Rapporter och meddelanden 141

# Geology of the Northern Norrbotten ore province, northern Sweden

Paper 12 (13)

**Editor: Stefan Bergman**




SGU
Sveriges geologiska undersökning
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# Geology of the Northern Norrbotten ore province, northern Sweden

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***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.

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# 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).

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# 12. Age and character of late-Svecokarelian monzonitic intrusions in northeastern Norrbotten, northern Sweden

Olof Martinsson, Stefan Bergman, Per-Olof Persson & Fredrik A. Hellström

## ABSTRACT

Palaeoproterozoic magmatism in northern Norrbotten shows a complex evolution, with several different plutonic suites ranging in age 1.93–1.70 Ga. Here we present data for three monzonitic intrusions from different parts of the area. They are petrographically and chemically similar, consisting mainly of perthite, augite and orthopyroxene, with megacrysts of poikilitic biotite as a characteristic minor component, and with high Sr and Ba. The intrusions have been dated at 1.80 Ga and may be part of a more extensive magmatic event in northern Sweden, including other chemically similar monzonitic and gabbroic intrusions, which often occur as ring dykes at the Merasjärvi gravity high (MGH) in northeastern Norrbotten. The monzonitic intrusions have A-type signatures and chemical characteristics overlapping those of rocks in arc and within-plate settings. These intrusions may thus have formed in either a back arc setting related to eastward subduction associated with the Transscandinavian Igneous Belt further west (TIB 1), or through a separate igneous event caused by a mantle plume.

## INTRODUCTION

Palaeoproterozoic magmatism in northern Norrbotten has a complex evolution, with several different plutonic suites ranging in age 1.93–1.70 Ga (Bergman et al. 2001, Martinsson et al. 1999, Romer et al. 1992, 1994, Skiöld 1988, Skiöld et al. 1988, 1993). Due to a rather limited chronological dataset and somewhat similar petrographical and geochemical characteristics of the different suites, classification of individual plutons has been rather arbitrary. However, the classification was revised during the project "Synthesis bedrock maps of northern Norrbotten", and six plutonic suites were identified by differences in age and composition (Bergman et al. 2001).

One of the results from the new geochronological data obtained during that project was the identification of 1.8 Ga ages of some monzonitic rocks in the northeastern part of northern Norrbotten. Plutonic rocks of this age and composition were previously unknown in this area, and based on this new information, it was suggested that they represent TIB-type magmatism extending far eastward from the Transscandinavian Igneous Belt proper (Bergman et al. 2001). In this paper, petrographical,

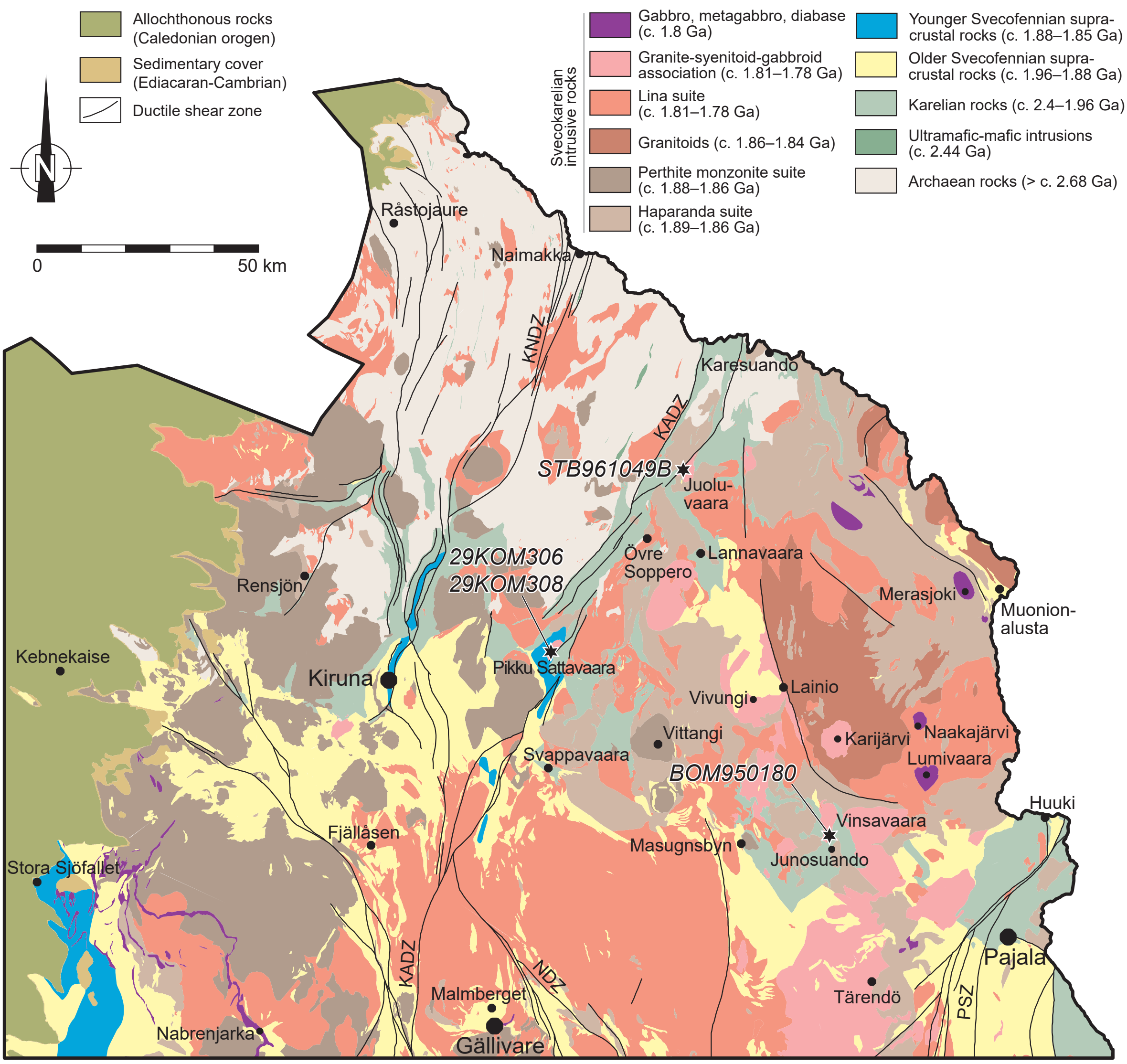


Figure 1. Bedrock map of northern Norrbotten County, modified from Bergman et al. (2001), with location of analysed samples.

geochemical and geochronological data are presented for 1.8 Ga monzonitic intrusions at Pikku Sattavaara, Juoluvaara and Vinsavaara, situated 37 km east of Kiruna, 18 km northeast of Soppero and 50 km northwest of Pajala, respectively (Fig. 1).

## GEOLOGICAL SETTING

The Precambrian bedrock in northern Norrbotten includes a c. 2.8 Ga Archaean granitoid-gneiss basement, which is unconformally overlain by greenstone, porphyry and sedimentary successions of Palaeoproterozoic age. Stratigraphically lowest of these successions are rift-related 2.5–2.0 Ga Karelian units, which in the Kiruna area are represented by the Kovo Group and the overlying Kiruna Greenstone Group (Martinsson 1997). The later c. 1.9 Ga Svecofennian successions comprise the Porphyrite Group, the Kurravaara Conglomerate, the Kiirunavaara Group and the Hauki Quartzite (Martinsson 2004). Most of these Palaeoproterozoic units extend outside the Kiruna area, and may be considered to be regionally developed in northern Norrbotten (Bergman et al. 2001).

