Rapporter och meddelanden 141

Geology of the Northern Norrbotten ore province, northern Sweden

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Editor: Stefan Bergman

SGU
Sveriges geologiska undersökning
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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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3. Stratigraphy and ages of Palaeoproterozoic metavolcanic and metasedimentary rocks at Käymäjärvi, northern Sweden

Olof Martinsson, Stefan Bergman, Per-Olof Persson, Hans Schöberg,
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ABSTRACT

The northern part of the Fennoscandian Shield predominantly comprises a 3.5–2.6 Ga Archaean craton, 2.5 to 2.0 Ga Karelian rocks linked to its rifting and breakup, and 1.9–1.8 Ga Svecofennian rocks related to destructive plate processes along its southwestern margin. Although the main aspects of the geological evolution during Palaeoproterozoic are fairly well constrained in northern Sweden, the chronostratigraphy of individual metavolcanic and metasedimentary units is poorly known. In this paper we define stratigraphic units within the Palaeoproterozoic supracrustal rocks at Käymäjärvi in northeastern Norrbotten that represent Karelian (inferred age c. 2.3–2.0 Ga) and Svecofennian supracrustal units (≤1.9 Ga). We also present geochronological data from three stratigraphically different volcanic units at Käymäjärvi.

The Karelian rocks studied belong to the Veikkavaara greenstone group and are subdivided into the Käymäjärvi formation, mainly consisting of pyroclastic metameimechite, and the overlying Vinsa formation, which includes mafic metatuffite, graphitic metatuffite, banded iron formation and dolomite. The local Svecofennian supracrustal rocks constitute the Sammakkovaara group, which includes the metaandesitic Muotkamaa formation in the lowest part, followed by the metasedimentary Hosiokangas formation and the uppermost metaandesitic Hosiovaara formation. U-Pb zircon data for a metameimechite from the Käymäjärvi formation were obtained using both multi-grain techniques (TIMS measurements), laser ablation and SIMS in situ methods. However, the data are difficult to interpret, probably mainly due to a heterogeneous zircon population of mixed magmatic and metamorphic origin. A preliminary interpretation of U-Pb age results, in combination with carbon isotope evidence from carbonate rocks, indicates an emplacement age close to 2.05 Ga. Two metaandesites from the Muotkamaa and Hosiovaara formations, respectively, yield similar zircon ages close to 1.88 Ga, although some evidence may point to a somewhat older magmatic age for the Muotkamaa formation. This may derive some support in the 1.89 Ga age of metaandesite in the Kalixälv formation, which is tentatively correlated with the Hosiovaara formation. In addition, several zircon fractions from these rocks record a metamorphic disturbance at c. 1.8 Ga.

The Käymäjärvi and Vinsa formations may be correlated with other greenstone units in northeastern

Norrbotten and correspond to the Jatulian–Ludikovian units in the northeastern Fennoscandian Shield. Both petrographic and geochronological data support the idea that rocks of the Sammakkovaara group can be correlated with the lower Svecofennian Porphyrite group in the Kiruna area, but also with the Muorjevaara group in the Gällivare area and other arenitic to clay-rich metasedimentary formations of Svecofennian age in northern Norrbotten.

INTRODUCTION

The northern part of the Fennoscandian Shield predominantly comprises a ~3.5–2.6 Ga Archaean craton, 2.5 to 2.0 Ga Karelian rocks linked to its rifting and breakup, and 1.9–1.8 Ga Svecofennian rocks related to destructive plate processes along its southwestern margin. Palaeoproterozoic 2.3 to 2.0 Ga ultramafic to mafic metavolcanic rocks are widely distributed in northern Finland and Norway, and these greenstone belts also extend into Norrbotten County in northernmost Sweden. Due to the remarkable similarity in stratigraphy and the predominantly tholeiitic character of the metavolcanic rocks in this region, Pharaoh (1985) suggested that they represent a major tholeiitic province. These 2.3–2.0 Ga mafic-ultramafic metavolcanic rocks were formed in response to continental rifting at ~2.06 Ga, along a line from Ladoga in the southeast to Lofoten in the northwest (Kohonen & Marmo 1992, Vuollo 1994, Martinsson 1997, Lahtinen et al. 2015), which culminated in the opening of an ocean. Subduction of oceanic crust along this continental margin started more than 100 Ma later, when juvenile crust was formed and added to reworked Archaean crust as a product of Svecofennian arc magmatism (Öhlander et al. 1993, Ekdahl 1993, Lahtinen 1994).

Although the main aspects of geological evolution during Palaeoproterozoic time are fairly well constrained in northern Sweden, the chronostratigraphy of individual metavolcanic and metasedimentary units is poorly known. This hampers detailed interpretations of the geological evolution and the correlation of these rocks with similar units in other parts of the shield. In this paper we present geochronological data from three stratigraphically distinct metavolcanic units at Käymäjärvi in northeastern Norrbotten. TIMS data on a metameimechite sample were found to be too complex to interpret, and single-grain, in situ techniques were used on that sample.

GENERAL GEOLOGY

In northern Sweden a Palaeoproterozoic succession of greenstones, porphyries and clastic metasedimentary rocks rests unconformably on a deformed 3.2–2.7 Ga old Archaean basement. Following the tectofacies concept of Laajoki (2005) and the subdivision of the Karelian cover sequence in the northeastern part of the Fennoscandian Shield proposed by Melezhik et al. (1997) and Hanski & Melezhik (2012), the Kovo group is regarded to be of Sumi–Sariolian age (2.5–2.3 Ga). Rocks of the Kovo group occupy the stratigraphically lowest position in the Kiruna area, and are overlain by the Jatulian (2.3–2.06 Ga) to Ludikovian (2.06–1.96 Ga) Kiruna greenstone group (Martinsson 1997, 1999). Karelian units are unconformably overlain by Svecofennian 1.9 Ga rocks including the Porphyrite group, the Kurravaara conglomerate, the Kiirunavaara group and the Hauki quartzite. Analogously, the Karelian greenstones in eastern Norrbotten are overlain by Svecofennian volcanic and sedimentary units (Martinsson 2004a).

Karelian greenstones in northern Sweden are best known from the Kiruna area, where a complete section of the well-preserved Kiruna greenstone group exists (Martinsson 1997). To the east, in the Masugnsbyn area, the Veikkavaara greenstone group is regarded as stratigraphic equivalent of the Kiruna greenstone group (Padget 1970, Martinsson 2004a). The Veikkavaara greenstone group is exposed in the Tärendö, Pajala and Lannavaara areas, and shows a strong consistency in lithological properties and stratigraphic relations. Compared to the greenstones in the Kiruna area, however, some differences in lithological properties can be observed. These are thought to reflect different depositional environments.

Rocks from the Veikkavaara greenstone group were deposited in a shallow marine environment, whereas rocks from the more westerly Kiruna greenstone group were formed in a failed rift arm during partly deeper water conditions (Martinsson 1997, 2004a).

The greenstones have been exposed to erosion in some areas, as evidenced by the loss of the upper part of the Kiruna greenstone group in the central Kiruna area (Martinsson 1997), before being overlain by Svecofennian successions of volcanic and clastic sedimentary rocks. The lowermost Svecofennian rocks are the Porphyrite group and the Kurravaara conglomerate, and stratigraphically equivalent units outside the Kiruna area (e.g. the Pahakurkio group, Kalixälv group and Muorjevaara group). These rocks were formed in relation to northward subduction at the southwestern margin of the Archaean palaeocontinent (Martinsson 2004a). Andesitic volcanic rocks of calc-alkaline character were formed from isolated volcanic centres separated by sedimentary basins fed by volcaniclastic material and epiclastic sediments from granite-gneiss terranes in the northeast (Martinsson 2004a). In the Kiruna area, the Porphyrite group is overlain by the Kiirunavaara group, comprising a bimodal volcanic unit formed in a back arc or intra-plate setting (Martinsson 2004a). It is mainly restricted to the Kiruna and Malmberget areas; only small and isolated occurrences are known further east. Quartzitic metasedimentary rocks constitute the youngest Svecofennian units and are represented by the Hauki and Maattavaara quartzites in the Kiruna area (Offerberg 1967, Eriksson & Hallgren 1975), and the Rissavaara quartzite in the Masugnsbyn area (Padget 1970).

The Palaeoproterozoic volcanic and sedimentary rocks were deformed and metamorphosed during the Svecokarelian orogeny (1.9–1.8 Ga). Abundant syn-orogenic 1.89–1.87 Ga intrusions of the Haparanda and Perthite monzonite suites range from gabbro to granite (Bergman et al. 2001, Martinsson 2004a). Minimum melt granites and pegmatites, represented by the Lina suite, formed c. 1.79 Ga (Skiöld et al. 1988), and are coeval with 1.80–1.78 Ga Transscandinavian igneous belt intrusions (TIB 1) of monzonitic to granitic composition (Romer et al. 1992, Martinsson 2004a). Limited data suggest the presence of at least two metamorphic and deformation events in northeastern Norrbotten at c. 1.88 and 1.80 Ga, respectively (Bergman et al. 2001), as well as a more local metamorphic event at 1.85 Ga (Bergman et al. 2006). The youngest plutonic rocks are the c. 1.71 Ga TIB 2 granitoids located in the Rombak window (Romer et al. 1992).

STRUCTURE AND STRATIGRAPHY OF THE KÄYMÄJÄRVI AREA

The geology of the Käymäjärvi area, situated 25 km northwest of Pajala, has previously been described by Eriksson (1954). The bedrock is partly well exposed with Palaeoproterozoic supracrustal rocks, including the stratigraphically upper part of the Veikkavaara greenstone group and overlying Svecofennian volcanic and sedimentary rocks. Greenstones occupy the central part of an anticline that is surrounded by younger Svecofennian units (Fig. 1). Fold axes plunge approximately 45 to 60° to the southeast, with more gently plunging dips found locally in the south. The western limb dips 30 to 60° to the southwest, whereas the eastern limb is tectonically more complex due to intersection with a shear zone running along the contact between andesitic and quartzitic units. Northeast of the deformation zone rocks are mostly overturned with a steep to moderate dip to the southwest. A second phase of deformation is recorded by locally occurring fold axes and mineral lineations plunging gently to the southwest. In the east of the area the two phases of folding have resulted in a dome and basin pattern outlined by Svecofennian metasedimentary rocks and metaandesites. In the central part of the anticline a metamorphic pressure-temperature of 2.6 kbars and 510 °C is reported (Bergman et al. 2001). Outside this core of relatively low metamorphic grade, rocks show an increasing metamorphic grade, with decreasing distance to the surrounding felsic intrusions.

