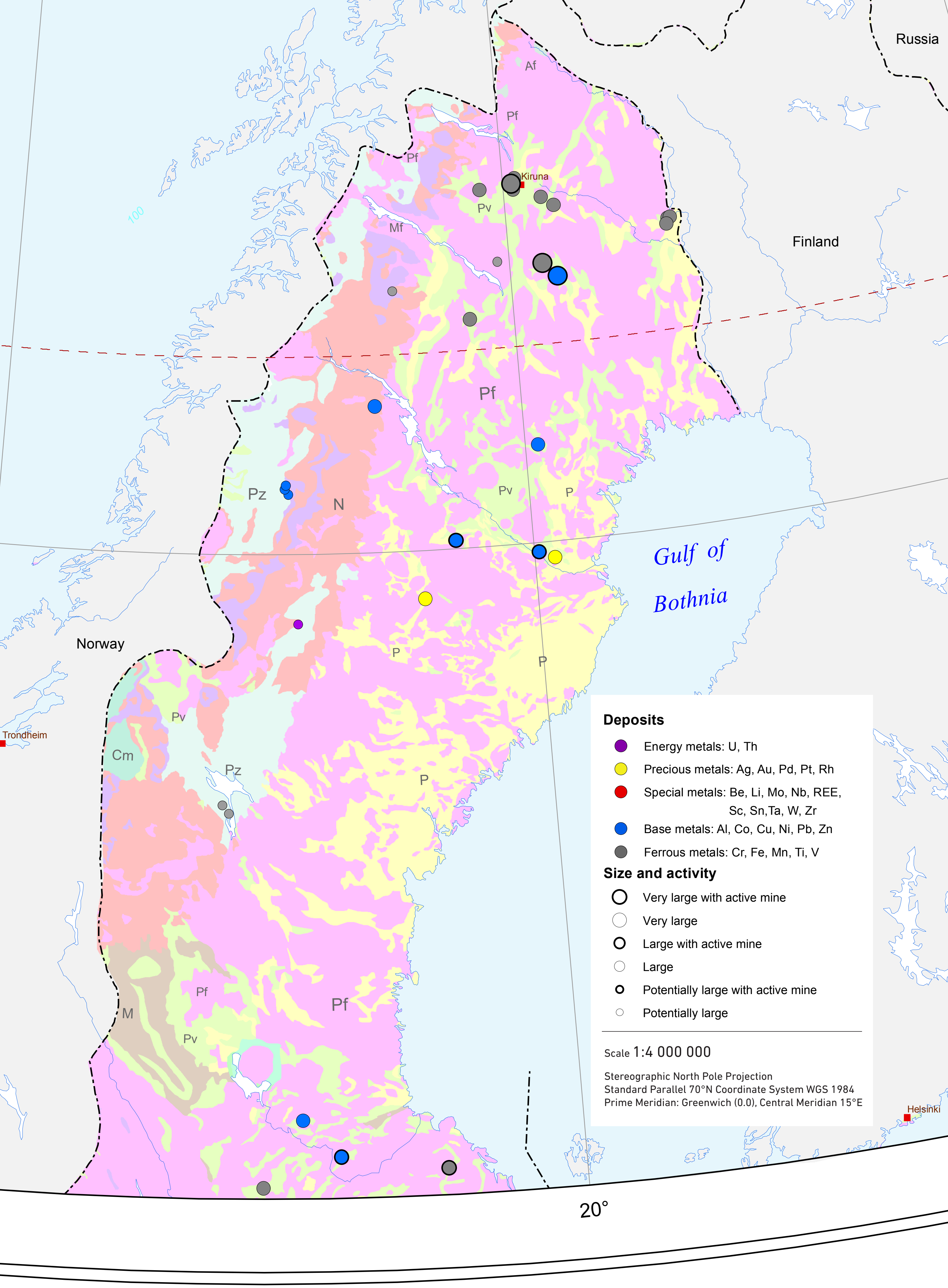

Russia
Finland
Norway
Kiruna
Trondheim
Helsinki
Gulf of Bothnia
Af
Pf
Pv
Mf
N
Pz
P
Cm
M
100
20°
Deposits
Energy metals: U, Th
Precious metals: Ag, Au, Pd, Pt, Rh
Special metals: Be, Li, Mo, Nb, REE, Sc, Sn,Ta, W, Zr
Base metals: Al, Co, Cu, Ni, Pb, Zn
Ferrous metals: Cr, Fe, Mn, Ti, V
Size and activity
Very large with active mine
Very large
Large with active mine
Large
Potentially large with active mine
Potentially large
Scale 1:4 000 000
Stereographic North Pole Projection
Standard Parallel 70°N Coordinate System WGS 1984
Prime Meridian: Greenwich (0.0), Central Meridian 15°E

CHAPTER 7

SWEDEN

Authors: Hallberg, A., Bergman, T., Gonzalez, J., Morris, G. A., Perdahl, J. A.*, Reginiussen, H., Ripa, M.,

Geological Survey of Sweden (*) present address: LKAB, Malmberget

GEOLOGY

The bedrock of Sweden can be divided into six major lithotectonic units (Figure 1): the Svecokarelian orogen (2.0-1.8 Ga), the Blekinge-Bornholm orogen (1.5-1.4 Ga), Post-Svecokarelian magmatic and sedimentary provinces, the Sveconorwegian orogen (1.1-0.9 Ga), the Caledonian orogen (0.5-0.4 Ga) and Neoproterozoic and Phanerozoic platformal cover and igneous rocks (References on geology at the end of the chapter).

Svecokarelian orogen

The Svecokarelian orogen in Sweden is inferred to have formed along an active continental margin in a convergent plate boundary setting between 2.0 and 1.8 Ga. Cycles of magmatic activity and sedimentation, up to 40–50 Ma long, are a characteristic feature of the Svecokarelian orogenic development. Metamorphism under low-pressure and, in large areas, amphibolite- and even granulite facies conditions prevailed during and after crustal shortening. Large parts of the bedrock of Sweden were formed or were tectonically affected by the Svecokarelian orogeny during this time. The main lithotectonic units of the Svecokarelian orogen in Sweden are Norrbotten, Bothnia-Skellefteå and Bergslagen. These units also host the three most important mining districts in Sweden. Minor lithotectonic units include Överkalix with a bedrock similar to Norrbotten but with a different tectonic history, Ljusdal dominated by 1.87-1.84 Ga metamorphosed granitoids and Småland with rhyolites, dacites and quartz latites dated to c. 1.8 Ga and occurring as megaenclaves in felsic intrusive rocks of the Transscandinavian Igneous Belt, similar in age.

The northernmost part of the **Norrbotten** lithotectonic unit consists of Archaean metagranitoids, with minor gneissic rocks of supracrustal origin (Bergman et al. 2001). In Palaeoproterozoic time the Archaean rocks were rifted and intruded by ultramafic to mafic rocks, followed by deposition of sedimentary, mafic volcanic and carbonate rocks in a rift-related tectonic setting. These rocks, the Karelian supracrustal rocks (c. 2.4-1.96 Ga), make up the oldest ore-bearing formation in Sweden with iron- and copper deposits (Bergman et al. 2001). During the Svecokarelian orogeny, the older rocks were deformed and metamorphosed, and extensive igneous activity resulted in calc-alkaline meta-andesite and a bimodal group of mafic and felsic metavolcanic rocks which, together with clastic metasedimentary rocks, were deposited on top of older rocks (Bergman et al. 2001). Several suites of intrusions in northern Sweden were formed during the orogeny.

The oldest rocks in the **Bothnia-Skellefteå** lithotectonic unit are turbiditic to coarse-grained sedimentary sequences with some mafic rocks. Magmatic activity during the orogeny formed the rocks of the Skellefte district, a province with both submarine and subaerial volcanic rocks deposited in volcanic arc environments. During the orogeny the supracrustal rocks were intruded by several generations of intrusive rocks of granitic to gabbroic compositions.

The oldest rocks in the **Bergslagen** lithotectonic unit are turbiditic metagreywackes of Palaeoproterozoic age. During the Svecokarelian orogeny intense felsic volcanism was coupled to rapid basin subsidence (Allen et al. 1996). After the waning of the volcanism the basins were filled with clastic sediments and carbonates. The main volcanic stage was followed by the intrusion of several generations of intrusive rocks (Stephens et al. 2009).

Sveconorwegian orogen

In the south-western part of Scandinavia, the bedrock shows evidence of an accretionary to terminal collisional orogenic system at 1.1–0.9 Ga. In Sweden, this orogenic system involved subduction of continental lithosphere with the

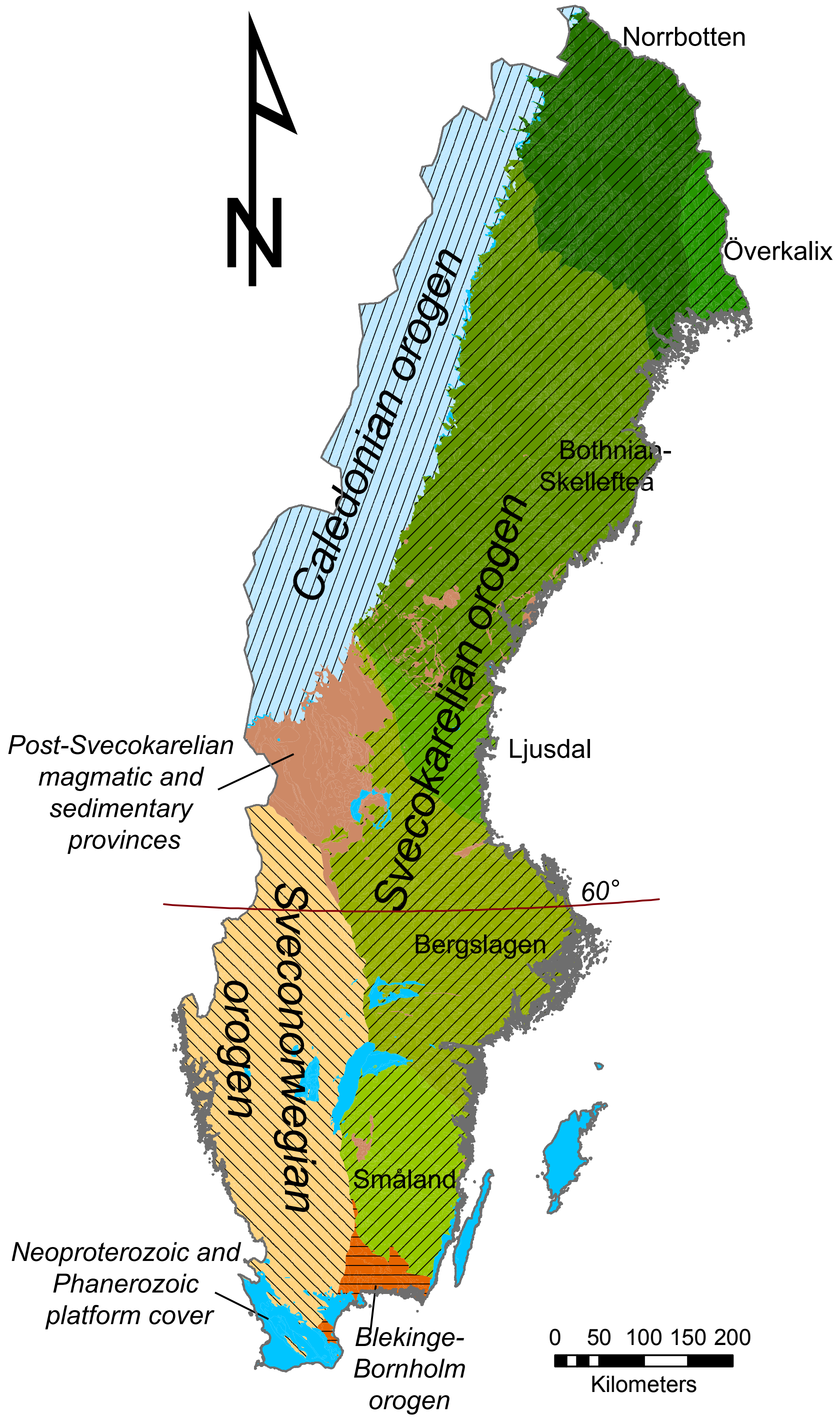


Figure 1. Geological overview of Sweden.

development of eclogite and high-P granulite. A significant feature of this orogenic system in Sweden is the dominance of pre-orogenic rocks (with respect to the Sveconorwegian orogeny) including reworked basement rocks from several previous orogens.

Caledonian orogen

In Neoproterozoic to Palaeozoic time newly formed rocks, including island arcs and sedimentary rocks together with older crust, was thrust eastward on the pre-existing crust during the Caledonian orogeny (Gee et al. 2008b). The Caledonian orogen forms Sweden´s fourth most important ore district with the Köli Nappe Complex hosting massive sulphide deposits formed in an island arc setting and the Seve Nappe Complex with what is believed to be sediment-hosted copper deposits.

Blekinge-Bornholm orogen

The bedrock in the near-surface realm in the Blekinge–Bornholm orogen is dominated by magmatic rocks that formed along a 1.8 Ga active continental margin in a convergent plate boundary setting. However, this bedrock differs from that further north, since it was affected by a younger orogenic event at 1.5–1.4 Ga, referred to as Hallandian or Danopolonian. This younger event is expressed by ductile deformation and amphibolite-facies metamorphism as well as by the intrusion of a suite of granites and syenitoids at c. 1.45 Ga.

Post-Svecokarelian magmatic and sedimentary provinces

Rock suites believed to be related to separate Proterozoic tectonic events and situated in the foreland to the Blekinge–Bornholm and Sveconorwegian orogens include:

- Mesoproterozoic magmatic rocks (1.6-1.5 Ga) consisting of granite with rapakivi texture and quartz syenite, spatially associated with gabbro, anorthosite and monzodiorite in central Sweden. These rocks are overlain by siliciclastic sedimentary rock and basalt, the latter inferred to have formed around 1.48–1.46 Ga.
- Predominantly basic dykes formed at 1.6 Ga as well as isolated intrusive bodies of nepheline syenite, probably Mesoproterozoic in age, and 1.45 Ga granite are also present in the south-eastern part of the country.
- Mesoproterozoic (1.27–1.25 Ga) dolerite sills and dykes as well as Neoproterozoic (0.98–0.95 Ga) dykes and subordinate clastic sedimentary rocks.

Platform cover rocks

Neoproterozoic to Phanerozoic sedimentary rocks occur as outliers at several locations in Sweden and also as basement cover rocks at the Caledonian front. In southernmost Sweden, Mesozoic and Tertiary sedimentary rocks similar to those in Denmark are found.

SWEDEN'S MINING HISTORY

Sweden's mining history goes thousands of years back in time. Early indications of iron ore mining in eastern Bergslagen come from archaeological excavations of bloomer furnaces with fragments of magnetite ore found north of the town of Uppsala. ^{14}C-dating of charcoal from the furnace indicates that the mining took place during Roman Iron age (0-400 AD). It has been suggested that the ore was extracted from the nearby Stenby-Lenaberg iron deposits located a few hundred meters north of the 60 degree latitude (Kresten 1993).

Results from pollen analysis and ^{14}C-dating of charcoal from the fire setting used in ore quarrying suggest that mining at the Falun copper mine, central Bergslagen, started in early Viking time, AD 400-800 (Eriksson & Qvarfort 1996). Since then the deposit was worked continuously until the closure of the mine in 1992, with a peak in copper production in the mid-17th century. The first written document mentioning the Falu mine is from 1288 and deals with shares in the mining activity, thus making the Falu mine one of the oldest, if not the oldest, limited company in the world (Tegengren 1924, Rydberg 1979). The current incarnation of the company is the Swedish-Finnish forestry company Stora Enso. The Falu mine site was registered as a World Heritage site in 2001.

Archaeological excavations and ^{14}C-dating of the Lapphyttan blast furnace in the Norberg area indicates that iron was produced with modern techniques during the 12th century (Almevik et al. 1992).

During the end of the 16th century and the beginning of the 17th century, the demand for iron and steel increased and paved the way for technological improvements in the mines, blast furnaces and smelters in Bergslagen. From being small-scale operations, operated by local farmers, the mines, smelters and blast furnaces became larger industrial units. The industrial revolution, which took place during the late 19th century, brought steam engines, efficient pumps, railways, explosives, methods to process

Figure 2. Panoramic view of the open pit at the Falu mine.
Photo taken in 2011 by Torbjörn Bergman, SGU

P-rich (apatite-bearing) iron ore and the use of coal instead of charcoal in the blast furnaces. These changes completely altered the industrial landscape in Bergslagen and in Sweden. The innovations, in particular the development of a Swedish railway network, made it possible to start large-scale mining of ores outside the Bergslagen district.

The iron ores in Norrbotten County, northernmost Sweden, were discovered already in the 17th century but it was not until a railway was built that they became economic. In 1888, the railway between Malmberget and the Baltic Sea coast was completed. The production at the Malmberget iron deposit then rose from 60 tons to 600 000 tons of ore annually. Four years later, the railway construction reached Narvik in Norway and opened up a link between the Baltic Sea and the Atlantic Ocean which passes several of the large iron deposits in Northern Sweden. In 1903, the production from the ores in Malmberget and Kiruna made up more than 50 % of all iron ore produced in Sweden. The mines in the north have held a leading position ever since. Today most of the iron ore produced in Sweden comes from these two mines.

The improved infrastructure in northern Sweden also opened the region for exploration for other commodities. In 1930, boulders from what was to become the large Aitik Cu-deposit were found (Malmqvist & Parasnis 1972). Several years of exploration work by Boliden AB eventually led to the opening of the mine in 1968. Initial production was 2 Mt per year and after several phases of expansion, the latest approved of in 2010, plans for an annual production of 36 Mt per year by 2015 were made. This goal was achieved and surpassed already in 2014, when 39.09 Mt @ 0.2 % Cu, 0.09 g/t Au and 2.14 g Ag was produced and milled (Boliden Annual Report 2014).

In 1973, a Cu-mineralised area was found 4 km west of the Kiruna iron ore deposit (Godin 1976). The initial exploration method was the recognition of the "copper plant", *Viscaria Alpina*, and the mine, which was named Viscaria after the flower, was in production from 1982 to 1997. Today there are advanced plans to re-open the mine.

During the first decades of the 20th century, several small holding companies called "emissionsbolag" were created by Swedish banks. One of these was Centralgruppens Emissionsbolag with the mission to acquire stocks in new mining companies and to develop mines. Thus, it was a kind of early junior exploration company. In 1924, at a time when the company was nearly bankrupt, the Boliden Au-Cu-As deposit was found. It was put into production two years later. During the following years several new massive sulphide deposits were found west of Boliden. Today these deposits, and their host rocks, form the Skellefte District, one of the most important ore-districts in Sweden with six producing mines. Discoveries are still being made here. For example, the Björkdal Au deposit was found using geochemical methods (till-sampling) by Terra Mining AB in 1985 and went into production in 1988. It is still in production by 2016 but with a new owner. The Åkerberg Au deposit was found in 1988 by Boliden Mineral AB and was in production from

1989 to 2001. One of the most Cu- and Zn-rich deposits ever found in the district, the Storliden deposit, was discovered in 1997 by North Atlantic Natural Resources (NAN) and was in production from 2002 to 2008. With the opening of the Kankberg Au-Te deposit in 2012 a new commodity, tellurium, was added to the list of metals produced from the Skellefte district.

The Caledonian nappe units constitute another important mineralised region whose metal potential has been known for a long time. Although the lack of infrastructure and, more recently, environmental protection policies, have limited exploitation, several mining attempts have nevertheless been made over the centuries. One of the oldest mining operations took place at the Nasafjäll Ag deposit close to the Norwegian border (Bromé 1923, Du Rietz 1949). The deposit was mined for a few years in the mid 17th century but was never profitable. The Fröå Cu deposit was found in the mid-18th century and was mined intermittently during several periods, the latest from 1910 to 1919. Ore production reached a peak in 1917-1918, but less than 100 000 tons of ore was produced during the mines lifetime (Helfrich 1967). Several significant deposits in the Caledonides were found and put into production during the 1940s. Galena-bearing sandstone boulders found in 1938 led to the discovery of the Laisvall Pb - Zn deposit. Exploitation started in 1943, mainly as a measure to secure domestic supplies of Pb during World War II (Rickard et al. 1979). It turned out however, to be economic in peace time as well, and mining lasted until 2001. Exploration for sandstone-hosted Pb-Zn led to several discoveries of similar mineralisations along the Caledonian front, and the Vassbo and Guttusjö deposits 500 km to the south-southwest of Laisvall have also been in production. Exploration by the Geological Survey of Sweden in the 1970s led to the discovery of several massive sulphide deposits in the Caledonides (Zachrisson 1969). However, the only deposit that has been in production is Stekenjokk which was mined for Cu and Zn between 1976 and 1988.

The most recent mining district to be recognised in Sweden is the so-called "Gold Line" in Västerbotten County. The Gold Line refers to a southeast-trending Au anomaly detected by the State Mining Property Commission (NSG) during a till geochemistry survey in the late 1980s. The anomaly attracted exploration to this new district, and the first deposit to be found, and later put into production by Dragon Mining Ltd., was the Svartliden Au deposit. Several other Au deposits in the area are under development.

Parallel to, and in interaction with the expansion of the exploration and mining industry, there was a tremendous development of the Swedish engineering industry supplying exploration, mining and mineral processing equipment during the late 19th and 20th centuries. In 1893, ASEA built Sweden's first three-phase electrical power transmission system for the Grängesberg iron mine. About a hundred years later, in 1987, ASEA merged with the Swiss company Brown Boveri to form ABB, a global leader in power and automation technologies. Atlas Copco was established in 1873 with the objective to manufacture and sell equipment for railway construction and operation. At the turn of the century, compressed air machinery and later pneumatic rock-drill equipment became important export products for the company. Today tools from Atlas Copco are found in mines around the world. Sandvik was founded in 1862 and from the very start, the company delivered rock-drilling equipment to the exploration and mining industries. Through mergers and acquisitions the Swedish and Finnish engineering industries have amalgamated to form multinational companies that today are market leaders as suppliers to the world's exploration and mining industries.

THE BERGSLAGEN DISTRICT: Fe, Zn-Pb-Cu-Ag-(W-Mo-REE)

The Bergslagen mining district in south-central Sweden makes up the southwestern part of the Palaeoproterozoic Svecokarelian orogen in the Fennoscandian Shield (Stephens et al. 2009). It forms one of Sweden's most important provinces for the exploitation of metallic mineral resources. More than 7000 iron deposits, 1500 base metal deposits, 150 special metal deposits (mainly tungsten deposits) but only a few precious metal deposits are known from the area (Figures 3 - 5). In this metal-rich province, there has been continuous mining for more than 1000 years, perhaps close to 2000 years.

Defined genetic deposit types and subtypes from the area (Stephens et al. 2009, Allen et al. 1996a) include:

- Skarn iron ore (magnetite ore hosted by skarn-altered carbonates and silicates)
  - Mn-poor skarn iron ore
  - Mn-rich skarn iron ore
- Apatite-iron ore (magnetite>hematite associated by apatite and hosted by felsic volcanic rocks)
- Banded iron formations (variably quartz-banded iron oxides, locally with other silicatebands)
- Sulphide ore (base metals, locally associated with skarn iron ore)
  - Stratiform, ash-siltstone associated Zn-Pb-Ag (Åmmeberg-type)
  - Stratabound, podiform, skarn-limestone associated Zn-Pb-Ag(-Cu-Au) (Falun type)
- Manganese ore (Mn oxides)
  - Stratiform Mn-oxide analogue to skarn iron ore
  - Breccia-hosted Mn-oxides
- Special and precious metals
  - Tungsten (scheelite in skarn and wolframite and scheelite in quartz veins)
  - REE in skarn iron ore and apatite iron ore
  - Molybdenite, granite-hosted porphyry-style or hosted by skarn

To the west and south-west, the Bergslagen district is bounded by younger batholiths, to the north by major northwest-trending, crustal-scale shear zones and to the east by the Baltic Sea (Stephens et al. 2009). It may possibly be correlated across the Baltic Sea to southwestern Finland where similar rocks and deposits can be found (Lundström & Papunen 1986). Most of the metal deposits occur in felsic metavolcanic rocks, associated with carbonate rocks and calc-silicate (skarn) rocks 1.9 to 1.8 Ga in age (Allen et al. 1996a). In a few places, the basement to the metavolcanic rocks, consisting of turbiditic metagreywacke grading upward into quartzitic rocks, is exposed (Lundström et al. 1998). A sequence of clastic metasedimentary rocks, including meta-argillite, quartzite and metaconglomerate lies stratigraphically above the volcanic rocks.

In most places the supracrustal rocks have been intruded by several suites of igneous rocks of which the oldest, a granitoid-dioritic-gabbroic suite, is broadly contemporaneous with the metavolcanic rocks. The supracrustal rocks and the older intrusive suite were affected by Svecokarelian deformation and metamorphism (Stephens et al. 2009).

The northern, and most mineralised part of Bergslagen, is located to the north of 60° latitude and is thus included on the Circum Arctic mineral map. Nearly half of all Swedish deposits registered in the national mineral deposit databases are located in the northern Bergslagen area.

The total amount of produced metals and metals in reserves and resources in the area is 0.49 Mt Cu, 5.7 Mt Zn, 2.2 Mt Pb, 358 Mt Fe, 46 t Au and 5185 t Ag; the precious metals are largely considered as by-products in most deposits.

Deposit, Mine field	When_mined	Resources (Mt)	Mined (Mt)	Cu (%)	Zn (%)	Pb (%)	Au (g/t)	Ag (g/t)	Ref.
Garpenbergsfältet	c. 1200-	110.9	37.60	0.1	3.7	1.7	0.37	115	2
Saxberget	1882-1988		6.43	5.7	7.1	2.2	0.40	42	1
Falu gruva	c. 1200-1992		11.39*	3.0	4.0	1.5	3.00	18	1
Ryllshyttegruvan	1888-1937		0.83	5.9	2.0	0.0			1
Svärdsjö gruva	1887-1989		1.04	0.6	4.5	1.5	0.40	66	1
Kalvbäcksfältet	1901-1963		0.56	3.6	10.4	3.6	0.30	100	1, 3
Lövåsfältet	1874-1954		0.31		2.0	4.0			1
Gruvberget	1909-1989		0.05		10.0	4.5		200	1
Skytt och Näverbergsgr.	1890-1948		0.10		35.0				1
Tomtebogruvan	1914-1968		0.12	4.2					1
Vallbergs- Lobergsfältet	1880-1917		0.01		20.0				1
Tvistbogruvan	1942-1945		0.00		3.2	2.6		31	1, 4
Gränsgruvan	1945-1978		0.71			2.1			1, 5
Bunsås koppargruva	1881-1920	0.96	0.01	0.5	1.9		0.36	18	1, 6
Dammbergsgruvan	1905-1917		0.02		40.0				1
Dannemorafältet	1880-1928		0.04		35.0				1, 7
Kallmorbergsfältet	1881-1931		0.07	12.0	16.0	25.0		300	1

Table 1. Overview of the most important sulphide deposits in the Bergslagen district.