The approximately 10 km thick pile of Palaeoproterozoic volcanic and sedimentary rocks was deformed and metamorphosed during the Svecokarelian orogeny (1.9–1.8 Ga), contemporaneous with intrusions of the 1.89–1.86 Ga Haparanda and Perthite-monzonite suites. These plutonic rocks have calc-alkaline to alkali-calcic character and are comagmatic with the Svecofennian volcanic rocks (Witschard 1984, Bergman et al. 2001; Martinsson, 2004). The 1.85 Ga Jyryjoki granite occurs in northeastern Norrbotten and is mainly of granitic composition (Bergman et al. 2001; Hellström & Bergman 2016). The Lina Suite comprises 1.81–1.78 Ga minimum-melt granites, aplites and pegmatites (Skiöld et al. 1988), which are widely distributed in Norrbotten and contemporaneous with TIB 1 intrusions in the Kiruna–Narvik area (Romer et al. 1992, 1994). A second metamorphic and deformation event occurred at that time (Bergman et al. 2001). The youngest plutonic rocks are c. 1.71 Ga TIB 2 intrusive rocks along the Swedish–Norwegian border (Romer et al. 1992).

## The Pikku Sattavaara monzonite

At Pikku Sattavaara, monzonite occurs as an oval intrusion extending over an area of 2 × 5 km. It is situated along the Karesuando-Arjeplog deformation zone (KADZ) and intrudes the contact between the Karelian greenstones and the unconformably overlying Maattavaara Quartzite. Exposures are rather sparse and mainly found at Pikku Sattavaara hill, situated 37 km east-northeast of Kiruna. Contacts with the surrounding rocks are not exposed. However, according to aeromagnetic data, the eastern boundary of the intrusion is partly controlled by the KADZ. The monzonite is generally undeformed, but brittle structures have developed locally in a northwesterly orientation. Brittle to ductile shearing in a NNE direction affects the monzonite in outcrops in the southeast.

The exposed parts of the monzonite show no major variation in composition or texture, and aeromagnetic data indicate that the intrusion is of a fairly homogenous nature. Texturally, it is medium-grained, with feldspar and pyroxene as the main constituents. Pyroxene constitutes 35–40% of the rock and includes both augite and hyperstene, the former being most abundant. A characteristic minor component is poikilitic megacrysts of biotite, whose colour is reddish-brown in thin section. Apatite and magnetite occur as accessory phases. The pyroxenes are partly altered to amphibole, particularly in areas affected by deformation. Close to the KADZ, the rock is greatly altered and partly veined by carbonate. Secondary biotite, chlorite and epidote have formed at the expense of pyroxene and amphibole.

### *Sample description*

Two samples were collected from Pikku Sattavaara for age determination (sample 29KOM306, 7542444/757142 and sample 29KOM308, 7542142/757036, coordinates in SWEREF99 TM). Both are from the south-central part of the intrusion and differ slightly in mineral composition and texture. Sample 29KOM308 shows the best preserved character, while sample 29KOM306 shows significant late- to post-magmatic alteration. Both samples have a grain size of 1 to 3 mm, with biotite as sparse 7–15 mm sized poikilitic megacrysts, having a brownish colour in thin section. Apatite is the most common accessory mineral, occurring in short prismatic to rounded grains. Sample 29KOM308 is a reddish-brown colour, and contains augite and some hyperstene. Augite is partly replaced by biotite and amphibole. Sample 29KOM306 is taken from a dark brownish-coloured monzonite. Pyroxene is largely altered to amphibole and the biotite contains abundant needles of rutile and minute grains of titanite.

## The Vinsavaara monzodiorite

Some intrusions of monzonitic to monzodioritic composition occur north of Junosuando in north-eastern Norrbotten (Witschard 1970). They are highly magnetic structures with a rounded to oval shapes and sizes of 10 to 15 km in the longest dimension (Vinsavaara, Karijärvi and Vivungi). The best exposed intrusion occurs at Vinsavaara, 3 km north of Junosuando. The predominant rock is a medium- to coarse-grained monzodiorite, consisting of perthite (70%), amphibole (10%), pyroxene (7%) and biotite (5%). The perthite comprises a complex mixture of microcline and plagioclase, with both perthitic and antiperthitic intergrowths. Locally, the perthite grains contain irregular cores of plagioclase (albite to andesine), which are corroded to a greater or lesser extent by the surrounding microcline. Pyroxene is mostly augite, although hyperstene is found in the Vinsavaara intrusion. Amphibole occurs as primary magmatic hornblende and as a secondary replacement after pyroxene. Magnetite and apatite are the main accessory minerals. Quartz is rare and when present occurs interstitially with feldspar. Its texture is generally granular, with irregular and sutured boundaries of perthite grains as a typical feature (Witschard 1970).

### *Sample description*

One sample of monzodiorite has been taken from the southern slope of Viiksvaara hill, situated in the southern part of the Vinsavaara intrusion (BOM950180, coordinates in SWEREF99 TM: 7501593/820409). The rock is reddish-brown in colour and medium- to coarse-grained (Fig. 2A). A characteristic feature is the occurrence of large poikilitic flakes of biotite randomly distributed in the rock. The matrix predominantly consists of perthitic feldspar, with approximately 10 and 5 per cent augite and hyperstene, respectively (Fig. 2B). A second type of biotite partly replaces inner parts of augite grains, but also occurs as secondary rims on grains of magnetite and pyroxene. Apatite is a common accessory mineral, forming short prismatic grains.

## The Juoluvaara intrusion

The Juolovaara intrusion is situated 18 km northeast of Soppero, close to the Karesuando–Arjeplog deformation zone, just east of exposed Archaean rocks of the Råstojaure complex. It intrudes Haparanda-type granodiorite and Karelian greenstones. The Juolovaara intrusion is oval in shape, 5 × 3 km,

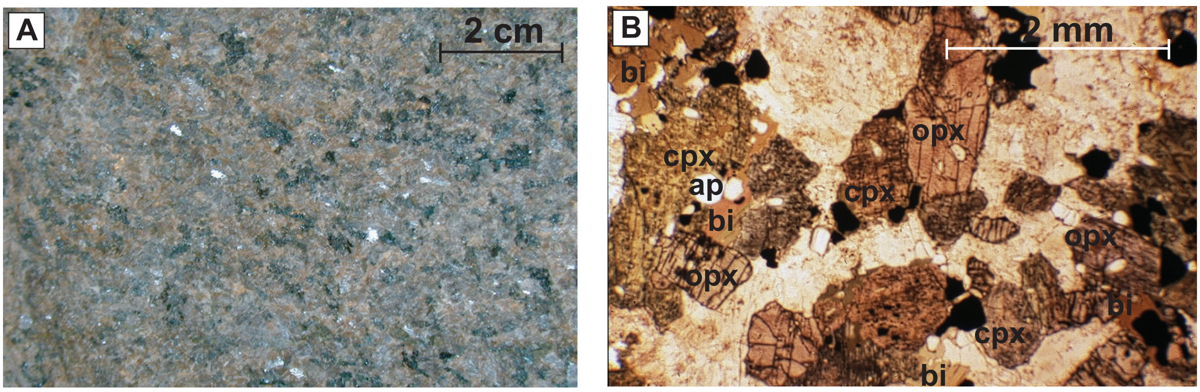


Figure 2. The Vinsavaara monzonite. **A.** Photograph of analysed sample. **B.** Photomicrograph of analysed sample showing orthopyroxene, clinopyroxene, biotite and apatite in a matrix of perthitic feldspar. opx - orthopyroxene, cpx - clinopyroxene, bi – biotite, ap - apatite. All photographs by Olof Martinsson.

with a mafic border zone up to 600 m wide and a monzonitic core. The rocks of the mafic border vary from olivine gabbro to anorthosite with a diffuse layering that conforms to the border of the intrusion. Mafic enclaves in the monzonite and mingling textures at the border zone suggest that monzonitic and gabbroic rocks are comagmatic.

The Peuravaara intrusion is situated less than 1 km to the east and is probably of similar age. It is more rounded and slightly smaller in size. Based on a few outcrops and aeromagnetic data, it has been suggested that it is predominantly gabbroic in character, including anorthosite and gabbro, locally containing up to 30% magnetite (Ambros 1980).

