Rapporter och meddelanden 141

Geology of the Northern Norrbotten ore province, northern Sweden

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Editor: Stefan Bergman




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New text: Mafic pyroclastic deposits are overlain by volcaniclastic rocks interlayered with carbonate rock, graphite schist, skarn-related iron oxide deposits, banded iron formation and chert (Martinsson 1993, Martinsson et al. 2018b, Lynch et al. 2018b). Most of these rocks were deposited before 2.14 Ga, and only minor assimilation of older continental crust occurred during magma ascent or storage (Lynch et al. 2018b).

Original text: Mafic pyroclastic deposits are overlain by volcaniclastic rocks interlayered with carbonate rock, graphite schist, skarn-related iron oxide deposits, banded iron formation and chert (Martinsson 1993, Martinsson et al. 2018b, Lynch et al. 2018b) show that most of these rocks were deposited before 2.14 Ga, and that only minor assimilation of older continental crust occurred during magma ascent or storage.

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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1. Regional geology of northern Norrbotten County

Stefan Bergman

The Precambrian bedrock in northernmost Sweden, including the Northern Norrbotten ore province, is part of the 2.0–1.8 Ga old Svecokarelian orogen. The orogen comprises both pre-orogenic rocks formed in the Archaean and early Palaeoproterozoic, as well as rocks formed during the orogeny itself. All the rocks were deformed and metamorphosed to variable degrees at different stages during the orogenic evolution. To the west the Precambrian rocks are overlain by Ediacaran–Cambrian platformal sedimentary cover rocks and nappes of the Caledonian orogen (Fig. 1).

The geology of northern Norrbotten County was first described by Fredholm (1886) and Svenonius (1900). More detailed work by Lundbohm (1910), Sundius (1915), Geijer (1931), Ödman (1939, 1957) and Eriksson (1954) followed these brief outlines. Summaries were presented by Witschard (1984), Bergman et al. (2001, 2007), Martinsson (2004), Martinsson & Wanhainen (2013) and Martinsson et al. (2016). A short summary is given here, including preferred nomenclature (Table 1), with reference to some of the main results from the papers in this volume.

The oldest rocks were formed in the Archaean and belong to the Råstojaure complex. The main component is gneissic granitoid of mainly tonalitic to granodioritic composition, which shows intrusive relationships with paragneiss, amphibolite and, locally, banded orthogneiss interpreted as metaandesitic to dacitic tuff. Bodies consisting of non-migmatitic metamorphosed granite are common in the east. Age determinations suggest crystallisation of granitoids at 2.8–2.7 Ga, and a regional metamorphic event is constrained at 2.7 Ga (Skiöld 1979, Skiöld & Page 1998, cf. Martinsson et al. 1999).

Layered mafic-ultramafic intrusions with an age of 2.5–2.4 Ga occur locally within the Råstojaure complex; more common are mafic dykes and felsic–mafic intrusions related to later events. A metamorphosed volcano-sedimentary sequence, deposited before 2.0 Ga and unconformably overlying the Archaean basement is commonly referred to as the Karelian supracrustal rocks (see also Gaál and Gorbatschev 1987). The lowermost unit in the Kiruna area is the Kovo group, which is composed of a basal clastic sequence of metamorphosed conglomerate and quartzite, overlain by tholeiitic metabasalt and metamorphosed calc-alkaline volcaniclastic rocks of andesitic composition. The eastern part of the Råstojaure complex is overlain by the Tjärro quartzite, along with subordinate metamorphosed conglomerate and phyllite. Locally, metavolcanic rocks of andesitic to dacitic composition occur below

