of Finland Bulletin 328*, 40 pp.

Kousa, J., Luukas, J., Huhma, H. & Mänttäri, I., 2013: Palaeoproterozoic 1.93−1.92 Ga Svecofennian rock units in the northwestern part of the Raahe–Ladoga zone, central Finland. *In:* P. Hölttä (Ed.): Current research: GTK Mineral potential workshop, Kuopio, May 2012. *Geological Survey of Finland Report of Investigation 198*, 91–96.

Kousa, J., Marttila, E. & Vaasjoki, M., 1994: Petrology, geochemistry and dating of Paleoproterozoic metavolcanic rocks in the Pyhäjärvi area, central Finland. *In:* M. Nironen & Y. Kähkönen (eds.): Geochemistry of Proterozoic supracrustal rocks in Finland. *Geological Survey of Finland, Special Paper 19*, 7–27.

Kumpulainen, R.A., 2000: The Paleoproterozoic sedimentary record of northernmost Norrbotten, Sweden. Unpublished report. *Sveriges geologiska undersökning BRAP 200030*, 45 pp.

Lahtinen, R. & Huhma, H., 1997: Isotopic and geochemical constraints on the evolution of the 1.93–1.79 Ga Svecofennian crust and mantle. *Precambrian Research 82*, 13–34.

Lahtinen, R., Huhma, H., Lahaye, Y., Jonsson, E., Manninen, T., Lauri, L.S., Bergman, S., Hellström, F., Niiranen, T. & Nironen, M., 2015: New geochronological and Sm–Nd constraints across the Pajala shear zone of northern Fennoscandia: Reactivation of a Paleoproterozoic suture. *Precambrian Research 256*, 102–119.

Lauri, L.S., Hellström, F., Bergman, S., Huhma, H. & Lepistö, S., 2016: New insights into the geological evolution of the Archean Norrbotten province, Fennoscandian shield. *32nd Nordic Geological Winter Meeting, Helsingfors*.

Ludwig, K.R., 2012: User's manual for Isoplot 3.75. A Geochronological Toolkit for Microsoft Excel. *Berkeley Geochronology Center Special Publication No. 5*, 75 pp.

Lundqvist, T., Vaasjoki, M. & Persson, P.-O., 1998: U-Pb ages of plutonic and volcanic rocks in the Svecofennian Bothnian Basin, central Sweden, and their implications for the Palaeoproterozoic evolution of the basin. *GFF 120*, 357–363.

Lundström, I., Persson P.-O. & Bergström U., 1999: Indications of early deformational events in the northeastern part of the Skellefte field. Indirect evidence from geological and radiometric data from the Stavaträsk-Klintån area, Boliden map-sheet. *In:* S. Bergman (ed.) Radiometric dating results 4: *Sveriges geologiska undersökning C 831*, 52–69.

Lundström, I., Vaasjoki, M., Bergström, U., Antal, I. & Strandman F., 1997: Radiometric age determinations of plutonic rocks in the Boliden area: the Hobergsliden granite and the Stavaträsk diorite. *In:* T. Lundqvist (ed.) Radiometric dating results 3: *Sveriges geologiska undersökning C 830*, 20–30.

Luth, S., Jönsson, C., Hellström, F., Jönberger, J., Djuly, T., Van Assema, B. & Smoor, W., 2016: Structural and geochronological studies of the crustal-scale Pajala Deformation Zone, northern Sweden. *32nd Nordic Geological Winter Meeting, Helsingfors.*

Luth, S., Jönsson, C., Jönberger, J., Grigull, S., Berggren, R., van Assema, B., Smoor, W. & Djuly, T., 2018: The Pajala Deformation Belt in northeast Sweden: Structural geological mapping and 3D modelling around Pajala. *In:* Bergman, S. (ed): Geology of the Northern Norrbotten ore province, northern Sweden. *Rapporter och Meddelanden 141,* Sveriges geologiska undersökning. This volume pp 259–285.

Lynch, E.P., Hellström, F.A., Huhma, H., Jönberger, J., Persson, P.-O. & Morris, G.A, 2018: Geology, lithostratigraphy and petrogenesis of c. 2.14 Ga greenstones in the Nunasvaara and Masugnsbyn areas, northernmost Sweden. *In:* Bergman, S. (ed): Geology of the Northern Norrbotten ore province, northern Sweden. *Rapporter och Meddelanden 141,* Sveriges geologiska undersökning. This volume pp 19–77.

Martinsson, O., Vaasjoki, M. & Persson, P.-O., 1999: U-Pb ages of Archaean to Palaeoproterozoic granitoids in the Torneträsk-Råstojaure area, northern Sweden. *In:* S. Bergman (ed.): Radiometric dating results 4. *Sveriges geologiska undersökning C 831*, 70–90.