### *Sample description*

At Juoluvaara a sample of monzonite was taken from the western part of the intrusion, close to the gabbroic border (STB961049B, coordinates in SWEREF99 TM: 7583891/786367). The monzonite is grey, fine- to medium-grained and isotropic, with sparse 5 mm sized phenocrysts of K-feldspar (Fig. 6A). Perthitic K-feldspar is the predominant mineral, with subordinate amounts of plagioclase, green pleochroitic hornblende, brown biotite and Fe-Ti oxides (Fig. 6B). Quartz, titanite, clinopyroxene, epidote, apatite, pyrite and zircon occur as accessory phases. Clinopyroxene is mostly replaced by hornblende, with irregular-shaped quartz inclusions. Titanite usually occurs as rims on ilmenite. According to the normative composition, the rock should contain both clino- and orthopyroxene.

## Geochemistry of the sampled intrusions

Three samples from Pikku Sattavaara and one each from Vinsavaara and Juoluvaara have been chemically analysed by ICP-AES and ICP-MS using lithium borate fusion for main and trace element composition (Table 1). All samples show general chemical similarities, particularly the Pikku Saattavaara samples, which are almost identical in terms of major and trace element composition. Only one sample, 29KOM309, from Pikku Sattavaara, affected by brittle to ductile deformation and containing biotite, epidote and chlorite as alteration minerals, differs, with lower concentrations of sodium and higher values for loss of ignition (LOI). Based on normative mineral compositions, the Vinsavaara intrusion is a monzodiorite, whereas the Pikku Sattavaara and Juoluvaara intrusions are monzonites.

Chemical results (red symbols) are plotted in the R1-R2 diagram of De la Roche et al. (1980) for classification (Fig. 3A). Included in the diagram are data from other petrologically similar intrusions from northeastern Norrbotten (blue symbols) and 1.8 Ga intrusions from elsewhere in northern Sweden (black symbols). The three samples analysed from Pikku Sattavaara plot close to each other in the monzonite field, while the sample from Vinsavaara plots within the syenodiorite field, and the Juoluvaara sample at the border between syenodiorite and syenite. Together with samples of similar intrusions in northeastern Norrbotten, they describe a trend from monzodiorite to more syenitic composition, and based on the Ta/Yb-Ce/Yb diagram (Pearce 1982), they have a shoshonitic character similar to that of ring gabbro complexes in northeastern Norrbotten (Fig. 3B). In the Y-Nb classification diagram (Pearce et al. 1984; Fig. 3C) the Pikku Sattavaara and Vinsavaara samples plot together with TIB 1 intrusions from Rombak at the border between within plate granites (WPG) and volcanic arc to syncollisional granites (VAG+SYN-COLG), while in a Zr-Ga/Al diagram (Whalen et al. 1987) samples plot in the A-type field (Fig. 3D). According to this classification, they are geochemically transitional between an intra-plate and destructive plate margin setting. A high concentration of Sr and Ba is typical of all three intrusions (Table 1).

Table 1. Chemical analysis of monzonites from Pikku Saattavaara, Vinsavaara and Juoluvaara. All elements were analysed by ICP-AES and ICP-MS for main and trace elements.

| Sample | 29KOM306 | 29KOM308 | 29KOM309 | BOM950180 | STB991049B |
|---|---|---|---|---|---|
| Locality | Pikku Saattavaara | Pikku Saattavaara | Pikku Saattavaara | Vinsavaara | Juoluvaara |
| wt % | | | | | |
| $SiO_2$ | 55.83 | 56.21 | 54.58 | 55.60 | 58.30 |
| $TiO_2$ | 1.54 | 1.59 | 1.60 | 1.29 | 1.30 |
| $Al_2O_3$ | 15.10 | 15.03 | 14.69 | 15.60 | 16.95 |
| $Fe_2O_3$ | 7.19 | 7.45 | 8.01 | 7.77 | 5.70 |
| MnO | 0.13 | 0.10 | 0.12 | 0.13 | 0.09 |
| MgO | 4.57 | 4.67 | 4.66 | 3.63 | 2.05 |
| CaO | 5.59 | 5.80 | 5.58 | 5.58 | 4.21 |
| $Na_2O$ | 3.55 | 3.63 | 2.88 | 4.24 | 4.74 |
| $K_2O$ | 4.42 | 4.42 | 4.98 | 4.08 | 4.93 |
| $P_2O_5$ | 1.04 | 1.03 | 1.13 | 0.71 | 0.64 |
| LOI | 0.63 | 0.13 | 1.92 | 0.10 | 0.29 |
| SUM | 99.58 | 100.07 | 100.16 | 98.73 | 99.83 |
| | | | | | |
| ppm | | | | | |
| Sr | 1473 | 1630 | 1161 | 1160 | 1545 |
| Ba | 3604 | 3534 | 3488 | 2310 | 4280 |
| Rb | 97.3 | 97.9 | 101.0 | 89.9 | 76.8 |
| Nb | 17.7 | 18.0 | 15.7 | 11.4 | 17.6 |
| Ta | 0.84 | 0.88 | 0.78 | 0.89 | 0.70 |
| U | 1.77 | 2.54 | 1.98 | 4.66 | 0.73 |
| Th | 7.00 | 7.30 | 6.30 | 13.60 | 1.98 |
| Zr | 337 | 378 | 338 | 298 | 272 |
| Hf | 8.27 | 9.19 | 8.07 | 7.75 | 6.30 |
| La | 101.3 | 98.4 | 91.6 | 93.0 | 84.9 |
| Ce | 148.8 | 186.3 | 140.1 | 190.0 | 188.5 |
| Pr | 24.7 | 26.4 | 24.7 | 22.80 | 20.9 |
| Nd | 91.8 | 90.8 | 85.5 | 86.1 | 84.0 |
| Sm | 14.00 | 13.41 | 13.04 | 12.10 | 13.65 |
| Eu | 3.10 | 3.21 | 3.00 | 2.93 | 3.75 |
| Gd | 10.14 | 10.18 | 10.80 | 8.52 | 7.48 |
| Tb | 1.01 | 1.00 | 0.98 | 1.05 | 0.93 |
| Dy | 4.53 | 4.31 | 4.22 | 4.94 | 4.42 |
| Ho | 0.75 | 0.80 | 0.76 | 0.88 | 0.79 |
| Er | 1.85 | 2.10 | 2.03 | 2.47 | 1.83 |
| Tm | 0.25 | 0.25 | 0.24 | 0.35 | 0.26 |
| Yb | 1.57 | 1.51 | 1.42 | 2.36 | 1.55 |
| Lu | 0.18 | 0.20 | 0.17 | 0.34 | 0.23 |
| Y | 22.0 | 22.0 | 23.0 | 25.4 | 20.3 |
| Sc | 14.0 | 14.0 | 15.0 | 11.2 | 9.0 |
| V | 123 | 125 | 126 | 144 | 93 |
| Cr | 130 | 126 | 132 | 75 | 20 |
| Ni | 23 | 18 | 18 | 46 | 7 |
| Co | 26 | 25 | 25 | 22 | 9 |
| Cu | 59 | 42 | 5 | 45 | 10 |
| Zn | 53 | 87 | 39 | 83 | 78 |
| Mo | 0.5 | 0.5 | 0.5 | 1.2 | |
| W | 0.2 | 0.2 | 0.9 | 1.0 | |
| Sn | 1.6 | 1.5 | 1.3 | 2.1 | |
| Be | 3.0 | 3.0 | 3.0 | 3.4 | |
| Ga | 21.0 | 20.1 | 18.5 | 14.8 | |