1. Official Statistics of Sweden, Metal and Mining industries. 2. Boliden Annual report 2014. 3. Tegengren 1924. 4. Press release 18 April 2012, www.kopparbergmineral. 5. Gränsgruvan-gruvkarta. Bergsstatens arkiv Falun. 6. www.wikingmineral.se. 7. www.dannemoramineral.se. (*)The mined tonnage only refer to what is reported in official statistics (1833 to present), a more correct figure for the total production is in the order of 25 Mt.

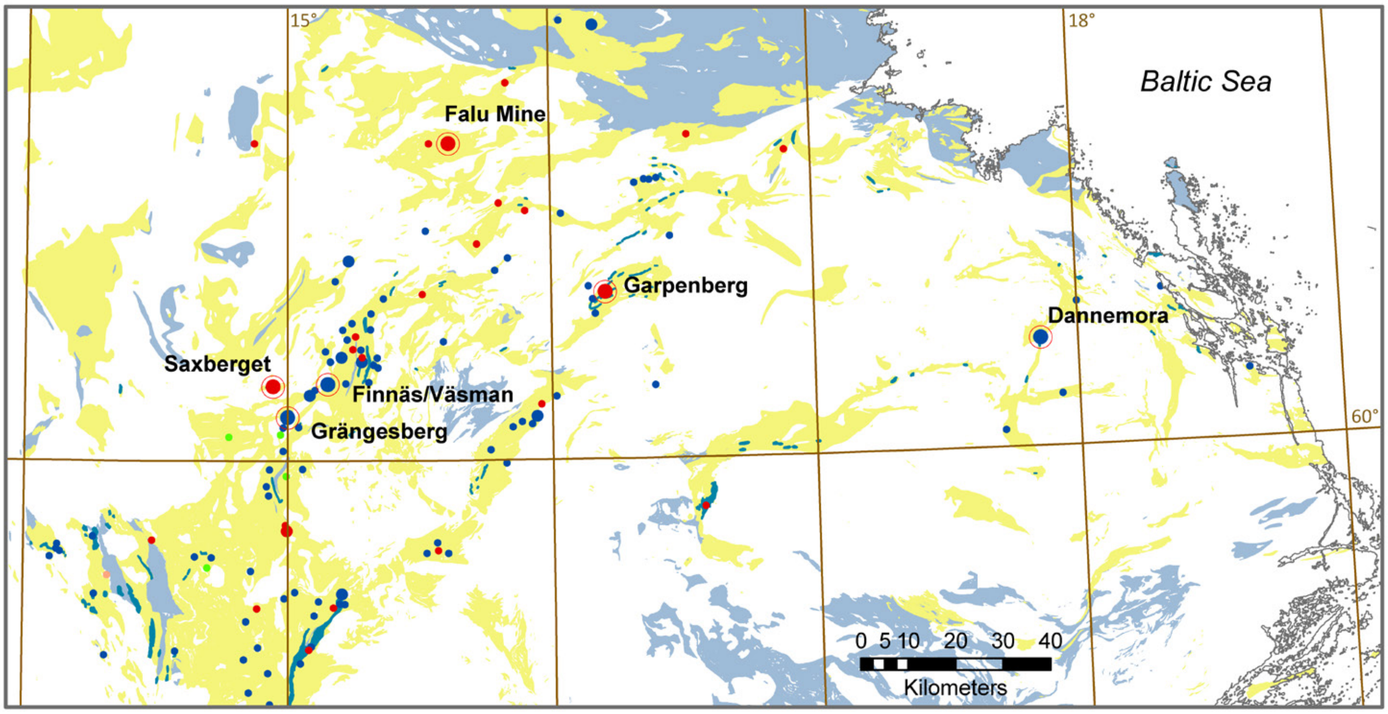


Figure 3. Simplified geological map showing the extent of Palaeoproterozoic supracrustal rocks in Bergslagen. Blue-grey: metasedimentary rocks, yellow: metavolcanic rocks, deep blue: marble. Red circles show location of large deposits included on the Circum Arctic map, blue dots show medium- and smaller size iron deposit, red dots medium- and small size base metal deposits and green dots show small other metal deposits (mainly tungsten deposits). The supracrustal rocks and the metavolcanic rocks in particular, define the Bergslagen metallogenetic area. Ore deposit data from the Fennoscandian Ore Deposit Database (Eilu et al. 2010), geology modified from SGUs digital Bedrock Sweden 1:1 M map.

Deposit. Mine field	When_mined	Resources (Mt)	Mined (Mt)	Fe (%)	Mn (%)	P (%)	S (%)
Grängesberg mining district	1783-1989	148	133	44.5		1.36	0.01
Dannemorafältet	c. 1200-1992. 2012-2014	62	32	38.6	1.98	0.00	0.21
Kölen	not exploited	70		40.0			
Norrberg-Morberg-Kallmorbergs-fälten	1858-1902	43	19	42.4	0.13	0.05	
Håksbergsfältet	1858-1979	37	20	35.4		0.18	0.07
Blötbergsfältet	1859-1979	40	16	40.0	0.16	1.45	0.02
Risbergsfältet	1783-1979		21	43.8		1.41	0.01
Idkerbergsfältet	1860-1977		11	63.1	0.10	1.57	0.02
Finnäs/Väsman	1858-1921	7	0	38.4		0.09	0.03
Vintjärnsfältet	1858-1978		6	39.1	0.47	0.06	0.01
Klackberg-Kolningsbergsfältenfältet	1858-1967		5	45.3	3.86	0.01	0.11
Intrångetsgruvor	1912-1969		5	46.8	0.20	0.04	0.83
Eskilsbacks-Mimerfältenfältet	1874-1979		5	43.0	0.44	0.06	0.10
Tuna Hästbergsfältet	1858-1968		5	33.1	4.29	0.05	0.49
Basttjärnsfältet	1875-1978		4	43.9	3.93	0.02	0.27
Ramhällsgruvor	1845-1975		4	35.2	1.53	0.04	0.18
Stollbergsmalmen	1874-1981		3	27.1	14.60		
Vingesbackegruvan	1950-1980		3	42.7	0.36	0.04	0.64
Nybergsfältet	1858-1967		3	44.7		0.02	0.53
Herrängsfältet	1845-1961		3	33.0		0.03	0.62
Lekombergsfältet	1867-1945		3	49.8		1.91	0.04
Semlafältet	1859-1967		3	40.5		0.01	0.03
Smältarmossen	1872-1979		3	43.9		0.01	3.06
Getbacks- och Rödbergsfälten	1860-1963		3	37.6			
Ormbergsfältet	1783-1926		2	61.0		0.18	0.02
Nyängsfältet	1845-1966		2	44.9	1.36	0.02	0.22
Bispbergsfältet	1845-1967		2	63.3	0.10	0.02	0.02
Hästefältet	1858-1948		1	36.1		0.02	0.04
Bodåsfältet	1858-1973		1	47.3		0.03	2.28
Storstrecksfältet	1865-1962		1	44.7	3.94	0.02	0.23
Hillängsgruvan	1858-1950		1	33.8	9.96	0.02	0.42

Table 2. Overview of the most important iron deposits in the Bergslagen district.

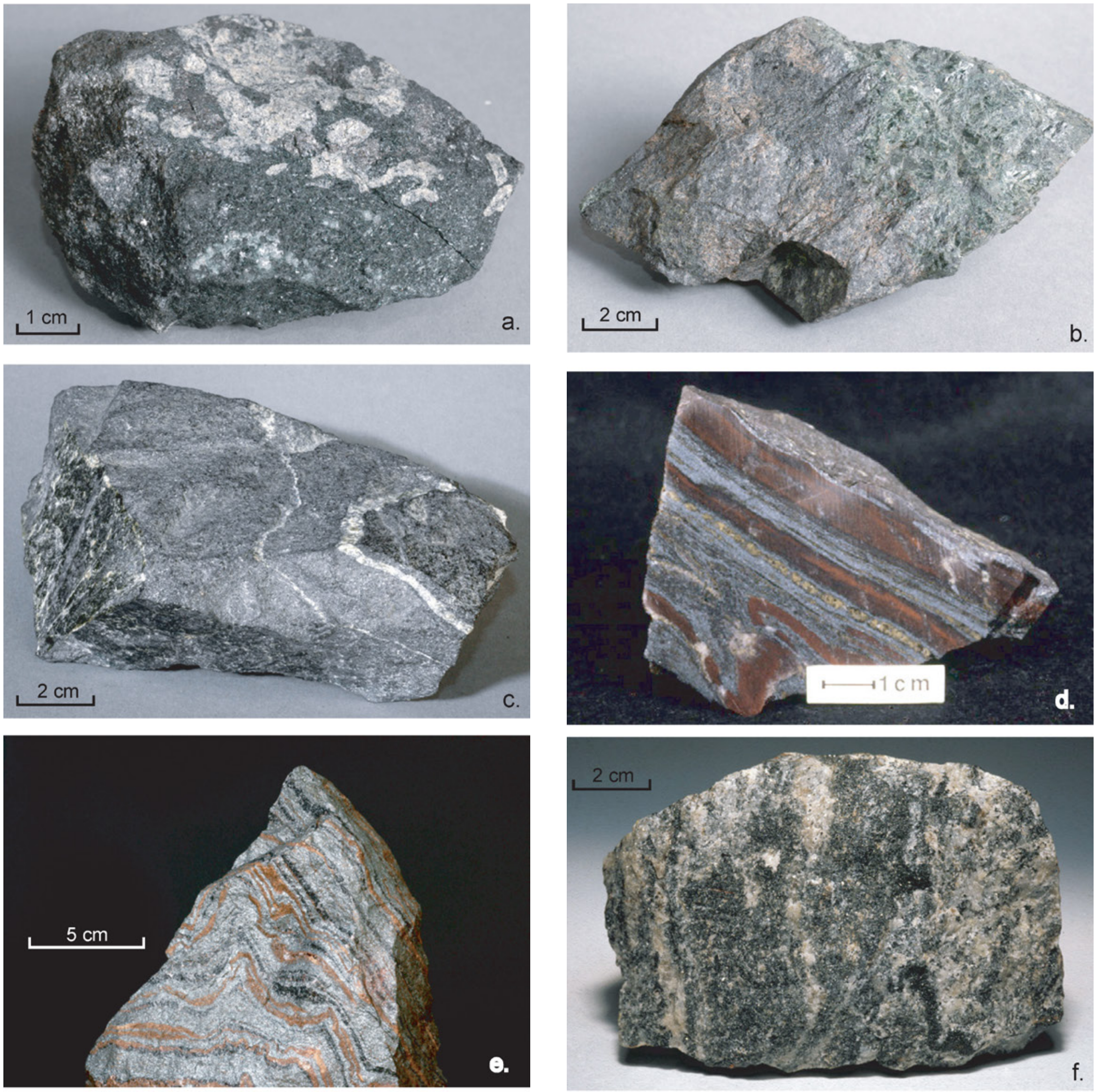


Figure 4. Examples of ferrous, mainly iron, ores from Bergslagen (Stephens et al. 2009). a. Apatite-bearing magnetite ore, Grängesberg deposit. b. Actinolite-garnet-magnetite skarn from Mn-poor skarn, Persberg deposit. c. Dannemorite-knebelite-magnetite in Mn-rich skarns, Dannemora deposit. d. Jasper-hematite layered banded iron formation, Pershytte district. e. Banded iron formation, Striberg deposit. f. Banded dolomitic marble impregnated by hausmannite, Långban deposit. g. Manganite (MnO(OH)), Bölet deposit. Figure f: photo: Erik Jonsson (SGU), sample NRM 31128, copyright: Naturhistoriska riksmuseet. Other photos: Torbjörn Bergman, SGU.

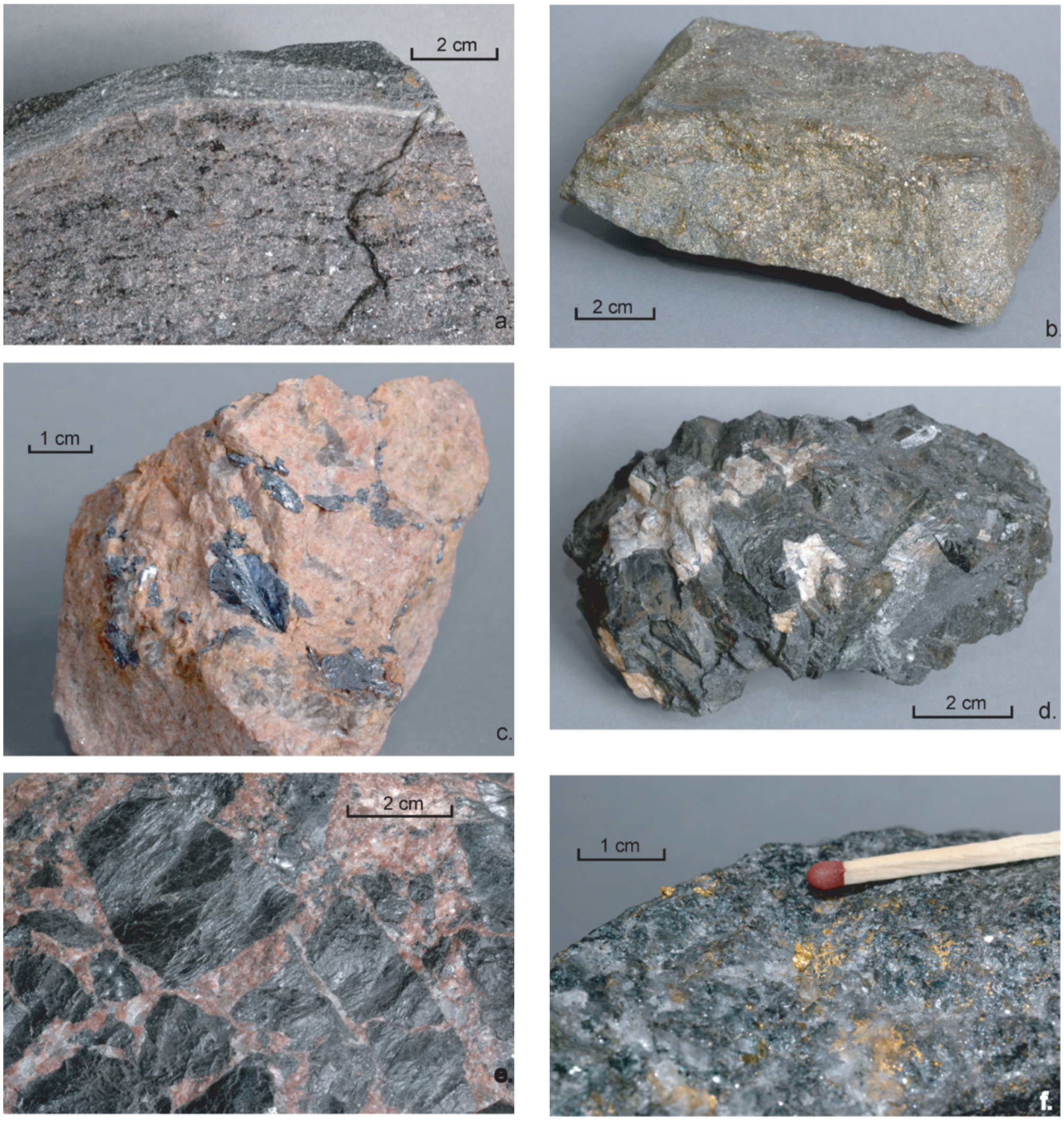


Figure 5. Examples of base, special and precious metal ores from Bergslagen (Stephens et al. 2009). a. Layered sphalerite dominated ore, Zinkgruvan deposit. b. Semi-massive, chalcopyrite-pyrite ore, Falu deposit. c. Molybdenite in granite, Bispbergsklack deposit. d. Pyroxene-hornblende-scheelite skarn, Yxsjöberg deposit. e. Wolframite breccia, Baggetorp deposit. f. Native gold in a quartz vein, Falu deposit.

Skarn iron ores

There are more than 3 200 known skarn iron deposits in northern Bergslagen, most of them have been mined in the past. The largest is the **Dannemora Fe-Mn- (Zn-Ag-Pb)** deposit which consists of about 25 individual ore bodies with both Mn-rich and Mn-poor parts, and some sulphide mineralisations. The deposit is hosted by sedimentary and felsic volcanic rocks, stromatolitic limestone and skarn-altered rocks (Figure 6). The supracrustal rocks, dated at 1894±4 Ma (Stephens et al. 2009) are interpreted to have been deposited in a submarine, saline caldera setting (Lager 2001, Dahlin 2014).

Mining at Dannemora has probably taken place since the 13th century or earlier, although the first written document on the mine dates from 1481 (Rydberg 1981). In the early days, the mining focused on a minor Zn-Pb sulphide occurrence. However, during the 16th century, iron-ore became the main commodity. It is estimated that the total iron ore production until the closure of the mine in 1992 was 54.3 Mt @ 52 % Fe and 2–3 % Mn (Allen et al. 1996a). In 2012, the Dannemora mines was re-opened but the decline in metal prices, especially the iron prices, forced the company into bankruptcy and the mine closed again in 2015.

The Fe deposit at Dannemora consists of massive and stratabound magnetite, often associated with Mn minerals (Figure 3c), diopside, actinolite, chlorite and serpentine (Lager 2001). The ore also contains calcite, dolomite, siderite and

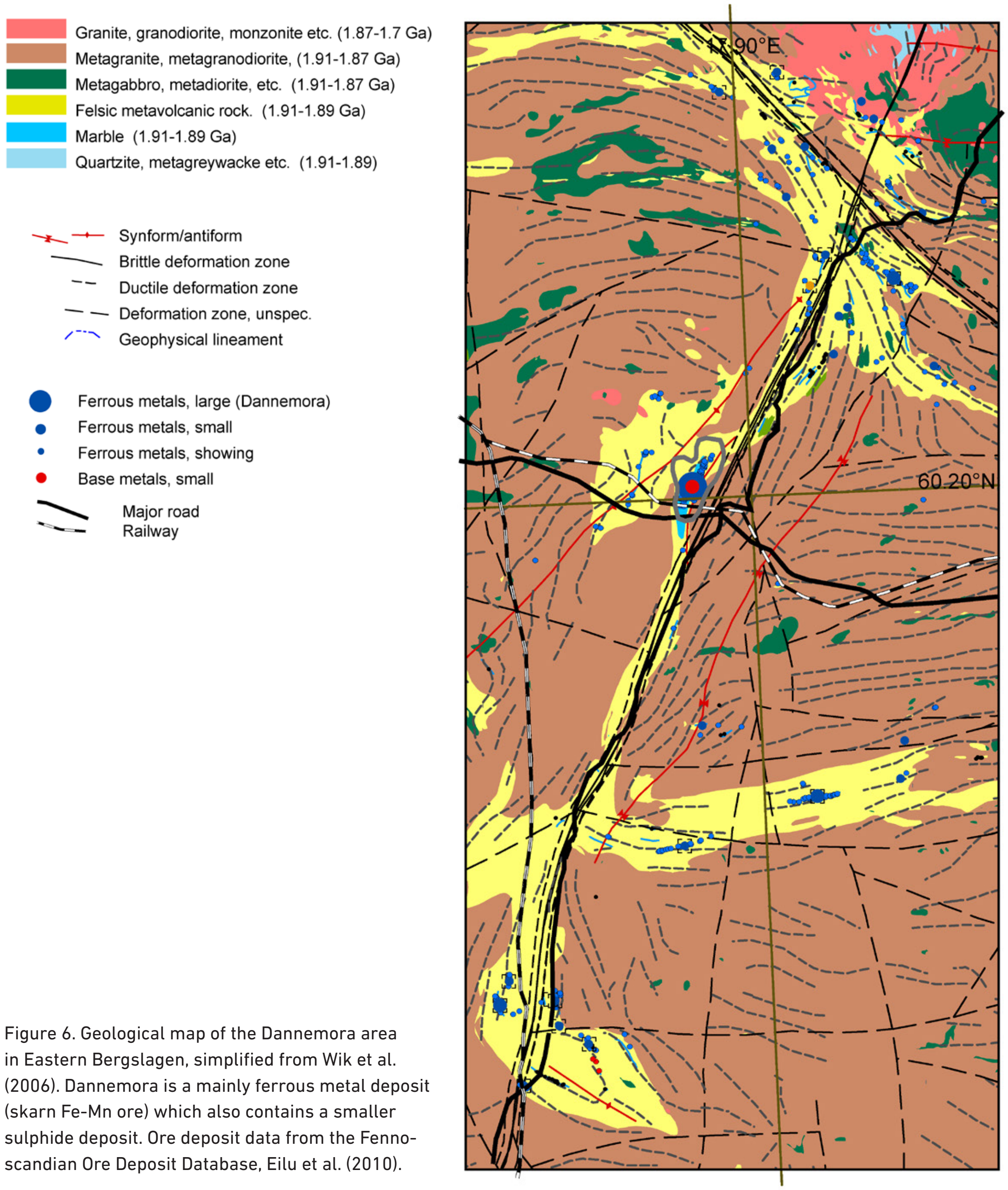


Figure 6. Geological map of the Dannemora area in Eastern Bergslagen, simplified from Wik et al. (2006). Dannemora is a mainly ferrous metal deposit (skarn Fe-Mn ore) which also contains a smaller sulphide deposit. Ore deposit data from the Fennoscandian Ore Deposit Database, Eilu et al. (2010).

rhodochrosite. It was traditionally divided into Mn-rich and Mn-poor varieties, where the Mn content of the skarn was 1–6 % and less than 1 %, respectively. In parts of the deposit, the magnetite itself is manganiferous. Of particular palaeo-environmental interest is the evidence of evaporites in the carbonate sequence (Lager 2001).

Apatite-iron ores

The Fe ores in Bergslagen have, on the basis of their metallurgical properties, been divided into apatite-rich iron deposits, with P contents >0.2 %, and non-apatite iron deposits, with P contents considerably less than 0.2 % (Geijer & Magnusson 1944). Apatite-iron ores in Bergslagen occur in a restricted belt in the northwestern part of Bergslagen (Figure 7). Within this belt there are four major apatite-iron deposits, **Grängesberg**, **Blötberget**, **Fredmundberg** and **Lekomberga**, each of which contains several ore bodies. The **Idkerberget** apatite iron ore, a type of ore similar to those in the vicinity of Grängesberg, is located some 20 km to the north, but a proper geological correlation between the Grängesberg subarea and the Idkerberget deposit cannot be made from the available information.