The lithostratigraphy of the area (Fig. 2) has been established in the present study, based on detailed mapping of well-exposed sections in combination with interpretation of geophysical magnetic and slingram ground measurements, in which iron formations and graphitic schist show up as good marker

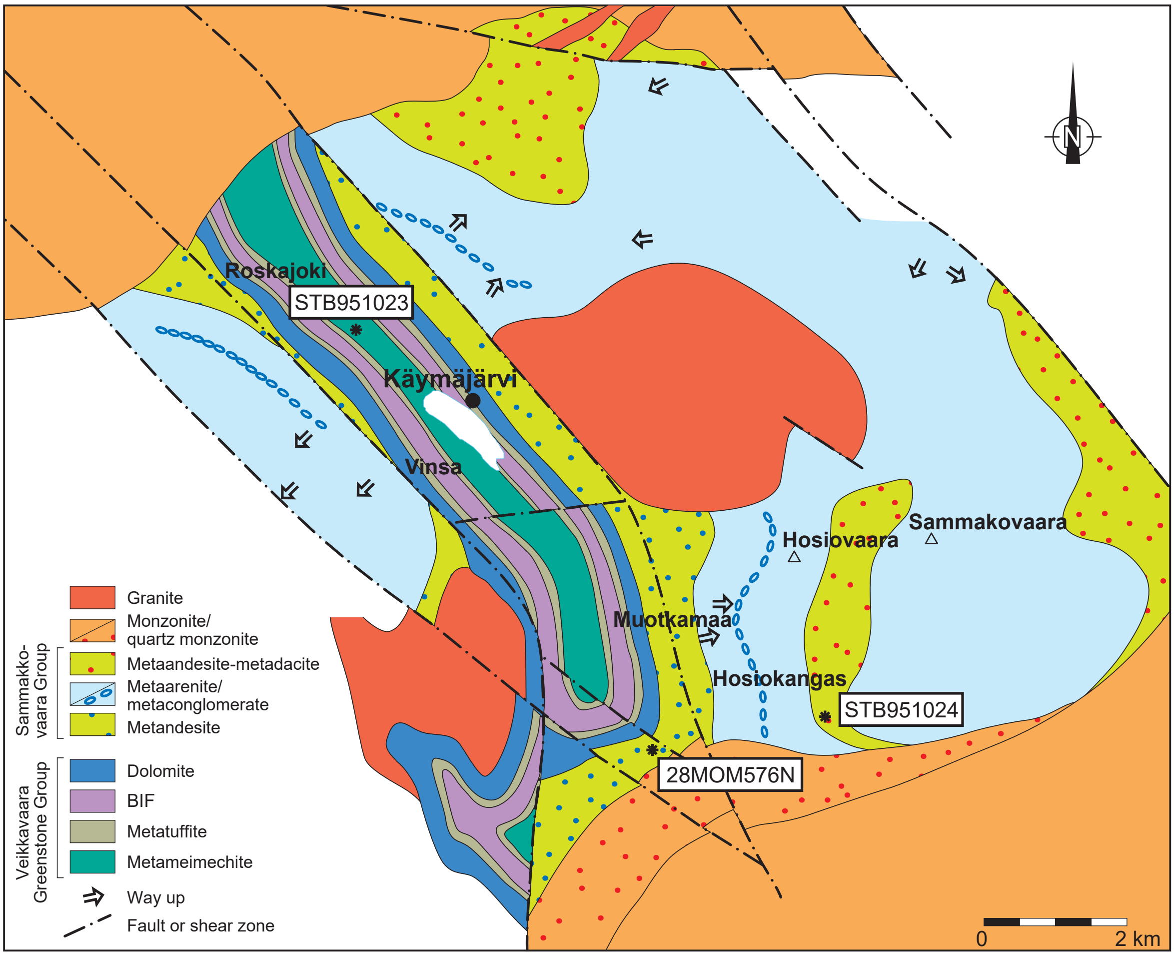

Figure 1. Bedrock map of the Käymäjärvi area with locations of samples analysed. Modified from Padget (1977).

horizons. Stratigraphic names refer to geographical names within the type areas for each unit. Lower and upper contacts are defined where possible and constitute boundaries between units having different lithological properties.

The Veikkavaara greenstone group

Metavolcanic rocks at Käymäjärvi belonging to the upper parts of the Veikkavaara greenstone group are located in the central part of an anticline and occupy an area 1.6 km wide and 10 km long. The core of the anticline consists of metameimechitic lapilli tuff constituting the Käymäjärvi formation, followed by the Vinsa formation, comprising metatuffite, graphite schist, banded iron formation (BIF), and dolomite (Fig. 1).

The Käymäjärvi formation

The Käymäjärvi formation is exposed northwest of Lake Käymäjärvi (Fig. 1). Ground geophysical measurements indicate that these rocks extend further to the southeast and northwest, thus occupying the core of the anticline in a belt approximately 400 m wide. Well-preserved metameimechite rocks occur close to the upper contact of this unit, while primary features in the central part of the anticline are largely obliterated by a strong schistosity. Within the anticline the metameimechite has an exposed thickness of about 150 m, which is taken as the minimum thickness of this unit.

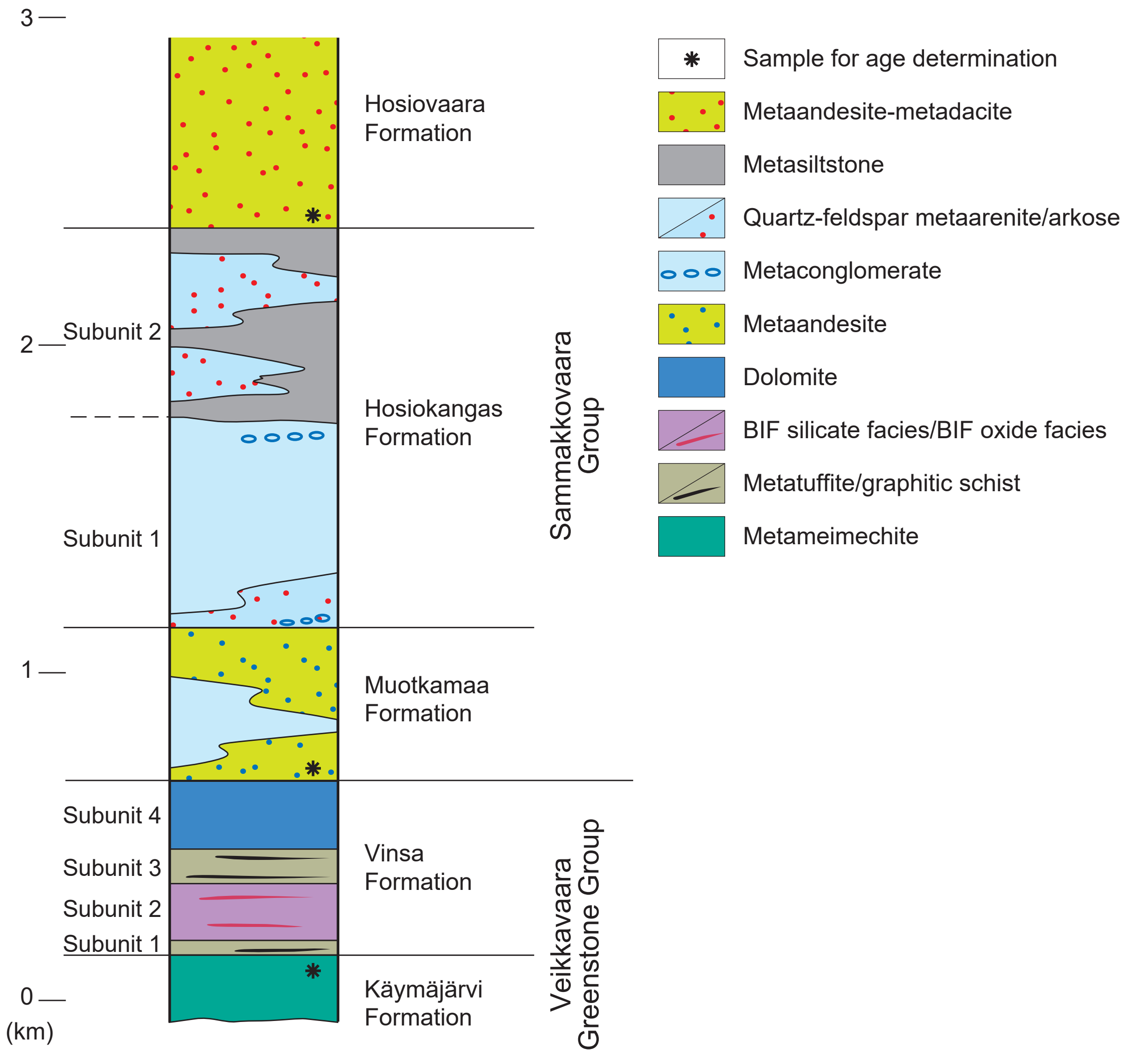

Figure 2. Lithostratigraphy of the Käymäjärvi area, including the Veikkavaara greenstone group and the Sammakkovaara group.

The metameimechite rocks have a pyroclastic character, with lapilli tuff, sometimes showing graded bedding, as a major component. Fragments are slightly vesicular, irregular in shape and mostly 5 to 30 mm in size (Fig. 3A). Lithic fragments of meimechite, with a size of up to 10 cm, are encountered locally. In thin section the rock is predominantly made up of irregularly orientated acicular actinolite porphyroblasts, occurring in a dense mass of less than 0.1 mm long needles (Fig. 3B). Slightly larger porphyroblasts of actinolite occur locally in patches or may replace the pyroclastic fragments. Coarser-grained amphibole is also present in the matrix between fragments. Chlorite, forming small rounded aggregates, and opaque minerals, are minor constituents. Ilmenite is a common accessory mineral, occurring as tabular grains up to 1.5 mm long, while magnetite is rare. The major and trace element content of two metameimechite samples are shown in Table 1. Samples are ultrabasic in composition with a MgO content varying between 19.2 and 21.1 wt %, while Cr and Ni content ranges from 1 050 to 1 460 and 713 to 1 250 ppm, respectively. The fairly high values for Fe_2O_3 (13.2–17.1 wt %), TiO_2 (1.4–1.7 wt %), and Zr (75–96 ppm) compared with komatiites and a lower total alkali content compared with picrites is characteristic of these rocks.

The Vinsa formation

The contact between the Vinsa formation and the Käymäjärvi formation is not exposed but is arbitrarily defined as the transition from ultramafic meimechite tuff to mafic tuffite. The stratigraphic distance between the nearest exposures representing the respective formations is less than 25 m. Exposures of all units of the Vinsa formation, except those in its lowest part, crop out on Vinsa hill 1 km southwest of Lake Käymäjärvi. Most conspicuous are thick units of BIF and dolomite occupying the lower and upper part, respectively. Other lithologies are predominantly mafic tuffites and graphitic metasedimentary rocks forming the base of the Vinsa formation, and also occurring as intercalations between the BIF and the dolomite. The approximately 450 to 550 m thick Vinsa formation is divided into four lithological sub-units as follows.

The tuffites constituting the lowermost sub-unit (unit 1) have a mafic composition and are locally graphite-bearing. Fe-sulphide content is high in places, whereas the amount of graphite rarely exceeds a few per cent by weight. Layers rich in garnet porphyroblasts occur locally in the middle part, whereas scapolite may be common close to the upper contact. The total thickness of this unit is 40 to 50 m.

The next sub-unit (unit 2) is a 150 to 200 m thick silicate facies BIF with locally developed oxide facies. It can be followed along strike in scattered outcrops and by magnetic ground measurements for a distance of approximately 18 km around the core of the anticline. It is best exposed at Ylijoki, northwest of Vinsa (close to sample site STB 9510124, Fig. 1). The BIF exhibits a distinct mesobanding with 5 to 30 cm thick bands of recrystallised chert alternating with silicate bands containing mainly pyroxene, amphibole, garnet and fayalite in different proportions (Fig. 3C). Grünerite is the predominant mineral in most silicate bands (Geijer 1925). Magnetite occurs locally as microbands within silicate bands, and as low-grade dissemination in some silicate and chert bands. The occurrence of rounded aggregates rich in disseminated magnetite was interpreted as former greenalite oolites by Geijer (1925), and indicates temporary deposition above the wave base. Some iron-poor parts of the unit differ in character only by their lack of iron-rich silicates and magnetite. Calc-silicate layered dolomite occurs locally as thick intercalations up to several metres thick. The iron content varies between 14 and 25 wt % Fe in silicate facies BIF, but in oxide facies it may reach 30 to 40 wt % over some metres of stratigraphic thickness. Both the silicate and oxide facies contain between 2.3 and 3.4 wt % MnO, and Ba may be enriched up to 1 wt % in the oxide facies BIF. The BIF records a minimum of clastic sedimentation (i.e. very low content of Al and Ti).