Martinsson, O., Van der Stilj, I., Debras, C. & Thompson, M., 2013: Day 3. The Masugnsbyn, Gruvberget and Mertainen iron deposits. *In:* O. Martinsson & C. Wanhainen (eds.): *12th Biennial SGA Meeting, Uppsala, Sweden. Excursion guidebook SWE5*, 37–44.

Martinsson, O., Billström, K., Broman, C., Weihed, P. & Wanhainen, C., 2016: Metallogeny of the Northern Norrbotten Ore Province, northern Fennoscandian Shield with emphasis on IOCG and apatite-iron ore deposits. *Ore Geology Reviews 78*, 447–492.

Martinsson, O., Bergman, S., Persson, P.-O. & Hellström, F.A., 2018: Age and character of late-Svecokarelian monzonitic intrusions in north-eastern Norrbotten, northern Sweden. *In:* Bergman, S. (ed): Geology of the Northern Norrbotten ore province, northern Sweden. *Rapporter och Meddelanden 141,* Sveriges geologiska undersökning. This volume pp 381–399.

Mellqvist, C., Öhlander, B. & Skiöld, T., 1999: Traces of Archean crust in the Jokkmokk area, northern Sweden: a way of defining the Archean-Proterozoic boundary. *In:* C. Mellqvist: Proterozoic crustal growth along the Archean continental margin in the Luleå and Jokkmokk areas, northern Sweden. Doctoral thesis, Luleå University, 24 pp.

Niiniskorpi, V., 1986: En Zn-Pb-Cu-mineralisering i norra Sverige, en case-studie. LKAB Prospektering K-8656, Licenciate thesis, geological department of Åbo Akademi, 74 pp.

Nironen, M., 1997: The Svecofennian orogen: a tectonic model. *Precambrian Research 86*, 21–44.

Öhlander, B., Hamilton, P.J., Fallick, A.E. & Wilson, M.R., 1987a: Crustal reactivation in northern Sweden: the Vettasjärvi granite. *Precambrian Research 35,* 277–293.

Öhlander, B., Skiöld, T., Hamilton, P.J. & Claesson, L.-Å., 1987b: The western border of the Archaean province of the Baltic shield: evidence from northern Sweden. *Contributions to Mineralogy and Petrology 95,* 437–450.

Öhlander, B., Skiöld, T., Elming, S.Å., Claesson, S. & Nisca, D.H., 1993: Delineation and character of the Archaean-Proterozoic boundary in northern Sweden. *Precambrian Research 64,* 67–84.

Padget, P., 1970: Beskrivning till berggrundskartbladen Tärendö NV, NO, SV, SO. *Sveriges geologiska undersökning Af 5–8*, 95 pp.

Romer, R.L., Kjösnes, B., Korneliussen, A., Lindahl, I., Skyseth, T., Stendahl, M. & Sundvoll, B., 1992: The Archean–Proterozoic boundary beneath the Caledonides of northern Norway and Sweden: U-Pb, Rb-Sr, and εNd isiotope data from the Rombak-Tysfjord area. *NGU rapport 91.225,* 67 pp.

Silvennoinen, A., 1991: Kuusamon ja Rukatunturin kartta-alueiden kallioperä. Geological map of Finland 1:100 000, *Explanation to the maps of pre-Quaternary rocks, Sheets 4524+4542 and 4616. Geological Survey of Finland,* 36 pp.

Skiöld, T. & Öhlander, B., 1989: Chronology and geochemistry of late Svecofennian processes in northern Sweden. *Geologiska Föreningen i Stockholm Förhandlingar 111*, 347–354.

Skiöld, T., Öhlander, B., Vocke Jr, R.D. & Hamilton, P.J., 1988: Chemistry of Proterozoic orogenic processes at a continental margin in northern Sweden. *Chemical Geology 69*, 193–207.

Skiöld, T. & Rutland, R.W.R., 2006: Successive ~1.94 Ga plutonism and ~1.92 Ga deformation and metamorphism south of the Skellefte district, northern Sweden: Substantiation of the marginal basin accretion hypothesis of Svecofennian evolution. *Precambrian Research 148*, 181–204.

Skiöld, T., Öhlander, B., Markkula, H., Widenfalk, L. & Claesson, L.-Å., 1993: Chronology of Proterozoic orogenic processes at the Archaean continental margin in northern Sweden. *Precambrian Research 64*, 225–238.

Smith, M.P., Storey, C.D., Jeffries, T.E. & Ryan, C., 2009: In Situ U-Pb and Trace Element Analysis of Accessory Minerals in the Kiruna District, Norrbotten, Sweden: New Constraints on the Timing and Origin of Mineralization. *Journal of Petrology 50*, 2063–2094.