The **Grängesberg** deposit, the largest apatite-iron ore deposit in Bergslagen, is the third

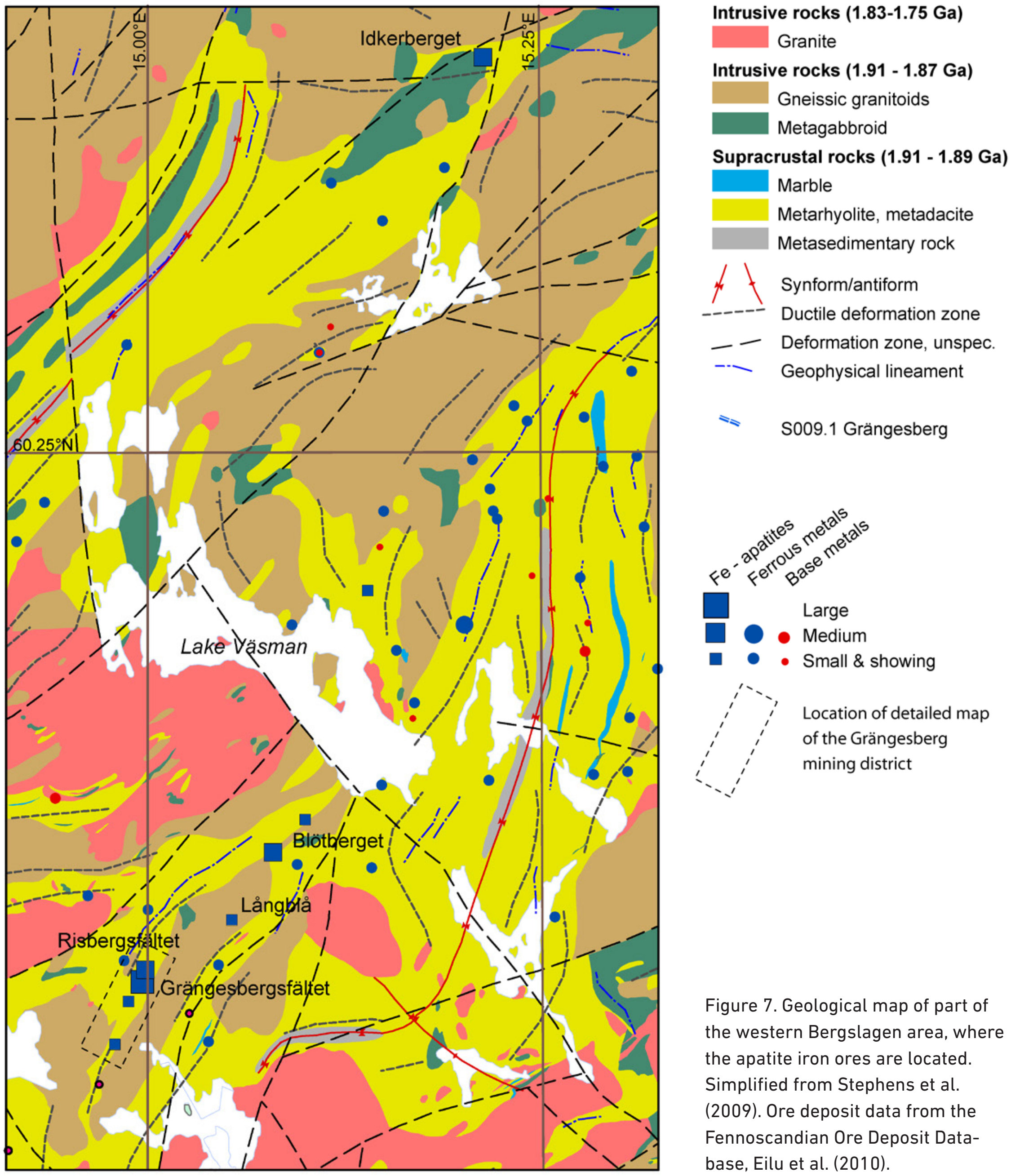
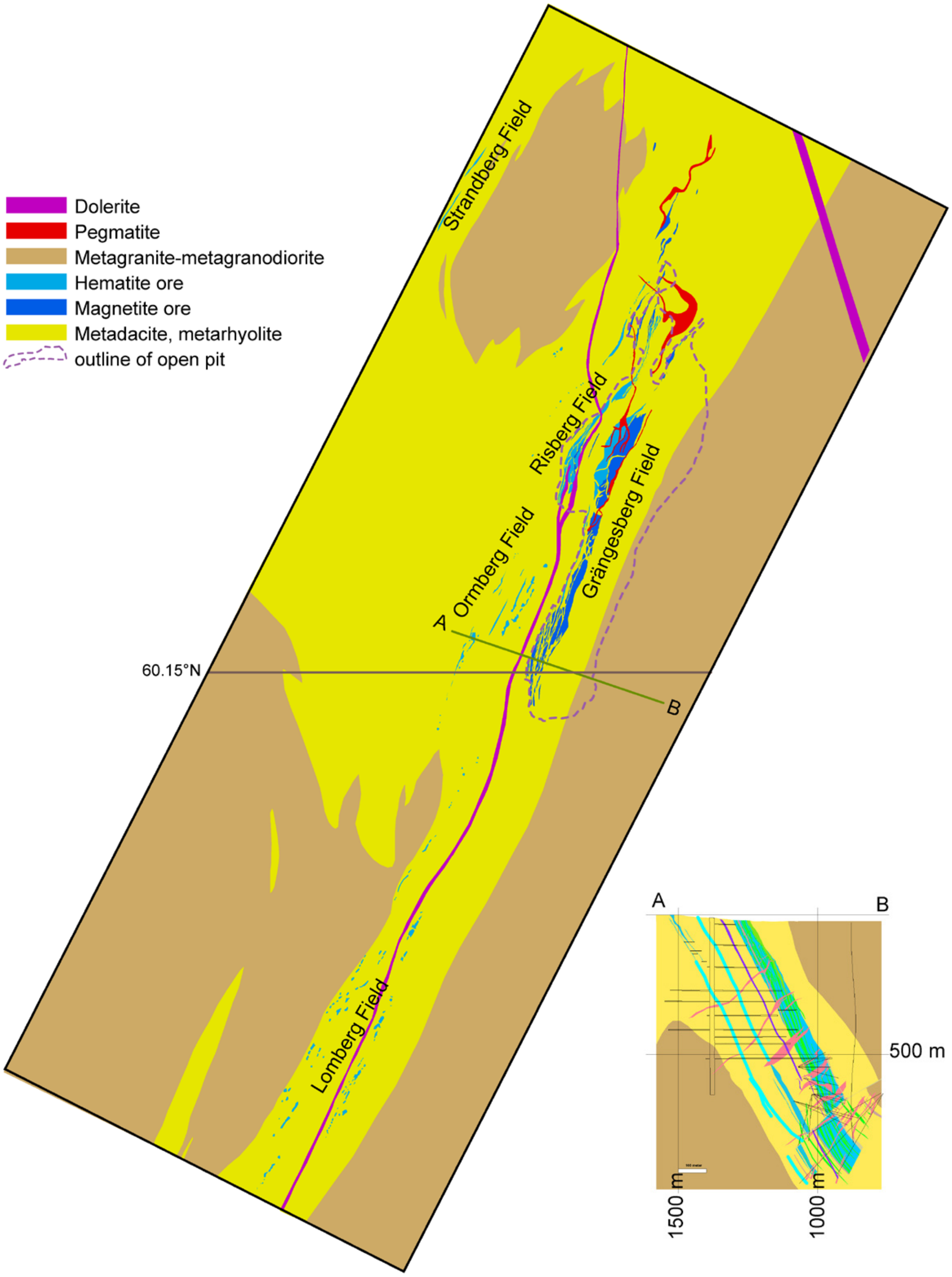


Figure 7. Geological map of part of the western Bergslagen area, where the apatite iron ores are located. Simplified from Stephens et al. (2009). Ore deposit data from the Fennoscandian Ore Deposit Database, Eilu et al. (2010).

largest iron deposit in Sweden, only outnumbered by the giant Kirunavaara and Malmberget deposits of northern Sweden. It is also the largest known metal deposit in the Bergslagen district, and the southernmost of the known apatite-iron deposits of Kiruna-type in Sweden. The major ore body at Grängesberg extends 1500 m along strike and is up to 100 m wide (Magnusson 1938). It has been mined down to 650 m depth, but is geophysically constrained to extend down to at least 1500 m. The ore consists of massive magnetite (80 %) and hematite (20 %) with up to a few percent of apatite (Figure 4a). Hematite is restricted towards the structural hanging wall and makes up the western part of the ore body. The iron ore is hosted by sodic-altered dacitic metavolcanic rocks, dated to 1904 ± 8 Ma (Hallberg et al. 2008). Ore and host rocks have been intruded by several generations of mafic dykes and pegmatites (Looström 1939). Less than 100 m to the west of the Grängesberg ore body (Figure 8), similar, but smaller ores of the **Risberg** field are found (Hedberg 1907). They carry somewhat more hematite, whereas the P contents are similar to those at Grängesberg. Further to the southwest and along strike from the Risberg field lies the **Ormberg** field (Hedberg 1907). The ores at Ormberg are dominated by hematite and the P content is significantly lower than at Risberg and Grängesberg. Still further to the southwest lies the **Lomberget** field (Hed-

Figure 8. Geological map of the Grängesberg mining district including the Lomberg Field, the Ormberg Field, the Risberg Field and the Grängesberg Field. All except the Ormberg Field contain apatite iron ore deposits. The profile shows a cross section of the southern part of the Grängesberg Field (the Lönnfallet deposit). From Hallberg et al. (2008).



berg 1907), where disseminated apatite-bearing hematite and magnetite ores have been mined in the past. Five kilometres northeast of Grängesberg are the Blötberget and Fredmundberget fields and about 10 km further to the north lies the Lekomberg field (Geijer & Magnusson 1944). The northernmost apatite-iron ore field in the Bergslagen metallogenic district is **Idkerberget**, 27 km to the north of Grängesberg (Geijer & Magnusson 1944).

Massive sulphide deposits

The **Garpenberg Zn-Pb-Ag-Cu** deposit is the largest massive sulphide deposit in Sweden with a total tonnage (production, reserves and resources) of 85 Mt @ 5.01 % Zn, 1.83 % Pb, 0.06 % Cu, 51 g/t Ag and 0.1 g/t Au (Boliden 2011a). It consists of several ore bodies that are interpreted as having been emplaced in a dolomitic carbonate rock (Allen et al. 1996a). The mineralizations are

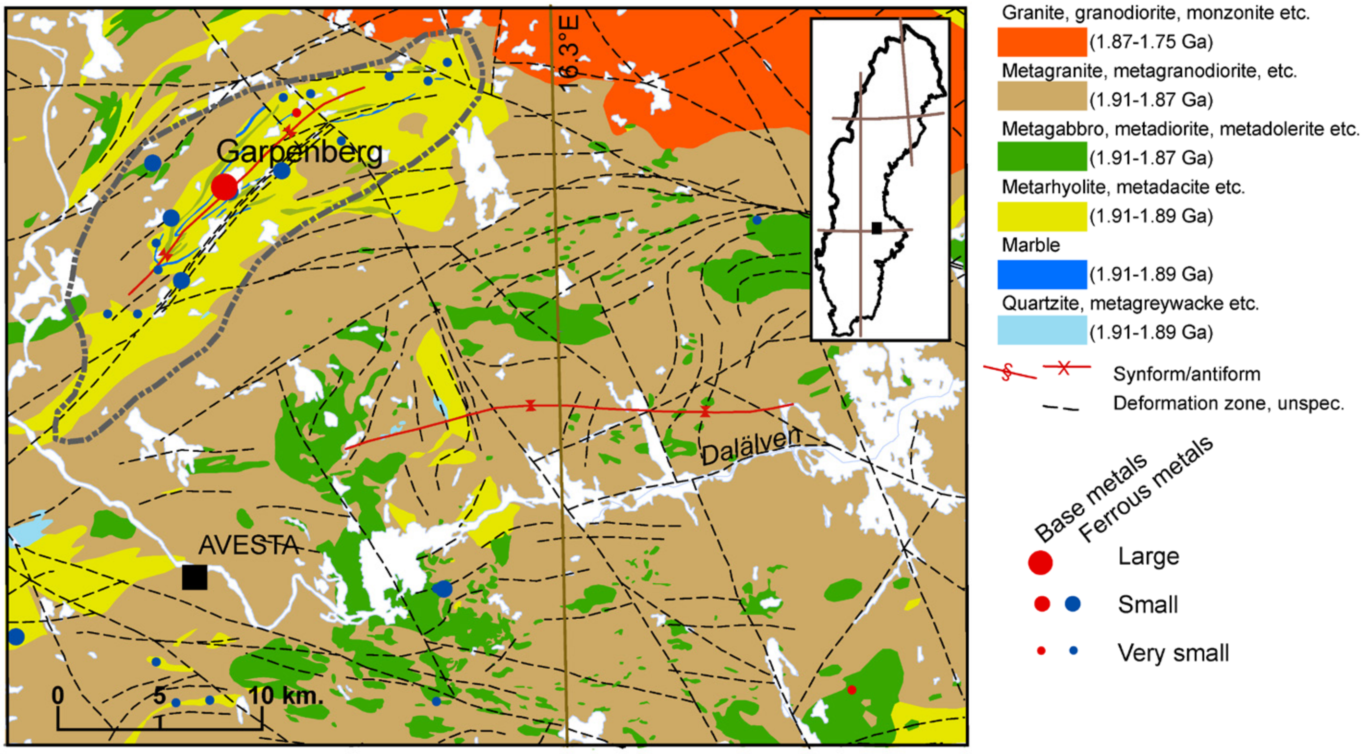


Figure 9. Geological map of the Garpenberg area in central Bergslagen. Map simplified from Stephens et al. (2009). Ore deposit data from the Fennoscandian Ore Deposit Database, Eilu et al. (2010).

located in the Garpenberg supracrustal inlier which consist of Paleoproterozoic supracrustal rocks bounded by early orogenic granitoids (Figure 9, Jansson & Allen 2011). Multiple folding and faulting have further redistributed and separated them. The oldest part of the Garpenberg mine (Garpenberg Odalfält) was mined for Cu in the 13th century, but Zn later became the most important commodity (Magnusson 1973). In 1972, the Garpenberg Norra mine, about 3 km to the north, was opened. The two mines were eventually connected through an underground drift and may since then be considered as one. During the last decade, several new blind ore bodies have been discovered to the east of the interconnecting drift. These include the Lappberget, Dammsjön, Kasperbo and Kvarnberget discoveries that have increased the reserves and resources significantly (Allen et al. 2010).

The Garpenberg deposit consists of lenses and pods of sulphides with varying proportions of pyrite, sphalerite, galena, chalcopyrite and pyrrhotite hosted in calc-silicate rocks (tremolite skarn) and mica schists (Christofferson et al. 1986). A more Cu-rich mineralisation forms a network of chalcopyrite-pyrite-pyrrhotite-bearing quartz and quartz-fluorite veins in the quartz-mica altered stratigraphic footwall. The deposit is interpreted to be a synvolcanic subsurface replacement mineralisation in limestone with the Cu mineralisation as a stringer to the Zn-Pb ore (Allen et al. 1996a). In the Garpenberg Norra deposit, stromatolitic structures indicate an organogenic origin for the limestone (Allen et al. 1996a). The Garpenberg supracrustal inlier (Figure 9) also hosts other Zn-Pb deposits and skarn iron deposits in carbonate rocks. At one of these, the Ryllshyttan Zn-Pb-Ag-magnetite deposit, it has been shown that both sulphide and magnetite mineralisation took place by replacement of carbonate rocks (Jansson & Allen 2015). Dating of critical lithologies has shown that the mineralisation is broadly contemporaneous with volcanism in the area, i.e. the mineralisation is epigenetic but broadly synvolcanic.

The **Falun Cu-Pb-Zn, Au-Bi-Se** deposit is one of the oldest mines in the country and has been in operation for at least a millennium. It has gained an almost mythical importance in both the Swedish society and mining history. Historically, it is without question the most important mineral deposit in Sweden. While it is impossible to obtain any exact figures on total ore production and grades of the deposit, it is estimated that during its lifetime 28 Mt of ore at 2–4 % Cu, 4 % Zn, 1.5 % Pb, 13–24 g/t Ag and 2–4 g/t Au has been mined (Figure 10, Table 1, see Allen et al. 1996a). In the mine, three types

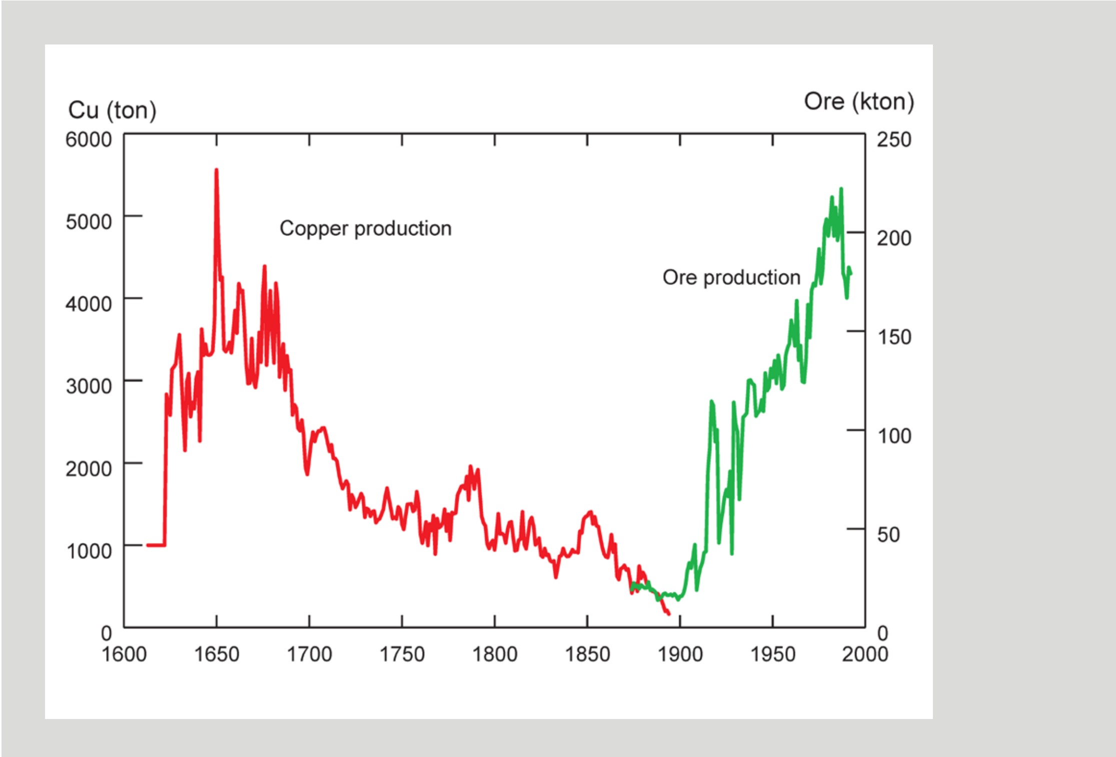


Figure 10. Documented copper production (1612–1894, red) and ore production (1874–1992, green) from the Falu mine. Note the peak in copper production in the 17th century. Data on copper production are from Tegengren (1924), and data on ore production from the "Official Statistics of Sweden, Metal and Mining Industries".

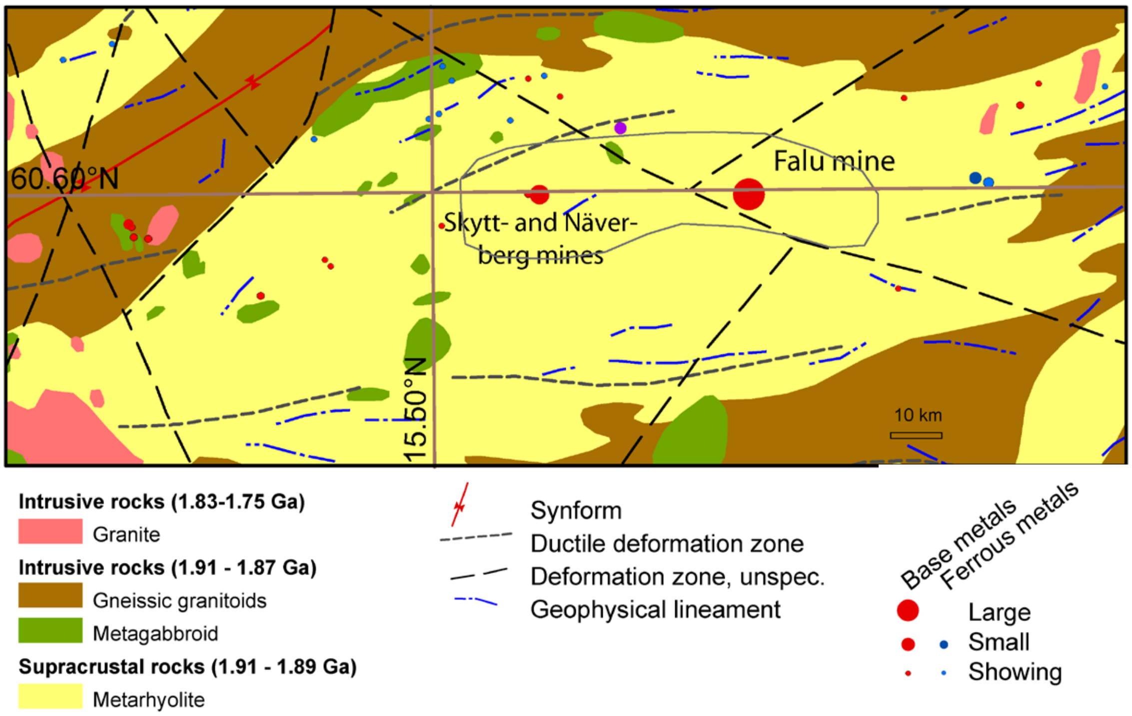


Figure 11. Geological map of the Falu region, simplified from Stephens et al. (2009). Base metal and ferrous metal data from the Fennoscandian Ore Deposit Database, Eilu et al. (2010).

of mineralisation have been worked: a massive pyrite-dominated sulphide ore with sphalerite, galena and chalcopyrite (Figure 5b); a Cu-Au stringer ore in intensely altered rocks; and younger Au-mineralised quartz veins (Figure 5f). The deposit is hosted by metavolcanic rocks (Figure 11), largely altered to mica schists and so-called ore quartzites, along with marble and skarn (Lasskogen 2010). The rocks were intruded by quartz-phyric subvolcanic intrusions and mafic dykes, then metamorphosed to upper amphibolite facies and experienced several phases of folding and faulting. The deposit has been interpreted as a stratabound volcanic-associated skarn sulphide deposit (Allen et al. 1996a).

An SGU mapping project and a research project at Luleå Technical University are presently ongoing at and around the Falu mine.

About 40 km west of Falun are the Skytt and Näverberg mines. According to available descriptions, they are similar to the Falu deposit, but significantly smaller with a total production amounting to less than 0.1 Mt.

Tungsten deposits

The Bergslagen district has been an important source of tungsten to Swedish industry. More than 100 W-Mo deposits are known from the area and four mines have been in production; the **Yxsjöberg**, **Sandudden**, **Wigström** and **Elgfall** deposits (Ohlsson 1979). The most important mine was the Yxsjöberg deposit with an estimated tonnage of 5 Mt @ 0.3-0.4 % W. It was mined until 1989 and was then the largest tungsten deposit in Scandinavia (Ohlsson 1980).

All known W occurrences in the area are skarn deposits hosted by Svecofennian felsic metavolcanic rocks and crystalline carbonate rocks (Figure 5d, e). They are mostly concordant or subparallel to bedding in the country rocks. Crystalline carbonate rock is generally found as remnants in the skarn, but is, in places, completely replaced. Scheelite, generally with a significant component of powellite ($CaMoO_4$), is the only economically important tungsten mineral (Ohlsson 1979). U-Pb dating of titanite that formed during the skarnification of the limestones yields an age of 1789 ±2 Ma, an age that agrees with the age of some of the post-kinematic granitoids from the area (Romer & Öhlander 1994, 1995).

Molybdenum deposits

Molybdenum deposits of "Climax-type", in which molybdenite is hosted by late-Svecofennian, 1.8 Ga granites and pegmatites, also occur in the area (Figure 5c). Examples are the **Bispbergsklack**, **Pingstaberg** and **Uddgruvan** deposits. All are minor (<0.1 Mt of ore) and have never had any significant economic importance (Hübner 1971).

REE-deposits

Some of the skarn deposits in Bergslagen, in particular those in the Riddarhyttan district, carry high contents of rare earth elements (REE) and have been mined in the past (Geijer 1961, Gustafsson 1990, Andersson 2004). During the period 1860–1919, about 160 t of cerite ore was produced from the **Nya Bastnäs** mine. In 1923, an additional 825 t was extracted from the waste dumps. The grade of the ore is unknown.

The REE occurrences formed mainly in skarns replacing dolomitic carbonate rocks and are associated with tremolite and talc (Geijer & Magnusson 1944, Geijer 1936, 1961). The main REE-bearing minerals are allanite and cerite, other REE phases include ferriallanite, törnebohmite and bastnäsite (Andersson 2004). The **Bastnäs** mine is the type locality for the latter. Sulphide minerals, mostly chalcopyrite, bismuthinite and molybdenite are commonly associated with the REE mineralisations. Most authors agree that the REE occurrences in the area are epigenetic replacement deposits. Observations indicate that REE-mineralisation is broadly contemporary with volcanic activity in the region and formed by fluids of igneous origin (Andersson et al. 2013, Jonsson & Högdal 2013).

PALAEOZOIC POLYMETALLIC (U-V-Mo-Ni-Zn-P) SHALE

Lower Palaeozoic U-rich shale, bitumenous black shale (alumshale), conglomerates and phosphoritic shales once covered large parts of the Fennoscandian Shield. Today, remnants of them are found in outliers within the southern and central parts of Sweden, along the eastern margins of the Caledonides, within nappes in the Caledonides, and in the Gulf of Bothnia (Gee & Snäll 1981, Gee et al. 1982a, 1982b, Andersson et al. 1985 and Figure 12). The shales and conglomerates were deposited in basins along the western margin of the Fennoscandian platform (Gee et al. 2008). These basins started to form during the initial breakup of Rodinia in the late Tonian to Cryogenian (c. 850 Ma) (Nystuen et al. 2008). The breakup led to the separation of the Fennoscandian and Laurentian Shields and the formation of the Iapetus Ocean. In the Lower Ordovician, the two continents started to converge, and in mid-Silurian to Lower Devonian times they collided. During the collision, rocks from the Proterozoic basement, the Neoproterozoic to Palaeozoic sediments, including the Palaeozoic shales, and outboard oceanic volcanic terranes were thrust onto each other and the Fennoscandian Shield, forming the present Caledonian nappes (Gee et al. 2008).

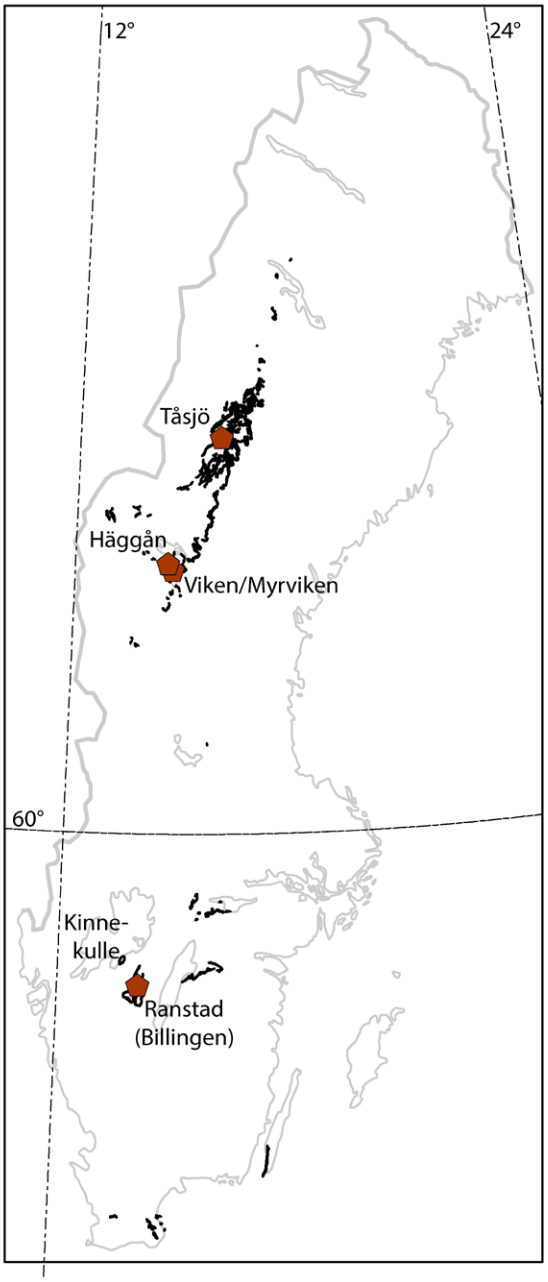


Figure 12. Distribution of Neoproterozoic to Palaeozoic alum shales in Sweden shown as black areas with location of larger U-polymetallic mineralisations. Deposits from Eilu et al. (2013), geology from Bedrock Map Sweden 1:1M.

Within the Caledonian shale area (Figure 12), two types of sediment-hosted U deposits occur; phosphate (phosphorite) deposits and black shale deposits, as classified according to the International Atomic Energy Association, IAEA. Cuney (2009), who based his classification of U deposits on their genesis, cathegorize both the black shale and the phosphate deposits as "synsedimentary uranium mineralisations". These U mineralisations were formed by sedimentation in shallow bays of inland seas that once covered large land areas at times of high sea level. In these inland seas, U was precipitated in phosphorous-rich sediments (phosphorites) or in organic-rich black shale. In both cases organic activity was essential to produce reducing conditions at the bottoms to reduce the solubility of U.