The BIF is overlain by an approximately 100-metre-thick unit (unit 3), which contains mafic tuffites with intercalated graphitic and calc-silicate-bearing beds. Rocks are partially laminated at a mm to cm scale. Scapolite is common and, together with diopside, constitutes a major component in some of the beds. The occurrence of finely laminated and almost monomineralic diopside rocks that grade into tuffitic rocks mainly consisting of diopside, scapolite and biotite is a prominent feature of these beds. Disseminated graphite and Fe-sulphides are locally common but the amount of graphite and sulphur is generally less than 10 and 3 wt %, respectively. This unit is geochemically anomalous with a particularly pronounced enrichment of Ca, Mg, K, Ba, Cl, and Br. Other elements showing elevated concentrations compared to mafic tuff-tuffite in other stratigraphical positions in the Veikkavaara greenstone group are Mn, P, Y, Cu, Zn, As, Sb, Mo, and V.

The uppermost unit (unit 4) of the Vinsa formation is a 150 to 200 m thick dolomite that is best exposed at Muotkamaa, 5 km southeast of Käymäjärvi. The dolomite has intercalations of tuffite early in the sequence. However, most of this unit consists of a fairly pure dolomite with 22.0–22.5 wt % MgO, 29.1–29.8 wt % CaO and 2.3–5.0 wt % SiO_2. Calc-silicates are found in small quantities and are predominantly actinolite, although humite minerals may be locally abundant. Calc-silicates become more common in the upper 20–50 metres, forming more massive calc-silicate units consisting mainly of amphibole and pyroxene in different proportions, but locally also knebelite.

The Sammakkovaara group

The Veikkavaara greenstone group is followed by metamorphosed Svecofennian volcaniclastic and clastic sedimentary rocks constituting the Sammakkovaara group. This unit is best exposed at Sammakkovaara hill, about 6 km east of Käymäjärvi (Fig. 1), which is the type locality for the Sammakkovaara group. Similar rock sequences are found overlying the greenstones in other parts of northeastern Norrbotten, suggesting that the Sammakkovaara group is of regional importance. The contact with the underlying Vinsa formation is rarely exposed, but layering within the Sammakkovaara group is mainly conformable to its substratum, indicating no major angular unconformity between these units at Käymäjärvi.

Based upon lithological properties, the Sammakkovaara group may be further divided into three formations: the Muotkamaa formation, comprising a lower andesitic metavolcanic unit together with minor intercalated clastic metasedimentary rocks; the Hosiokangas formation, which is predominantly made up of arenitic to clay-rich metasedimentary rocks; and an upper andesitic metavolcanic-dominated unit, which constitutes the Hosiovaara formation.

The Muotkamaa formation

The Muotkamaa formation is exposed at Muotkamaa, about 5 km southeast of Käymäjärvi and has also been intersected in drillholes at Roskajokki, 3 km northwest of Käymäjärvi (Lundmark 1985). The total thickness of this unit is approximately 400 to 550 m. It predominantly comprises andesitic rocks but also includes minor clastic metasedimentary units of arenitic composition.

Primary structures are poorly preserved in the metaandesite, and the nature of the rock is mostly unclear. But its fine-grained character and the common presence of a porphyritic texture indicate an extrusive origin. Phenocrysts of plagioclase are up to 3 mm in size. Aggregates of amphibole 1 to 3 mm in size constitute 5–10% and probably represent relicts of pyroxene or amphibole phenocrysts (Fig. 3D). The texture is mostly granoblastic to poikiloblastic with 0.05 to 0.2 mm large grains of plagioclase, hornblende and biotite enclosed within aggregates of hornblende and diopside. Minor constituents are microcline, quartz and calcite. Scapolite may be abundant occurring as poikiloblasts and in patches. The chemical composition of metaandesites from the Muotkamaa formation is shown in Table 1.

Metaarenite with varying feldspar content occurs as a 50 to 100 m thick intercalation at Muotkamaa. The contact to the metaandesite is not exposed. Arenitic metasedimentary rocks also occur in a drillcore at Roskajokki, close to the lower contact of the Muotkamaa formation.

The Hosiokangas formation

The Hosiokangas formation is well exposed at Hosiokangas, 6 km southeast of Käymäjärvi, and is a clastic unit of arenitic to more fine-grained sediments that has a total thickness of 1100 to 1300 m. The lower and upper contacts are gradual over a distance of some metres, with epiclastic rocks that grade into metaandesite. Metaconglomerate beds and tuffitic intercalations of andesitic composition occur as minor constituents.

Based on lithological properties, the Hosiokangas formation may be divided into two sub-units. The lower unit predominantly comprises feldspar-rich quartzite that partly grades into meta-arkose. Intercalations of metaconglomerate occur in its lower and upper part. The upper unit shows rapid lithological changes, with beds consisting of subarkose, arkose, clay-rich rocks and tuffite.

An approximately 1 m thick metaconglomerate at the base of the lower sub-unit contains gravel-sized clasts, mainly of quartz or quartzite (Padget 1977), and is associated with arkosic arenite. Most of the lower unit has fairly low feldspar content and displays a reddish to light grey colour. These arenitic metasedimentary rocks often show heavy-mineral laminae and cross-bedding. In its upper part, a 5 to

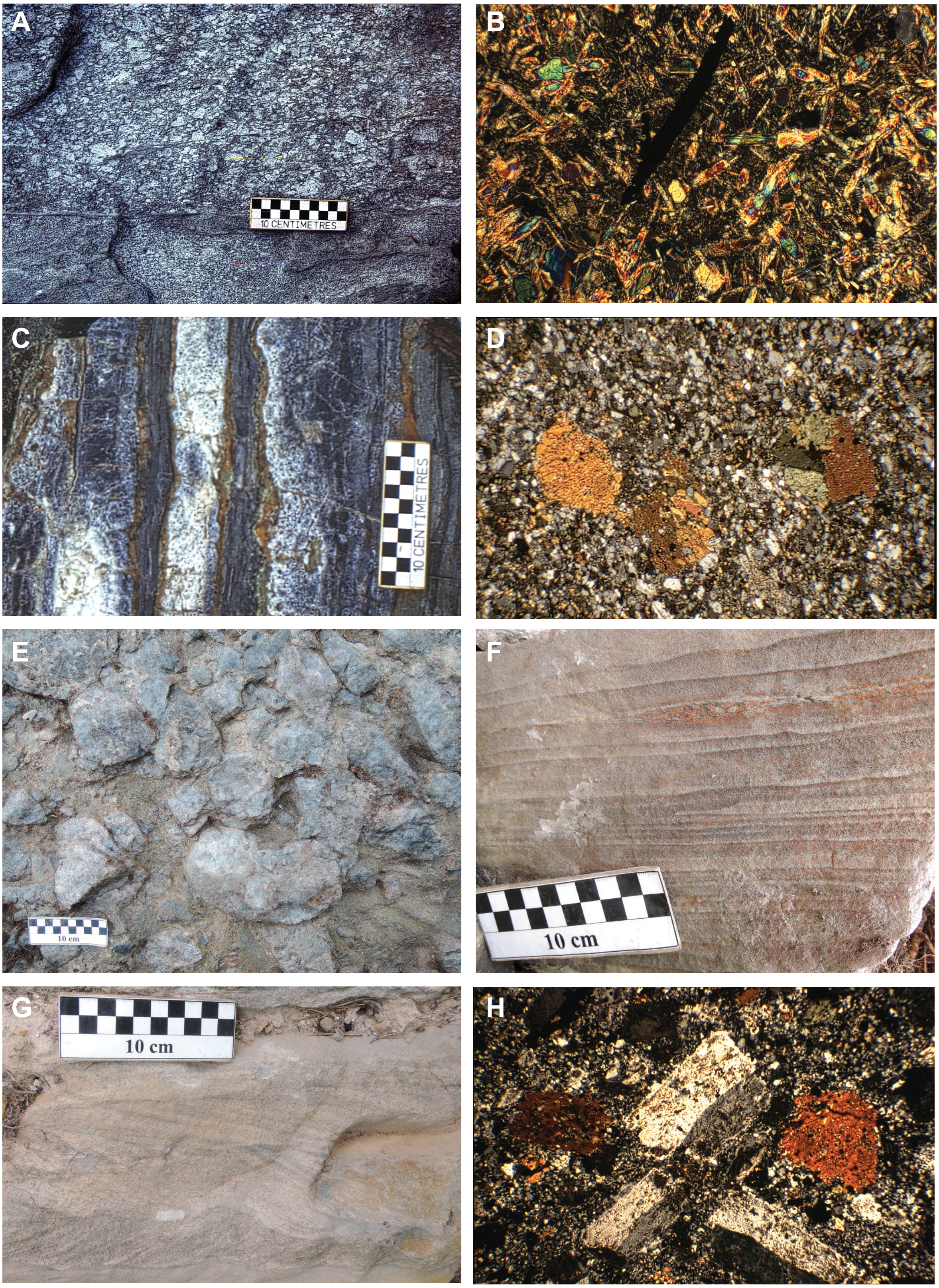

Figure 3. Photographs and photomicrographs of rocks from the Käymäjärvi area. **A** Meimechitic lapilli tuff from the Käymäjärvi formation. **B** Microphotograph of meimechitic lapilli tuff with tabular grains of ilmenite, sample STB951023, crossed nicols. **C** Silicate facies BIF from the Vinsa formation. **D** Photomicrograph of metaandesite with relict phenocrysts of amphibole or pyroxene, Muotkamaa formation, crossed nicols. **E** Quartz pebble conglomerate from the middle part of the Hosiokangas formation. **F** Graded bedding in andesitic volcaniclastitic metasandstone, upper part of Hosiokangas formation. **G** Herringbone cross-stratification from the upper part of the Hosiokangas formation. **H** Photomicrograph of plagioclase porphyritic metaandesite with relict pyroxene phenocrysts from the Hosiovaara formation, crossed nicols. Photos: Olof Martinsson.

30 m thick monomict metaconglomerate forms a laterally extensive intercalation. It contains up to 30 cm, well-rounded to more angular clasts of almost pure quartz (Fig. 3E). Minor constituents are pebbles of schist and magnetite ore. The metaconglomerate is mostly clast-supported, with a matrix consisting of quartz arenite. Quartz clasts are partly dusted by hematite, which also occurs as larger flakes in the matrix and within veinlets. Feldspar is very rare and mainly confined to the matrix. Small clasts with high iron oxides content are present in minor amounts.

In the upper sub-unit of the Hosiokangas formation, arenitic metasedimentary rocks are interlayered with more clay-rich rocks. Metaarenites are generally reddish in colour and have a feldspar content ranging from 20 to 40%. They grade into dark grey, smaller-grained and more clay-rich metasedimentary rocks with 20 to 30% biotite, which locally contain porphyroblasts of andalusite. Clay-rich rocks are partly migmatitic in character. Tuffitic units of andesitic composition occur locally as up to 50 m thick intercalations (Fig. 3F). Cross-bedding is common in the arenitic units and locally shows herringbone cross-stratification (Fig. 3G). In some beds, actinolite occurs disseminated or enriched in layers and may be the metamorphic expression of calcareous material.

The Hosiovaara formation

The Hosiovaara formation is poorly exposed. Only a few small outcrops occur close to its lower contact. However, andesite occurs in local boulders and in outcrops strongly affected by frost wedging, which are extensively distributed on the eastern slope of Hosiovaara hill, 5 km east of Käymäjärvi. At this locality, metavolcanic rocks constitute the core of a narrow syncline plunging to the south. The lower contact is gradual, with clay-rich metasedimentary rocks grading into volcaniclastic rocks of andesitic composition over a distance of several metres. Rocks are mostly porphyritic, and veins and patches of epidote-pyroxene-amphibole are locally common. The upper contact of the Hosiovaara formation is not preserved, and its total thickness is therefore unknown, but estimated to be at least 1 km.