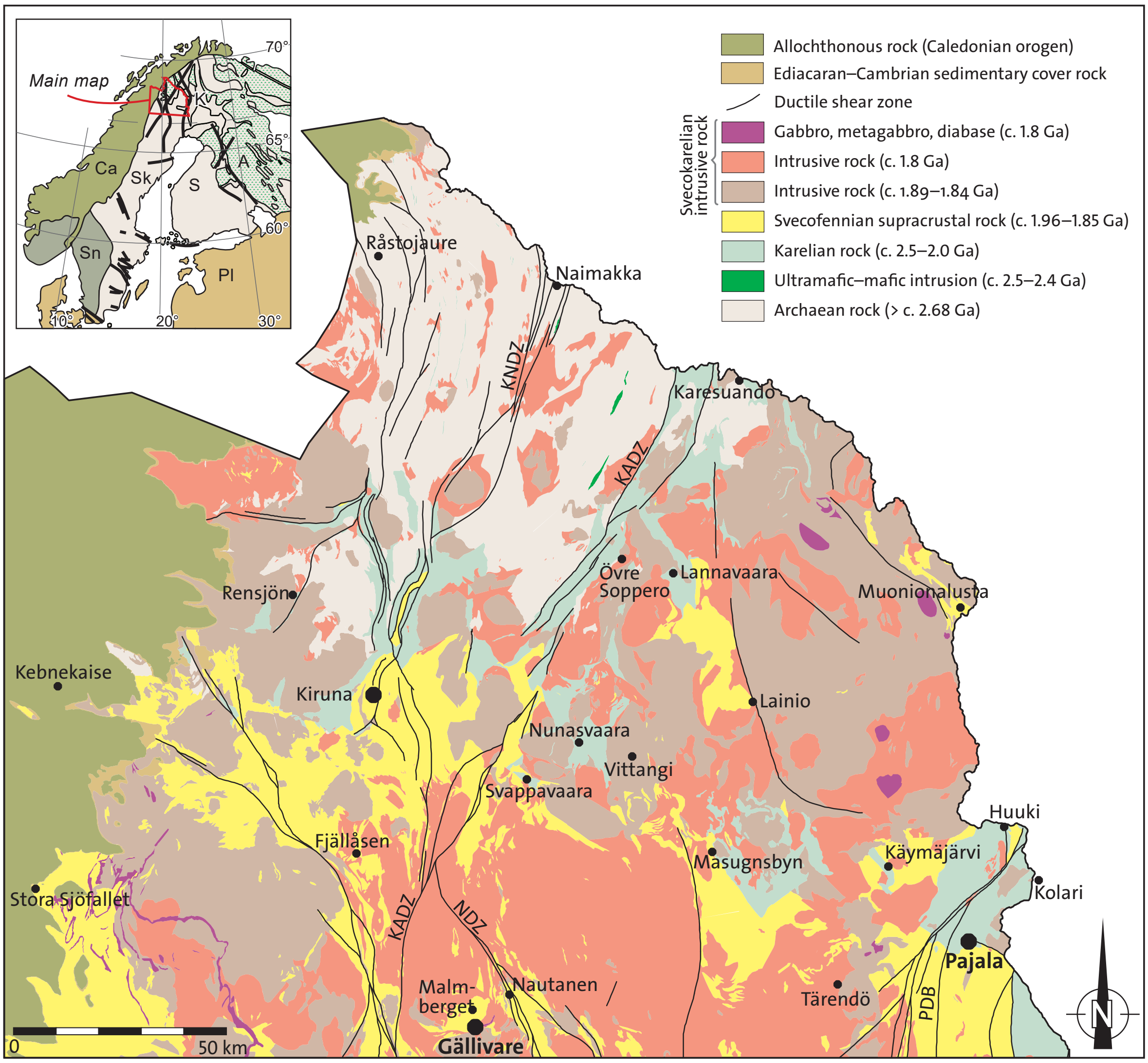

Figure 1. Simplified bedrock map of northern Norrbotten County, modified from Bergman et al. (2001). KNDZ = Kiruna–Naimakka deformation zone, KADZ = Karesuando–Arjeplog deformation zone, NDZ = Nautanen deformation zone, PDB = Pajala deformation belt. Inset map: Sk = Svecokarelian orogen, Sn = Sveconorwegian orogen, Ca = Caledonian orogen, Pl = Platformal sedimentary cover rocks, A (green ornament) = Archaean rocks in part reworked in the Palaeoproterozoic, K (grey ornament) = Karelian rocks, S (without ornament) = Svecofennian supracrustal rocks and Svecokarelian intrusive rocks; thick lines are major deformation zones.

the quartzite. Metasandstone, quartzite and quartzo-feldspathic gneiss in the Pajala area and to the south are spatially associated with both Karelian and younger metavolcanic rocks. The presence of several originally clastic units, with distinctly different detrital zircon age populations, is confirmed by recent results of Lahtinen et al. (2015).