The black shale deposit at **Myrviken** (Figure 13), with U-V-Mo-Ni-Zn mineralisation, formed

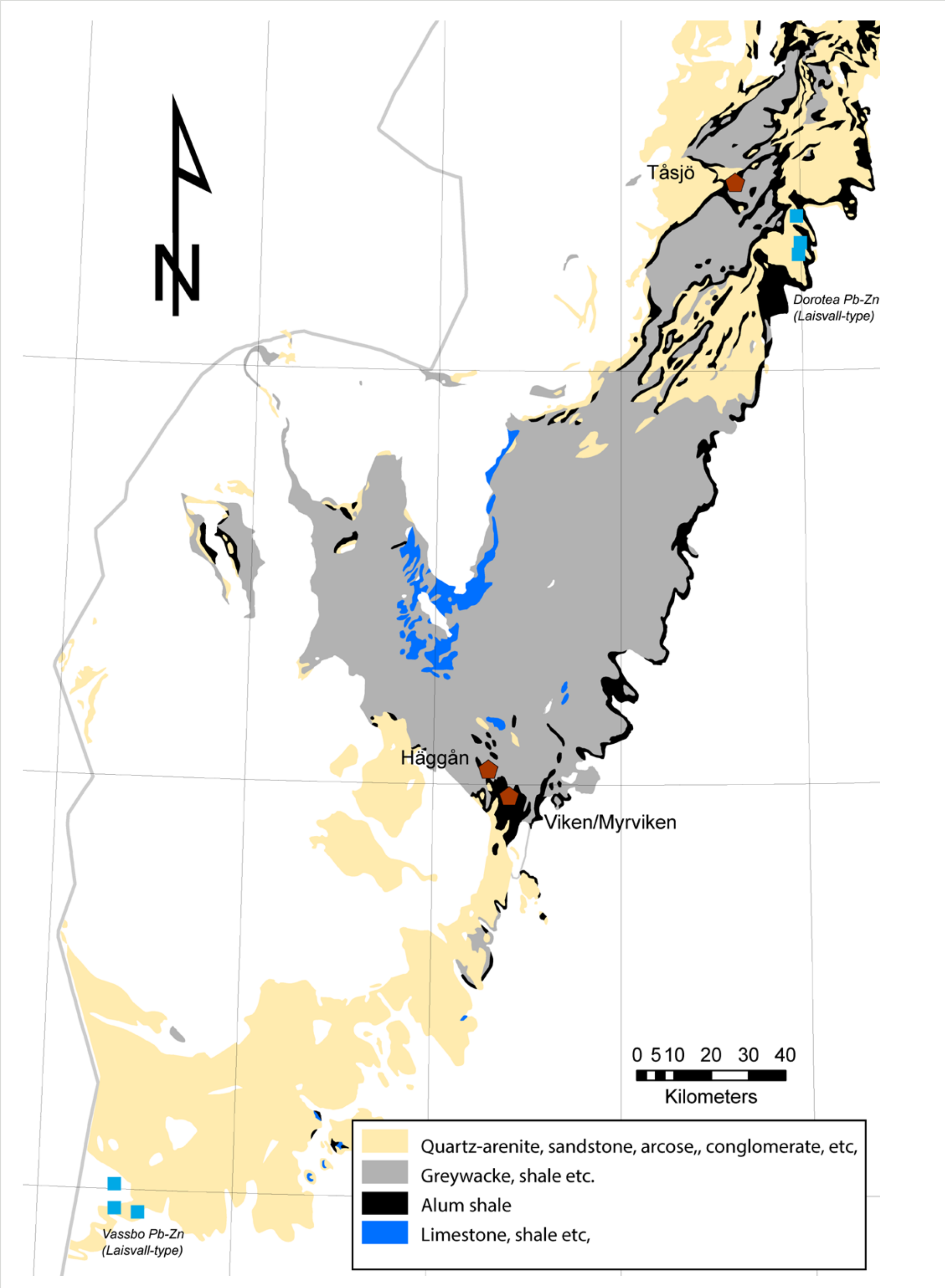


Figure 13. Neoproterozoic to Palaeozoic sedimentary rocks at the eastern rim of and as nappes within the Caledonides. Geological map from SGUs digital Bedrock Map Sweden, 1:1M, mineral deposit from Eilu et al. (2013).

Table 3. Metal resources in the deposits within the Palaeozoic polymetallic shales (alum shales and phosphorites).

Deposit	Reporting	Tonnage (Mt)	Cu (%)	Zn (%)	Ni (%)	Mo (%)	U (%)	Ref.
Tåsjö	historic	200					0.020	1
Myrviken	NI43-101	3062	0.012	0.042	0.034		0.015	2
Häggån	not given	1790		0.045	0.032	0.014	0.014	3

1. Gustafsson, 1979. 2. Continental Precious Minerals Inc., Updated Resource Estimate and Preliminary Economic Assessment Estimates - Viken Project, www.czqminerals.com. 3. Aura Energy, Updated scooping study further supports Häggån project viability, May 29 2012, www.auraenergy.com.au

in the Middle Cambrian to Lower Ordovician and shares characteristics with black shale deposits elsewhere in Sweden, for example those at Billingen and Kinnekulle in southern Sweden (Andersson et al. 1985 and Figure 12). The geology of the black shales in the Myrviken area is well known due to extensive exploration (27 drill holes) conducted by the State Mining Property Commission (NSG) in the 1970s and early 1980s (Gustafsson 1979, Gee 1979, Gee et al. 1982b).

The stratigraphy at Myrviken consists of Lower Cambrian sandstone resting on top of a weathered Proterozoic basement. The sandstones grade upwards into conglomerates, commonly phosphorite-bearing, which are in turn overlain by a grey siltstone that grades into the black shales of the middle and upper (Furongian) Cambrian. Some black shales also occur in the Lower Ordovician. Near the village of Myrviken the Upper Cambrian black shale was tectonically thickened from 20–30 m to approximately 180 m by Silurian thrusting and folding. The black shales may be traced across the Caledonides in nappes to the Norwegian border (Gee 1979).

The black shale has, on average, 10.4 % organic carbon. In certain, 20–30 m thick layers, the organic C content may reach 13–14 % and U 200–240 g/t (Gee et al. 1982a). Recent exploration in the area (under the name Viken) has resulted in the resource estimate shown in table 3.

The poorly exposed U-rich rocks in the **Tåsjö** area are composed of phosphatic and calcareous sandstone to greywackes of Lower Ordovician age resting on top of alum shale (Gee et al. 1978, Gustafsson 1979). The U-bearing phosphate deposit at Tåsjö was discovered in the mid-1950s. The area was further explored in the 1970s by the Geological Survey of Sweden and by the companies Stora Kopparberg and Boliden (Armands 1970). In an area of 500 km^2, approximately 100 holes were drilled, of which c. 25 crossed the U-rich layer. Historic resource estimates for the entire field gave 40 000 t U and 6 Mt P_2O_5, of which c. 1200 t of uranium and 180 000 t of P_2O_5 were considered to be covered by less than 50 m of overburden (Gustafsson 1979). More recent exploration work (Mawson Resouces Ltd., press release January 05, 2006) have not resulted in any further information on the uranium resources for the Tåsjö area. None of the known deposits in the Palaeozoic shales within the area have been exploited.

The area also includes some Pb-Zn mineralisations in Neoproterozoic to Lower Cambrian sandstones. These are essentially similar to the Laisvall Pb-Zn type, but occur within the Caledonian nappes (Christofferson et al. 1979, Chelle-Michou 2008 and Figure 13).

THE GOLD LINE

The gold potential of central Västerbotten county was recognized in the late 1980s when a regional till geochemistry sampling project revealed a southeast-trending gold anomaly, the so called Gold Line (Lindroos 1989, Lindroos et al. 1992, Bark 2008, Figure 14). Intense exploration in the following years resulted in the discovery of several gold prospects, most of which occur in quartz veins or disseminations along deformation zones, i.e. orogenic gold. Two mines have been in production: **Blaiken** Zn-Au (closed in 2007) and **Svartliden** Au, still in production, and ore resource estimated have been published for the Fäboliden and Barsele deposits (Table 4).

The bedrock geology of the Gold Line area (Figure 15) consists of metasedimentary rocks and metabasalts of the Bothnian Supergroup, which was intruded by several phases of granitoids (Kathol & Weihed 2005). The metabasalts were emplaced as sills or submarine lava flows. Pillow lavas, spilites and volcanoclastic breccias are common. Granodiorites intruded at an early stage of the orogeny and were deformed together with the supracrustal rocks. Late- to post-orogenic granites (Revsund-type granites) occur

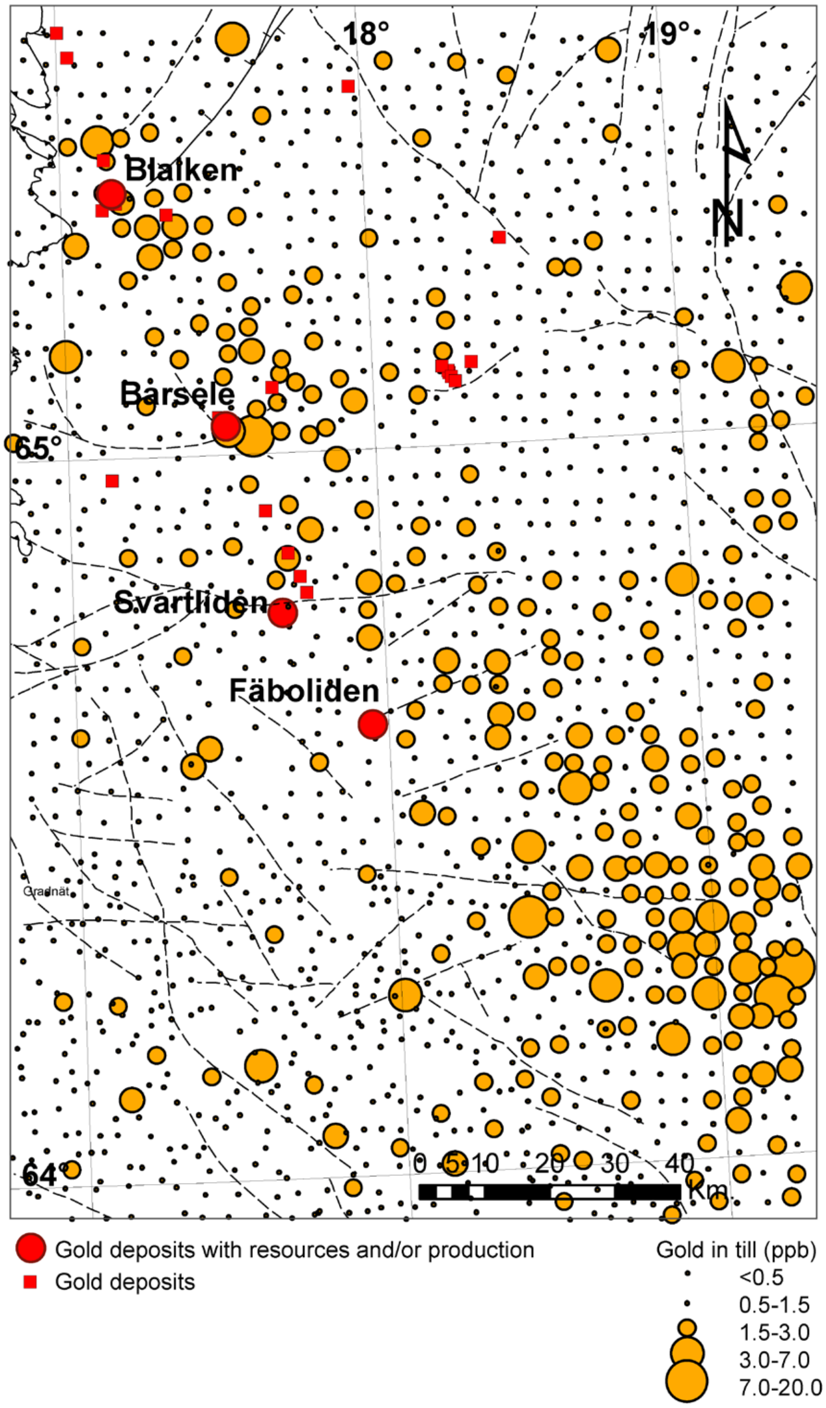


Figure 14. Map showing the gold anomalies from the till sampling program that defines the Gold Line. Red dots show gold deposits with production and/or resources of gold ore (Table 4), red squares show smaller gold deposits in the area. Data on till samples from SGUs digital geochemical database, larger gold deposits from Eilu et al. 2013, smaller deposits from SGUs digital mineral resources database.

as large massifs in the region.

The Ersmarksberget gold mineralisation, part of the **Blaiken** Zn-Au deposit, occurs in north-south striking, discontinuous quartz veins in the contact between a tonalitic intrusion and meta-greywackes. The mineralisation is localised within sulphide-rich, carbonaceous metasedimentary rocks. Gold occurs as electrum in free grains within quartz grain boundaries, intergrown with arsenopyrite, and around the arsenopyrite-quartz grain boundaries (Essuka 2011). The Blaiken mine was in operation for only two years and mainly focused on zinc ore. During these two years the mine produced 785 kton of ore at an unknown grade.

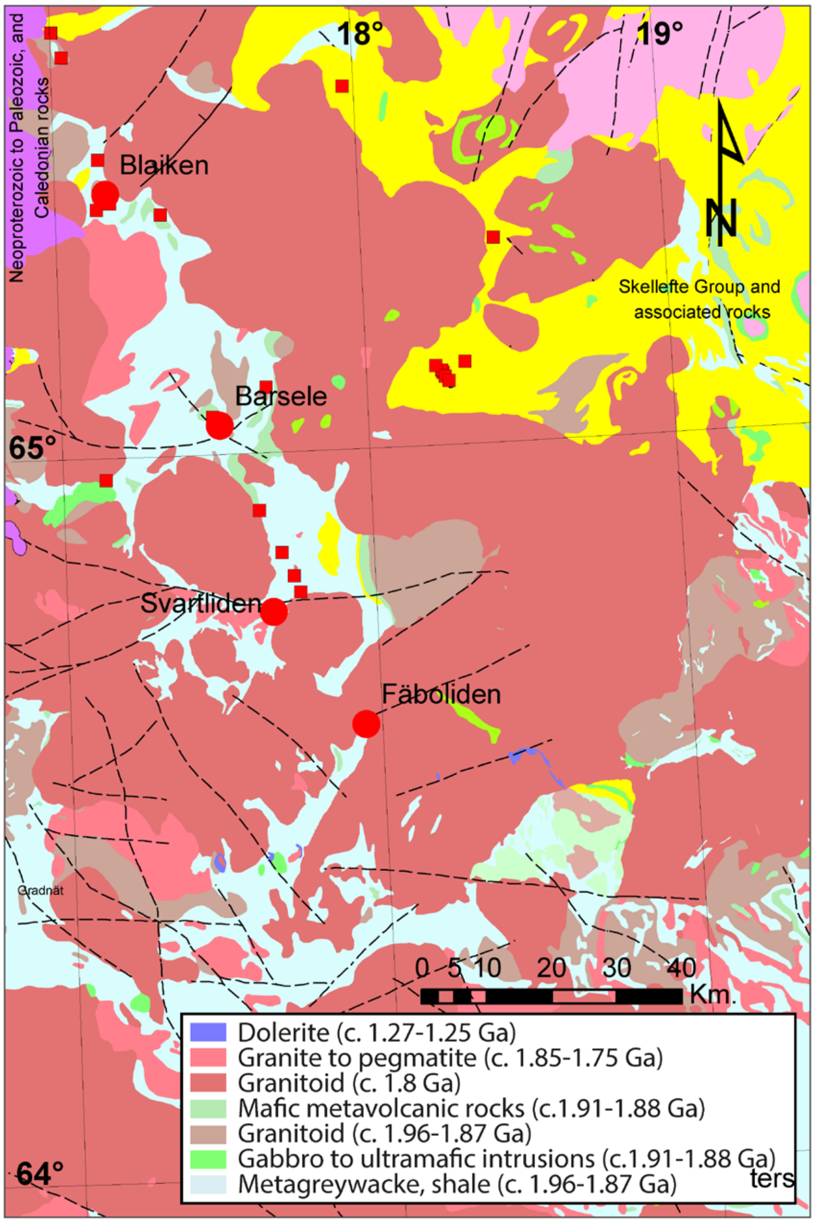


Figure 15. Geological map of the Gold Line area, simplified from SGUs digital Bedrock Sweden 1M. Areas in yellow show the western part of the Skellefte district volcanic, violet area in the upper left part of the map indicates Caledonian rocks.

The **Svartliden** Au deposit comprises epigenetic Au and Ag in hydrothermally altered ductile shear zones that have been metamorphosed to mid-amphibolite facies. Minerals detected in the ore include native silver, native gold, electrum, actinolite, grunerite, diopside, amphibole, pyroxene, löllingite, arsenopyrite, native bismuth and pyrrhotite (Eklund 2007). In 2005, the deposit was put into production. Until 2015, 2.84 Mt of ore at 4.5 g/t gold was mined, yielding 368,612 ounces of gold. Today mining has ceased at Svartliden but the concentration plant continues to process low-grade ore (http://www.dragon-mining.com.au).

The mineralisation at **Fäboliden** is mainly hosted by arsenopyrite-bearing quartz veins within a roughly N-striking, steeply dipping shear zone cutting amphibolite facies volcano-sedimentary host rocks (Bark 2005, 2008). The narrow belt of supracrustal rocks is surrounded by Revsund granites. The gold is fine-grained (2–40 µm) and closely associated with arsenopyrite-löllingite and stibnite, and occurs in fractures and as inclusions in the arsenopyrite-löllingite grains. Gold also occurs as free grains in the silicate matrix of the host rock. Bark (2008) suggested, from his observations at Fäboliden, that favourable places for future exploration for orogenic gold would be areas associated with N-S trending tectonic zones active at around 1.8 Ga.

Gold mineralisation at **Barsele** predominantly occurs within a medium-grained, highly frac-

Deposit	Production (Mt)	Resources (Mt)	Au (g/t)	Ag (g/t)	Ref.
Svartliden	2.8362		4.5		1
Svartliden		1.202	2.8		2
Blaiken	0.785				1
Fäboliden		65.557	1.06	2.8	3
Barsele		34.72	1.08		4

Table 4. Production and resources for the larger gold deposits in the central Västerbotten area.

1. Statistics of the Swedish Mining Industry, SGU. 2. Dragon Mining Annual report 2013. 3. Bedömning av Fäbolidens mineraltillgång maj 2011. 4. Barsele

tured granodiorite and associated metavolcanic and metasedimentary rocks. Three broad types of mineralisation is recognised: 1) orogenic or mesothermal intrusive-hosted gold mineralisation, 2) high-grade gold-silver-lead-zinc mineralisation hosted by syn-tectonic quartz-sulphide veins and 3) massive sulphide (VMS) where gold is probably mobilised and enriched by a later epithermal mineralisation phase (Orex 2012, technical report).

SKELLEFTE DISTRICT (Zn-Cu-Pb-Ag-Au-Te)

The Skellefte District and adjacent areas in northern Sweden (Figure 16) is one of the most prominent gold and base-metal districts in the Fennoscandian Shield with c. 150 known precious and base-metal deposits. Around 30 of these have been in production since 1924, when the first mine, at Boliden, was opened (Boliden`s history, at www.boliden.com, dec 2015). Today (2015), there are six active mines: Kristineberg, Maurliden, Maurliden Östra, Renström, Kankberg and Björkdal. Approximately 30 additional deposits with historical mineral resources, as well as modern resource data, have not been exploited yet. The total production from the district (1924–2009) was 105 Mt @ 2.4 g/t Au, 60 g/t Ag, 0.94 % Cu, 4.6 % Zn and 0.5 % Pb. Reported reserves and resources are 7.45 Mt and 25 Mt, respectively, at somewhat lower grades (Boliden Annual Report 2015, http://www.mandalayresources.com/reserves-and-resources/)

The district is defined as a 140 x 50 km, WNW-trending, Palaeoproterozoic (1.96–1.86 Ga) magmatic region formed in a volcanic arc environment. It has a large number of pyritic massive sulphide deposits hosted by metavolcanic rocks (Allen et al. 1996, Kathol & Weihed 2005, Rickard 1986). In this report, rocks in areas to the east of the magmatic rock-dominated Skellefte district proper, which are dominated by metasedimentary rocks, including marble and belong to the Bothnia basin (Kathol & Weihed 2005) have been included since they are host to important gold deposits. The Jörn granitoid complex north of the Skellefte district proper is hosting porphyry copper mineralisation (Weihed 1992a, 1992b) and is, in this report, included in the Skellefte district area.

Most of the deposits are massive to semimassive, complex pyritic Zn-Cu-Pb-Au-Ag occurrences, generally located in the upper parts of the metavolcanic sequence close to overlying metasedimentary rocks (Allen et al. 1996). Economically important exceptions, for example the Boliden and the Kristineberg deposits, occur at lower stratigraphic levels. Orogenic gold deposits, low-grade porphyry Cu, one Ni and numerous sub-economical Au-As quartz vein deposits has also been reported from the district (Grip & Fri-

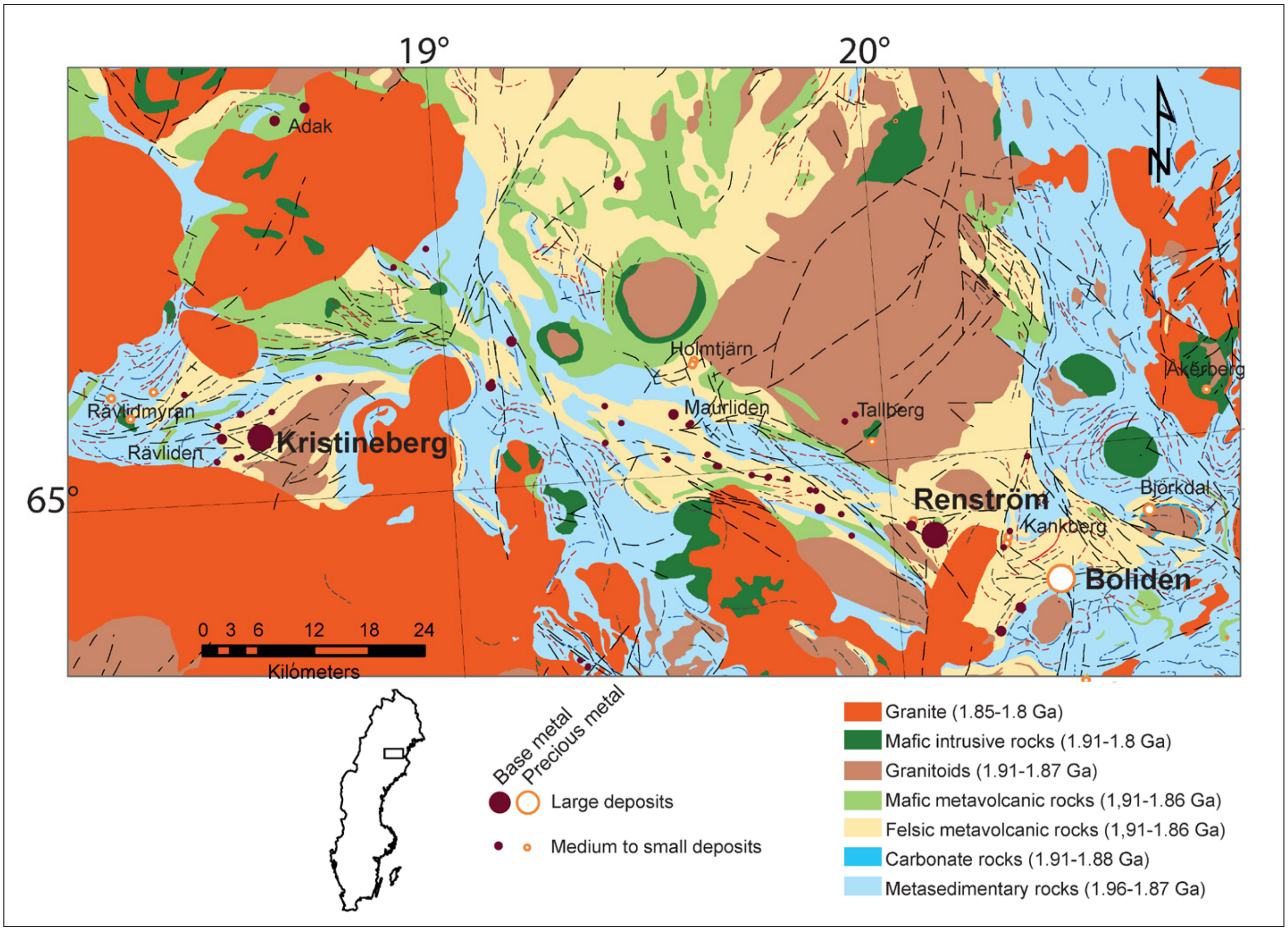


Figure 16. Simplified geological map of the Skellefte district with location of large, medium and small base and precious metal deposits. Map from SGUs digital Bedrock Map Sweden 1:1M, deposit data from Eilu et al. 2013.

etsch 1973, Kathol & Weihed 2005). More than 50 % of all the gold produced in Sweden comes from the Skellefte district and in particular from the eastern part of the area where the massive sulfide deposits tend to be more gold-rich and where orogenic gold deposits are found. The individual gold or gold-rich massive sulfide deposits in the area show different characteristics, have different host rocks, and were most likely formed at different times and by different processes. Collectively they point out the gold potential of the area. A selection of the larger deposits is listed in Table 5 and some of them are further described below.

Mineralised metavolcanic rocks of the metallogenic area (the Skellefte Group) are generally overlain by metasedimentary rocks. In detail, however, the stratigraphy of the supracrustal rocks is complex with large variations across and along the district (Allen et al. 1996). The basement to the supracrustal sequences is not exposed. The supracrustal rocks were intruded by a broadly coeval intrusive suite, the Jörn suite, deformed, metamorphosed and subsequently intruded by a younger suite, the so-called Revsund granites (1.82–1.68 Ga). To the south, the Skellefte district is bordered by metasedimentary rocks belonging to the Bothnian basin. To the north, there is a less well-defined boundary against the Arvidsjaur Group, which predominantly consists of continental volcanic rocks, with minor metasedimentary and intrusive rocks (Kathol & Weihed 2005).