At Hosiovaara the metaandesites are fairly well preserved and mostly porphyritic. Plagioclase phenocrysts form 10 to 40% in a matrix with a grain size of 0.02 to 0.04 mm (Fig. 3H). Phenocrysts commonly show Karlsbad twinning in combination with albite twinning and are 0.5 to 3 mm long. Larger grains and aggregates of hornblende, representing altered amphibole or pyroxene phenocrysts, are less abundant. The matrix has a granoblastic texture consisting of plagioclase together with smaller amounts of hornblende, microcline, diopside and epidote. Scapolite may occur as porphyroblasts, whereas titanite and calcite occur as accessory components. South of Hosiovaara outcrops of metaandesite are found close to the lower contact of the Hosiovaara formation. Here the rock shows a higher degree of alteration, recrystallisation, and skarn veining. The porphyritic texture is almost obliterated and scapolite is a common secondary mineral. The scapolite porphyroblasts are partly altered and replaced by epidote, hornblende, and biotite. A large granitoid intrusion exists 600 m to the south, and the volcanic rocks show migmatitic veining close to this contact. The chemical composition of metaandesites from the Hosiovaara formation is shown in Table 1. Compared to metaandesites from the Muotkamaa formation samples, they have a slightly more fractionated and silica-rich character, with higher concentrations of Si, Th, Zr, and REEs, and lower concentrations of Fe, Mg, Ca, Sc, and V. The Zr-Ti diagram (Pearce 1982) is used to compare the metaandesites from the Muotkamaa and Hosiovaara formations with other rocks, and shows them to occupy the same area as metaandesitic rocks from the Porphyrite group in the Kiruna area (Fig. 4).

Table 1. Chemical analysis of metavolcanic rocks from the Käymäjärvi area. Samples 28MOM544, 28MOM576 and 28MOM583 were analysed by ICP-AES and INAA. The other samples were analysed by ICP-AES and ICP-MS.

Sample	28MOM544 Meta-meimechite	STB951023 Meta-meimechite	28MOM576N Meta-andesite	28MOM583 Meta-andesite	STB951024 Meta-andesite	BOM950047B Meta-andesite
Formation	Käymäjärvi Fm	Käymäjärvi Fm	Muotkamaa Fm	Muotkamaa Fm	Hosiovaara Fm	Hosiovaara Fm
wt %						
SiO_2	43.50	44.50	56.30	57.50	61.30	62.70
TiO_2	1.49	1.39	0.73	0.76	0.72	0.74
Al_2O_3	7.55	7.48	14.90	15.50	16.00	15.50
Fe_2O_3	13.80	17.10	8.28	8.55	6.02	6.44
MnO	0.25	0.49	0.38	0.13	0.09	0.08
MgO	21.10	19.20	3.89	4.08	2.42	2.18
CaO	8.99	5.39	8.15	6.94	5.45	4.55
Na_2O	0.69	0.67	2.96	4.05	5.07	4.85
K_2O	0.11	0.36	3.63	2.44	2.50	3.47
P_2O_5	0.15	0.13	0.31	0.33	0.29	0.30
LOI	3.40	2.90	1.20	0.80	0.40	0.40
SUM	**101.10**	**99.60**	**100.70**	**101.10**	**100.30**	**101.20**
ppm						
Sr	58	42	310	897	1230	1020
Ba	47	280	1060	1130	1630	1560
Rb	ND	15.1	97.0	87.0	49.5	88.5
Nb	NA	6.3	NA	NA	12.3	13.1
Ta	ND	0.63	1.40	ND	0.97	1.05
U	ND	0.38	1.80	1.80	2.73	3.60
Th	1.10	0.94	7.90	7.80	15.10	15.10
Zr	84	83	124	130	230	239
Hf	3.0	2.8	4.0	3.0	7.8	8.4
La	9.2	6.6	41.0	36.0	52.5	53.8
Ce	29.0	19.2	80.0	67.0	108.0	111.0
Nd	14.0	13.3	32.0	28.0	43.1	46.2
Sm	4.10	2.57	4.50	4.30	6.53	6.58
Eu	1.30	0.69	1.50	1.50	0.82	1.50
Gd	NA	3.45	NA	NA	4.39	4.84
Tb	ND	0.54	ND	ND	0.59	0.59
Dy	NA	2.81	NA	NA	2.90	3.09
Ho	NA	0.46	NA	NA	0.51	0.52
Er	NA	1.64	NA	NA	1.45	1.64
Tm	NA	0.19	NA	NA	0.17	0.19
Yb	1.90	1.38	1.70	1.80	1.49	1.40
Lu	0.30	0.25	0.29	0.30	0.17	0.18
Y	13.2	11.8	13.0	14.6	13.7	13.8
Sc	23.9	22.9	17.6	18.2	8.5	8.1
V	207	231	161	162	119	119
Cr	1270	1300	103	100	43	49
Ni	713	1090	29	27	30	26
Co	87.1	90.5	12.4	24.2	12.8	15.0
Cu	80	167	27	50	ND	ND
Zn	168	718	55	29	108	183
Ga	NA	12.3	NA	NA	17.8	17.4

NA = not analysed, ND = not detected

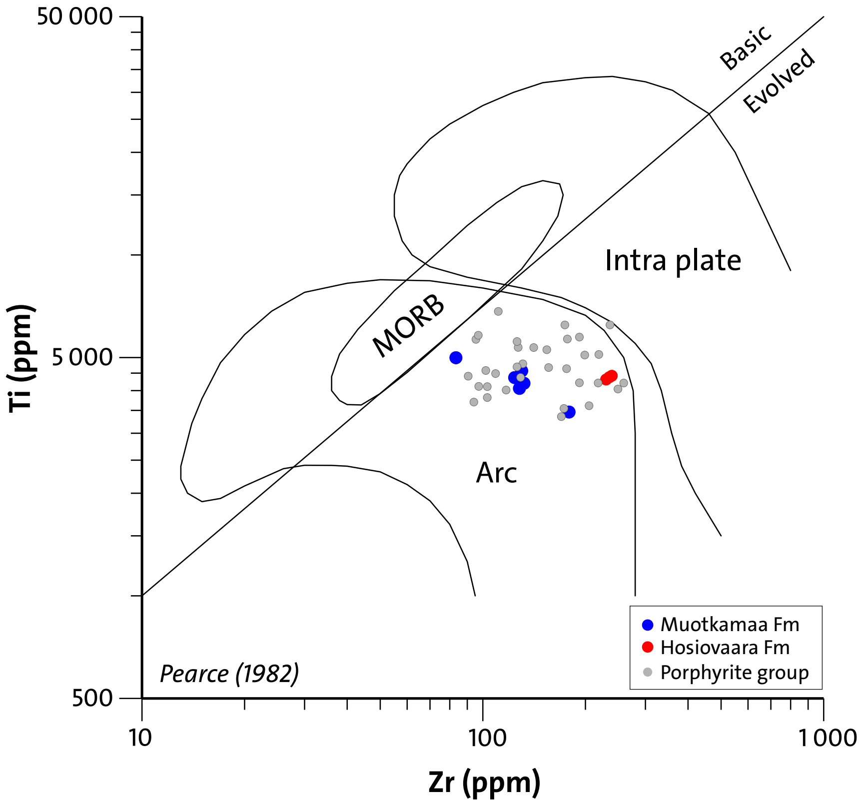

Figure 4. Geochemical comparison of metavolcanic rocks from the Sammakkovaara group with Porphyrite group metavolcanic rocks from the Kiruna area (Martinsson, unpublished data) using the Zr-Ti diagram from Pearce (1982).

SAMPLE DESCRIPTION

Sample STB951023, metameimechite from the Käymäjärvi formation

(coordinates in the Swedish National Grid SWEREF99 TM: 7497684/839675)

A sample was taken from the uppermost part of the meimechitic unit (approximately 10–20 metres from the contact with the overlying Vinsa formation). Graded bedding is seen in the outcrop, with decreasing grain size stratigraphically upwards. The meimechitic lapilli tuff has a greenish colour and consists of up to 2 cm sized fragments with a rounded shape and vesicular texture. Amphibole is the major mineral (about 95%), with ilmenite as the most important accessory mineral (about 5%). Grain size is mainly 0.05 to 0.1 mm, although porphyroblasts, clots and schlieren of actinolite with a grain size of up to 0.3 mm have partly replaced the more fine-grained matrix. Chlorite occurs in rounded aggregates that are partly replaced by amphibole. The rock is foliated; two directions of foliation are outlined by platy ilmenite and acicular amphibole.

Sample 28MOM576N, metaandesite from the Muotkamaa formation

(coordinates in the Swedish National Grid SWEREF99 TM: 7492691/843243)

The metaandesite was sampled close to the contact with the underlying dolomite within the Vinsa formation. The sample has a greenish-grey colour, is massive in character and has a granoblastic to crystalloblastic texture with a 0.05 to 0.1 mm grain size. Sparse phenocrysts of pyroxene and plagioclase occur as 0.5 to 2 mm sized relicts composed of amphibole-biotite and scapolite-biotite, respectively. Amphibole and diopside occur (approximately 15%) in a matrix of plagioclase and varying amounts of microcline. Biotite is locally abundant and scapolite is common as poikiloblasts and patches. Carbonate is found as an accessory mineral irregularly distributed in the rock. Scapolite is partly replaced by biotite, and amphibole may be replaced by diopside.

Sample STB951024, metaandesite from the Hosiovaara formation
(coordinates in the Swedish National Grid SWEREF99 TM: 7493092/845668)
The metaandesite from the Hosiovaara formation was sampled close to its lower contact. Veinlets and patches of epidote-pyroxene are common, and granitic veins are locally present in the surrounding outcrops of metaandesite. The rock has a pale grey colour and is slightly banded, locally with a diffuse clastic structure. Phenocrysts of plagioclase 0.5 to 3 mm in size consititute 10 to 30% of the sample. Amphibole pseudomorphs after pyroxene phenocrysts are sparse. The texture is granoblastic to poikiloblastic and, due to strong recrystallisation, the primary porphyritic texture is only locally well preserved (Fig. 3H). The matrix grain size is 0.05 to 0.2 mm, mainly consisting of plagioclase with some microcline. Amphibole, diopside, and scapolite occur in poikiloblastic aggregates. Epidote is a paragenetic late mineral that replaces both scapolite and amphibole. Titanite is a common accessory mineral forming part of the metamorphic assemblage. Small and rounded grains of zircon are less abundant.

ANALYTICAL METHODS

The zircons were separated using standard magnetic and heavy liquid techniques, and examined using optical microscopy. Samples were analysed using the conventional (multi-grain TIMS) technique at the Department of Geosciences at the Swedish Museum of Natural History; and for the metameimechite, also by in situ (SIMS and LA-ICP-MS) analyses. CL imaging was conducted on some grains.

Most zircon fractions selected for TIMS were abraded according to the method used by Krogh (1982). After decomposition (Krogh 1973) and aliquoting, a mixed ^{208}Pb-$^{233-235}$U tracer was added to the ID aliquots. The sample aliquots were loaded onto anion exchange columns for extraction of Pb and U. These were later loaded onto Re single filaments with silica gel and H_3PO_4. Most samples were measured in static mode using a MAT 261 mass spectrometer. Small Pb and U amounts, yielding low signals, were measured in peak jumping mode on a secondary electron multiplier. The total Pb blank was 4–7 pg and the U blank less than 2 pg. Titanite was processed using HBr chemistry to achieve better purification of lead and uranium.

The preparation of zircon grains for in situ analyses was the same for SIMS and LA-ICP-MS. Individual zircon grains, remaining after the TIMS session, were mounted in epoxy, along with the 91500 standard zircon (Wiedenbeck *et al.* 1995) and polished to approximately half their thickness. Polished grains were investigated by SEM (Scanning Electron Microscope) equipped with a CL (cathodeluminescence) detector. Images were used for choosing areas suitable for U-Pb dating. U-Th-Pb SIMS geochronological data were obtained using the Cameca 1280 ion microprobe at the Nordsim facility, at the Swedish Museum of Natural History. The analytical method follows that described by Whitehouse & Kamber (2005). A Thermo-Scientific Element 2 XR sector field ICP-MS coupled to a New Wave UP-193 Excimer Laser System, at the Museum für Mineralogie und Geologie (GeoPlasma Lab, Senckenberg Naturhistorische Sammlungen Dresden, Germany), was used for the LA-ICP-MS data set. For further details on the analytical protocol and data processing, see Gerdes & Zeh (2006).