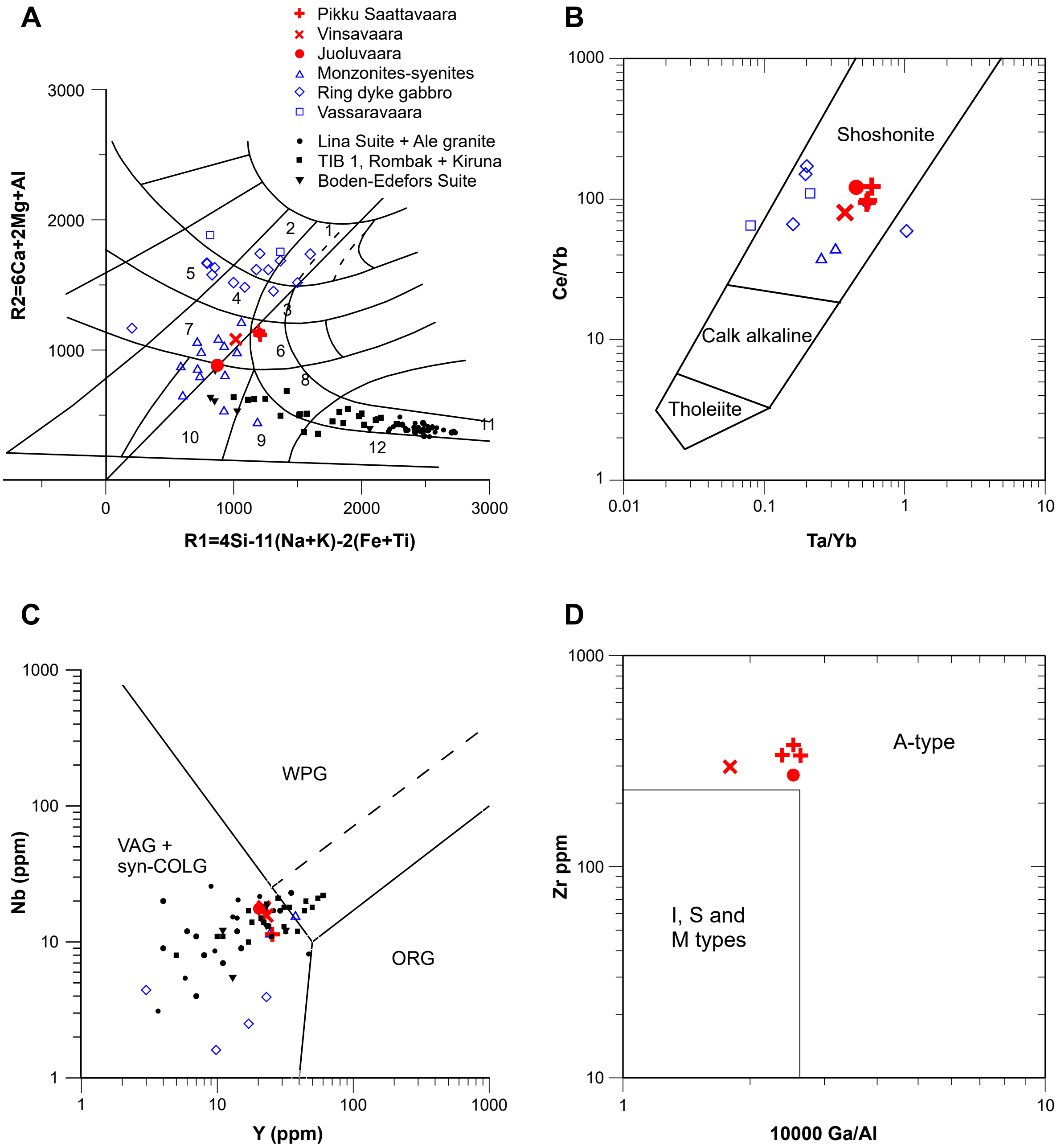


Figure 3. Chemical classification of monzonitic rocks from Pikku Sattavaara, Vinsavaara and Juoluvaara (red symbols). Included are data from petrographically similar intrusions in northeastern Norrbotten (blue symbols) and other 1.8 Ga plutonic rocks in northernmost Sweden (black symbols, data from Öhlander & Schöberg 1991, Öhlander & Skiöld 1994, Öhlander et al. 1987, Lindroos & Henkel 1981, Romer et al. 1992, Skiöld et al. 1988, Witschard 1970). **A.** R1-R2 diagram from de la Roche et al. (1980), 1-olivine gabbro, 2-alkali gabbro, 3-monzo gabbro, 4-syenogabbro, 5-essexite, 6-monzonite, 7-syenodiorite, 8-quartz monzonite, 9-quartz syenite, 10-syenite, 11-granite, 12-alkali granite. **B.** Ta/Yb-Ce/Yb diagram from Pearce (1982). **C.** Y-Nb diagram from Pearce et al. (1984). **D.** 10000*Ga/Al diagram from Whalen et al. (1987). For Figure B, C and D symbols as in Figure 3A.

## ANALYTICAL METHODS

Zircons from the Vinsavaara and Pikku Sattavaara intrusions were separated using standard magnetic and heavy liquid techniques. Most fractions were abraded using the Krogh (1982) method. They were dissolved in $HF:HNO_3$ in Teflon® capsules in autoclaves using the Krogh (1973) method. After decomposition, the samples were dissolved in HCl and split into 2 aliquots. A mixed $^{208}Pb$-$^{233\text{-}235}U$ tracer was added to the ID aliquots. Some of the smaller samples were spiked with a mixed $^{205}Pb$-$^{233\text{-}235}U$ tracer before 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 at the Laboratory for Isotope Geology (now Department of Geosciences) at the Swedish Museum of Natural History, 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 corrected isotope ratios and error propagation were calculated using the PBDAT program of Ludwig (1991a), with the decay constants recommended by Steiger & Jäger (1977). The intercept ages were calculated and the concordia plot drawn using the Ludwig (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 using the Pb evolution model of Stacey & Kramers (1975), which is a reasonable 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 $^{233\text{-}235}U$ ratio of the spike. All analytical errors are given as 2σ.

Zircons from the Juoluvaara monzonite sample (STB961049B) were analysed by high-spatial resolution secondary ion mass spectrometer (SIMS) analysis in November 2013, using a Cameca IMS 1280 at the Nordsim facility at the Swedish Museum of Natural History in Stockholm. Zircons were obtained from a density separate of a crushed rock sample using a Wilfley water table. Magnetic minerals were removed using a hand magnet. Handpicked crystals were mounted in transparent epoxy resin together with chips of reference zircon 91500. The zircon mounts were polished and, after gold coating, examined by cathodoluminescence (CL) imaging using electron microscopy at the Swedish Museum of Natural History in Stockholm. 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 approximately 10–15 µm. U/Pb ratios, elemental concentrations and Th/U ratios were calibrated relative to the Geostandards zircon 91500 reference, which has an age of c. 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). All age uncertainties are presented at the 2σ or 95% confidence level. CL imaging of the dated zircons was performed using electron microscopy at the Department of Geology, Uppsala University to confirm the location of the analytical spot.

## ANALYTICAL RESULTS

### The Pikku Sattavaara monzonite

Zircons from the two samples of the Pikku Sattavaara monzonite have similar appearance. Most of the grains recovered are crystal fragments of larger zircon grains. They are elongate and fractured or anhedral, making it difficult to determine the original morphology. The pyramids present are all sharp. Magmatic zonation is common and both cores and overgrowths are found in some grains, but were avoided when selecting grains for analysis. Grains are either colourless to pale yellow, pink or pale brown. All grains analysed were thoroughly abraded.