In the Kiruna area the Kovo group is overlain by the Kiruna greenstone group, which predominantly comprises metamorphosed, tholeiitic basalt lava flows, including pillow lava, less important komatiitic lava, tholeiitic tuff and andesitic to dacitic tuffaceous rocks, and minor conglomerate, black schist and carbonate rock (Martinsson 1997). The Viscaria Cu-rich sulphide deposit is hosted by metamorphosed volcaniclastic and associated sedimentary rocks belonging to the Kiruna greenstone group. The stratigraphic sequence is similar but less complete in the area between Kiruna and Pajala, where mainly the upper parts are exposed in the Veikkavaara greenstone group. Mafic pyroclastic

Table 1. Lithostratigraphic and lithodemic unit names preferred in this volume.

Approximate age (Ga)	Lithostratigraphic units	
< 1.88	Snavva-Sjöfallet group[1]	
		Hauki quartzite[2] Maattavaara quartzite[3]
1.89–1.87	Kiirunavaara group[4]	Matojärvi formation[4] Luossavaara formation[4] Hopukka formation[4]
1.89–1.88	Porphyrite group[5]	
		Kurravaara conglomerate[6]
	Pahakurkio group[7] Sakarinpalo suite[20] Kalixälv group[7] Muorjevaara group[8]	
	Sammakkovaara group[4]	Hosiovaara formation[4] Hosiokangas formation[4] Muotkamaa formation[4]
2.3–2.0	Kiruna greenstone group[9]	Linkaluoppal formation[9] Peuravaara formation[9] Viscaria formation[9] Pikse formation[9] Ädnamvare formation[9] Såkevaratjah formation[9]
	Vittangi greenstone group[3]	Nunasvaara member[21]
	Veikkavaara greenstone group[7]	*West:* Masugnsbyn formation[21] Tuorevaara greenstone formation[21] Suinavaara formation[21] Nokkokorvanrova greenstone formation[21] *East:* Vinsa formation[10] Käymäjärvi formation[10]
2.7–2.3		Tjärro quartzite[12]
	Kovo group[9]	Harrejaure formation[11] Rautojaure formation[11]
	Lithodemic units	
1.80–1.79	Edefors suite[13]	Nabrenjarka diabase[14]
1.81–1.78	Lina suite[15]	
1.86–1.85	Jyryjoki granite[16]	
1.88–1.86	Perthite monzonite suite[17]	
1.89–1.88	Haparanda suite[18]	
>2.7	Råstojaure complex[19]	

[1]Ödman (1957), [2]Lundbohm (1898), [3]Eriksson & Hallgren (1975), [4]Martinsson (2004), [5]Offerberg (1967), [6]Sundius (1912), [7]Padget (1970), [8]Zweifel (1976), [9]Martinsson (1997), [10]Martinsson & Wanhainen (2013), [11]Martinsson (1999a), [12]Ödman (1939), [13]Öhlander & Skiöld (1994), [14]Witschard (1975), [15]Holmqvist (1906), [16]Witschard (1970), [17]Witschard (1984), [18]Ödman et al. (1949), [19]Martinsson (1999b), [20]Hellström et al. (2018), [21]Lynch et al. (2018b).

deposits are overlain by volcaniclastic rocks interlayered with carbonate rock, graphite schist, skarn-related iron oxide deposits, banded iron formation and chert (Martinsson 1993, Martinsson et al. 2018b, Lynch et al. 2018b). Most of these rocks were deposited before 2.14 Ga, and only minor assimilation of older continental crust occurred during magma ascent or storage (Lynch et al. 2018b).