The procedure used for calculating corrected isotope ratios and error propagation, was the same for all types of analytical protocol (using the PBDAT program of Ludwig (1991a) for TIMS data, and described elsewhere for the other types of analysis (Whitehouse and Kamber 2005, Gerdes & Zeh 2006). The decay constants recommended by Steiger & Jäger (1977) were used. Calculation of intercept ages and drawing of concordia plots were carried out using Ludwig's (1991b, 2012) ISOPLOT program. The total Pb blank was 4–10 pg and the U blank less than 2 pg. The assigned composition of common Pb was calculated according to the Pb evolution model of Stacey & Kramers (1975), which is a sufficient approximation for analyses with high ^{206}Pb/^{204}Pb (>~1000). For samples with low ^{206}Pb/^{204}Pb, the uncertainty in the common Pb correction will result in large error ellipses. The mass fractionation for Pb is 0.10 ±0.04% per a.m.u. U mass fractionation was monitored and corrected for by means of the $^{233-235}$U ratio of the spike.

ANALYTICAL RESULTS

STB951023, metameimechite from the Käymäjärvi formation

Very few zircons were recovered from this rock. The majority are small with distinct, prismatic zircon shape and are generally severely fractured. They constitute a heterogeneous population and some have visible cores. A second group of grains are very small and anhedral. Their length/width ratio is approxmately 1. Both types were analysed using the multi-grain TIMS method. Due to the small size of the crystals, none of the analysed fractions were abraded. Fractions 1, 4 and 5 have prismatic shapes, whereas 2, 3 and 6 are small and anhedral or rounded with a length/width ratio of around 1.

Analytical results are shown in Table 2 and Figure 5. The small grains are low in U and Pb, and two out of three fractions are strongly discordant. Due to the low Pb content and small sample size the total Pb concentration is only 17 and 30 pg for fractions 2 and 3, respectively. The corrected ratios are therefore very sensitive to the chosen blank concentration and composition, as well as to the chosen composition of the initial Pb. Consequently, the analyses of fractions 2 and 3 are uncertain. Fraction 1 has a higher total Pb concentration but a high common Pb content, causing great uncertainty. Only fraction 4, with a higher U and Pb concentration and low common Pb, gives a small error ellipse.

The concordia diagram shows a large scatter, indicating that the zircon population is highly heterogeneous. A discordia is calculated from fractions 2, 3, 4 and 5, giving intercept ages of 2 055 ±130 and 445 ±230 Ma, and an MSWD of 43. This result is similar to the 2 038 ±6 Ma $^{207}Pb/^{206}Pb$ age of fraction 4. However, due to the strong discordance and different morphology, it is doubtful whether fractions 2 and 3 belong to the same generation as the other fractions. A regression made using fractions 4 and 5 only yields intercept ages of 2 236 ±52 and 1 059 ±103 Ma. Fraction 6, which consists of anhedral, clear, colourless to pale brown crystals has a very low $^{206}Pb/^{204}Pb$ due to low Pb content, small sample size and high initial Pb. The data point is concordant at c. 1800 Ma and the zircons clearly belong to a later generation. It is possible that fraction 6 belongs to the same generation as fraction 1, which has a similar $^{207}Pb/^{206}Pb$ age.

Table 2. TIMS U-Pb isotopic data for samples STB951023, 28MOM576N and STB951024.

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)
STB951023	**Metameimechite from the Käymäjärvi formation**									
1	2	4	244.0	80.7	9.17	331	82.6-9.1-8.3	0.2814±19	4.258±55	1795±19
2	2	7	49.9	10.1	0.97	154	71.2-7.4-21.4	0.1516±53	2.181±130	1703±92
3	2	25	71.9	10.3	0.57	242	77.7-7.1-15.2	0.1224±13	1.538±26	1449±32
4	12	5	214.5	72.5	0.43	4176	81.5-10.2-8.3	0.3184±15	5.514±31	2 038±6
5	5	7	451.0	145.3	0.81	532	78.3-9.4-12.3	0.2917±15	4.812±31	1 951±11
6	2	4	34.5	27.2	13.90	65.6	75.2–8.0–19.5	0.3251±46	4.937±289	1802±96
28MOM576N	**Metaandesite from the Muotkamaa formation**									
1 < 74	123		368	102	3.0	1600	72.7–8.4–18.9	0.2266±59	3.615±95	1890±6
2 74-100	223		175	69	0.24	12000	72.4–8.3–19.3	0.3315±70	5.262±12	1881±2
3 100-150	60		107	7.4	0.48	345	73.1–8.4–18.5	0.0554±48	0.877±11	1878±16
4 > 150	10		1244	202	4.7	1200	71.1–8.2–20.7	0.1310±52	2.083±13	1884±8
5 100-150 ab	40		137	48	2.4	675	72.0–8.3–19.7	0.2274±12	4.409±34	1884±11
STB951024	**Metaandesite from the Hosiovaara formation**									
Zircon 1	34	5	222.1	74.3	0.54	4614	77.0-8.5-14.5	0.2968±14	4.5439±23	1817±3
Zircon 2	16	8	99.0	40.4	0.25	3594	70.5-8.1-21.4	0.3328±18	5.2694±33	1877±5
Zircon 3	16	12	135.0	53.4	0.34	2691	70.8-8.2-21.0	0.3231±18	5.1314±33	1883±5
Zircon 4	22	15	173.9	66.8	0.57	3267	74.3-8.5-17.2	0.3288±12	5.2113±23	1879±5
Titanite 1	98	30	23.9	11.8	1.42	255	53.1-6.1-40.8	0.2672±37	4.2190±91	1872±27
Titanite 2	143	25	153.5	34.8	1.86	665	61.0-0.7-38.3	0.1429±6	2.2238±17	1846±10

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

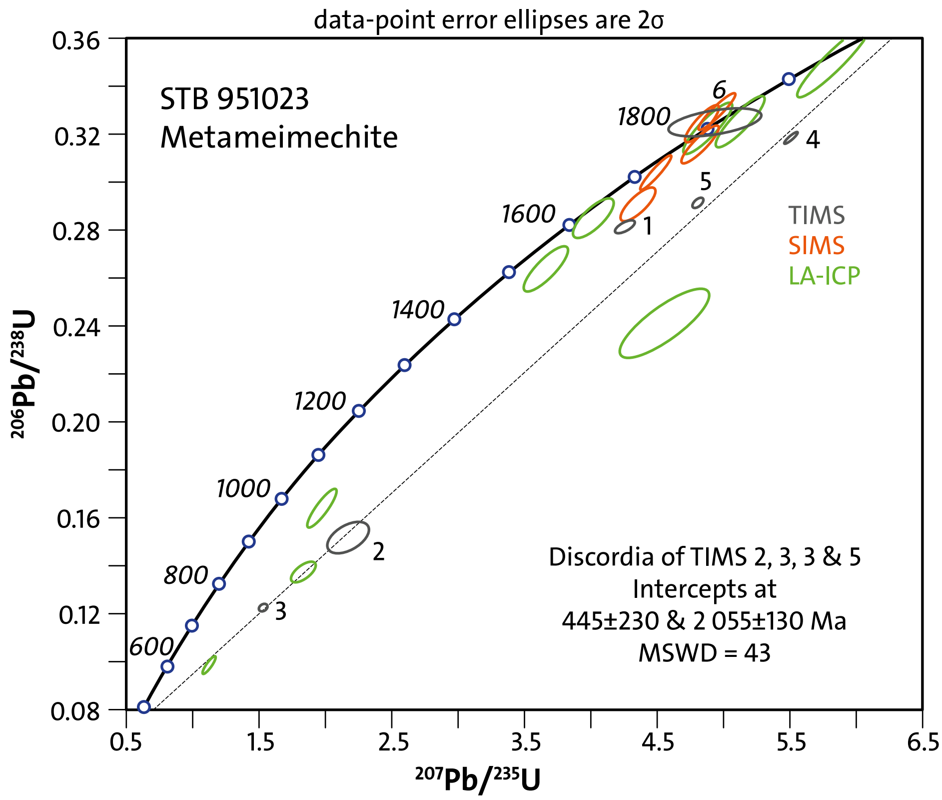

Figure 5. Concordia diagram, combining TIMS. SIMS and LA-ICP-MS data, for analysed zircon fractions from a metameimechite (sample STB951023) from the Käymäjärvi formation.

SIMS data (6 points, Fig. 6A) have produced a different analytical picture, where data show little scatter, and fit a discordia that yields a relatively well-constrained event at c. 1770 Ma, and near concordant ages of c. 1790 Ma (Table 3, Fig. 5). An averaged ^{207}Pb/^{206}Pb age for the concordant spots 1, 2 and 5a yields 1781 ±9.5 Ma. LA-ICP-MS data (n=10) shows a highly diverse age spread, however. One spot is concordant at c. 3.0 Ga (not shown in the diagram), and the remainder record a series of near-concordant ages defined at c. 1.97 Ga, 1.81 Ga, 1.65 Ga (Table 4, Fig. 5). A few other discordant to highly discordant analyses suggest an apparent age of around 0.4 Ga.

28MOM576N, metaandesite from the Muotkamaa formation

The heavy mineral concentrate from the metaandesite predominantly comprises pyrite; the zircon content was low. Most of the zircon crystals have irregular shape or form subhedral prisms with rounded edges and pitted or irregular surfaces. Zircons are translucent with a pale brown colour and show a length/width ratio of approximately 1–3. Inclusions and fractures are rare and no visible cores or overgrowths were observed. Based on size distribution, four fractions were obtained. Clear and well-formed crystals grains were selected for analysis from the predominant 74–100 µm fraction. Some of the zircons from fraction 100–150 µm were abraded before analysis.

Analytical results are presented in Table 2 and Figure 7. The single zircon crystal in fraction >150 µm shows higher uranium content compared to the other fractions, while fraction 100–150 µm has an abnormally low lead content. A regression line based on all fractions defines a discordia with intercept ages of 1 884 ±7 and -1 ±19 Ma, with a MSWD of 3.1. Excluding the fraction <74 µm, where the control of zircon quality is poorer, the upper and lower intercept ages are 1 882 ±2 and 0.3 ±5.4 Ma, respectively, with a MSWD of 0.5. The two least discordant fractions define a similar upper intercept age of 1 881 ±2 Ma.