Base-metal and gold mineralisation at **Boliden** (Figures 17-19) occur as massive arsenopyrite ore, massive pyrite+pyrrhotite ore, as veins and as disseminated mineralisation within intensely altered rocks below the massive sulphide ore, and in brecciated parts of the massive sulphide ore (Bergman Weihed et al. 1996). Ore-related hydrothermally altered rocks form a symmetric pattern around the ore with a central zone of intense alteration (andalusite+sericite+quartz) surrounded by less altered rocks (sericite+chlo-

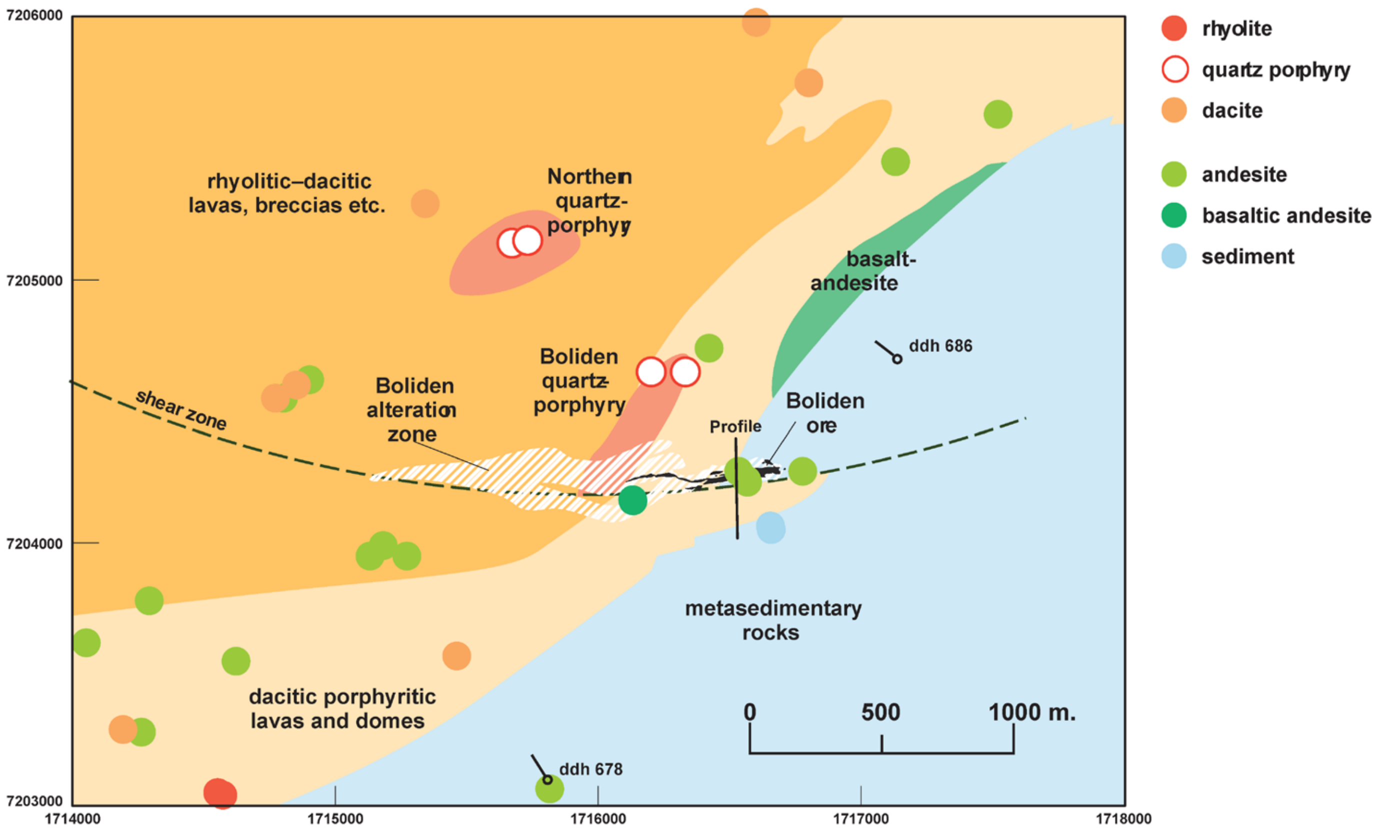


Figure 17. Geological map of the Boliden area from Hallberg (2001). Dots show location of analysed rock samples from outcrops and drill cores and the color indicate the rock classification based on the lithogeochemistry. Coordinates in the Swedish RT90 grid. Vertical black line show location of the profile in figure 19.

Figure 18. Aerial photo of the Boliden deposit with the open pit, head frame and dressing plant. In the upper part of the image the waste rock from the Björkdal gold deposit is seen. Copyright: Boliden Mineral AB.

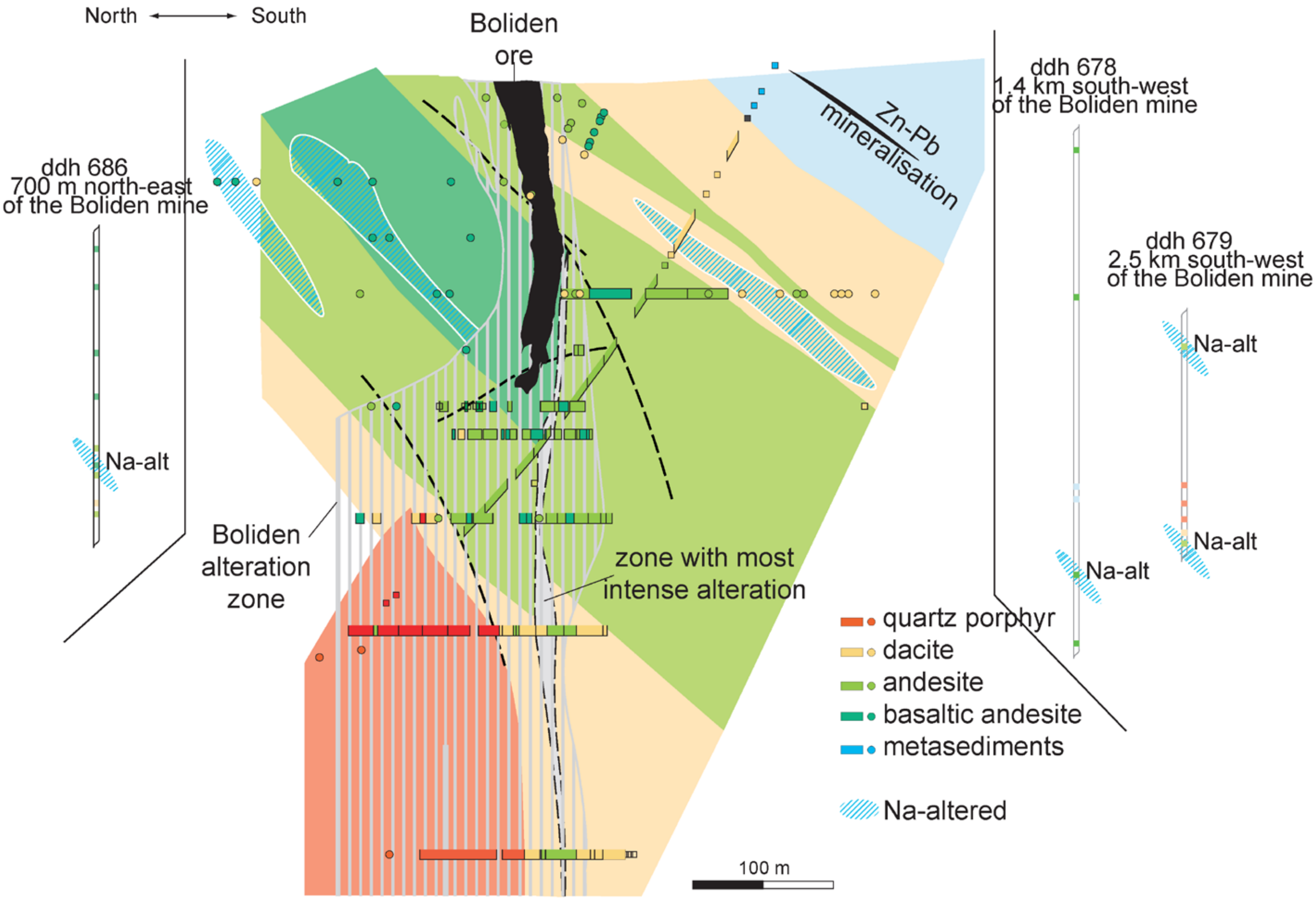


Figure 19. Vertical section across the Boliden deposit (Hallberg 2001). Modified and reinterpreted from Ödman (1941) and Bergman Weihed et al. (1996). Coloured bars and dots show the position rocks sampled for lithogeochemistry and rock classification. Areas with light blue tight hatching indicate the position of rock samples that show sodic alteration. Light grey vertical hatching around and below the Boliden ore (black) indicates a domain of variable alteration and the grey area indicates the most intense alteration. The location of the section is shown in Figure 17.

rite) that in turn grade into a chlorite schist more distal to the ore (Nilsson 1968, Hallberg 2001). The massive ore, the altered rocks and the veins all crosscut the local stratigraphy (Figure 19). The deposit is exceptional among the Skellefte district massive sulphide deposits in terms of its extremely high Au grade (15.5 ppm), high As concentration and intense alteration. These features may suggest an alternative genesis for the deposit, and an epithermal high-sulphidation model, possibly overprinted by an orogenic gold-type event, has been suggested (Bergman Weihed et al. 1996). Recent dating of volcanic host rocks yielded ages of 1894±2 and 1891± Ma (Mercier-Langevin et al. 2013).

The **Kristineberg** massive sulfide deposit (Figure 20) was discovered in 1918, making it one of the first known deposits in the Skellefte district (Du Rietz 1953). Production started in 1935 and is still on-going. According to official statistics, the mine has, up to 2009, produced 29.3 Mt @ 1.0 % Cu, 3.64 % Zn, 0.24 % Pb, 1.24 g/t Au and 36 g/t Ag. The ore consists of two main massive sulphide zones, the A and the B ores, in addition to the Einarsson zone of Cu- and Au-rich stockwork ores with sulphide lenses in altered and deformed rocks (Årebäck et al. 2005). The ore zones are hosted by hydrothermally altered felsic to intermediate metavolcanic rocks. The deposit was formed at a lower stratigraphic level within the Skellefte Group compared to other deposits in area, including the nearby **Rävliden** and **Rävlidmyran** deposits. The mineralisation of the A and B zones is interpreted as synvolcanic massive sulphide type, whereas the Einarsson zone, within strongly altered, andalusite-bearing rocks and rich Au-Cu dissemination, lacks clear evidence of a synvolcanic origin (Årebäck et al. 2005).

Mineralisation in the **Adak** area was discovered in 1930 during regional exploration conduct-

Figure 20. Aerial photo of the Kristineberg deposit with open pits and the head frame. Copyright: Boliden Mineral AB.

ed by the Geological Survey of Sweden (Ljung 1974). Mining started in 1934 and the last mine in the area closed in 1976. The Adak field consists of the **Adak**, **Lindsköld**, **Karlsson östra**, **Karlsson södra** and **Brännmyran** mines. In total, 6.35 Mt @ 0.80 % Cu, 3 % Zn, 0.1 % Pb and some silver and gold were extracted between 1934 and 1976. The Rudtjebäcken deposit, a few kilometres to the east, was in operation from 1947 to 1975 and produced 2.96 Mt @ 0.92 % Cu, 2.96 % Zn, 0.1 % Pb as well as some Au and Ag (Table 5). Mineralisation in the Adak field consists of chalcopyrite, sphalerite, arsenopyrite, galena, pyrite and pyrrhotite, occurring as massive bodies, veins and disseminations within altered mafic to felsic metavolcanic rocks with carbonate interlayers (Ljung 1974). In addition to base metals and associated low-grade precious metals, the deposits of the Adak field contain Co-bearing pyrite and arsenopyrite. The deposits are also among the most Se-rich in the Skellefte district, and grades of In have been demonstrated. (Ljung 1974).

The **Maurliden** (Maurliden Västra, Norra and Östra) massive sulfide deposits occur in the central part of the Skellefte district (Figure 16) and are among the most studied deposits in the district (Claesson & Isaksson 1981, Montelius 2005, Montelius et al. 2007). They consist of pyritic massive sulfides (Figure 21) hosted by a thick succession of volcanic rocks, a typical example of the pyrite-dominated massive sulfide deposits with a relatively low base-metal grade that are found in the central Skellefte district.

The **Åkerberg** gold deposit consists of a zone of east–west-trending, subvertical cm-wide gold-bearing quartz veins in a layered gabbro (Mattson 1991, Dahlenborg 2007). The mineralised zone is 10–30 m wide and 350 m long, and can be followed to a depth of c. 150 m. Outside of the mineralised zone, the quartz veins pinch out to altered veinlets and eventually disappear further to the east. The western end of the mineralised zone is not exposed.

The **Björkdal** gold deposit is located at the contact between an intrusive granodiorite to tonalite and supracrustal rocks belonging to the Skellefte Group. Gold mineralisation consists of cm- to m-wide, subvertical, auriferous quartz veins within the granodiorite (Weihed et al. 2003, Gold Ore Resources 2011). The veins mainly trend NE and NNE. The gold occurs as both free milling and associated with pyrite.

The **Åkulla Östra** deposit lies in an area with several other small massive sulfide deposits that have been mined in the past. It was known at an early stage that the deeper parts of the Åkulla Östra mine carried auriferous quartz veins in altered rocks (Grip & Frietsch 1973). Further drilling in the area revealed an Au-Te mineralisation below the massive sulfide deposit. Underground mining of the Au-Te mineralisation commenced

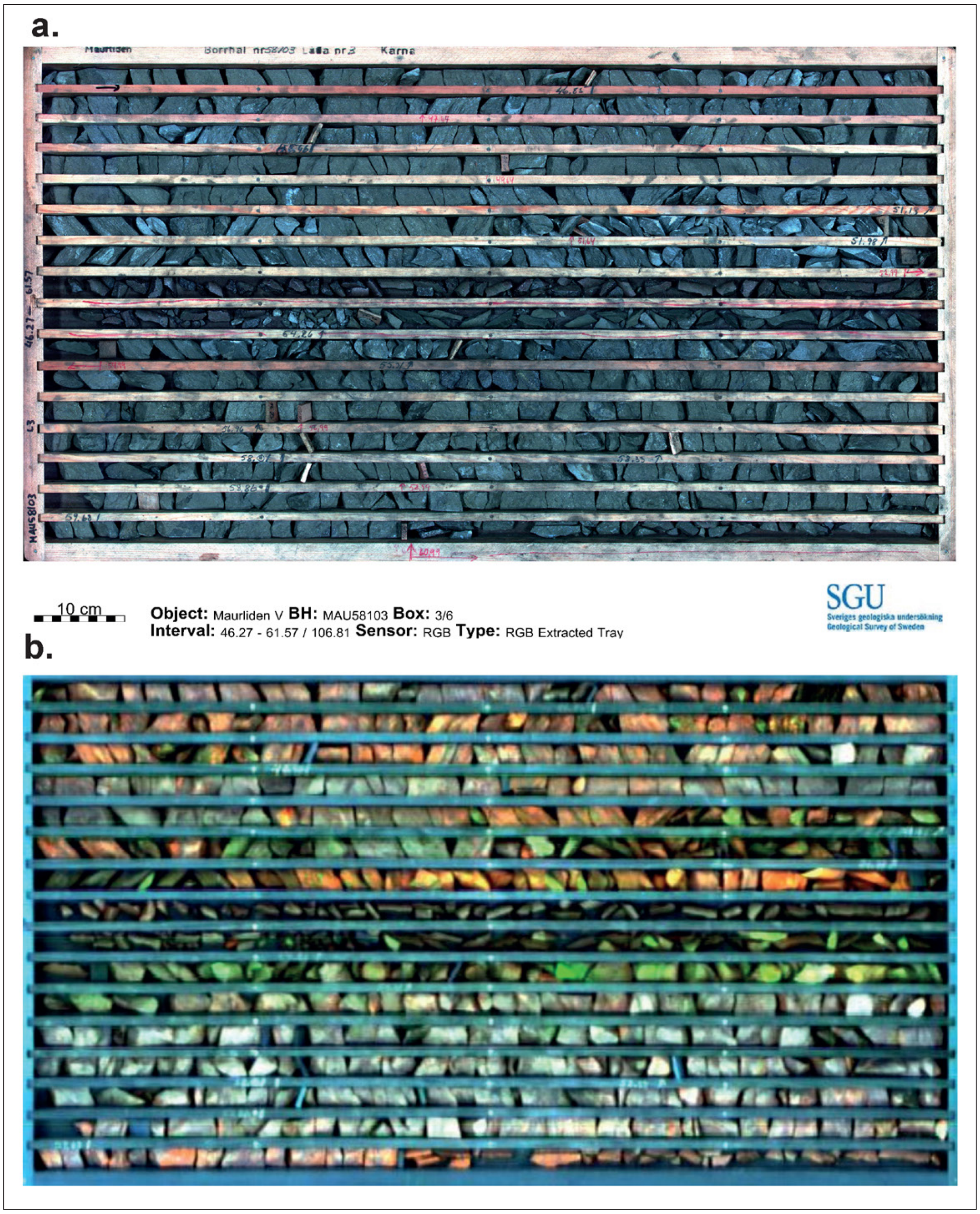


Figure 21. Drillcore box from Maurliden ddh 58103, 46.27 – 62.57 m showing massive sulfide mineralisation with some shale between 51.64-52.99. The average composition of the drillcore box is 0.10 % Cu, 5.1 % Zn, 0.4 % Pb, 0.99 g/t Au and 46.7 g/t Ag (Drillcore protocol Maurliden bh: 58103.

a. Natural colour (RGB) photo

b. False colour composite image in long wave infrared light. Three infrared bands (R=8611 nm, G=10022 nm and B=11810 nm) compose the image and they represent a color rendition of data from sensors measuring across the long wavelength portion of the infrared spectrum. The image has not been further processed to a mineral map but the orange colored core probably represents the shale intercalation between 51.64-52.99 meters. The following section, 53.01-54.17, dark grey in the image is a very zinc-rich part of the core with 21 % Zn.

Color images and false color composite images of the full core, other cores from Maurliden as well as other drillcores from Swedish mineralisation can be seen at www.sgu, choose MapViewer; Drill cores. The location of the drill core in relation to the ore is shown in Montelius et al. 2004.

Operating mines	Prod. (Mt)	Res. (Mt)	When mined	Au (g/t)	Ag (g/t)	Cu (%)	Zn (%)	Pb (%)	Ref.
Operating mines									
Kristineberg	29.17	12.50	1935-in operation	1.2	48	1.1	6.1	0.3	1, 2
Björkdal	20.14	25.30	1988-in operation	1.8					8
Renström	12.19	7.70	1948-in operation	2.8	151	0.8	7.3	1.4	1, 2
Maurliden Västra	2.58	2.80	2000-in operation	0.9	49	0.2	3.4	0.4	1, 2
Maurliden Östra	1.73	0.56	2010-in operation	1.08	23.7	1.61	0.77		7
Kankberg nya	0.84	5.40	2012-in operation						
Closed mines									
Långsele	11.20		1951-1991	0.9	25	0.6	3.9	0.3	1
Rävliden	7.54		1936-1991	0.5	90	1.0	4.2	0.8	1
Adakfältet	6.34		1932-1977			0.8	3.0	0.1	1, 5
Udden	5.95		1971-1990	0.8	39	0.5	4.8	0.3	1
Boliden	5.89		1926-1968	15.5	50	1.4	0.9	0.3	1
Petiknäs södra	5.40		1989-2007	2.4	102	0.9	4.9	0.9	1, 2
Rudtjebäcken	4.74		1947-1975	0.3	10	0.9	3.0	0.1	1, 6
Långdal	4.48		1950-1999	1.9	160	0.1	5.7	1.7	1
Näsliden	4.03		1963-1989	1.4	37	1.2	2.9	0.3	1
Rävlidmyran	1.90		1942-1976	0.8	51	1	3.9	0.6	7
Storliden	1.70		2002-2008	0.3	30	4.0	10.0		1, 3
Åkerberg	1.48		1989-2000	3.14	3.2	0.04		0.06	7
Kankberg	1.16		1966-1997	2.6	52	1.4	1.8	0.3	7
Åkulla Västra	0.98		1938-1957	0.7	12	1			7
Rakkejaur	0.72		1934-1988	1.0	45	0.3	2.3	0.2	1
Kedträsk	0.69		1969-2000	0.5	24	0.4	2.9	0.2	7

Table 5. Larger base- and precious metal deposits in the Skellefte district area with produced tonnage, combined reserves and resources, information on operating dates and metal grades with references.

1. Official Statistics of Sweden, Metal and Mining industries. 2. Boliden (2009). 3. Lundin Mining (2008). 4. Gold Ore Resources (2011). 5. Boliden Mineral Adak closure map (in the archives of the Mining Inspectorate of Sweden). 6. Boliden Mineral Rudtjebäcken closure map (in the archives of the Mining Inspectorate of Sweden). 7. Bauer et al. 2014. 8. Gold Ore Resources (2011)

in 2012 through a tunnel from the then closed Kankberg mine. The new mine is named **Kankberg nya** in this publication in order to avoid confusion with the old Kankberg mine.

The **Tallberg** deposit, located to the north of the Skellefte District proper, is interpreted as a Palaeoproterozoic porphyry copper deposit hosted by a 1.9 Ga granitoid (Weihed 1992a, 1992b). The deposit is of low grade, 0.27 % Cu and 0.2 g/t Au, but the large tonnage could make it mineable in the future.

The **Holmtjärn gamla** (Old Holmtjärn) deposit was found in the early 1920s and was mined out in two years. The upper parts of the ore were strongly weathered and carried gold grades of more than 1000 g/t. The massive arsenopyrite and pyrite ore beneath the weathered zone also showed high gold grades (Grip & Frietsch 1973). Although no detailed description exists, it seems from the available information that Holmtjärn gamla in many ways resembles the Boliden deposit.

Throughout the Skellefte district, several gold- and arsenopyrite-bearing quartz veins have been found (Högbom 1937, Grip & Frietsch 1973). In a few places, they have been mined on a small scale in the past, but small tonnage and scattered gold make them uneconomic.

LAISVALL Pb-Zn-Ag

Sandstone-hosted Pb-Zn deposits of the Laisvall-type are found in Neoproterozoic to Lower Cambrian sandstones exposed along the eastern rim of the Caledonian orogen and in nappes of the same rocks that have been thrusted eastward during the Caledonian orogeny (Figure 22). The majority of the deposits are found in Sweden (Grip & Frietsch 1973, Rickard et al. 1979, Casanova 2010, Saintilan et al 2014, 2015), but some occur in Norway (Björlykke and Sangster, 1981).

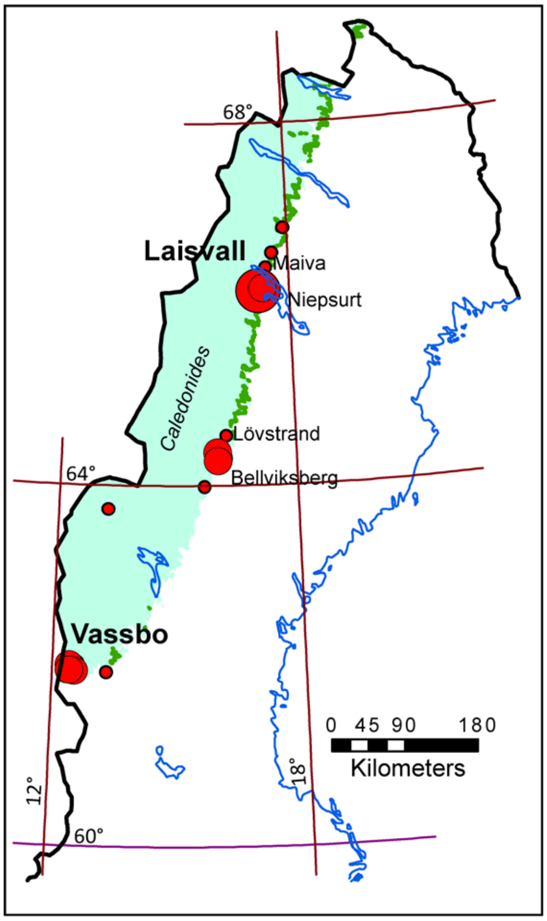


Figure 22. Map of northern and central Sweden showing the location of Laisvall-type Pb-Zn mineralisations in relation to the Caledonides (light green) and Neoproterozoic to Lower Paleozoic platform cover (green) at the margin of the Caledonides. Based on data from SGUs digital Bedrock Map of Sweden 1:1M, Eilu et al. 2013 and SGUs mineral resources database.

Mineralisation consists of galena and sphalerite filling up pore space in the sandstones forming stratabound mineralisations. A characteristic feature of the Laisvall-type deposits in Sweden and Norway is the strongly radiogenic composition of galena (Rickard et al. 1981).

The largest and best-described of the sandstone-hosted Pb-Zn deposits in Scandinavia is the **Laisvall** deposit (Rickard et al. 1979, Willden 2004, Casanova 2010, Saintilan et al. 2015 and references therein, Figure 23). The deposit was discovered in 1939, the development of the mine started in 1941 and the first ore was produced in 1943 (Willden 2004, Bergshanteringen 1943). When the mine closed in 2001 it had produced 64,256 Mt of ore with an average grade of 4.0 % Pb, 0.6 % Zn and 9 g/t Ag (Willden 2004).

Pb-Zn mineralisation at Laisvall is hosted in two distinct, nearly horizontal sandstone sequences, the Lower Sandstone-ore horizon (Kautsky Ore Member) and the Upper Sandstone-ore horizon (Nadok Ore Member), Figure 24 and 25. These two ore-horizons are separated by the barren Middle Sandstone (Tjalek Member). In addition, there is minor mineralisation in sandstones of the Neoproterozoic Ackerselet Formation stratigraphically below the main mineralisation (Casanova 2010). The Pb-Zn mineralisation at Laisvall has been dated to Middle Ordovician (467 ± 5 Ma, Saintilan et al., 2015), indicating that it took place about 100 million years after the deposition of the host rocks.