Stacey, J.S. & Kramers, J.D., 1975: Approximation of terrestrial lead isotope evolution by a two-stage model. *Earth and Planetary Science Letters 26*, 207–221.

Steiger, R.H. & Jäger, E., 1977: Convention on the use of decay constants in geo- and cosmochronology. *Earth and Planetary Science Letters 36*, 359–362.

Storey, C.D., Smith, M.P. & Jeffries, T.E., 2007: In situ LA-ICP-MS U-Pb dating of metavolcanics of Norrbotten, Sweden: Records of extended geological histories in complex titanite grains. *Chemical Geology 240*, 163–181.

Vaasjoki, M. & Sakko, M., 1988: The evolution of the Raahe–Ladoga zone in Finland: isotopic constraints. *In:* K. Korsman (ed.): Tectono-metamorphic evolution of the Raahe–Ladoga zone. *Geological Survey of Finland Bulletin 343,* 7–32.

Vaasjoki, M., Huhma, H., Lahtinen, R. & Vestin, J., 2003: Sources of Svecofennian granitoids in the light of ion probe U-Pb measurements on their zircons. *Precambrian Research 121*, 251–262.

Wasström, A., 1993: U-Pb zircon dating of a quartz-feldspar porphyritic dyke in the Knaften area; Västerbotten County; northern Sweden. *In:* T. Lundqvist (ed.): Radiometric dating results 2. *Sveriges geologiska undersökning C 82*8, 34–40.

Wasström, A., 1996: The Knaften granitoids of Västerbotten County, northern Sweden. *In:* T. Lundqvist (Ed.): Radiometric dating results. *Sveriges geologiska undersökning C 823*, 60–64.

Wiedenbeck, M., Allé, P., Corfu, F., Griffin, W.L., Meier, M., Oberli, F., Quadt, A.V., Roddick, J.C. & Spiegel, W., 1995: Three natural zircon standards for U-Th-Pb, Lu-Hf, trace element and REE analyses. *Geostandards Newsletter 19*, 1–23.

Wiedenbeck, M., Hanchar, J.M., Peck, W.H., Sylvester, P., Valley, J., Whitehouse, M., Kronz, A., Morishita, Y., Nasdala, L., Fiebig, J., Franchi, I., Girard, J.P., Greenwood, R.C., Hinton, R., Kita, N., Mason, P.R.D., Norman, M., Ogasawara, M., Piccoli, P.M., Rhede, D., Satoh, H., Schulz-Dobrick, B., Skår, O., Spicuzza, M.J., Terada, K., Tindle, A., Togashi, S., Vennemann, T., Xie, Q. & Zheng, Y.F., 2004: Further characterisation of the 91500 zircon crystal. *Geostandards and Geoanalytical Research 28*, 9–39.

Whitehouse, M.J., Claesson, S., Sunde, T. & Vestin, J., 1997: Ion-microprobe U–Pb zircon geochronology and correlation of Archaean gneisses from the Lewisian Complex of Gruinard Bay, northwestern Scotland. *Geochimica et Cosmochimica Acta 61*, 4429–4438.

Whitehouse, M.J., Kamber, B.S. & Moorbath, S., 1999: Age significance of U–Th–Pb zircon data from Early Archaean rocks of west Greenland: a reassessment based on combined ion-microprobe and imaging studies. *Chemical Geology (Isotope Geoscience Section) 160*, 201–224.

Whitehouse, M.J. & Kamber, B.S., 2005: Assigning Dates to Thin Gneissic Veins in High-Grade Metamorphic Terranes: A Cautionary Tale from Akilia, Southwest Greenland. *Journal of Petrology 46*, 291–318.

Wikström, A. & Persson, P.-O., 1997: U-Pb zircon and monazite dating of a Lina-type leucogranite in northern Sweden and its relationship to the Bothnian shear zone. *In:* T. Lundqvist (ed.): Radiometric dating results 3. *Sveriges geologiska undersökning C 830*, 81–87.

Wikström, A., Skiöld, T. & Öhlander, B., 1996: The relationship between 1.88 Ga old magmatism and the Baltic–Bothnian shear zone in northern Sweden. *Geological Society, London, Special Publications 112,* 249–259.

Witschard, F., Nylund, B. & Mannström, B., 1972: The Masugnsbyn iron ore. Report concerning the results of Sveriges geologiska undersökning:s investigations in the years 1965–1970. *Sveriges geologiska undersökning BRAP 734*, 95 pp.

Geological Survey of Sweden
Box 670
SE-751 28 Uppsala
Phone: +46 18 17 90 00
Fax: +46 18 17 92 10
www.sgu.se

Uppsala 2018
ISSN 0349-2176
ISBN 978-91-7403-393-9
Tryck: Elanders Sverige AB