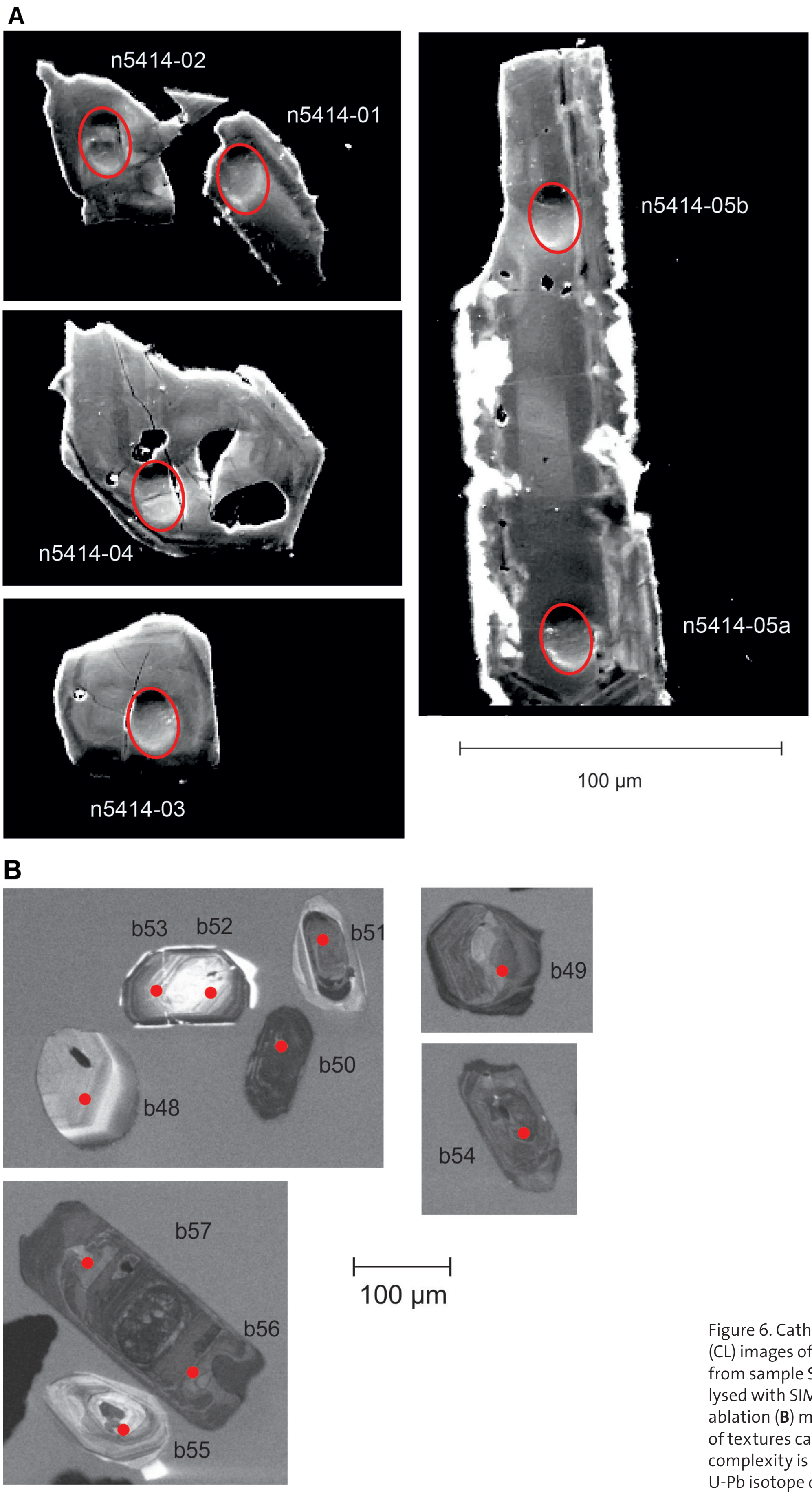

Figure 6. Cathodoluminescence (CL) images of zircon crystals from sample STB951023 analysed with SIMS (**A**) and laser ablation (**B**) methods. A variety of textures can be seen and this complexity is also noted in the U-Pb isotope data obtained.

Table 3. Ion microprobe (SIMS) U-Th-Pb zircon data for the metameimechite (STB 951023).

spot	$^{207}Pb/^{206}Pb$	1σ	$^{206}Pb/^{238}U$	1σ	$^{207}Pb/^{235}U$	1σ	$^{206}Pb/^{204}Pb$ (meas)	f206 (%)[a]	Disc.[b]	$^{207}Pb/^{206}Pb$ age	$^{206}Pb/^{238}U$ age	U (ppm)	Pb (ppm)	Th/Ucalc[c]
n5414-01	0.1083	0.53	0.3247	0.91	4.846	1.05	8 029	0.23	2.7	1770	1812	277	112	0.50
n5414-02	0.1089	0.46	0.3238	0.91	4.860	1.02	48 710	0.04	1.8	1780	1808	323	128	0.40
n5414-03	0.1108	0.62	0.3153	0.95	4.819	1.13	5 912	0.32	-2.9	1813	1767	247	96	0.38
n5414-04	0.1087	0.73	0.2907	0.98	4.356	1.22	2 124	0.88	-8.4	1777	1645	283	100	0.33
n5413-05a	0.1093	0.39	0.3295	0.96	4.966	1.04	8 559	0.22	3.1	1788	1836	749	302	0.40
n5413-05b	0.1073	0.32	0.3039	0.90	4.494	0.95	3 871	0.48	-2.8	1753	1711	811	310	0.50

All errors are 1 sigma (%); ages in million years (Ma).
[a] fraction (percentage) of common Pb detected. Calculated from measured ^{204}Pb assuming t=0 Ma in the Stacey and Kramers (1975) model.
[b] degree of discordance as a percentage
[c] calculated from measured ThO intensity

Table 4. Laser ablation (ICP-MS) U-Pb zircon data for the metameimechite (STB 951023).

spot	$^{207}Pb/^{206}Pb$	1σ	$^{206}Pb/^{238}U$	1σ	$^{207}Pb/^{235}U$	1σ	$^{206}Pb/^{204}Pb$ (meas)	Rho[a]	$^{207}Pb/^{206}Pb$ age	$^{206}Pb/^{238}U$ age	U (ppm)	Pb (ppm)	Th/U
b48	0.2180	1.3	0.6031	2.2	18.131	2.6	36 471	0.87	2 966	3 042	39	28	0.39
b49	0.1146	1.3	0.3245	2.6	5.128	2.9	12 705	0.90	1874	1812	121	40	0.13
b50	0.1374	3.3	0.2407	5.0	4.560	6.0	889	0.83	2 194	1390	264	82	0.51
b51	0.0879	2.2	0.1638	4.1	1.985	4.6	43 467	0.88	1380	978	272	50	0.27
b52	0.1022	2.1	0.2850	2.5	4.015	3.3	49 807	0.77	1664	1616	51	16	0.35
b53	0.1008	2.1	0.2634	2.9	3.662	3.6	9 505	0.80	1639	1507	52	15	0.42
b54	0.1099	1.6	0.3224	2.8	4.884	3.2	2 787	0.87	1797	1801	122	44	0.48
b55	0.1206	1.4	0.3489	3.1	5.800	3.4	20 077	0.91	1965	1929	70	29	0.60
b56	0.0975	3.3	0.1372	2.4	1.845	4.0	8 824	0.59	1577	829	232	32	0.13
b57	0.0830	1.1	0.0982	2.7	1.125	2.9	7 211	0.93	1270	604	272	26	0.15

All errors are 1 sigma (%); ages in million years (Ma).
Isotope ratios are corrected for background, mass bias, laser induced U-Pb fractionation, and common Pb (if detectable) using Stacey & Kramers (1975) model Pb composition. Errors are propagated by quadratic addition of within-run errors (2SE) and the reproducibility of GJ-1 (2SD).
[a] correlation coefficient; defined as error206Pb/238U/error207Pb/235U.

STB951024, metaandesite from the Hosiovaara formation

The metaandesite had a very low zircon yield. The colour of the zircons varies from light brown to pink, but colourless crystals were also found. Most of the crystals are short prismatic with length/width ratios of 1–3. The shape may be either euhedral, rounded or anhedral. Some colourless, elongate (length/width ratios of approximately 4–6) zircons are also found, along with a small number of dark brown short grains with length/width ratios of approximately 1–2. Cores or overgrowths were not observed. All analysed grains were thoroughly abraded. Fraction 1 consists of large, pink grains, while in fractions 2–4 the zircons are small and colourless to light brown.

The sample also contains titanite, the colour of which may be pale yellow, brown or reddish-brown. Yellow and brown crystals were selected for analysis. The reddish-brown titanites are turbid and inclusion-rich, and were therefore rejected. Many titanite grains are anhedral or fragmented, but euhedral crystals are found among the yellow and brown ones. Both fractions were abraded.

TIMS results are shown in Table 2 and Figure 8. With the exception of one fraction (Zr 1 with a Pb-Pb age of 1 817 ±3 Ma), the remaining titanite and zircons fractions define a discordia with intercept ages of 1 880 ±3 and 49 ±5 Ma and an MSWD of 1.1. Using the three zircon and the two titanite fractions separately gives intercept ages of 1 874 ±11 for zircon fractions and 1 879 ±62 Ma

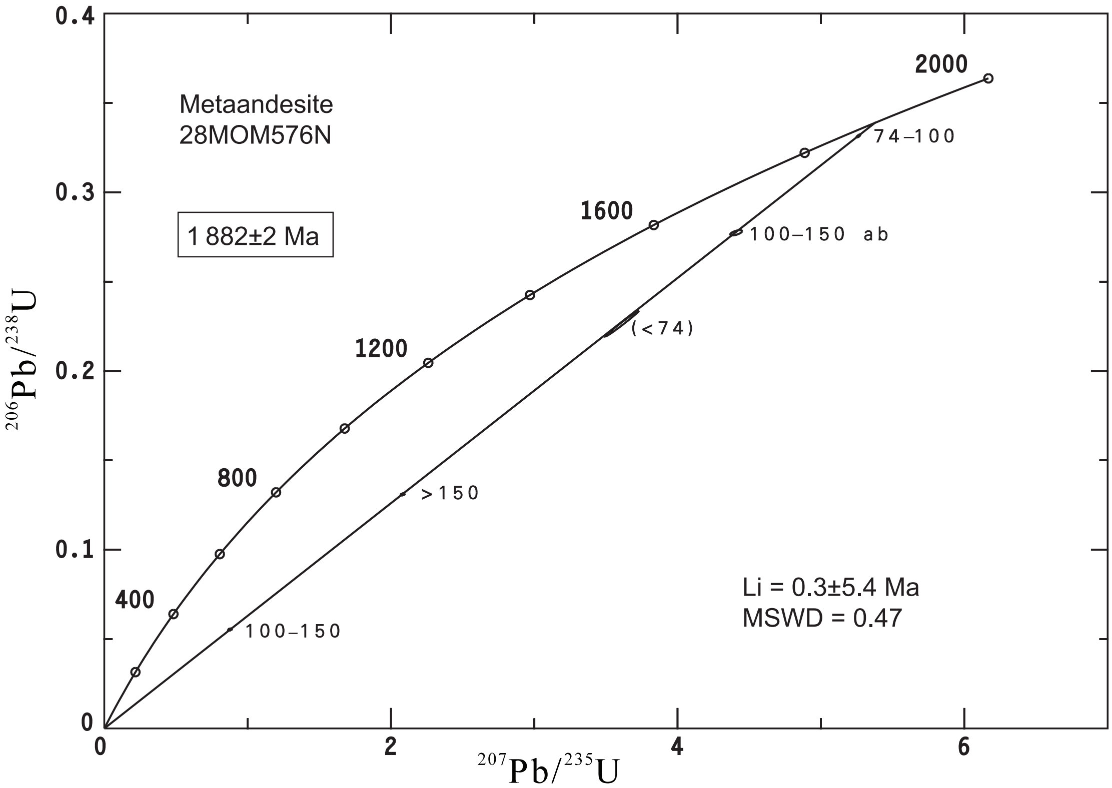

Figure 7. Concordia diagram for (TIMS) analysed zircon fractions from a metaandesite (sample 28MOM576N) from the Muotkamaa formation.