The autochthonous sedimentary sequence of the Laisvall Group, which also includes the Grammajukku Formation on top of the mineralised sandstones, rests unconformably on a weathered surface of Palaeoproterozoic (1.87–1.66 Ga) granitoids to syenites. The Neoproterozoic and younger sedimentary successions hosting the Pb-Zn occurrences of Laisvall type were formed during crustal extension and formation of sedi-

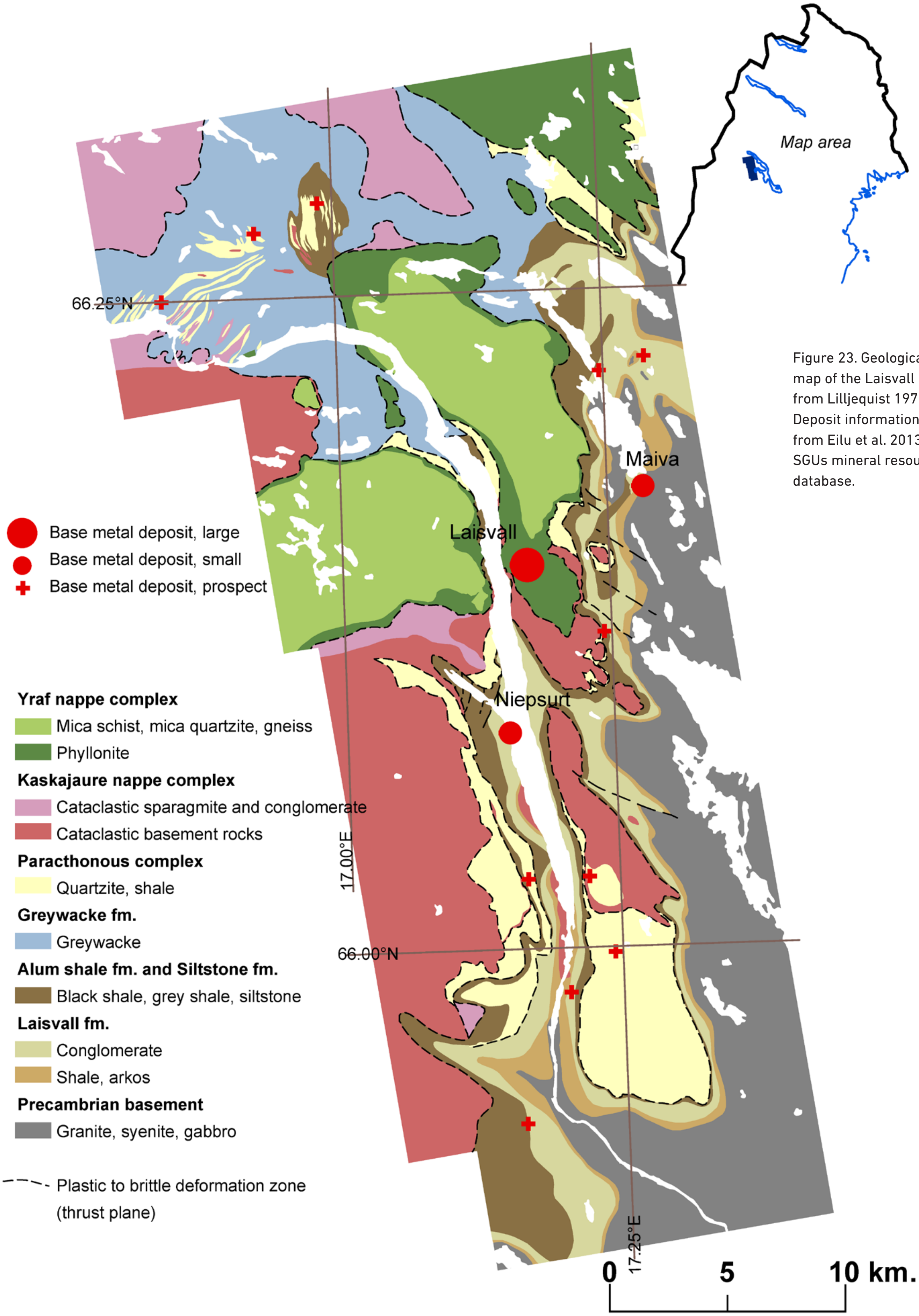


Figure 23. Geological map of the Laisvall area, from Lilljequist 1973. Deposit information from Eilu et al. 2013 and SGUs mineral resources database.

mentary basins along the margins of continental Baltica (Gee et al. 2008).

Saintilan et al. (2015) showed that the basement structures underneath the mineralised sandstones played an essential role, both in localizing the sediments forming the host rocks and as feeders for Pb-Zn fluids. Sulphur isotopes indicate that most of the sulphur comes from thermogenic sulphate reduction of seawater sulphur but also a contribution from pyrite in the overlying black shales and reduced sulphur brought up with the Zn-Pb fluids (Saintilan et.al. 2014). Nobel gas isotopes in fluid inclusions in ore minerals indicate low temperature crustal fluids, the halogen compositions of fluid inclusions suggests that the fluids was derived from evaporation of seawater beyond halite saturation (Kendrick et al. 2005).

Two similar, unexploited Pb-Zn deposits have been identified in the vicinity of Laisvall. They are **Maiva**, with about 1 Mt of ore, 7 km to the northeast of Laisvall, and **Niepsurt** with 1.75 Mt of ore located less than 10 km to the south (Lilljequist 1973, Figure 23 and Table 6). In addition, there are another 15 known sandstone-hosted Pb-Zn deposits in the Laisvall area (Grip & Frietsch 1973).

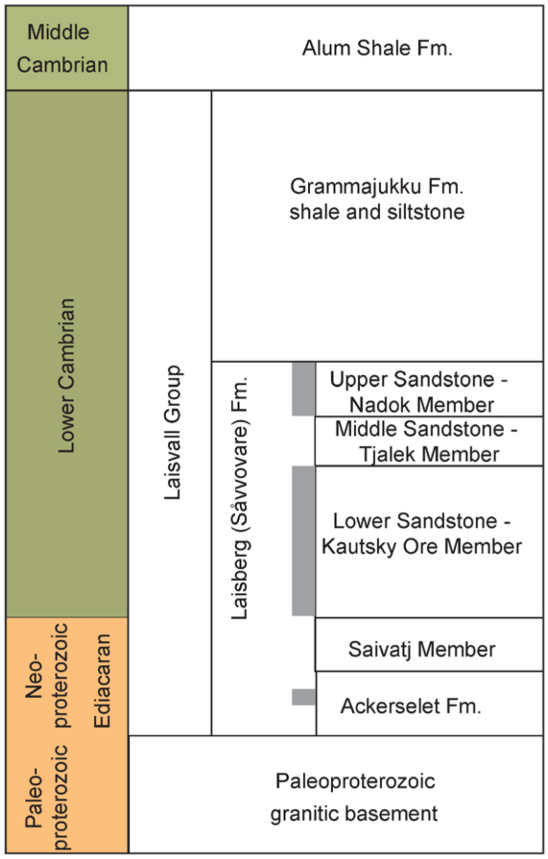


Figure 24. Stratigraphy of the Laisvall area, from Casanova (2010), Saintilan (2014) and references therein.

Deposit	When mined	Resources (Mt)	Mined (Mt)	Ag (g/t)	Pb (%)	Zn (%)	References
Laisvall	1943–2001		64.3	9	4.0	0.6	1
Maiva		1.00		10	5.1	0.1	2
Niepsurt		1.75		8	3.2	0.3	3

Table 6. Sandstone-hosted Pb-(Zn) deposits in the Laisvall area.

1. Willdén (2004). 2. Grip & Frietsch (1973). 3. Mineral deposit register.

Figure 25 a. Natural colour (RGB) photo of drillcore box from Laisvall ddh 34, 92.97-110.3 m. The upper part of the core box contains core from the mineralized Upper Sandstone-ore horizon (Nadok Ore Member), the uncut core in the central parts of the core box contains core of the barren Middle Sandstone (Tjalek Member) and the lower part of the core box contains core of the mineralized Lower Sandstone-ore horizon (Kautsky Ore Member).
b. Magnification of the lower right corner of the core box shows the typical speckled appearance of Pb-Zn mineralisation of Laisvall type. Colour photos and false colour composite image of infrared imaging of the full core, other cores from Laisvall as well as other drillcores from Swedish mineralisation can be seen at www.sgu, choose MapViewer; Drill cores.

KALLAK AREA

Several quartz-banded iron deposits (Proterozoic banded iron formation, Frietsch 1997, Grip & Frietsch 1973) occur in the Kallak area (Figure 26). The host rocks to the deposits consist of felsic to intermediate volcanic rocks and metasedimentary rocks (banded gneisses) belonging to the Kiruna-Arvidsjaur Group (Porphyry group) with an age of 1.88-1.86 Ga (Bergman et al. 2001). The supracrustals have been intruded by several generations of both mafic and felsic compositions.

At the Kallak (a.k.a. Björkholmen) deposit, the largest and best-known deposit in the area, magnetite and hematite occur interlayered with quartz and feldspar with accessory hornblende, diopside and chlorite in a 1 km long and up to 300 m wide zone (Eriksson 1983). Layers of skarn, with garnet and epidote, locally form thick layers between the iron mineralisation and the host rocks (Frietsch 1997).

The iron-ore potential of the area was recognized in the 1940s by SGU when the Kallak deposit was discovered and drilled. Continued exploration in the 1970s found several deposits similar to Kallak. These include, from south to north, Akkihaure, Tjårovarats, Southern Parkijaure, Parkijaure, Southern Kallak, (Kallak), Maivesvare, Åkosjägge and Pakko. Historic resource estimates based on ground magnetic and gravimetric surveys exist for four of the deposits, modern resource estimates according the JORC code exist for Kallak and Southern Kallak (Table 7). Documentation from exploration work in the Kallak area includes several drillcores and ground magnetic surveys (digitised), mainly from SGU exploration, but also from exploration companies.

Exploration in the late 1970 revealed copper mineralisation hosted by intrusive rocks at Iekelvare to the south-west of the Kallak area (Weihed 2001, Sundberg et al. 1980). Several objects in the area were explored and drilled around 2005, but with poor results.

None of the deposits in the Kallak area have been exploited so far, but the company Beowulf plc. is currently developing the Kallak deposit (www.beowulfmining.com)

Deposit	Resources (Mt)	Standard	Fe (%)	Reference to deposit size
Kallak	144.1	JORC	35	Press release 3 April 2013 Beowulf Mining
Åkosjägge	10	JORC	23	Hannans Reward annual report 2012
Akkihaure	12	historic	25	Frietsch 1997
Parkijaure S	6	historic	35	Frietsch 1997
Parkijaure	23	historic	38.5	Frietsch 1997
Kallak Södra	6	historic	30	Johansson 1980, Frietsch 1997

Table 7. Resources and Fe-content of the iron deposits in the Kallak area with references.

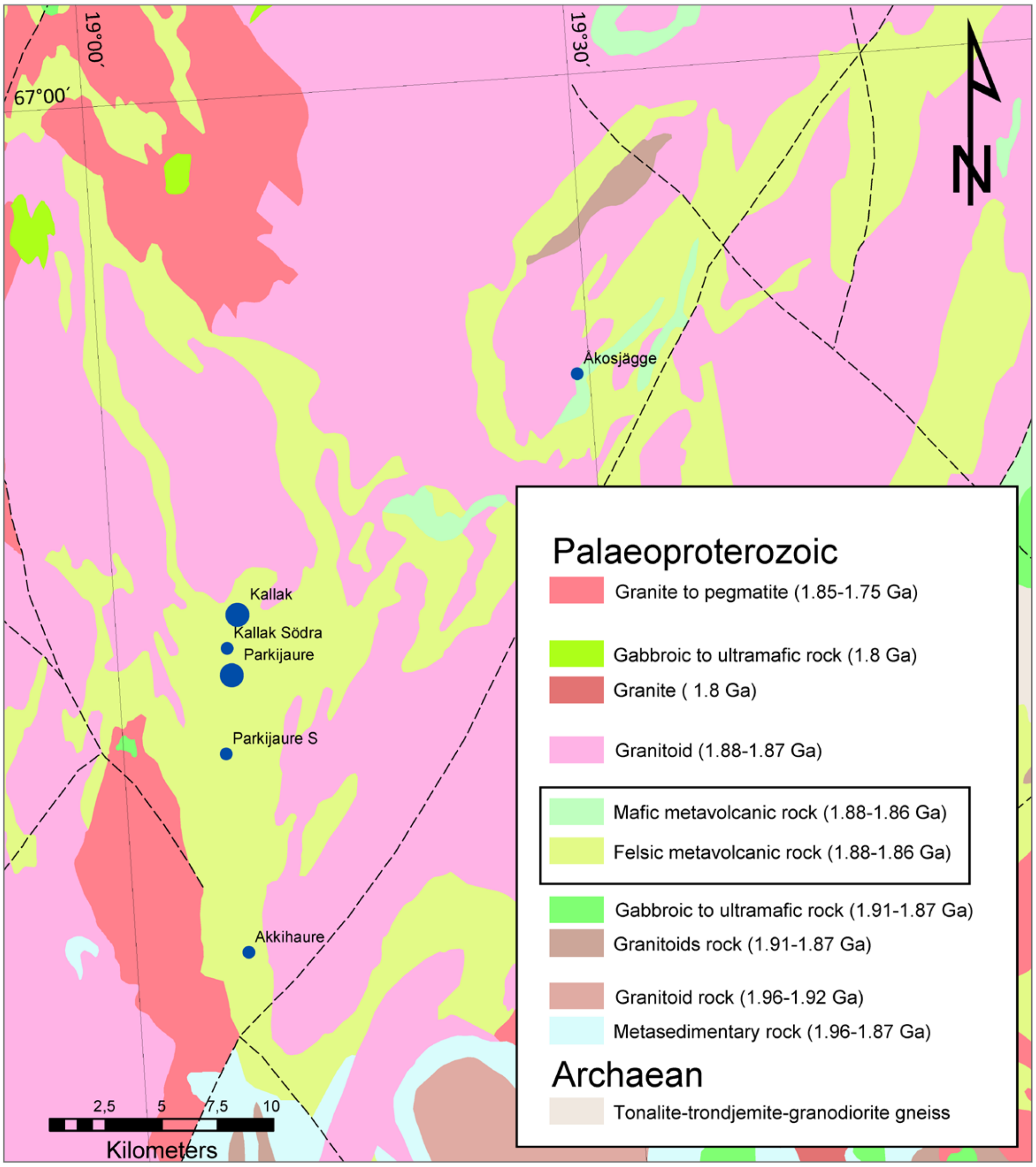


Figure 26. Geological map of the Kallak area simplified from SGUs digital map Bedrock of Sweden 1:1M. The mafic and felsic metavolcanic rocks of the Kiruna-Arvidsjaur Group (Porphyry group) and hosting the iron deposits are framed in the legend. The iron deposits, from Eilu et al. (2013), are marked with blue dots where the size of the dot indicate the size of the deposit, see table 7.

AITIK-NAUTANEN

The **Aitik** Cu-Au-Ag mine is located some 15 km southeast of Gällivare and is presently Europe's largest open-pit copper producer (Figs. 27 and 28). From a modest production of less than 2 Mt during the first year of operation (1968) to the present (2013) production of c. 39 Mt (New Boliden 2014) the deposit has produced 632 Mt @ 0.35 % Cu, 0.18 g/t Au and 3.4 g/t Ag (New Boliden 2014). Reported reserves are 756 Mt @ 0.22 % Cu, 0.15 g/t Au, 1.5 g/t Ag and 24 g/t Mo, while measured and indicated resources are 1643 Mt @ 0.16 % Cu, 0.10 g/t Au, 1.0 g/t Ag and 23 g/t Mo (New Boliden 2014).

The ore at Aitik is hosted by a biotite-sericite schist or gneiss and amphibole-biotite gneiss (Zweifel 1976, Monro 1988). The precursor to the altered, metamorphosed and deformed host rock is a ca. 1.9 Ga volcanosedimentary sequence formed during the Svecokarelian orogeny (e.g., Witschard 1996, Wanhainen et al. 2006). Stratigraphically, the sequence belongs to the Muorjevaara Group (Martinsson and Wanhainen 2004) and is correlative with the regional Porphyrite Group of Bergman et al. (2001). A summary of the local stratigraphy is presented in Lynch et al. (2015).

The Mineralisation consists of veinlet and disseminated chalcopyrite, pyrite, pyrrhotite, molybdenite and magnetite. Accessory minerals include bornite, chalcocite, malachite, sphalerite, galena, arsenopyrite, scheelite, uraninite and apatite. Native gold, electrum and amalgam mainly occur in fractures, along grain boundaries and as inclusions in sulphide and silicate

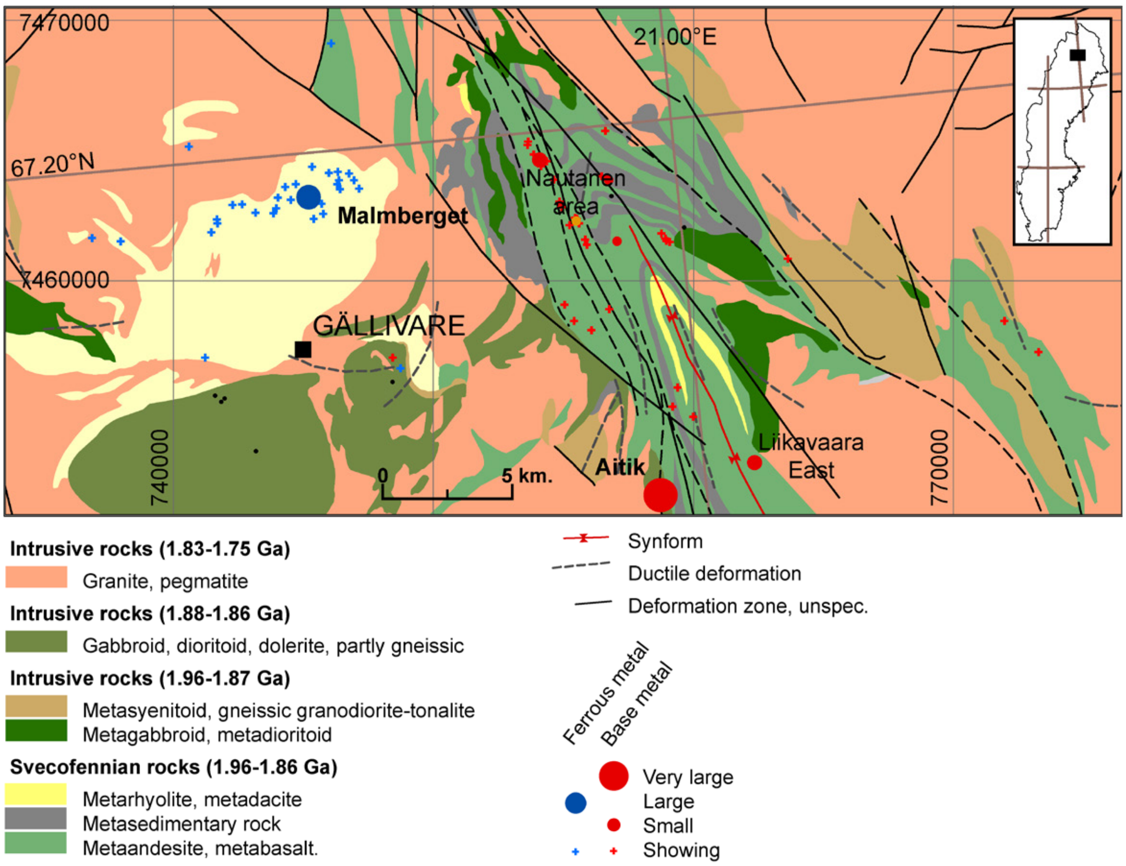


Figure 27. Geological map of the Gällivare area with the locations of deposits included in the Fennoscandian Ore Deposit Database (Eilu et al. 2013) and also smaller occurrences from SGU's Mineral Deposit Database. Simplified from Bergman et al. (2001). The grids shown are SWEREF-99 and Latitude-Longitude.

Figure 28. Aerial photo looking north showing the Aitik open pit. Copyright: Boliden Mineral AB.

minerals (Sammelin (Kontturi) et al. 2011). In the footwall, a deformed quartz monzodiorite with sub-economic Cu grades has yielded a U-Pb zircon age of 1887 ± 8 Ma (Wanhainen et al. 2006). Reported Re-Os and U-Pb ages for hydrothermal minerals have identified mineralisation-alteration stages at ca. 1.88, 1.85, 1.80 and 1.78 to 1.73 Ga, and suggest an episodic and protracted metallogenic evolution (Wanhainen et al. 2005). Both the monzodioritic stock and the host volcanosedimentary rocks were affected by ore-related potassic alteration. In general, Aitik is interpreted as a Palaeoproterozoic porphyry Cu deposit formed at ca. 1.89 Ga that was subsequently overprinted by an iron oxide-copper-gold-style mineralization event some 100 million years later (Monro 1988, Wanhainen 2005). A deposit similar to Aitik with respect to the style of mineralisation, grade and host rocks, but of much smaller size (ca. 9.5 Mt), is located at **Liikavaara East**, about 4 km to the east of Aitik (Sammelin 2011).

Further to the north of Aitik, the NNE-trending Nautanen Deformation Zone (NDZ; Witschard 1996) hosts several relatively small Cu-Au prospects (typically < 3 Mt), including the **Nautanen** and **Liikavaara** deposits (Martinsson and Wanhainen 2004, 2013 and Figure 29). The Mineralisation occurs as disseminations, veinlets and local semi-massive lenses of chalcopyrite, bornite and pyrite (± magnetite). Deformed and altered host rocks in the area are lithologically and geochemically correlative with the wall rocks at Aitik (i.e., Muorjevaara Group meta-volcano-sedimentary rocks; Lynch et al. 2015). Smith et al. (2009) report U-Pb ages ranging from ca. 1.79 to 1.78 Ga for hydrothermal alteration at the Nautanen deposit and inferred temporal and genetic links between deformation, granitic magmatism, fluid mobilisation and Cu-Au mineralisation. To the east of the NDZ, the **Ferrum** and **Friedhem** prospects are examples of mainly quartz vein-hosted Cu-Au mineralisation.

Figure 29. Historical mine workings at the Nautanen copper-gold deposit, with the 29th (29:an) shaft in the foreground. View looking to the east. From Lynch et al. (2015). Photo: Edward Lynch

MALMBERGET

The **Malmberget** apatite iron ore deposit (Figure: see chapter Aitik-Nautanen, figure 27) is the second largest iron deposit in Sweden with a combined total production plus reserves and resources of 1177 Mt (Mineral statistics of Sweden and www.lkab.com). The deposit consists of several ore bodies over an area of around 15 square kilometers (Figure 30). In the western and northern part of the Malmberget ore field, the ore forms an almost continuous horizon, whereas the eastern part is made up of several isolated lenses of iron ore. (Figure 30, Bergman et al. 2001). One of the ore bodies, the blind Printzsköld ore body at 700 m depth and below have been investigated in detail by Debra (2010).

The dominant ore mineral in the Malmberget iron ore bodies is magnetite but hematite-rich ore becomes more frequent in the western parts of “Stora Malmlagret” at the ore bodies Välkomnan, Baron, Johannes and Skåne (Bergman et al. 2001).

Host rock to the deposit mainly consists of metamorphosed and deformed volcanic rocks of rhyolitic to dacitic composition belonging to the Kiruna-Arvidsjaur Group (Porphyry Group) and with an age of 1,88-1.86 Ga (Bergman et al. 2001). The felsic metavolcanic host rocks are commonly rich in K-feldspar, whereas albite-rich rocks occur locally as hosts to ore. At some places amygdules have been observed in the host rocks indicating an extrusive character of the rocks. The mafic rocks in the area mainly occur close to the iron ores. They are interpreted to be dykes, sills and possibly also extrusives. To the north the ore-bearing metavolcanic rocks are intruded by a large granite-pegmatite (Lina granite) with an age of 1.85-1.75 Ga. Recrystallisation of the metavolcanic rocks increases towards the granite-pegmatite. Granite dykes and pegmatites are common in the iron ore and in their host rocks (Bergman et al. 2001, Witschard 1996).

The Malmberget deposit and metavolcanic host rocks are highly metamorphosed. Ductile deformation has formed the present shape of the deposit with a large scale fold with a fold axis dipping moderately to the SSW and intense stretching of ore bodies parallel to the fold axis (Geijer 1930, Grip and Frietsch 1973, Bergman et al. 2001). Younger dikes, believed to belong to the younger granite-pegmatite association, are similarly deformed suggesting that deformation took place after ca. 1800 Ma (Bergman et al. 2001).

To the west of the ore bodies making up the Malmberget ore field there are some smaller deposits believed to be of the same type of iron ore as Malmberget. These include the Sikträsk and the Norregruvan deposits, occurring in enclaves of supracrustal rocks in the granite-pegmatite (Lina granite, Grip and Frietsch 1973, Geijer 1930).

The deposits in the Malmberget area were probably known already in the 17th century, but it was not until technical development (the Thomas process for treating P-rich iron ore) and infrastructure, in the form of a railway to a port in Luleå at the Baltic Sea and later on a railway to the Atlantic port in Narvik, Norway, that large-scale iron ore production commenced. From 1885 to 1905 the production of lump ore increased from less than 100 tons/year to 1 million tons/year.

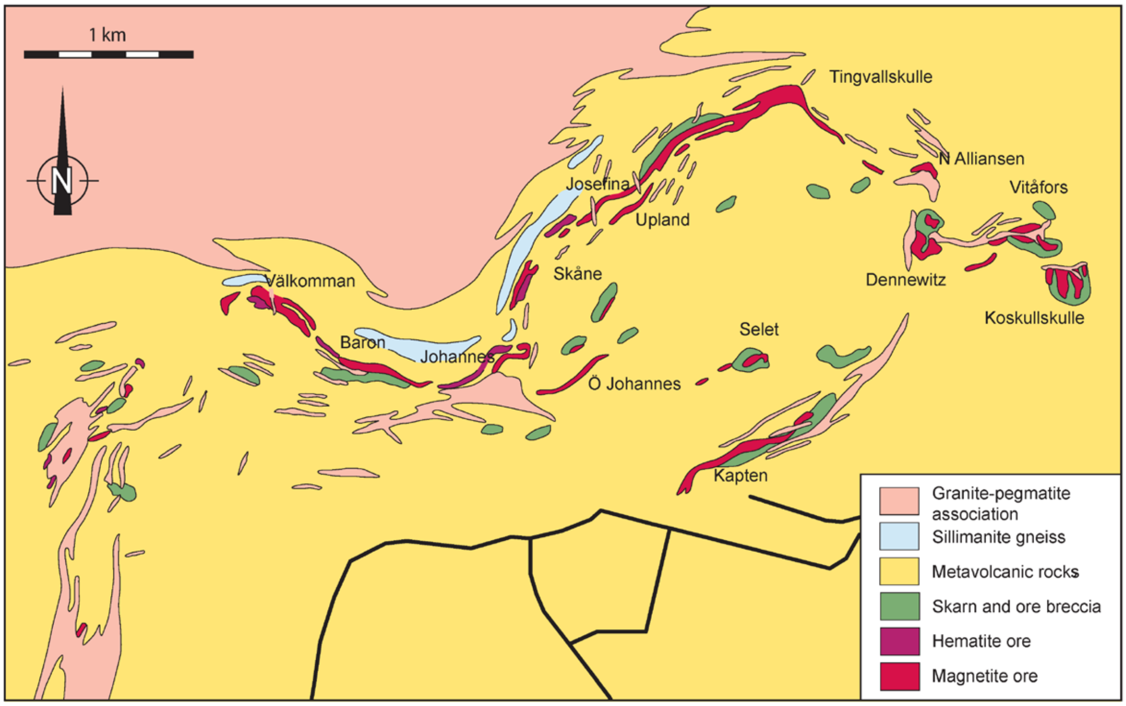


Figure 30. Geological map of the Malmberget area, from Bergman et al. 2001. All rocks belong to the Porphyry group, except the rocks of the Granite-pegmatite association.