Svecofennian supracrustal rocks, recording the onset of the Svecokarelian orogeny, unconformably to disconformably overlie the Kiruna greenstone group and related units. The lower part of the sequence is characterised by calc-alkaline, metavolcanic rocks of andesitic composition. On a regional scale, these rocks show extensive interlayering, with metamorphosed, siliciclastic sedimentary rocks. They contain both Palaeoproterozoic and Archaean detrital zircons (Hellström et al. 2018), consistent with their origin in both local and remote source areas (Martinsson 2004). Metavolcanic and metasedimentary rocks are traditionally included in the Porphyrite group, defined in the low-grade rocks southwest of Kiruna. Equivalent units occur in other areas; see Table 1. Available age determinations show crystallisation ages of 1.89–1.88 Ga (Edfelt et al. 2006, Martinsson et al. 2018b, Hellström et al. 2018, Lynch et al. 2018a).

The Kiirunavaara group stratigraphically overlies the Kurravaara conglomerate in the Kiruna area and the Porphyrite group to the southwest of Kiruna. In Kiruna metamorphosed andesitic to trachyandesitic lava flows comprise the footwall of the Kiruna apatite iron oxide ore deposit. This deposit is overlain by porphyritic metadacite of pyroclastic origin (Martinsson 2004). The age of the host rocks is 1.89–1.87 Ga, and the ore has been dated at 1.88–1.87 Ga (Westhues et al. 2016). The uppermost unit in the Kiirunavaara group mainly consists of metamorphosed ignimbritic tuff, basalt and siliciclastic sedimentary rock. Southwest of Kiruna a thick sequence of metamorphosed, high-Ti and high-Zr tholeiitic basaltic lava is overlain by a unit predominantly comprising pyroclastic metadacite. There are subordinate intercalations of metamorphosed andesite, locally ignimbritic rhyolite, conglomerate, sandstone and siltstone (Offerberg 1967, Perdahl & Martinsson 1995, Martinsson 2004).

The youngest supracrustal unit consists of sandstone with subordinate conglomerate and mudstone, and in some areas basaltic intercalations. The sequence is best developed in the Snavva–Sjöfallet group, where it exceeds a thickness of 6 000 ms (Witschard & Zachrisson 1995), resting on metavolcanic rocks similar to the Kiirunavaara group. Although the contacts are tectonic in most other areas, including the Hauki quartzite in the Kiruna area, there is a locality northwest of Vittangi where a metaconglomerate rests unconformably on a metadiorite (Ödman 1939). The metadiorite is 1.88 Ga old (Bergman et al. 2002a), representing the maximum age of the clastic deposition in this area.

The more or less gneissic rocks in the Haparanda suite are commonly grey and medium-grained, but fine-grained types are also present; porphyritic varieties are uncommon. Magma mingling textures are common in some areas. According to published modal data (Ödman 1957, Bergman et al. 2001), there is a wide spectrum of rock types, from predominantly gabbroid and dioritoid, through quartz monzonite, tonalite and granodiorite, to subordinate granite.

The intrusive rocks in the Perthite monzonite suite, formed between 1.88 and 1.86 Ga, mainly occur in the westernmost part of the area. Quartz-poor rocks, including monzonite, quartz monzonite and quartz monzodiorite, predominate over granite. Many large intrusions of gabbro and diorite, inferred to belong to this suite, are also present. Magmatic layering has been observed in some of these bodies, and several show a concentric, banded magnetic pattern. Ultramafic rocks such as pyroxenite and serpentinite are present in some areas. Perthite-bearing granite is commonly red and medium- to coarse-grained. Enclaves and hybridisation phenomena show that magma mingling and mixing processes were prevalent. The rocks in the Perthite monzonite suite are typically isotropic but there are also areas where a tectonic fabric is prominent. Witschard (1975, 1984) pointed out the geochemical similarity between the Perthite monzonite suite and the Kiirunavaara group, suggesting that the former was emplaced under sub-volcanic conditions. The rock types in the Perthite monzonite suite are similar to those in the Haparanda suite, but have traditionally been considered separate on the basis of several lines of evidence, including field relationships and lithogeochemical characteristics.

A suite of granite and granodiorite that has yielded an age of c. 1.85 Ga (Bergman et al. 2006, Hellström & Bergman 2016), the Jyryjoki granite, occurs in a large area east of Lainio (Fig. 1). The granitoids are spatially associated with pegmatite, and in many places contain biotite-rich seams and partly assimilated remnants of older rocks. The granitoids are porphyritic, have an unequigranular matrix and are weakly foliated.