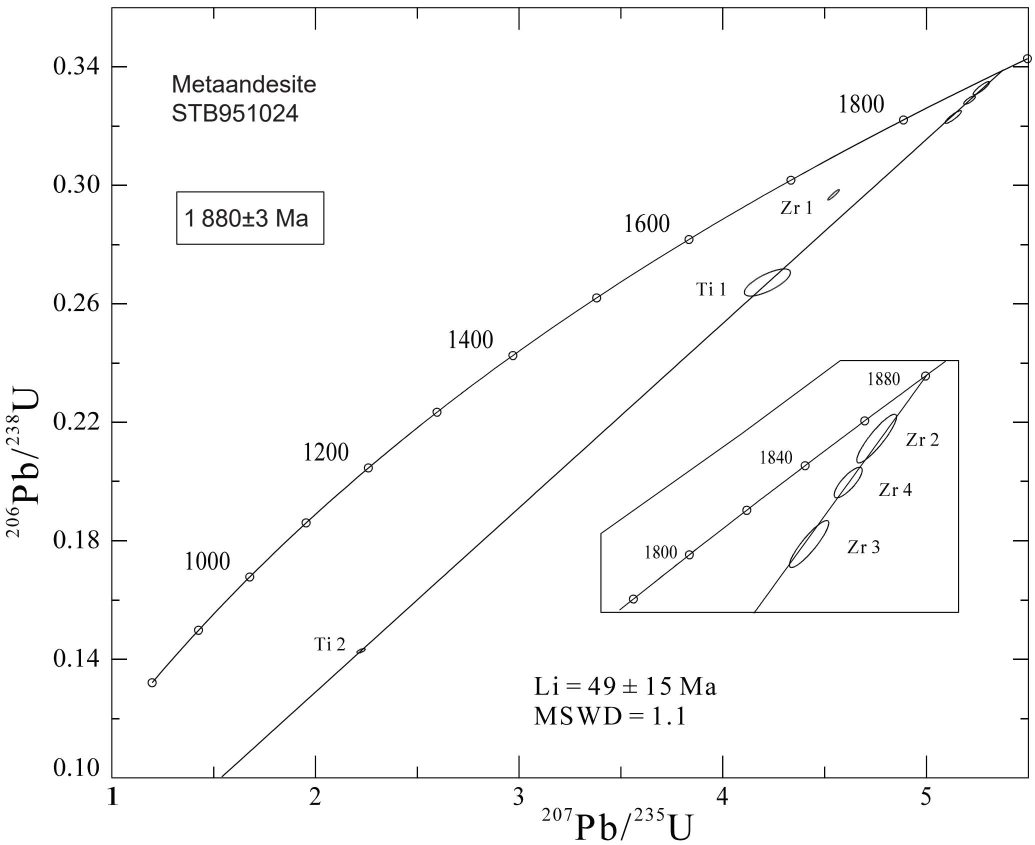

Figure 8. Concordia diagram for (TIMS) analysed titanite and zircon fractions from a metaandesite (sample STB951024) from the Hosiovaara formation.

for titanite fractions. This may indicate that titanite and zircon crystallised during the same event. Zircon fractions 2, 3 and 4 are only slightly discordant, so their age is considered to be well defined. The diverging zircon fraction 1 has the lowest ^{208}Pb and highest U content and a somewhat differing appearance (see above). It may thus contain zircon grains of a different generation than the other three fractions. The titanite fractions, especially the brown crystals, are strongly discordant. No obvious explanation for the discordance can be found. Titanite fraction 2 has a Pb-Pb age of 1 846 ±10 that is within an error range similar to titanite fraction 1.

DISCUSSION

Depositional environment of the Käymäjärvi formation and the Vinsa formation

The metameimechite within the Käymäjärvi formation consists of pyroclastic material, sometimes showing graded bedding, with fragments varying from 3 to less than 1 cm. These units of pyroclastic rocks probably formed as subaqueous pyroclastic flows fed by phreatomagmatic eruptions, occurring in fairly shallow water. The younger Vinsa formation reflects calmer conditions, with deposition of tuffitic sediments of mainly basaltic composition and partly mixed with organic material within units 1 and 3. Unit 3 also often contains abundant scapolite in partly laminated diopside-rich beds. The Vinsa formation also contains thick units of chemical sedimentary rocks, with silicate facies BIF in unit 2 and dolomite in unit 4.

The geochemical composition of the Vinsa formation indicates deposition in an evaporitic environment and slightly anoxic conditions resulting in enrichment of Cl and the occurrence of graphite, respectively. It is suggested that the BIF in unit 2 is of Algoma-type and formed as a distal exhalite in response to more local and high temperature hydrothermal input to the basin (Martinsson et al. 2016). The enrichment of Ba, Mn, Cu, Zn, As, and Sb in unit 3 was probably caused by such hydrothermal activity. Dolomite in unit 4 is suggested to have formed on a shallow marine carbonate platform similar to the dolomites in the Kalix area (Wanke & Melezhik 2005), with dolomite formed at elevated water temperatures or during evaporitic conditions (Machel & Mountjoy 1986, Warren 2000).

Depositional environment for the Sammakkovaara group

The rocks constituting the Sammakkovaara group probably formed in a shallow water environment with contemporaneous andesitic volcanism and clastic sedimentation. Rapid facies changes are recorded by different proportions of metavolcanic and metasedimentary rocks in the Muotkamaa formation and variations in grain size and composition of the metasedimentary rocks within the Hosiokangas formation. Herringbone cross-lamination occurring locally in the upper part of the Hosiokangas formation indicates a tidal depositional environment. An evolution from shallow water to terrestrial deposition is indicated in the Hosiovaara formation, and may be related to the growth of volcanic cones above sea level.

Age of metameimechite from the Käymäjärvi formation and stratigraphic correlations

The only previous chronological data from the Greenstone successions in Sweden come from the Kiruna area (Skiöld & Cliff 1984, Skiöld 1986) and indicate an age of deposition between c. 2.2 and 2.0 Ga for the Kiruna greenstone group (Martinsson 1997). The TIMS zircon age 2 055 ±130 Ma (using four fractions) of meimechitic lapilli tuff from the Käymäjärvi formation suffers from large errors and does not contribute to a more accurate age for the Veikkavaara greenstone group. However, the analysed zircons constitute a heterogeneous population; some have visible cores, while others are very small and anhedral (cf. CL images in Fig. 6). Zircons also exhibit large variation in common Pb content and in ^{206}Pb/^{204}Pb ratio, suggesting that they represent different generations. Additional results from the SIMS and LA-ICP-MS analysis add further complexities. Unfortunately, only crystals of lesser quality were available for microanalysis after completion of the TIMS multi-grain analyses.

However, the minimum age of the Käymäjärvi formation is given by fraction 4, consisting of euhedral zircon grains with the lowest content of common Pb and the highest $^{206}Pb/^{204}Pb$ ratio, giving a Pb-Pb age of 2 038 ±6 Ma. This age is probably close to the depositional age of the Kämyäjärvi formation and is supported by the carbon isotope signature of carbonate rocks in the Veikkavaara greenstone group in the Pajala area (Martinsson 2004b). Carbonate rocks in the Vinsa formation vary from -2.9 to +2.3‰, whereas carbonate rocks in the Pajala area, situated stratigraphically below metavolcanic rocks corresponding to the Käymäjärvi formation, return ratios of between +7.1 and +7.6‰ (Martinsson, unpublished data). Since the global Lomagundi-Jatuli excursion from positive values to more normal marine carbon isotope signatures for carbonate rocks ended at 2 056.6 ±0.8 Ma (Martin et al. 2013), the Käymäjärvi formation should have an age of around 2.05 Ga. Based on these data, the Vinsa formation is of Ludikovian age, whereas the Käymäjärvi formation is possibly older and of Jatulian age.

Taken together, and including a comparison with similar rocks in Finland (see below), an approximate 2.05 Ga emplacement age is suggested for the metameimechite. However, this rock has undergone a complex geological evolution. First, the old 3.0 Ga LA-ICP-MS age (point b48, Table 4) indicates assimilation of older crustal rocks. Further, this age is among the oldest zircon ages known for rocks from Sweden, with previously reported ages from northern Norrbotten falling within the range 2.7 to 3.2 Ga (Martinsson et al. 1999, Lauri et al. 2016). But even older detrital zircons with ages of 3.29, 3.38 and 3.58 Ga have been reported from metaarenites from the Pahakurkio and Kalixälv groups (Hellström et al. 2018). At least two stages of metamorphic growth or metamorphic resetting of the metameimechite, at c. 1.8 Ga and 1.65 Ga, respectively, are indicated from the zircon age data. The 1.8 Ga event is regionally well constrained (Bergman et al. 2001, Martinsson 2004a), but no significant 1.65 Ga geological event has previously been documented in northern Norrbotten. It is worth noting that certain laser spots are related to highly discordant data, suggesting a disturbance of the U-Pb system at around 0.4 Ga. A similar young age, implying a Caledonian event, was also obtained for the lower intercept of the TIMS regression, yielding an imprecise upper intercept age close of 2.05 Ga. A few 400 Ma zircons, interpreted to be of metamorphic origin, have recently been analysed from Svecofennian rocks close to Kiruna, demonstrating the impact of the Caledonian event (Billström et al., in prep.).

Stratigraphic comparisons on a local and a more regional scale help to place the approximate 2.05 Ga metameimechite age in a geological context (Fig. 9). Rocks stratigraphically equivalent to the Käymäjärvi and Vinsa formations also exist east of Käymäjärvi in the Kaunisvaara area, and at Veikkavaara in the Masungsbyn area, west of Käymäjärvi. In these areas, rocks corresponding to the Käymäjärvi formation mainly consist of volcanoclastic rocks of basaltic character, with meimechite occurring as a minor constituent, whereas rocks corresponding to the Vinsa formation generally show great similarities (Martinsson et al. 2013a,b). The Vinsa formation may also correlate with the Linkaluoppal formation in the uppermost part of the Kiruna greenstone group (Martinsson 1997). At Masugnsbyn a mafic sill intruding volcaniclastic rocks belonging to the Veikkavaara greenstone group in a stratigraphic position below the Vinsa formation returns an age of 2 131 ±5 Ma (Lynch et al. 2018b), giving an upper age limit for these rocks.

High quality geochronological data from extrusive rocks are fairly limited for Jatulian to Ludikovian greenstones in other parts of the Fennoscandian Shield. Zircon ages of metabasaltic rocks from Finland yield ages of 2 105 ±15, 2 106 ±7 and 2 115 ±6 Ma (Huhma 1986, Pekkarinen & Lukkarinen 1991, Karhu et al. 2007). Felsic metavolcanic rocks from the Koivusaari formation in the Kuopio-Siilinjärvi area occur interlayered with metabasaltic pillow lavas and have an age of 2 062 ±2 Ma (Lukkarinen 1990, Pekkarinen & Lukkarinen 1991). A similar age of 2 050 ±8 Ma is recorded for a felsic porphyry from the upper part of the Peräpohja Belt (Pertunen & Vaasjoki 2001). Metarhyolite intercalated with metabasaltic lava in the Vesmajärvi formation from the upper part of the Kittilä group is significantly younger, with a U-Pb zircon age of 2 012±3 Ma (Lehtonen et al. 1998). Sm-Nd ages of