The analytical data are shown in Table 2 and Figure 4. Seven of the eight data points define a discordia, with intercept ages of 1 799 ±2 and 25 ±149 Ma and an MSWD of 0.09. The eighth fraction is

Table 2. U-Pb isotopic data for samples 29KOM306, 29KOM308 and BOM950180.

| 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) |
|---|---|---|---|---|---|---|---|---|---|---|
| **29KOM306 Pikku Saattavaara monzonite** | | | | | | | | | | |
| 1 | 25 | 4 | 124.3 | 51.0 | 0.04 | 14769 | 65.3 - 7.2 - 27.5 | 0.3109±11 | 4.714±19 | 1799±4 |
| 2 | 20 | 1 | 69.6 | 28.5 | 0.17 | 4225 | 66.6 - 7.3 - 26.2 | 0.3139±8 | 4.761±17 | 1800±5 |
| 3 | 21 | 1 | 69.6 | 28.9 | 0.28 | 3165 | 67.0 - 7.3 - 25.7 | 0.3196±20 | 4.823±36 | 1790±7 |
| 4 | 21 | 5 | 105.1 | 43.8 | 0.01 | 13508 | 65.4 - 7.2 - 27.4 | 0.3162±9 | 4.794±16 | 1799±3 |
| **29KOM308 Pikku Saattavaara monzonite** | | | | | | | | | | |
| 1 | 18 | 2 | 74.4 | 28.3 | 0.70 | 1518 | 68.1 - 7.5 - 24.4 | 0.2929±11 | 4.438±24 | 1798±7 |
| 2 | 22 | 1 | 63.2 | 26.2 | 0.07 | 6088 | 66.1 - 7.3 - 26.6 | 0.3178±10 | 4.819±19 | 1799±4 |
| 3 | 23 | 1 | 84.5 | 34.8 | 0.14 | 5951 | 66.0 - 7.3 - 26.7 | 0.3146±19 | 4.771±31 | 1799±3 |
| 4 | 21 | 1 | 140.6 | 55.3 | 0.01 | 19229 | 69.4 - 7.6 - 23.0 | 0.3166±12 | 4.803±20 | 1800±3 |
| **BOM 950180 Vinsavaara monzonite** | | | | | | | | | | |
| 1 | 31 | 2 | 1024.0 | 395.0 | 0.53 | 26310 | 67.3 - 7.4 - 25.3 | 0.3011±7 | 4.567±11 | 1800±1 |
| 2 | 30 | 2 | 269.7 | 94.2 | 0.22 | 12527 | 73.5 - 8.1 - 18.4 | 0.2974±7 | 4.498±13 | 1794±2 |
| 3 | 35 | 1 | 436.8 | 147.4 | 0.21 | 21815 | 73.7 - 8.1 - 18.2 | 0.2886±10 | 4.371±16 | 1797±1 |
| 4 | 38 | 1 | 153.6 | 53.6 | 0.17 | 9046 | 72.4 - 8.0 - 19.6 | 0.2925±7 | 4.438±12 | 1800±3 |
| 5 | 33 | 7 | 151.6 | 55.1 | 0.35 | 7835 | 72.9 - 8.0 - 19.1 | 0.3062±9 | 4.637±15 | 1798±2 |

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

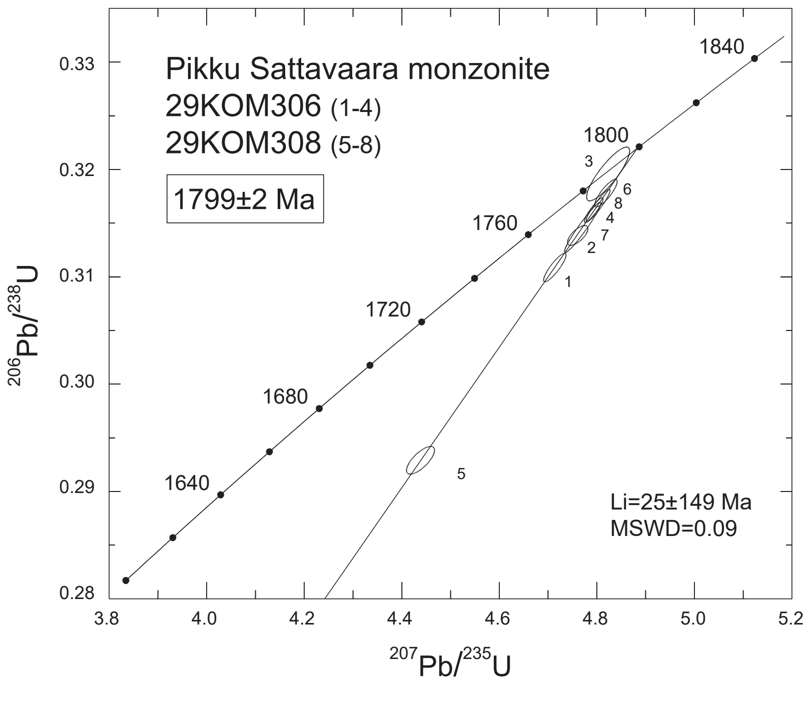


Figure 4. Concordia diagram for analysed zircon fractions from the monzonite samples 29KOM306 and 29KOM308, Pikku Sattavaara.

the least discordant and has a $^{207}Pb/^{206}Pb$ age of 1790 ±7 Ma. Since this point displays great uncertainty and diverges distinctly from the others, it is justifiable to omit it from the age calculation. There is no difference between the chemistry and morphology of the zircons from the two samples.

## The Vinsavaara monzodiorite

Separated zircons were divided into five fractions, consisting mainly of crystal fragments >150 µm, implying that the original zircon grains were unusually large. However, fraction 5 consists of small, generally euhedral, non-fractured zircons. No signs of cores or overgrowths were observed and the grains are either pink, brown or colourless. Fractions 3, 4 and 5 were thoroughly abraded.

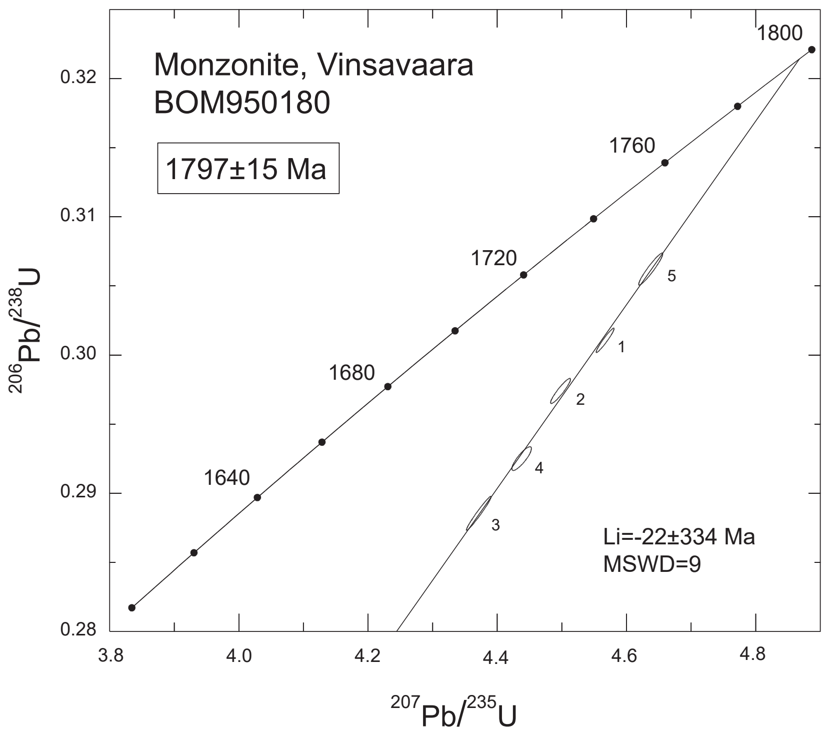


Figure 5. Concordia diagram for analysed zircon fractions from the monzodiorite sample BOM950180, Vinsavaara.

The analytical data are shown in Table 2 and Figure 5. Fractions 2, 4 and 5, which consist of colourless or pale brown grains, have lower uranium content than fractions 1 and 3, which consist of brown crystals. The discordia has concordia intercepts at 1799 ±15 and -22 ±334 Ma and an MSWD of 9. The upper intercept age is interpreted as the intrusion age of the rock.