Large bodies of intrusive rocks belonging to the Lina suite, which formed around 1.8 Ga (Skiöld 1988, Bergman et al. 2002b), are common throughout the area, and dykes or veins of rocks belonging to this suite commonly cut older rocks. The Lina suite is mainly composed of greyish-red, medium-grained and weakly porphyritic granite; red, fine-grained and equigranular varieties are also common.

The granite is usually weakly foliated, associated with pegmatite, and fragments of assimilated country rock are common. Dykes or veins in older rocks consist of granite, pegmatite or aplite. A suite of intrusive rocks consisting of gabbro to granite, with quartz monzonite, monzonite, quartz monzodiorite and monzodiorite as intermediate members is found in the east of the area. Syenite has been reported from southwest of Kiruna. They have ages close to 1.8 Ga (Romer et al. 1994, Martinsson et al. 2018a) and the latter authors suggest a genetic relationship to ring-shaped gabbroic intrusions. The Nabrenjarka diabase, west of Gällivare, is a conspicuous, flat-lying, bowl-shaped and sill-like intrusion with an exposed length of more than 50 km. It intrudes the Lina suite and is 1.8 Ga or younger.

Ductile deformation includes several phases of folding and the formation of major crustal-scale shear zones. The metamorphic grade within the region varies from greenschist facies to upper amphibolite facies, and the intensity of deformation varies from strong penetrative foliation to texturally and structurally well-preserved rocks, both on a regional and local scale. Firm control of the geometry of folds, shear zones and other structures, as well as structural evolution is essential to correctly interpret stratigraphic sequences. The major structures in the Kiruna–Vittangi–Masugnsbyn areas have been modelled in 2D and 3D using a range of geophysical data (Bastani et al. 2018, Jönberger et al. 2018) and evaluation of existing geological data and models. This has provided a broad structural framework for more local studies. Grigull et al. (2018) describe the styles of folds and folding phases, concluding that the Kiruna area only experienced one major ductile deformation phase, whereas the deformation history further east is more complex. Up to four separate phases of deformation have been identified in the east (Grigull et al. 2018, Lynch et al. 2018b). New kinematic data, 3D models and a reconstructions of the deformation history of the Pajala deformation belt and the Vakko and Kovo zones north of Kiruna are provided by Luth et al. (2018a, 2018b). Together, these contributions provide new insights into the three-dimensional structural geometry, as well as a refined view of the structural evolution.

An event of deformation and metamorphism at c. 1.88 Ga, previously inferred from local field observations and indirect dating (e.g. Skiöld & Öhlander 1989, Bergman et al. 2001), has now been confirmed by U-Pb zircon dating of a migmatite in the Masugnsbyn area (Hellström 2018). A younger metamorphic event at 1.86–1.85 Ga is recorded by monazite ages from the same area (Bergman et al. 2006). A protracted event or several separate events during the time interval 1.83–1.78 Ga (Bergman et al. 2001, 2006, Lahtinen et al. 2015, Hellström & Bergman 2016), including movement along the Pajala deformation belt, concluded the ductile deformation in the region.

The most important types of mineralisation are stratiform copper deposits, iron formations, Kiruna-type apatite iron ores and epigenetic copper-gold deposits. Hydrothermal alterations are both of regional character and spatially associated with mineralisations. The most characteristic alteration products are scapolite and albite, but skarn, biotite, carbonate, K-feldspar, sericite, tourmaline, epidote and chlorite are also common (e.g. Bergman et al. 2001, Martinsson et al. 2016, Lynch et al. 2018a). The geochemical composition of till overlying the bedrock reflects these alterations as enrichment in e.g. Ba, Ca, Cl, K, Na, Sr, La, Rb and P (Ladenberger et al. 2018a). New age determinations show that major mineralisation events occurred at 1.88–1.86 Ga and 1.79–1.74 Ga (Martinsson et al. 2016), i.e. close in time to major phases of magmatism, deformation and metamorphism.

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