Figure 31. Aerial photo of the Malmberget area. Photo Fredric Alm, LKAB

KIRUNA AREA APATITE-IRON ORES

Northern Norrbotten hosts a large number of apatite iron ores of the Kiruna type (Frietsch 1997, Bergman et al. 2001 and Figure 32). The largest, and economically most important deposit of this type is the **Kirunavaara** iron deposit, also being the "type locality" for apatite e-iron ores, but there are several other large-scale iron ore producers as well as unexploited deposits of this type in the area (Bergman et al. 2001, Frietsch 1997, Grip & Frietsch 1973).

The iron ore potential of the Kiruna area has been known since the 17th century, but large-scale mining did not start until the arrival of infrastructure, in the form of railways to the Baltic Sea and the Atlantic coast during the first years of the 20th century (Frietsch 1997). This, together with new metallurgical methods that made it possible to produce iron and steel from apatite-bearing iron ore (the Thomas process) opened up the area for mining. From modest and intermittent mining in the 19th century through the last 110 years of large-scale mining, 1714 Mt of apatite iron ore @ c. 60 % Fe have been produced from Northern Norrbotten (including the Malmberget deposit, see the Malmberget chapter). Present day reserves and resources of apatite e-iron ores in Norrbotten is 2372 Mt (Data from LKAB 2014 and Official statistics of Sweden).

The apatite-iron deposits in the Northern Norrbotten area occur in, or have a spatial relation to the Porphyry Group (Figure 32), a bimodal sequence of mafic to felsic metavolcanic rocks and metasedimentary rocks, or in a few cases in the underlying Porphyrite Group, which predominantly consists of meta-andesites (Bergman et al. 2001). These rocks were deposited between

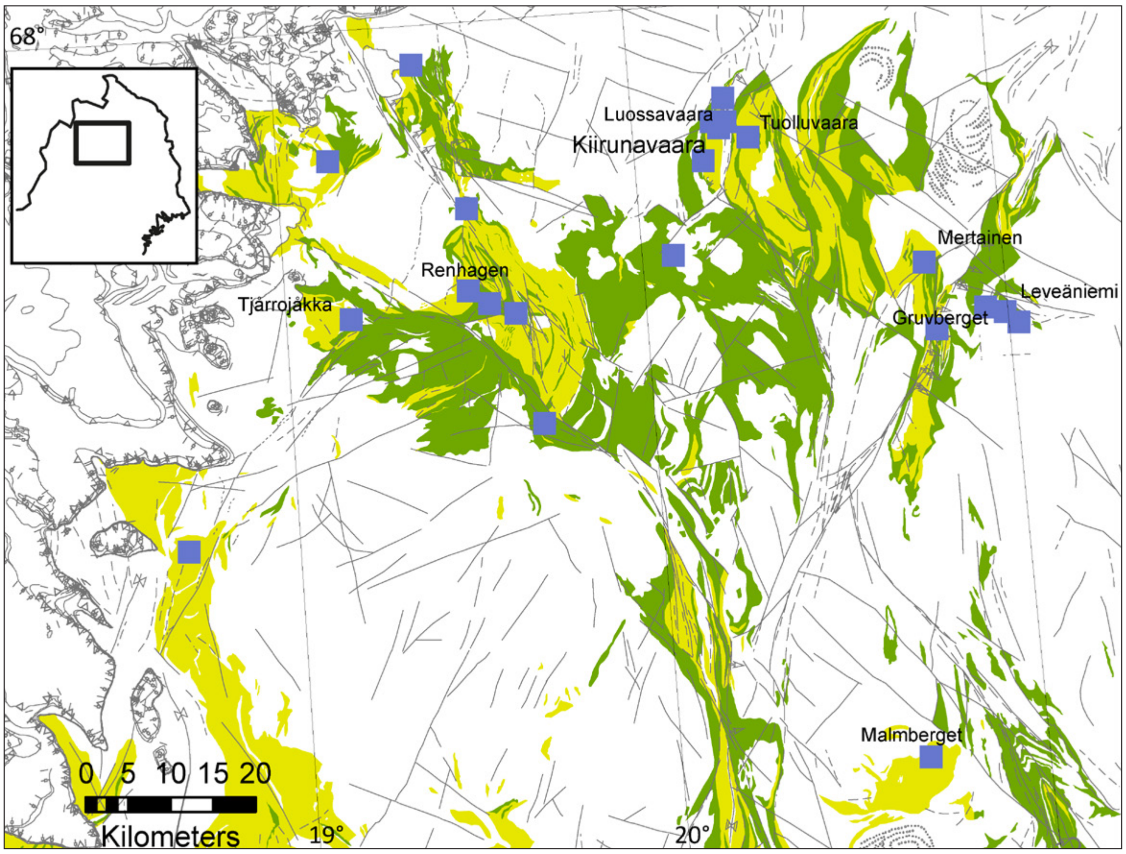


Figure 32. Distribution of supracrustal rocks belonging to the Porphyry Group (also Arvidsjaur-Skellefte Group) in Northern Norrbotten, from Bergman et al. 2001. Yellow colour for felsic metavolcanic rock, green colour for mafic metavolcanic rock. Data for deposits from Eilu et al. 2013.

1.96 and 1.86 Ga. In the Kiruna area, the Porphyry Group is overlain by the Lower Hauki Group, which consists of quartz-sericite altered metavolcanic and metasedimentary rocks (Parak 1975a, Bergman et al. 2001).

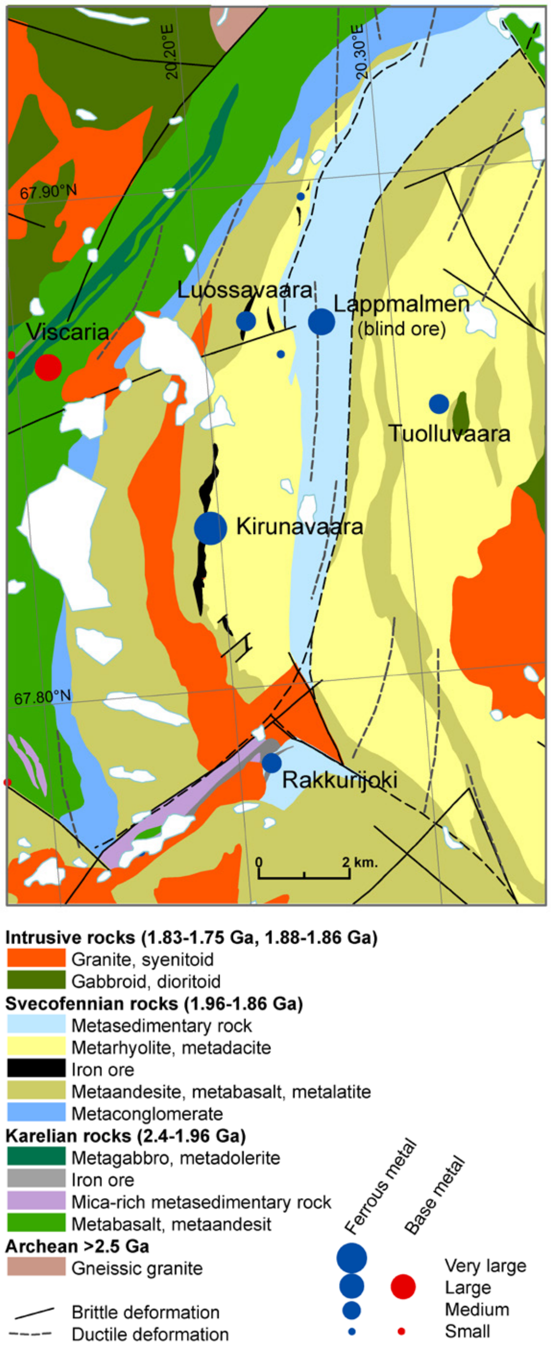


Figure 33. Geological map of the Kiruna area and major deposits of the region included in the Fennoscandian Ore Deposit Database (Eilu et al 2013). The Viscaria base metal deposit is discussed in the Norrbotten greenstone chapter. Note that Lappmalmen is a blind deposit and its position is shown as a surface projection of the deep-seated ore. Geological map simplified from Bergman et al. (2001).

In most cases, magnetite is the dominant mineral and with variable amounts of apatite, commonly F-apatite, and actinolite, albite and scapolite as gangue. A few deposits are hematite-dominated and there the gangue consists of apatite, quartz and carbonates. In general, the hematite-dominated deposits are found higher in the stratigraphy of the Porphyry Group. The phosphorous content of the Kiruna-type deposits in Sweden is c. 0.5-1.0 % P but smaller sections of ore bodies as well as the host rocks can contain several percent of P. The contents of Ti and S are very low, in contrast to nelsonites, rich in titanium and skarn iron ores which generally are sulfide-bearing. Most of the apatite iron deposits are also enriched in rare earth elements (REE), which are mainly concentrated in the apatite (Frietsch & Perdahl 1995).

The **Kirunavaara** deposit is a tabular ore body that can be followed for about 5 km along strike, is up to 100 m thick and has been shown to extend to a depth of more than 1300 m (Parak 1975a, Bergman et al. 2001, Figure 33). Calculations based upon geophysical measurements indicate that the ore body continues below a depth of 1500 m. The ore is at the contact between a thick sequence of trachyandesitic lava flows and the overlying rhyodacitic pyroclastic rocks (Figure 33). The entire sequence strikes N–S and dips steeply to the E. The massive magnetite-apatite ore grades into magnetite-actinolite breccias towards the wall rocks. The P content of the ore varies and shows a bimodal distribution of either <0.05 % or >1.0 %. In the faulted southern end of the Kirunavaara deposit, three small ore bodies, Konsuln, Sigrid and Viktor, are situated. To the north, the mineralisation may be followed at depth under Lake Luossajärvi (today partly drained). Two kilometres further north is the **Luossavaara** deposit, showing the same characteristics as Kirunavaara. At the surface, Luossavaara can be traced for 1200 m along strike. Deposits occurring further to the north, **Nukutus** and **Henry**, are so-called Per Geijer ores (Geijer 1919, Frietsch 1997). The Per Geijer ores differ from the larger Kirunavaara and Luossavaara deposits, in size, dominant iron oxide and gangue mineralogy, alteration style and in stratigraphic position. In general, they contain more apatite and hematite. Locally, hematite is the dominant oxide. Gangue consists of quartz and sericite and, in places, also carbonates and albite. These deposits occur in the upper parts of the Porphyry Group, stratigraphically above the Kirunavaara and Luossavaara deposits. The **Rektorn** and **Haukivaara** deposits, to the east of Kirunavaara, are also Per Geijer ores. The blind **Lappmalmen** deposit, discovered in the 1960s, shows the same characteristics as the Per Geijer ores (Parak 1969).

Figure 34. Aerial view of the town of Kiruna looking southwest with the open pit of the Kirunavaara mine in the background. Photo Fredric Alm, LKAB.

From modest and intermittent mining at **Kirunavaara** in the 19th century through the last 110 years of large-scale mining, 1034 Mt of iron ore @ c. 60 % Fe have been produced. Present day reserves and resources are 682 Mt and 304 Mt, respectively, giving a total tonnage of the Kirunavaara deposit of more than 2 Gt (LKAB 2014, Official statistics of Sweden, Metal and Mining Industries). In the area there are several other historical producers (Figure 33, Table 8), including **Luossavaara** which produced 21.2 Mt between 1858 and 1985, **Nukutus** (5.3 Mt) and **Haukivaara** (2.4 Mt). A few km to the E of Kirunavaara lie the **Tuolluvaara** deposit, in operation between 1902 and 1982 with a total production of 25.4 Mt. The **Mertainen** deposit is located 30 km to the ESE. During the short lifetime of this mine, from 1956 to 1959, the deposit produced 0.4 Mt of iron ore but the mine is planned to be re-opened soon. A large unexploited resource, the blind Lappmalmen deposit, is located 2 km east of the Luossavaara deposit (Figure 33).

Leveäniemi, 40 km southeast of Kirunavaara is the third largest apatite-iron deposit in Northern Norrbotten with a total tonnage (resources and mined tonnage) of 168 Mt @ 55.4 % Fe and 0.45 % P (Frietsch 1966, 1997, LKAB 2010). The Leveäniemi deposit was mined from 1964 to 1982 but was recently (2014) re-opened. The deposit is dominated by massive magnetite ore, massive hematite ore and calcite-rich magnetite ore. Large volumes of magnetite breccia (not included in the resources) occur in an up to 100-m-wide zone in the surrounding biotite schist. The contacts between massive ores and ore breccias are mostly distinct. The nearby **Gruvberget** apatite-iron deposit (Frietsch 1966), geologically similar to Leväniemi, was recently (2010) put into production by LKAB. In older days, vein-hosted copper was mined at Gruvberget. During intermittent production between 1644 and 1785, about 1740 tons of raw copper was produced (Tegengren 1924).

The Kiruna area also hosts small epigenetic Cu deposits. These are mainly hosted by the Greenstone Group rocks, which form the basement to the Porphyrite and Porphyry groups. The only deposit of this kind that has been mined in recent times is Pahtohavare (Martinsson 1997), which is immediately outside the Kiruna metallogenic area. The **Rakkurijärvi** Cu deposit, a few km S of Kirunavaara, has recently been subject of detailed exploration (Smith et al. 2007). Other deposits of this kind include **Tjårrojåkka**, where part of the Cu occurrence is hosted by an apatite-iron ore (Edfelt 2007), and the **Sierkavara** (Pikkujärvi) deposit (Weihed 2001, Hedin 1988).

The genesis of Kiruna-type deposits has been

Mine	In operation	Ore production (Mt)	Resources (Mt)
Kirunavaara	1864-	1033.8	986
Malmberget *	1845-	561.6	580
Leveäniemi	1964-1982, 2014-	57.3	332
Tuolluvaara	1902-1982	25.4	
Luossavaara	1846-1985	21.2	
Gruvberget	1860-1892, 2010-	6.4	81
Nukutus	1964-1986	5.3	
Haukivaara	1965-1972	2.4	
Mertainen	1956-1959	0.4	393

Most of the ore contained more than 60 % Fe and c. 0.58 % P. Data from LKAB (2014) and Official statistics of Sweden.
* The Malmberget deposit is discussed elsewhere in this publication.

Table 8. Larger apatite-iron deposits with mining periods, production and resources.

discussed for almost a hundred years without any conclusive evidence for any of the ore-forming models. The discussion on the genesis for this type of deposits started in Southern Sweden through studies of the Grängesberg apatite e-iron ore in the Bergslagen district. In the first modern description of the Grängesberg deposit Johansson (1910) included a model for the genesis of the ores. He suggested that the iron deposits together with the host-rocks to the deposit were formed by in situ differentiation, that is the iron ore was segregated from the surrounding metavolcanic rocks. Looström (1929a, 1929b, 1939) argued against that interpretation and favoured an intrusive origin for the deposits. He also suggested that the intrusive iron ore was coupled to a metallogenic gas phase in order to explain the disseminated nature of some part of the iron deposits at Grängesberg and the iron skarn in the hanging wall. Looström (1939) was the first to point out the similarities between Grängesberg and the large apatite-iron deposits in northernmost Sweden and his statements was based on the model for the large apatite-iron deposits at Kiruna, Gällivare, and Tuollavara in northern Sweden (Geijer 1910, 1918, 1920, 1930,)

From the early 1970s and onwards the focus for the discussions on the genesis of apatite-iron ores shifted towards the deposits in Northernmost Sweden and to similar deposits around the world. Parak (1975a, 1975b) argued against the magmatic model for the Kiruna deposit and suggested a sedimentary origin. This was criticised by Frietsch (1978, 1984) and others (Gilmour 1985, Wright 1986). In 1994 the discussion continued by a publication by Nyström & Henriquez (1994) in which they showed the similarities between the Kiruna deposit and much younger apatite-iron deposits in Chile. The discussion continued by contributions by Nyström & Henriquez (1995), and Bookstrom (1995). Throughout these years there were also publications on other apatite-bearing iron deposits in US and in Canada (Panno & Hood 1983, Hildebrand 1986), both in favour of a hydrothermal genesis for the apatite-iron deposits they described.

In the early 1990s Hitzman et al (1992) published a paper in which they discussed the genetic relations between apatite-iron deposits of the ”Kiruna-type”, the giant Olympic Dam Cu-U-Au-Ag deposit, and other deposits. They proposed that these deposits, characterised by their age, tectonic setting, mineralogy, and alteration should be referred to as Iron-Oxide Cu-U-Au-REE deposits. Later on the name became Iron Oxide Copper Gold (IOCG) deposits. In their model, in which apatite-iron deposits of the ”Kiruna-type” make up a subset, the mineralisation is caused by hydrothermal processes. This new concept has triggered a lot of exploration for IOCG-deposits around the world and in Sweden. To the genetic discussion on apatite-iron deposits Sillitoe & Burrows (2002) contributed with a description of the El Laco apatite-iron deposits in Chile. There they argued for a hydrothermal replacement genesis for the deposit, a model that was questioned by Henriquez et al (2003).

NORRBOTTEN GREENSTONES

In Paleoproterozoic time, at around 2.44 Ga, a rifting event commenced in Northern Fennoscandia with intrusion of ultramafic to mafic rocks. This was followed by deposition of sediments, mafic volcanics and carbonate rocks in a rift-related tectonic setting (Figure 35). Numerous intrusions of mafic dykes and sills of the same age are also found in the area. The deposition of these rocks, **the Karelian supracrustal rocks**, occurred approximately at 2.4 to 1.96 Ga ago. The Karelian supracrustal rocks are found in Northern Sweden, Northern Norway, Northern Finland and in Northwestern Russia (Bergman et al 2001).

In Northern Sweden the Karelian supracrustal rocks are subdivided into the older Kovo Group (2.4-2.3 Ga) and the younger Greenstone Group (2.3-1.96 Ga). In the Kiruna area the **Kovo Group** consist of conglomerates, quartzites and other sediments unconformably overlying the Archaean basement (Figure 36). The stratigraphy of the Greenstone Group has been described from many places in Northern Sweden as well from Finland and Norway and there are several names for this group, i.e. Kiruna greenstones, Kiruna greenstone group, Vittangi greenstone group, Veikkavaara greenstone group, Käymäjärvi group, Kolari greenstones, Greenstone formation, Iron ore formation, Schist formation etc. (Bergman et al. 2001) In the following text we use the term Greenstone Group to describe these rocks.

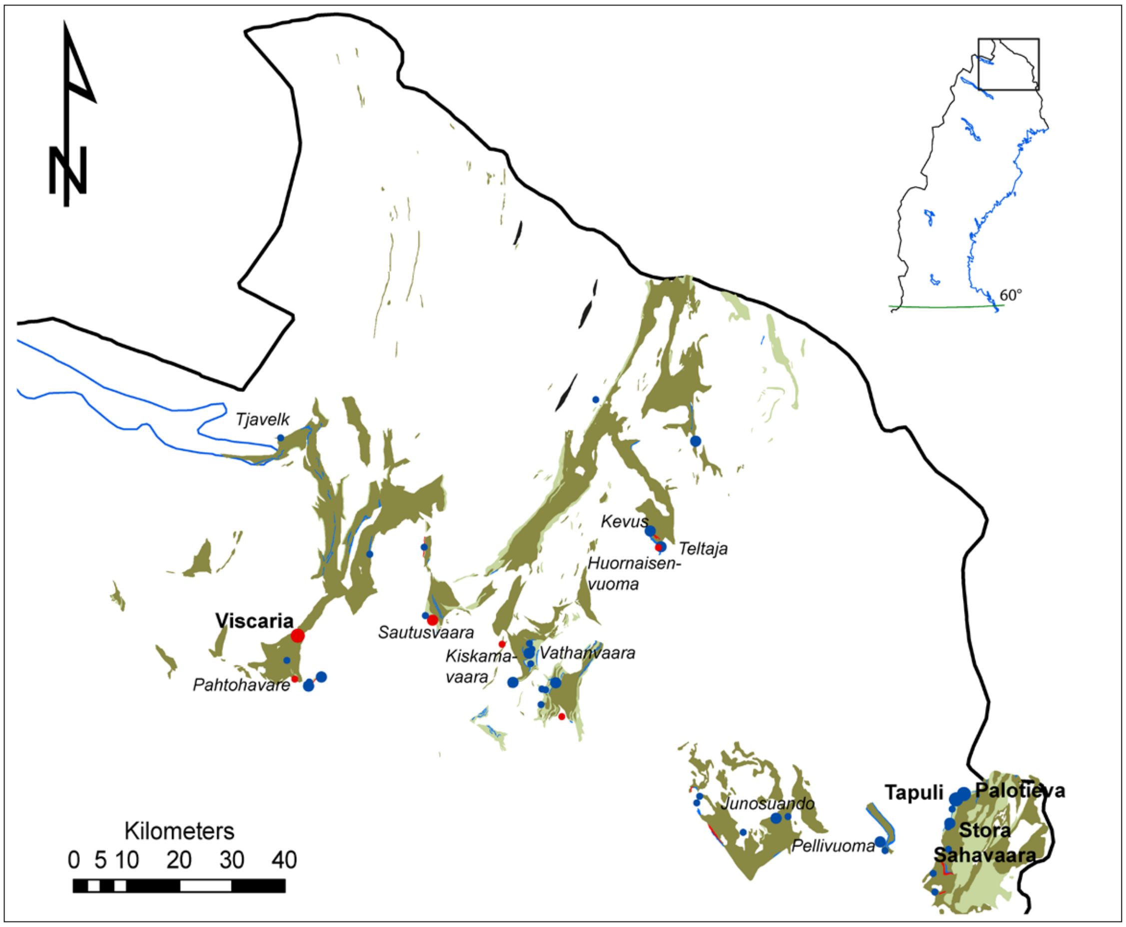


Figure 35. Distribution of Karelian (2.4 – 1.96 Ga) supracrustal rocks (the Greenstone Group) in Northern Norrbotten, from Bergman et al. 2001. Pale green for metasedimentary rock, olive green for mafic metavolcanic rock and blue for carbonate rock. Red dots show location of base metal and precious metal deposits, blue dots show iron deposits. Data for deposits from Eilu et al. 2013.

The main rock types in the **Greenstone Group** are metabasalt, graphite bearing meta-argillites, crystalline carbonate rocks and ultramafic rocks (Martinsson 1997, Bergman et al 2001, Grigull & Jönberger 2014).

The Greenstone Group hosts several types of mineralisations (Frietsch 1997, Eilu et al. 2013, Figure 35, Table 9, Table 10). Most common are stratabound skarn iron formations, copper mineralisations, copper-cobalt mineralisations, graphite deposits and carbonate deposits.

For the convenience of the reader the deposits in the Norrbotten Greenstones are described from west to east, divided into three areas; western, central and eastern area. This division does not refer to any major difference in composition or stratigraphy in the Greenstone Group going from west to east.

Western area

The most important deposit in the western part of the Greenstone Group is the **Viscaria** Cu deposit. It consists of several stacked units showing a variation from magnetite-bearing Cu-rich sulphide ore in the A zone to sulphide poor magnetite ore in the B and D zones (Figure 37; Martinsson 1997). The economically important A zone occurs in a marble between two units of black schist, on top of a volcaniclastic unit and immediately below pillow lavas. It is capped by an extensive thin chert unit. The ore consists of fine-grained chalcopyrite, magnetite, pyrrhotite and minor sphalerite. The ore minerals are disseminated or form thin intercalations and semi-massive accumulations. According to Martinsson (1997), the ore was formed by fissure-controlled exhalative events in a fault-controlled basin. The deposit was in operation 1982-1997 (Table 10). Ongoing exploration has resulted in new resource data for the Viscaria deposit including both copper and iron resources (http://avalonminerals.com.au/).