## The Juoluvaara monzonite

The heavy mineral concentrate contained euhedral, prismatic transparent and colourless zircons. Most grains were angular fragments, however. CL images of the zircon show a broad oscillatory or sector zonation, but large areas of the zircon lack zonation and show a homogenous CL intensity (Fig. 6C). The ten analyses carried out are all concordant and show low concentrations of common lead. The analyses show 22–139 ppm U and have Th/U ratios of 0.53–1.14 (Table 3). A Concordia age is calculated at 1804 ±6 Ma (Fig. 6D, 2σ, MSWD of concordance = 0.53, probability of concordance = 0.47, n = 10) and a weighted average $^{207}Pb/^{206}Pb$ age at 1803 ±8 Ma (2σ, MSWD = 0.70, probability = 0.71, n = 10). The concordia age at 1804 ±6 Ma (2σ) is chosen as the best age estimate, interpreted to date igneous crystallisation of the monzonite. This age also applies to the surrounding gabbro intrusion, since this is considered contemporaneous, evident from mingling in the contact zone.

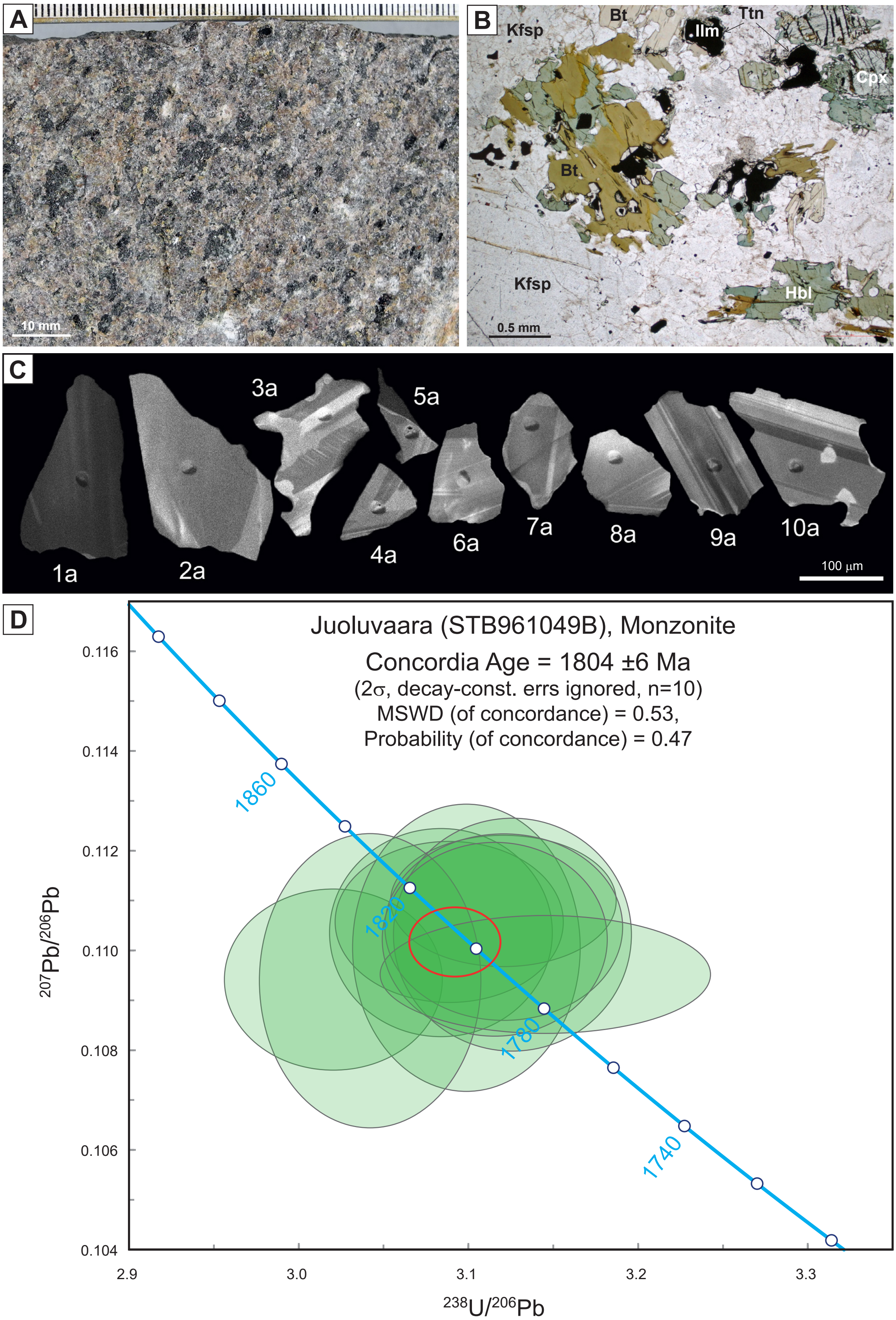


Figure 6. Geochronolgy of the Juoluvaara monzonite. **A.** The dated rock sample. **B.** Photomicrograph of dated sample. **C.** Cathodoluminescence (CL) images of analysed zircon grains. Numbers refer to analytical spot number in Table 3. **D.** Tera Wasserburg diagram showing U-Pb SIMS data of of analysed zircon from monzonite sample STB991049B, Juoluvaara. Error ellipse of calculated weighted mean age is shown in red. All photographs by Fredrik Hellström.

Table 3. U-Pb isotopic data for sample STB991049B (n4835).

| Analysis | Comment | U ppm | Th ppm | Pb ppm | Th/U calc *1 | $^{207}Pb/^{235}U$ | ±s % | $^{238}U/^{206}Pb$ | ±s % | $^{207}Pb/^{206}Pb$ | ±σ % | ρ *2 | Disc. % conv. *3 | $^{207}Pb/^{206}Pb$ age (Ma) | ±σ | $^{206}Pb/^{238}U$ age (Ma) | ±σ | $^{206}Pb/^{204}Pb$ measured | $f_{206}$% *4 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 01a | Osc zon | 115 | 74 | 48 | 0.65 | 4.906 | 1.00 | 3.120 | 0.87 | 0.1110 | 0.48 | 0.87 | -1.5 | 1816 | 9 | 1792 | 14 | 213129 | * 0.01 |
| 02a | CL-hom. | 60 | 54 | 26 | 0.92 | 4.882 | 1.15 | 3.120 | 0.92 | 0.1105 | 0.69 | 0.80 | -1.0 | 1807 | 13 | 1792 | 14 | 76857 | {0.02} |
| 03a | Osc zon | 22 | 11 | 9 | 0.54 | 4.960 | 1.41 | 3.041 | 0.88 | 0.1094 | 1.10 | 0.62 | 2.8 | 1790 | 20 | 1833 | 14 | 76975 | {0.02} |
| 04a | Osc zon | 45 | 27 | 19 | 0.63 | 4.936 | 1.16 | 3.083 | 0.87 | 0.1104 | 0.77 | 0.75 | 0.3 | 1806 | 14 | 1811 | 14 | >1e6 | * 0.00 |
| 05a | Osc zon | 57 | 37 | 25 | 0.70 | 4.996 | 1.10 | 3.020 | 0.87 | 0.1094 | 0.68 | 0.79 | 3.5 | 1790 | 12 | 1844 | 14 | 120605 | {0.02} |
| 06a | Osc zon | 51 | 32 | 21 | 0.64 | 4.880 | 1.13 | 3.115 | 0.87 | 0.1102 | 0.72 | 0.77 | -0.5 | 1803 | 13 | 1795 | 14 | 193629 | {0.01} |
| 07a | Osc zon | 75 | 65 | 33 | 0.89 | 4.937 | 1.07 | 3.088 | 0.89 | 0.1106 | 0.60 | 0.83 | 0.0 | 1809 | 11 | 1808 | 14 | 272646 | * 0.01 |
| 08a | Osc zon | 40 | 21 | 16 | 0.53 | 4.898 | 1.39 | 3.098 | 0.88 | 0.1101 | 1.07 | 0.64 | 0.2 | 1800 | 19 | 1803 | 14 | 39065 | * 0.05 |
| 09a | Osc zon | 139 | 155 | 63 | 1.14 | 4.803 | 1.34 | 3.145 | 1.26 | 0.1095 | 0.44 | 0.94 | -0.7 | 1792 | 8 | 1780 | 20 | 380321 | {0.00} |
| 10a | Osc zon | 69 | 57 | 30 | 0.82 | 4.867 | 1.26 | 3.125 | 0.92 | 0.1103 | 0.86 | 0.73 | -1.0 | 1805 | 16 | 1790 | 14 | 244324 | {0.01} |

osc. = oscillatory, CL = Cathodoluminescence, hom. = homogenous

Isotope values are common Pb corrected using modern common Pb composition (Stacey & Kramers 1975) and measured 204Pb.