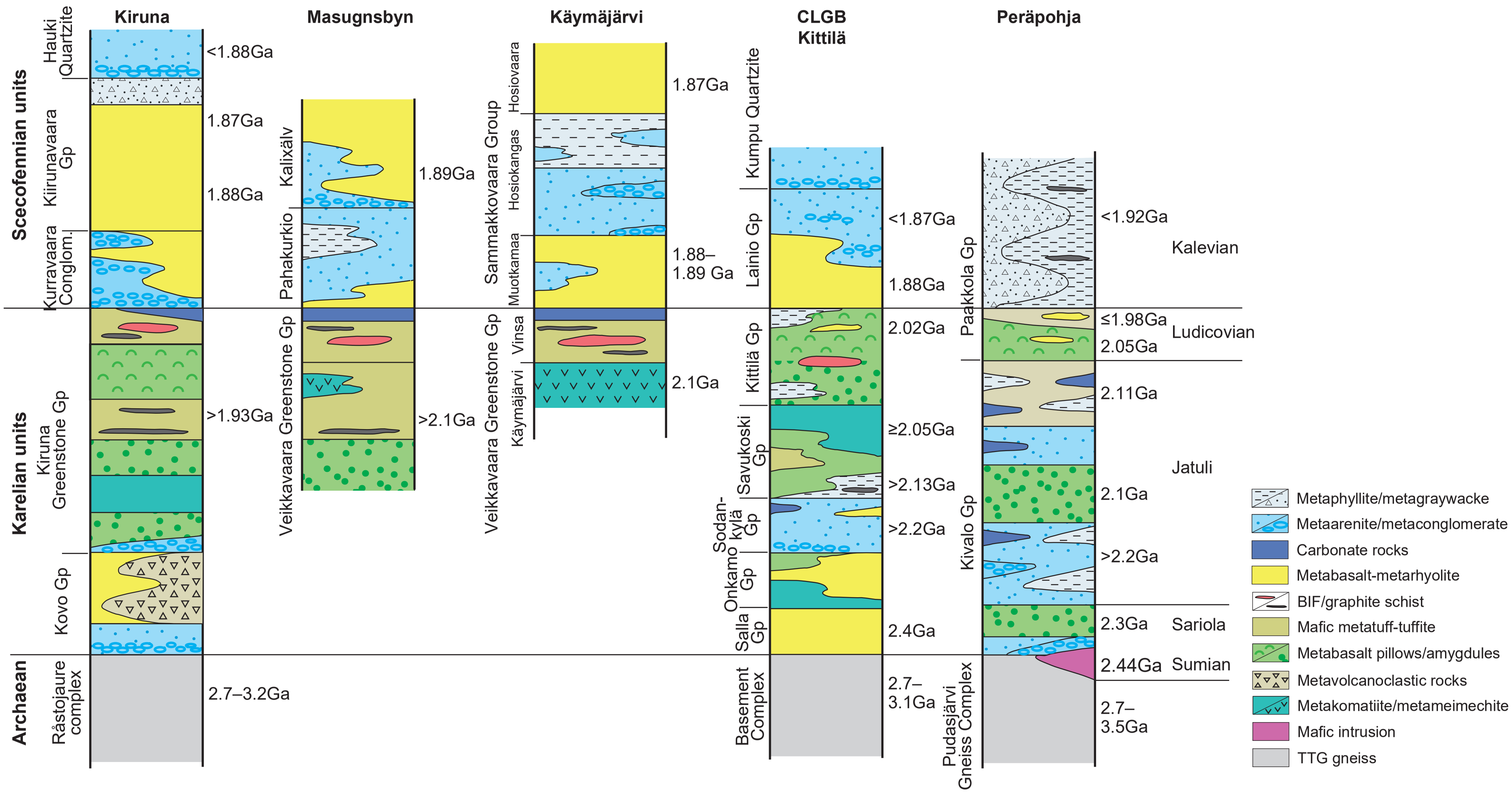

Figure 9. Stratigraphic correlation of Karelian and Svecofennian units in northern Sweden and Finland. Data for the Kiruna area from Skiöld (1979, 1986), Skiöld & Page (1998) Martinsson et al. (1999), Martinsson (2004), Bergman et al. (2000), and Westhues et al. (2016). Data for the Masugnsbyn area from Padget (1970), Martinsson (1995), Martinsson et al. (2013a), Hellström et al. (2018), and Lynch et al. (2018b). Data for the Käymäjärvi area from Martinsson (1995), Martinsson et al. (2013b) and this study. Data for the Central Lapland Greenstone Belt (CLGB) from Lehtonen et al. (1998), Rastas et al. (2001), Manninen et al. (2001), Hanski et al. (2001a, 2001b). Data for the Peräpohja Belt from Huhma et al. (1990), Perttunen & Vaasjoki (2001), Hanski et al. (2001b), Mutanen & Huhma (2003), Hanski et al. (2005), Karhu et al. (2007), and Ranta et al. (2015).

metabasaltic to metakomatiitic rocks in Finland and northern Norway give less precise ages: around 2.3 and 2.1 Ga (Krill et al. 1985, Huhma 1986, Huhma et al. 1990, Pekkarinen & Lukkarinen 1991, Hanski et al. 2001a, Perttunen & Vaasjoki 2001).

Intrusions associated with the Jatulian-Ludikovian evolution occur as dyke swarms in the Archaean granite-gneiss basement and as gabbroic plutons and sills in Karelian cover units (Gorbatschev et al. 1987, Vuollo 1994). These more precise isotopic ages indicate magmatic peaks at c. 2.3, 2.2, 2.1, 2.05 and 2.0 Ga (Vuollo et al. 2000, Hanski et al. 2001b), supporting the 2.3 and 2.1 to 2.0 Ga ages of the metavolcanic rocks. Metasedimentary rocks from the upper part of the greenstone successions give Pb-Pb ages of 2 080 ±45 Ma for an iron formation from Kainuu (Sakko & Laajoki 1975), and 2 119 ±243 Ma for a dolomite at Kalix (Öhlander et al. 1992). These fairly limited and often imprecise geochronological data, including those from the current study, indicate an age of 2.1–2.0 Ga for most of the mafic-ultramafic volcanism forming the Jatulian to Ludikovian greenstones in Finland, northern Norway and Sweden.

Age of andesites from the Sammakkovaara group and stratigraphic correlations

Within the margins of error, zircon and titanite in sample STB951024 from the Hosiovaara formation give similar ages, but with a much larger error for the titanite fractions. The three zircon fractions alone give an age of 1 874 ±11 Ma and, combined with the titanite fractions, an age of 1 880 ±3 Ma, identical, within the margin of error, to the 1 882 ±2 Ma age of sample 28MOM576N from the Muotkamaa formation. Based on the texture of the STB951024 metaandesite, the titanite is probably of metamorphic origin, supported by the rare occurrence of titanite as a primary igneous mineral in extrusive rocks. This implies that either both extrusion and metamorphism of the andesitic rocks occurred within a short time interval close to 1 880 Ma, or that the zircons also record a metamorphic event. As both of the studied andesitic rocks are fairly strongly recrystallised under middle-upper amphibolite facies conditions, and are partly affected by strong scapolitisation, a metamorphic growth of zircons or a resetting of pre-existing magmatic zircons during metamorphism should be considered. That might be reflected in the morphology of certain zircon grains that either have an irregular shape or occur as subhedral prisms with rounded edges and pitted or irregular surfaces. The 1 890 ±6 Ma Pb-Pb age of the <74 µm zircon fraction from sample 28MOM576N from the Muotkamaa formation may be evidence of an older magmatic age.

In Finland, an early Svecofennian 1.93–1.91 Ga arc magmatic event is documented from the Savo Schist Belt (Ekdahl 1993, Lahtinen 1994). The existence of c. 1.93 Ga intrusive rocks of tonalitic-granodioritic composition in the Jokkmokk and Rombak areas (Skiöld et al. 1993, Romer et al. 1992, Hellström 2015) indicates that this arc magmatism extended further to the northwest for a distance of at least 500 km along the margin of the Karelian domain. If the 1 882 ±2 Ma age for the metaandesite from the Muotkamaa formation is of metamorphic origin, this lower volcanic unit may belong to the earliest 1.93–1.91 Ga, or slightly younger 1.89 Ga, Svecofennian magmatism. If not, the metavolcanic and metasedimentary units (Muotkamaa Fm, Hosiokangas Fm and Hosiovaara Fm) constituting the Sammakkovaara group must have been deposited and subsequently metamorphosed within a few million years.

Similar ages (1 883 ±5 Ma) have been reported from volcanic rocks within the Latvajärvi formation, which belongs to the Lainio group in northern Finland (Lehtonen et al. 1998). Although the Latvajärvi metavolcanics are geochemically slightly different from the Sammakkovaara metaandesites, the Sammakkovaara group is regarded as stratigraphically equivalent to the Lainio group (Lahtinen et al. 2015).

It is suggested that the Sammakkovaara group is stratigraphically correlated to the Porphyrite group in the Kiruna area (Martinsson 2004a, Martinsson et al. 2016), supported by chemical similarity (Fig. 4). No age determinations exist from the Porphyrite group at Kiruna, but the 1 884

±4 Ma age of the Hopukka formation in the lower part of the overlying Kiirunavaara group (Westhues et al. 2016) gives it a minimum age. Consequently, the upper age limit for the Porphyrite group must be 1880 Ma, which accords with the 1 878 ±7 Ma minimum age for a "Porphyry group" metaandesite at Tjårrojåkka, west of Kiruna (Edfelt et al. 2006). Similar 1.88 Ga ages are recorded for the Muorjevaara group in the Gällivare area (Claeson & Antal Lundin 2012, Lynch et al. 2018a), suggested to correlate with the Porphyrite group (Martinsson & Wanhainen 2004). Metavolcanic rocks at Sakkarinpalo in the Masungsbyn area correlated with the Porphyrite group and have a zircon age of 1 890 ±5 Ma (Hellström et al. 2018). A similar age (1 887 ±5 Ma) is recorded from the metaandesite rocks within the Kalixälv formation (Hellström et al. 2018), which may be correlated with the Hosiovaara formation. These two zircon ages close to 1.89 Ga support a possible older 1.89 Ga depositional age of the Muotkamaa formation, indicated by the 1 890 ±6 Ma Pb-Pb age.

In a regional context, the Sammakkovaara group is regarded as stratigraphically equivalent to Svecofennian clay-rich to ruditic metasedimentary rocks in the Kiruna area (i.e. the Kurravaara conglomerate and the metasedimentary rocks at Vuotnavare and Väkkerijärvi; Offerberg 1967), and to metasedimentary rocks within the Muorjevaara group in the Gällivare area (Martinsson & Wanhainen 2004). In eastern Norrbotten, it is suggested that the Hosiokangas formation and the Hosiovaara formation correlate with the Pahakurkio and Kalixälv groups, respectively, in the Masugnsbyn area (Padget 1970; Fig. 9). These latter two groups consist of arenitic to clay-rich metasedimentary rocks with minor intercalations of quartz-pebble conglomerate and metavolcanic rocks similar to the Sammakkovaara group, and have maximum depositional ages of 1.91 and 1.88 Ga, respectively (Hellström et al. 2018).

The 1 879 ±62 Ma metamorphic titanite in sample STB951024 may relate to the suggested c. 1.88 Ga syn-magmatic metamorphic and deformation event in northern Norrbotten (Bergman et al. 2001), or to the younger, c. 1.85 Ga metamorphic event, in eastern Norrbotten (Bergman et al. 2006). An even younger, c. 1.81-1.78 Ga, metamorphic event has been documented by chronological data from the Pajala area (Bergman & Skiöld 1998, Bergman et al. 2001). This later metamorphism is probably seen in the c. 1.81 Ga zircons in sample STB951023 and the 1.82 Ga Pb-Pb age of one zircon fraction in sample STB951024. In contrast, the c. 1.65 Ga age recorded in sample STB951023 cannot be related to any known event in northern Norrbotten.

CONCLUSIONS

Petrographic, stratigraphic and geochronological data from Käymäjärvi in eastern Norrbotten are presented for 2.1–2.0 Ga Karelian and 1.9 Ga Svecofennian supracrustal units. The Karelian rocks are subdivided into the Käymäjärvi formation and overlying Vinsa formation. The Svecofennian supracrustal rocks constitute the Sammakkovaara group, which includes the Muotkamaa formation in the lowest part, followed by the Hosiokangas formation and, at the top, the Hosiovaara formation.

Zircon age determinations indicates that pyroclastic metameimechite from the Käymäjärvi formation was deposited at c. 2.1–2.0 Ga, and in combination with carbon isotope evidence this age can be narrowed down to close to 2.05 Ga. Metaandesites from the Muotkamaa and Hosiovaara formations both give zircon ages close to 1.87–1.88 Ga. But the metaandesites from the Muotkamaa formation have a zircon fraction with a Pb-Pb age of 1.89 Ga, possibly suggesting a slightly older age for this rock. Zircon evidence from the analysed samples also records a metamorphic disturbance at c. 1.8 Ga.

The Käymäjärvi and Vinsa formations can be correlated with other greenstone units in northern Norrbotten and correspond to the Jatulian-Ludikovian units in the northeastern Fennoscandian Shield. The Sammakkovaara group is correlated with the lower Svecofennian Porphyrite group in the Kiruna area, with the Muorjevaara group in the Gällivare area and other arenitic to clay-rich metasedimentary formations in northern Norrbotten.

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