*1 Th/U ratios calculated from $^{208}Pb/^{206}Pb$ and $^{207}Pb/^{206}Pb$ ratios corrected for $Pb_{com}$, 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 % of common $^{206}Pb$ in measured $^{206}Pb$, estimated from $^{204}Pb$ assuming a present day Stacey and Kramers (1975) model.

Figures in parentheses are given when no correction has been applied.

## DISCUSSION

### Possibly related intrusions in northeastern Norrbotten

Monzodioritic to syenitic intrusions with petrographic and geochemical similarities to the 1.8 Ga Vinsavaara, Pikku Sattavaara and Juoluvaara intrusions also occur at Karijärvi and Vivungi, north of Vinsavaara (Fig. 1). At Vivungi, a magnetic anomaly with a diameter of approximately 15 km shows a more or less concentric internal pattern. The area is poorly exposed but an approximately 500 m wide dyke of syenitic composition is found in the west of the structure, and a similar rock is reported from its northern part (Witschard 1970), suggesting that the magnetic structure is caused by syenitic ring dykes. The Karijärvi intrusion is 8 km in diameter and has a more magnetic rim in its northeastern part. Only the magnetic part is exposed, consisting of monzonite similar to that of the Vinsavaara intrusion (Witschard 1970). The unexposed parts have been investigated using geophysical methods and sampled by drilling in a profile crossing the structure. These results showed the internal part to consist mainly of Lina granite or Jyryjokki granite, with minor occurrences of peridotite and monzonite. Thus, the core predominantly comprises rocks similar to those found outside the structure. The monzonite is interpreted to form a cone sheet dipping inwards and converging at a depth of approximately 5 km (Westin 1983).

Several ring dyke complexes of gabbroic rocks are found in this part of northeastern Norrbotten, and two occur close to the Vinsavaara and Karijärvi intrusions (Fig. 1). The complexes are rounded to oval in shape and 3 to 7 km in their longest dimension. Gabbroic rocks are usually rich in Fe, Ti and P, and show an alkalic character, but locally include anorthositic varieties. Mineralogically, rocks show some variations, with amphibole as the predominant mafic mineral in most intrusions, and clinopyroxene as a minor component in several of them. The Merasjoki intrusion (Fig. 1) also contains some orthopyroxene. Geophysical interpretations indicate an inward-dipping shape and a convergence of the steeply dipping cone sheets at approximately 5 km for the Lumivaara and Nakajärvi intrusions (Fig. 1), while the Merasjoki intrusion only comprises two concentric dykes of a more lopolitic shape (Lindroos & Henkel 1981). The Juoluvaara intrusion has the characteristics of both the gabbroic ring dykes (its gabbroic outer margin) and the 1.8 Ga monzonitic intrusions (its core).

All the monzonitic-syenitic to gabbroic rocks forming composite intrusions, ring dykes or cone sheets appear to postdate the 1.89–1.86 Ga Haparanda and Perthite-monzonite suite plutons (Lindroos & Henkel 1981, Bergman et al. 2001). Gabbroic cone sheets occur within a conspicuous positive gravimetric anomaly centred close to Merasjärvi. A large mafic intrusion with an upper surface at a depth of 6 to 9 km may explain this gravimetric anomaly, as well as the high T/low P metamorphic regime in the region (Bergman et al. 2001). It is proposed that this suggested intrusion is the magmatic source of the cone sheets in its roof. The monzonitic to syenitic intrusions occur along the southern and western margin of this gravimetric anomaly. Based on similarities in petrology, intrusion character and their spatial relationship to the Merasjärvi gravity high (MGH, Fig. 7), it is suggested that these mafic to intermediate intrusions are part of the same magmatic event. This c. 1.8 Ga magmatism in northeastern Norrbotten shows a shoshonitic character, with alkaligabbro, monzonite, syenodiorite and syenite as predominant compositions (Fig. 3A).

### Other 1.8 Ga intrusive rocks in the northern Fennoscandian Shield

Intrusive rocks with an age of c. 1.8 Ga are common in the Fennoscandian Shield, and in the north include the 1.77 Ga Nattanen granite (Haapala et al. 1987), 1.81–1.78 Ga Lina type granites (Öhlander et al. 1987, Bergman et al. 2001), 1.79–1.77 Ga TIB 1 intrusions (Skiöld 1988, Romer et al. 1992, 1994) and 1.80 Ga Edefors-Boden granitoids (Öhlander & Skiöld 1994).

The Lina granites are of a predominantly minimum (eutectic) melt composition, with quartz, microcline and oligoclase occurring in approximately similar proportions (Ödman 1957, Öhlander &

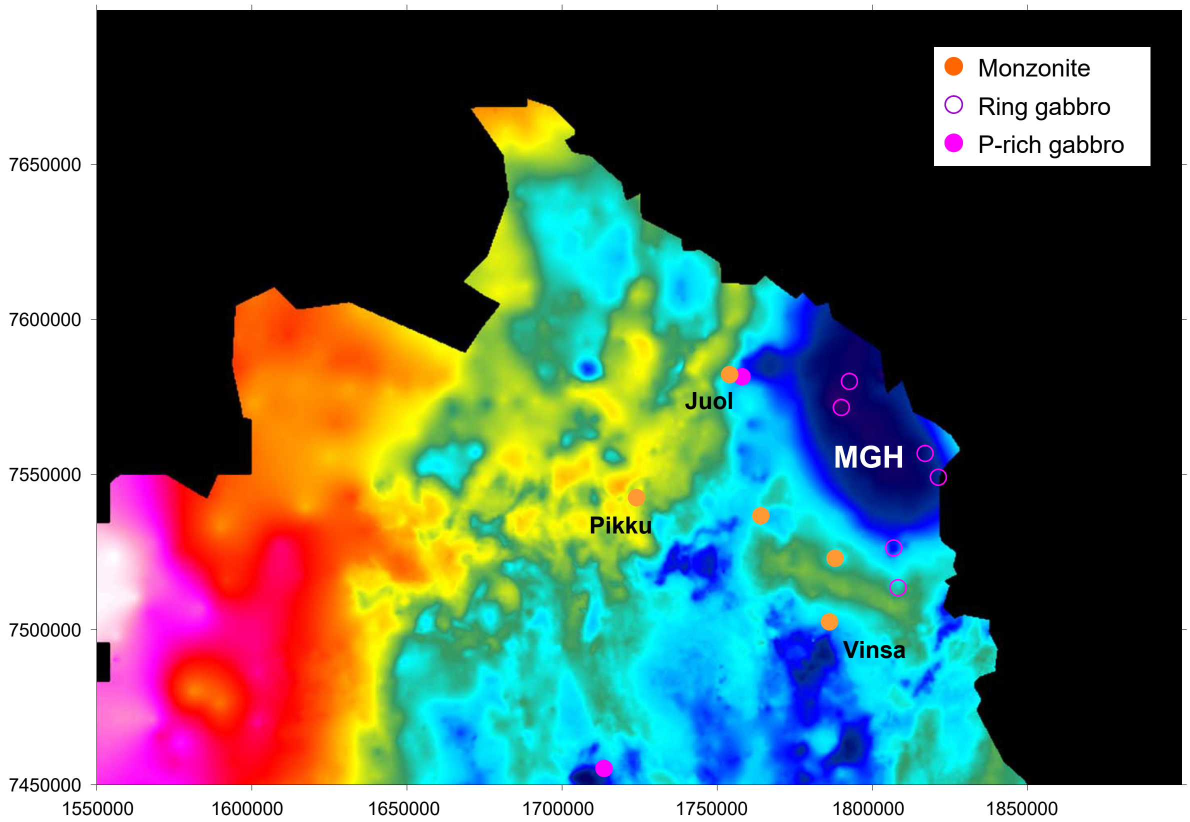


Figure 7. The regional Bouguer anomaly over the map area in Figure 1. Dark blue relates to high density rocks and red to low density rocks. Location of 1.8 Ga monzonitic intrusions (Vinsa: Vinsavaara, Juol: Juoluvaara, Pikku: Pikku Sattavaara), and geochemically similar 1.8 Ga gabbroic intrusions are indicated.

Skiöld 1994). A larger compositional variation is exhibited by the Edefors intrusive rocks northwest of Luleå, and the TIB 1 intrusions occurring in the westernmost part of Norrbotten and adjacent areas of Norway. Intrusions vary from monzonitic or syenitic to quartz monzonitic and granitic composition (Romer et al. 1992, 1994, Öhlander & Skiöld 1994).

The Edefors intrusions also include some gabbroic to anorthositic units (Wikström & Söderman 2000). The occurrence of clinopyroxene and, locally, olivine or orthopyroxene in felsic intrusive rocks predominantly made up of perthite is typical of the Edefors intrusions (Ödman 1957, Öhlander & Skiöld 1994). In the Lofoten area, TIB 1 is represented by monzonites containing orthopyroxene and olivine (mangerite), gabbro and anorthosite (Griffin et al. 1978). Further east, in the Rombak window, quartz monzonites and granites predominate (Romer et al. 1992). A local occurrence of syenite is found in the Kiruna area (Romer et al. 1994).

The 1.8 Ga plutonic rocks in Norrbotten show geochemical similarities. In the R1–R2 diagram (Fig. 3A), intermediate and felsic members describe a shoshonitic trend from monzodiorite-syenodiorite to syenite-quartz syenite and into the granite field, represented by the Jyrijokki and Lina granites. Mafic rocks are subordinate and include alkalic gabbros from the MGH in northeastern Norrbotten. The Vassaravaara intrusion at Gällivare is chemically similar to the ring gabbros at the MGH, with an alkaline character and containing significant amounts of apatite and magnetite (Martinsson 1994). It has an age of 1 798±4 Ma (Sarlus et al. 2017), and although it occurs outside the MGH, it supports the petrogenetic relation between monzonite and gabbroic intrusions of shoshonitic to alkalic character in northern Norrbotten. Common to both types of intrusion are high concentrations of Sr and Ba.

## Tectonic setting

The Transscandinavian Igneous Belt (TIB) is a major Palaeoproterozoic magmatic province in the Fennoscandian Shield. It is suggested to have formed as a result of eastward subduction (Wilson 1980, Nyström 1982, Andersson 1991, Romer et al. 1992), possibly during a period of extensional conditions (Wilson et al. 1986, Åhäll & Larsson 2000). However, the Edefors intrusive rocks are interpreted to be products of plate convergence, but related to a collision event further south caused by northward subduction. During collision, extensional conditions may have formed in response to delamination, causing melting of the astenosphere. The Edefors monzonitic to granitic rocks then formed from the juvenile mantle melts by differentiation and crustal interaction (Öhlander & Skiöld 1994). Lina-type granites are typical minimum-melt granites created by melting of 1.9 Ga granitoids during the collision event (Öhlander et al. 1987, Öhlander & Skiöld 1994).

Considering the tectonic models presented for the 1.8 Ga magmatism in northern Sweden, a complex scenario is outlined, with contemporaneous westward and northward plate convergence, including processes generating local extension. But an alternative intra-cratonic extensional setting has been suggested for the TIB magmatism, with mantle-derived melts interacting with continental crust (Wilson et al. 1985, Andersson 1997).

Geochemical approaches to deciphering the tectonic environment for the 1.8 Ga magmatism generally yield ambiguous results. This is illustrated by the Nb-Y diagram, with most samples clustering at the border between convergent to intraplate settings, except for the Lina granites that occupy the field of volcanic arc and syn-collisional granites (Fig. 3C).

Although the scattered occurrence of mafic to felsic 1.80 Ga intrusions in northern Norrbotten east of the TIB proper show temporal and petrological similarities to typical TIB 1 intrusions, they also resemble intraplate magmatic complexes related to mantle plumes in their composition and intrusion character. Examples include the Jurassic ring complexes in Nigeria, the Permian Oslo rift and the North Atlantic Tertiary igneous province. In Nigeria, ring dyke complexes have diameters of 8 to 15 km and comprise olivine- and pyroxene-bearing granitoids associated with minor anorthosite intrusions (Turner 1963, Black & Girod 1970). Ring complexes are also characteristic of the Oslo rift, with syenitic to granitic ring dykes associated with alkali-gabbroic, monzonitic and granitic plutons (Ihlen 1986). Tertiary mafic to felsic magmatic centres in east Greenland and western Scotland include classic cone sheet complexes related to mantle plume activity during the opening of the North Atlantic (Upton 1988). In Scotland these intrusions are related to a significant positive gravimetric and magnetic anomaly interpreted to be caused by an underlying dense body of mafic rocks (Bott & Tantrigoda, 1987), resembling the MGH in northeastern Norrbotten. Mafic to felsic 1.8 Ga intrusions also exist in southern Finland, and have petrographical and chemical similarities to the 1.8 Ga monzonites and related gabbroic ring dyke intrusions in northeastern Norrbotten. Some of these intrusions also occur as ring dykes and are strongly enriched in Sr and Ba. Associated mafic rocks have high concentrations of Ti and P (Eklund et al. 1998). It is suggested that they formed from melting of lithospheric mantle enriched by carbonatite metasomatism (Eklund et al. 1998).

The 1.8 Ga mafic to intermediate intrusions in northeastern Norrbotten may thus be isolated and slightly more alkaline expressions of subduction-related TIB 1 magmatism east of the main TIB belt, or may represent a separate igneous event caused by mantle plume activity. In northeastern Norrbotten there may exist a genetically related large mafic intrusion at depth within the MGH (Bergman et al. 2001), and these 1.8 Ga intrusions could be part of a major mafic magmatic event of intraplate character. A back arc setting related to TIB 1 is an alternative possibility.

## CONCLUSIONS

Three monzonitic intrusions (Pikku Sattavaara, Juoluvaara and Vinsavaara) in northern Norrbotten have been dated at 1.80 Ga. They are petrographically and geochemically similar, with a shoshonitic character. The Juoluvaara intrusion is distinct in having a gabbroic border zone and a monzonitic core.

Intrusions predominantly consist of perthite, augite and hyperstene, with megacrysts of poikolitic biotite as typical minor constituents. It is suggested that other chemically similar monzonitic and gabbroic intrusions in northeastern Norrbotten, often occurring as ring dykes, are part of the same 1.8 Ga magmatic event.

Most of these intrusions occur within, or at the margin of, the Merasjärvi gravity high (MGH) and may represent higher-level intrusions related to a much larger mafic intrusion deeper in the crust. Monzonitic intrusions have A-type signatures and chemical characteristics overlapping those of rocks in arc and within plate settings. They may have formed in a back arc setting related to eastward subduction generating the Transscandinavian Igneous Belt further west (TIB 1), or may represent a separate igneous event caused by a mantle plume.

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