The **Tjavelk** deposit is a magnetite skarn iron ore, which is approximately 600 m long and up to 30 m wide. It is estimated to have 6.8 Mt @ 35 % Fe, 3.6 % S and 0.12 % Cu (Frietsch 1997). The skarn is composed of tremolite-actinolite

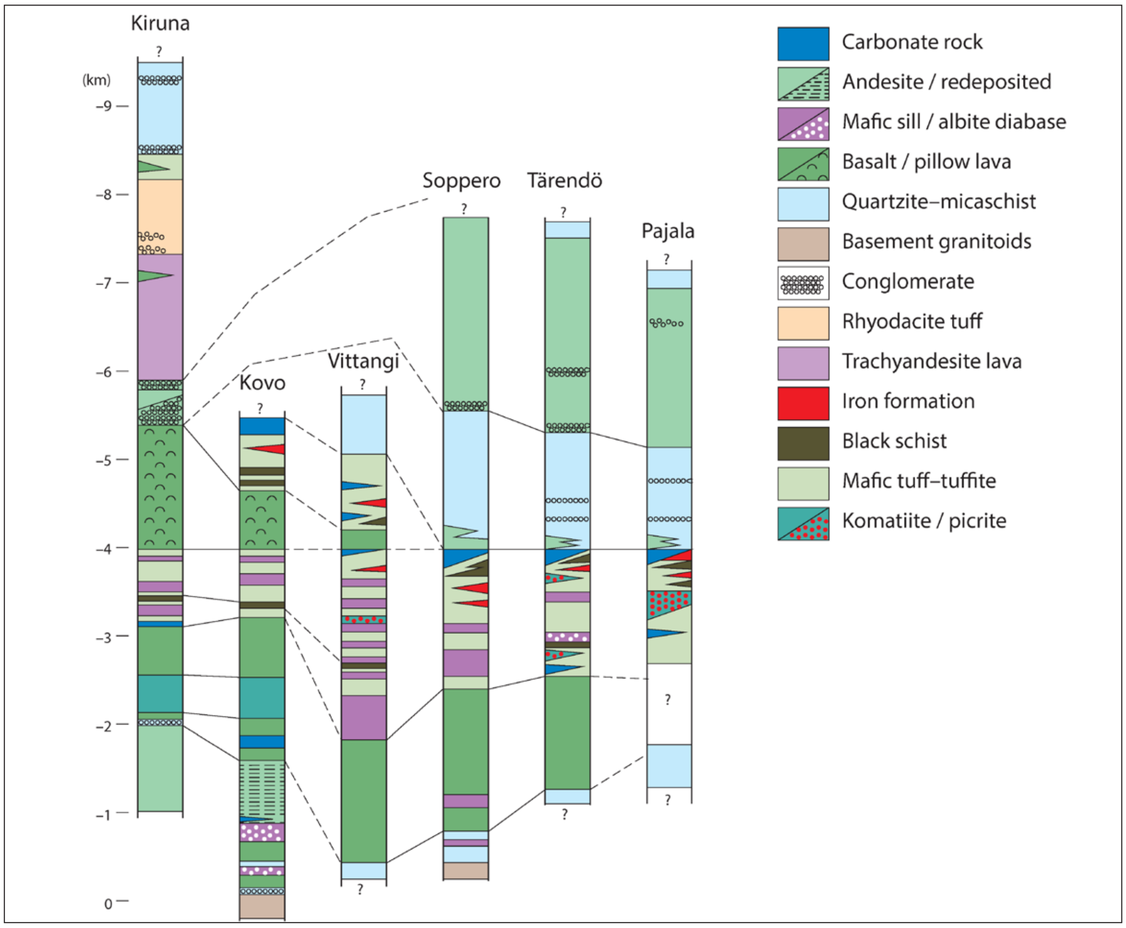
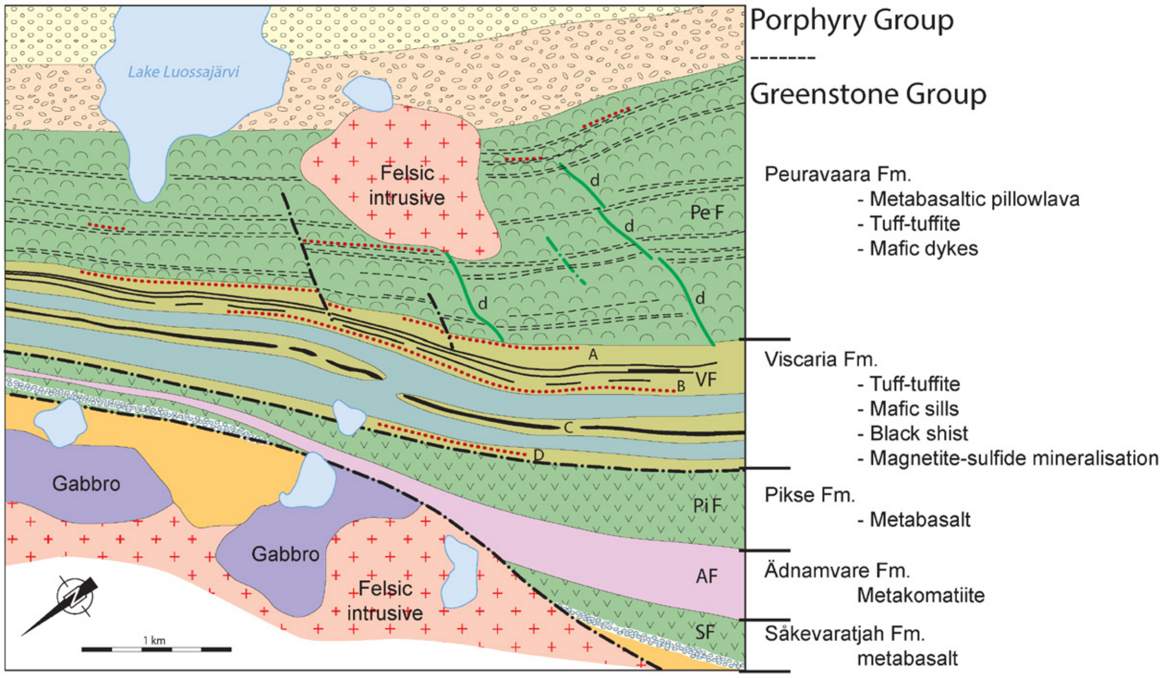


Figure 36. Stratigraphic columns of the Greenstone Group at different location in Northern Norrbotten. After Martinsson (1995) in Grigull et al. 2014.

Figure 37. Geological map of the Viscaria area, from Martinsson (1997) in Bergman et al. 2001.



and serpentine with a banded pattern in places. Sulfide minerals are pyrrhotite, pyrite, chalcopyrite and some pentlandite. Apatite is relatively common both as impregnations and as schlieren in the magnetite ore. The average phosphorus content is 1.3 % P, the highest found in a skarn iron ore in northern Sweden.

The iron ore zone at **Sautusvaara** is approximately 2500 m long and strikes NW–SE. The deposit consists of two ore bodies separated by a fault (Hallgren 1970). The smaller northern ore body has been estimated to have 13.3 Mt @ 42.1 % Fe, the southern ore body 42.1 Mt @ 37.2 % Fe (Hallgren 1970). The mineralisation consists of bands of magnetite and skarn minerals (diopside and tremolite). In places, chlorite and biotite are abundant. The dominant sulfide mineral is pyrite, generally occurring as fissure veins. At least two generations of pyrite occur and the content of cobalt in the coarse grained pyrite varies between 1.1–1.6 % Co. Traces of chalcopyrite and pyrrhotite have been detected. The rock underlying the iron ore zone is a well-stratified scapolite-diopside-biotite-bearing sediment. This unit is underlain by graphite-bearing schists and minor marble with skarn. These rocks are stratigraphically situated in the upper part of the Greenstone Group.

The **Pahtohavare** deposit SW of Kiruna comprises three epigenetic Cu-Au ore bodies (Martinsson 1997). Two of them have been mined (the Southern and the Southeastern ores). The ore bodies are located in an antiformal structure, bordered towards south by a shear zone (Martinsson 1997). Southern Pahtohavare is the largest ore body, with a maximum length of 270 m and a thickness of up to 25 m. It occurs in an altered black schist unit close to a thick mafic sill. Early albitisation of tuffite along the contact of the sill was later overprinted by ore-related alteration. Adjacent black schist was albitised and its graphite replaced resulting in a rock commonly called 'albite felsite'. The main ore minerals, chalcopyrite and pyrite, mainly form veinlets and breccia fill in the albite rock. The third ore body at Pahtohavare, Central, shows indications of supergene control of mineralisation and consist mainly of secondary Cu minerals.

Central area

The most important deposits in the central area are two iron deposits associated with calc-silicate rocks; the **Teltaja** deposit with 43 Mt @ 41 % Fe and the **Kevus** deposit with 38,8 Mt @ 28 % Fe (Frietsch 1985, 1997). In the poorly explored and exposed northern part of the Lannavaara area several smaller iron deposits are found.

The **Teltaja** iron deposit consists of magnetite and hematite in cherty rocks with minor calc-silicate minerals (Frietsch 1985). The deposit is made up of two mineralised horizons. The first consists of a 70 m wide magnetite-hematite-bearing body with an average iron content of 47 % Fe, hosted by jaspilitic quartzite. The second is a 15 m wide calc-silicate-bearing magnetite-dominated ore body with average iron content of 33 % Fe. This ore horizon has an anomalously high Mn content (Ambros 1980). The Teltaja mineralisation is almost totally devoid of sulphides. The mineralisation is hosted by supracrustal rocks belonging to the Greenstone Group.

The **Kevus** iron deposit is composed of magnetite with diopside, scapolite and hornblende (Frietsch 1997). The host rock to the mineralization is impregnated with magnetite. In addition to iron, the mineralization carries manganese (0.2-0.5 % Mn) and some copper (>0.1 % Cu). The host rock to the mineralization is metamorphosed, tuffitic basalt. The mineralization and host rock were highly brecciated and deformed by subsequent tectonic activity.

Another large skarn iron ore is the **Vathanvaara** deposit (51 Mt @ 39.4 % Fe, 0.049 % P and 2.91 % S, Frietsch 1997) hosted by metasediments of the Greenstone Group. The ore and host rocks are locally strongly fractured and kaolin-weathered to a depth of at least 100 m. The deposit consists of magnetite with some amphibole. A dark serpentine-bearing ore is also present. The mineralisation is rich in pyrite and pyrrhotite, and small amounts of chalcopyrite occur sporadically. The host rock is a layered graphite-bearing biotite schist. Subordinate to the schist is a scapolite-bearing quartzite with magnetite impregnations.

The **Huornaisenvuoma** deposit is the only Zn-Pb deposit of any economic significance in northern Norrbotten (Bergman et al. 2001). The deposit is hosted by a thick dolomite unit in the upper part of the Greenstone Group (Frietsch et al. 1997). The mineralisation consists of sphalerite, magnetite and pyrite occurring both as disseminated mineralisation and as almost massive layers. The mineralisation generally has a thickness of 1–2 m and its maximum length is 950 m. The country rocks comprise metamorphosed mafic tuff and tuffite, manganiferous iron formation, and black schist. These volcanic and sedimentary rocks were metamorphosed under middle to upper amphibolite facies conditions. Historic ore resource estimates give 0.56 Mt @ 4.8 % Zn, 1.7 % Pb, 0.2 % Cu, and 12 ppm Ag (Frietsch 1991).

The **Kiskamavaara** Cu-Co deposit comprises disseminated and fissure-fill mineralisations of cobalt-bearing pyrite, chalcopyrite, magnetite, hematite and minor amounts of bornite and molybdenite. The host rocks consist of metamorphosed rhyolitic tuffs, intermediate tuffs and mafic volcanic rocks belonging to the Porphyrite Group. Historic ore resource calculations give 3.42 Mt @ 0.37 % Cu and 0.09 % Co at Kiskamavaara (Persson 1981).

Eastern area

The most important deposits in the eastern part of the Norrbotten Greenstones are found in a NE-trending, steeply northwest dipping greenstone sequence where the **Tapuli, Palotieva** and **Stora Sahavaara** deposits are found (Lindroos 1974 and Table 9).

The **Tapuli** iron deposit is the largest by tonnage in the area and it is the only deposit that has been mined in recent time (2012-2014 by Northland Resources). Similar to the other deposits in the area, the ore body consists of stratiform layers or lenses with a northeastern strike and a dip at 50–65° to the NW. The iron ore is entirely made up of magnetite and skarn minerals, hematite is very rare or absent. Two main types of skarn exist (Lundberg 1967, Lindroos 1972, Lindroos et al. 1972): 1) a serpentine skarn that makes up the gangue or wraps around the iron ore, and 2) a diopside-tremolite skarn that forms a zone between the iron ore and the hanging-wall metasedimentary units, or occurs between the iron ore–serpentine mass and the dolomite. All serpentine is retrograde, replacing tremolite-diopside and all other high-temperature skarns. Most of the ore has accumulated in a fold structure where the ore continues to at least 300 m depth. An important feature of the Tapuli deposit compared to other deposits in the area is the low sulfide content, on average <0.2 % S. The Greenstone sequence hosting the deposits can be followed across the border into Finland.

Stora Sahavaara is the third largest deposit in the area (Frietsch 1997, Northland Resources 2007, Northland Resources 2010d). The stratiform deposit forms an arcuate 1300 m long by 40 m thick body that strikes NE and dips 50–70°

Figure 38. Drillcore box from Stora Sahavaara ddh 62001, 63.42 – 77.58 m showing skarn iron ore mineralization. The drillcore log (in Swedish) says;

53,83-75,25 Dark-grey, fine grained, foliated and partly chlorite-altered rock. The last meters with green skarn and decimeter-wide sections with serpentine minerals

75,25-111,14 Sharp border to fine grained, skarn bearing and partly graphic-bearing magnetite ore (white) with sections of serpentine minerals.

a. Natural colour (RGB) photo

b. False colour composite image in long wave infrared light. Three infrared bands (R=8611 nm, G=10022 nm and B=11810 nm) compose the image and they represent a color rendition of data from sensors measuring across the long wavelength portion of the infrared spectrum. The image has been further processed to a mineral map. Color images and false color composite images of the full core, other cores from Stora Sahavaara as well as other drillcores from Swedish mineralisation can be seen at www.sgu, choose MapViewer; Drill cores.

Deposit	When_mined	Resources (Mt)	Mined (Mt)	Fe (%)	Mn (%)	P_2O_5 (%)	S (%)
Tapuli	2012-2015	124	7.5	31.3			
Palotieva		120		27.4	1.4		0.1
Sahavaara Stora		88		33.2			
Pellivuoma		87		29.9	0.2		0.5
Rakkurijoki		75		39.7		0.6	0.9
Rakkurijärvi		70		28.5		0.2	0.9
Discovery Zone		59		38.7		0.1	1.0
Vathanvaara		51		39.4		0.1	2.9
Kuusi Nunasvaara		46		30.5		0.2	1.6
Paljasjärvi		40		30.0			
Teltaja		43		41.0			
Kevus		39		28.0	0.4		
Sahavaara Southern		33		32.1	0.1		0.6
Sautusvaara Southern		42		37.2		0.1	1.8
Tervaskoski E		30		48.0		0.1	3.0
Mänty Vathanvaara		16		31.3		0.1	2.5
Sautusvaara North		12		42.1		0.1	0.5
Tjärro		9		40.0		0.0	0.1
Ruutijärvi		8		40.9			
Tjavelk		7		38.6		2.7	3.6
Luovinjunanen		7		32.5		0.1	0.3
Nunasjärvenmaa		7		30.9		0.1	0.8
Suksivuoma		6		43.5			
Suolojoki		6		25.0		0.0	0.0
Sorvivuoma		6		39.7		0.2	0.3
Leppäjoki Northern		5		32.0			
Tributary Zone		5		28.6		0.1	1.1
Jänkkä		5		36.3		0.1	2.1
Sahavaara Östra		4		40.5		0.0	0.2
Karhujärvi		4		42.0			2.0
Erkheikki		3		32.5			
Vähävaara		3		28.8		0.1	2.7
Marjarova		3		25.0			1.5
Tornefors		3		20.0			
Junosuando Norra		3		30.0		0.9	

Table 9. Iron deposits hosted by Karelian supracrustal rocks (the Greenstone Group) (2.4-1.96 Ga). Data from the Fennoscandian Ore Deposit Database (Eilu et al. 2013)

Deposit	When mined	Resources (Mt)	Mined (Mt)	Cu (%)	Co (%)	Zn (%)	Pb (%)	Fe (%)	S (%)	Ag (g/t)	Au (g/t)
Viscaria	(1982-1997)	21.6	12.5	1.4		0.7				4.0	0.1
Sautusvaara S.		38.8						35.5	1.7		
Viscaria B-Zon	(1982-1997)	19.7		0.8							
Viscaria D-Zon		2.9		0.6				24.1			
Kiskamavaara		2.9		0.4	0.1						
Äijärvi Östra		0.5		1.2					12.7		
Huornaisenvuoma		0.1		0.2		4.5	2.6			12.0	
Pahtohavare	(1990-1997)		1.7	1.9							0.9

Table 10. Base and precious metal deposits hosted by Karelian supracrustal rocks (the Greenstone Group) (2.4-1.96 Ga). Data from the Fennoscandian Ore Deposit Database (Eilu et al. 2013)

to the northwest. The bulk of the deposit consists of magnetite and serpentine in diopside-tremolite rocks (Figure 38). There is very little carbonate rock at Stora Sahavaara. Estimates of the ore resources made in the 1960s gave 82 Mt @ 41.0 % Fe, 0.08 % Cu and 2.5 % S to a depth of 435 m (Lundberg 1967). Recent assessment has increased the resource, as shown in Table 9.

Some 15–20 km WSW of Stora Sahavaara is the **Pellivuoma** iron occurrence. The setting of the Pellivuoma ore bodies, host rocks, ore and gangue minerals, and the relations between the local rock units is similar to that of Tapuli and Stora Sahavaara, except that the deposit is located next to a granite intrusion (Ros et al. 1980; Northland Resources 2010c).

Several smaller skarn iron ores are found in a smaller greenstone area to the west including the **Junosuando, Tornefors**, **Vähävaara** and **Leppäjoki** deposits (Padget 1970, Frietsch 1997). Both skarn iron ores and quartz-banded iron ores are represented in the area. The skarn iron deposits of the Tärendö area are often hosted by carbonate rocks intercalated in the Greenstone Group. They are composed of magnetite which is often Mg-bearing, tremolite, actinolite, diopside, phlogopite, biotite, serpentine and some hornblende. The Ca-Mg-silicates are either evenly distributed throughout the iron ore or occur as layers within the ore. Small amounts of pyrite, pyrrhotite and, locally, chalcopyrite occur.

The quartz-banded iron mineralisations are found at a stratigraphic position similar to the skarn iron ores but are usually made up of quartzites with magnetite and Fe-Mg-Mn silicates; hornblende, grunerite, clinoenstatite, hedenbergite and garnet. The deposits commonly contain some sulfides and minor amounts of manganese. The phosphorous content in both the skarn iron deposits and the quartz-banded deposits is generally very low.

The first deposits in the Tärendö area were already known by 1644 (Frietsch 1997). Between 1846 and 1861 c. 120 tons of iron ore of unknown grade was produced from the Junosuando deposits. None of the other iron deposits in the area have been exploited.

REFERENCES

Allen, R.L., Lundström, I., Ripa, M., Simeonov, A., Christofferson, H., 1996a, Facies analysis of a 1.9 Ga, contintental margin, back-arc, felsic caldera province with diverse Zn-Pb-Ag-(Cu-Au) sulfide and Fe-oxide deposits, Bergslagen region, Sweden. Economic Geology v. 91. p. 979-1008.

Allen, R., Danielsson, S., Eklund, D., Fagerström, P., Jonsson, R., Lundstam, E., Munck, M., Nilsson, P. & Pantze, R., 2010. Discovery and geology of the Lappberget Zn-Pb- Ag-(Cu, Au) deposit, Bergslagen Sweden. In: Nakrem, H. A., Harstad, A. O. & Haukdal, G. (eds) 29th Nordic Geological Winter Meeting, Oslo, January 11–13, NGF Abstracts and Proceedings of the Geological Society of Norway 1, p. 4.

Allen, R. L., Weihed, P. & Svensson, S. Å., 1996, Setting of Zn-Cu-Au-Ag massive sulfide deposits in the evolution and facies architecture of a 1.9 Ga marine volcanic arc, Skellefte district, Sweden. Economic Geology 91, 1022–1053.

Almevik, G., Eriksson, P. & Pawlak, E. 1992. Nya Lapphyttan: en rekonstruerad medeltid. Göteborgs universitet, Institutionen för kulturvård, 1101–3303; 1992:22. 73 p. (in Swedish)

Ambros, M., 1980. Beskrivning till berggrundskartorna Lannavaara NV, NO, SV, SO och Karesuando SV, SO. Sveriges geologiska undersökning serie Af 25–30, 111 p.

Andersson, L.G. 1986. The Wigström tungsten deposit. In: Lundström, I. & Papunen, H. (eds.) Mineral deposits of southwestern Finland and the Bergslagen province, Sweden. 7th IAGOD symposium and Nordkalott project meeting, excursion guide No. 3. Sveriges geologiska undersökning serie Ca 61, 41.

Andersson U.B. (ed.) 2004. The Bastnäs-type REE mineralisations in north-western Bergslagen, Sweden – a summary with geological background and excursion guide. Sveriges geologiska undersökning, Rapporter och meddelanden 119. 34 p.

Andersson, A., Dahlman, B., Gee, D. G. & Snäll, S. 1985. The Scandinavian alum shales. Sveriges geologiska undersökning, serie Ca 56. 50 p.

Andersson, U. B., Holtstam, D. & Broman, C. 2013: Additional data on the age and origin of the Bastnäs-type REE deposits, Sweden. In E. Jonsson et al. (eds.) Mineral deposit research for a high-tech world, Proceedings of the 12th biennial SGA meeting, 1639-1642.

Armands, G. 1970. A uranium-bearing layer from the Lower Ordovician, Sweden. Geologiska Föreningens i Stockholm Förhandlingar (GFF) 92, 481–490.

Bark, G., 2008. On the origin of the Fäboliden orogenic gold deposit, northern Sweden. Doctoral thesis, Luleå University of Technology 2008:72 142 p.

Bauer, T., Skyttä, P., Hermansson, T., Allen, R. & Weihed,

P., 2014, Correlation between distribution and shape of VMS deposits, and regional deformation patterns, Skellefte district, northern Sweden. Mineralium Deposita. 49, 5, s. 555-573 19 p.
Bergman, S., Kübler, L. & Martinsson, O., 2001, Description of regional geological and geophysical maps of northern Norrbotten County (east of the Caledonian orogen). Sveriges geologiska undersökning Ba 56, 110 p.
Bergman, T. 1994. The Wigström deposit western Bergslagen, Sweden: A contact metasomatic tungsten skarn deposit related to a late Svecofennian granite. Abstract 21st Nordic geological winter meeting, Tekniska Högskolan i Luleå, 21.
Bergman Weihed, J., Bergström, U. & Weihed, P., 1996, Geology, tectonic setting, and origin of the Paleoproterozoic Boliden Au-Cu-As deposit, Skellefte district, Northern Sweden. Economic Geology 91, 1073–1097.
Bergshanteringen 1943: Sveriges officiella statistik, Industri och bergshanteringen, Berättelse för år 1943. Kommerskollegium. Stockholm 1945, K.L. Beckmans boktryckeri.
Bingen, B., Andersson, J., Söderlund, U. & Möller, C., 2008. The Mesoproterozoic in the Nordic countries. *In* Gee, D. G., Ladenberg, A. (eds.) Special issue for the 33rd International Geological Congress Oslo, Norway, 6-14 August, 2008, Episodes vol. 31 29-34.
Bjørlykke, A., and Sangster, D. F., 1981, An overview of sandstone-lead deposits and their relationships to redbed copper and carbonate hosted lead-zinc deposits: Economic Geology 75th Anniversary Volume, p. 179–213.
Boliden 2015: www.boliden.com, Mines in the Boliden Area (20151211).
Bookstrom, A.A., 1995, Magmatic features of iron ores of the Kiruna type in Chile and Sweden: Ore textures and magnetite geochemistry - a discussion. Economic Geology 90, 469-473.
Bromé, J. 1923. Nasafjäll: ett norrländskt silververks historia. Stockholm: Nordiska bokhandeln. 352 p. (in Swedish).
Carlsson, E. 1979. Kölen-malmen ”överlistad” – storfynd i Svärdsjö, Jernkontorets Annaler med Bergsmannen 163, 2/79, 54–56. (in Swedish)
Casanova, V., 2010, Geological and geophysical characteristics of the Pb-Zn sandstone-hosted autochthonous Laisvall deposit in the perspective of regional exploration at the Swedish Caledonian Front. Master’s thesis, Chemical Engineering and Geosciences LTU-PB-EX--10/039--SE
Chelle-Michou, C. 2008. Geology and Mineralization of the Bellviksberg Sandstone-Hosted Pb(-Zn) Deposit, Dorotea Area, Sweden. Luleå University of Technology, master thesis, 2008:054 PB. 54 p.
Christofferson, H., Lundström, I. & Vivallo, W. 1986. The Garpenberg area and zinc-lead-copper deposit. In: Lundström, I. & Papunen, H. (eds) Mineral deposits of Southwestern Finland and the Bergslagen province, Sweden. Sveriges geologiska undersökning, serie Ca 61. 44 p.
Christofferson, H., Wallin, B., Selkman, S. & Rickard, D. T. 1979. Mineralization controls in the sandstone leadzinc deposits at Vassbo, Sweden. Economic Geology 74, 1239–1249.
Claesson, L.-Å. & Isaksson, H., 1981, Västra Maurliden prospekteringsrapport: BRAP 81060, Sveriges Geologiska Undersökning (SGU), unpublished report, (in Swedish).
Cuney, 2009, The extreme diversity of uranium deposits, Mineralium Deposits vol. 44 p. 3-9.
Dahlenborg, L., 2007, A Rock Magnetic Study of the Åkerberg Gold Deposit, Northern Sweden. Examensarbeten i geologi vid Lunds universitet, Nr. 208. 32 p.
Dahlin, P. 2014. Stratigraphy and Geochemistry of the Palaeoproterozoic Dannemora inlier, north-eastern Bergslagen region, central Sweden.. Digital Comprehensive Summaries of Uppsala Dissertations from the Faculty of Science and Technology 1209. 50 pp. Uppsala: Acta Universitatis Upsaliensis.
Debras, C., 2010, Petrology, geochemistry and structure of the host rock for the Printzsköld ore body in the Malmberget deposit. Master Thesis, Dept. of Chemical Engineering and Geosciences / Ore Geology, Luleå University of Technology, 2010:052
Du Rietz, T., 1949. The Nasafjäll region in the centre of the Scandinavian Caledonides. Geologiska Föreningen I Stockholm Förhandlingar (GFF) 71, 243–252.
Du Rietz, T., 1953, Geology and Ores of the Kristineberg Deposit, Vesterbotten, Sweden. Sveriges geologiska undersökning, serie C 524. 91 p.
Edfelt, Å., 2007, The Tjårrojåkka Apatite-Iron and Cu (-Au) Deposits, Northern Sweden – Products of One Ore Forming Event. PhD thesis 2007:17, Luleå University of Technology, Department of Chemical Engineering and Geosciences, Division of Ore Geology and Applied Geophysics. 167 p.Frietsch, R. 1966. Berggrund och malmer i Svappavaarafältet, norra Sverige. Sveriges geologiska undersökning, serie C 604. 282 p. (in Swedish)
Eilu, P., Hallberg, A., Bergman, T., Feoktistov, V., Korsakova, M., Krasotkin, S., Lampio, E., Litvinenko, V., Nurmi, P. A., Often, M., Philippov, N., Sandstad, J. S., Stromov, V. & Tontti, M. 2010. Fennoscandian Ore Deposit Database. Updated 30 June 2010. Available at: http://gtkdata.gtk.fi/fmd/
Eilu, P., Bergman, T., Bjerkgård, T., Feoktistov, V ., Hallberg, A.,Korsakova, M., Krasotkin, S ., Litvinenko, V ., Nurmi, P.A., Often, M., Philippov, N.,S andstad, J .S . , Voytekhovsky, Y .L., 2013, Metallic Mineral Deposit Map of the Fennoscandian Shield 1:2 000 000. Revised edition.
Geological Survey of Finland, Geological Survey of Norway, Geological Survey of Sweden, The Federal Agency of Use of Mineral Resources of the Ministry of Natural Resources of the Russian Federation.
Mineral deposit data from the Fennoscandian ore deposit Database; http://gtkdata.gtk.fi/fmd/
Eklund, D., 2007, Mineralogy of the hypozonal Svartliden gold deposit, northern Sweden, with emphasis on the composition and paragenetic relations of electrum. Undergraduate thesis, Department of Earth Sciences, Uppsala University. Vol. 139. 34 p.
Eriksson, J. A. & Qvarfort, U. 1996. Age determination of the Falu coppermine by 14C-datings and palynology. GFF 118, 43–47.
Eriksson, T., 1983, Järnmalmen vid Björkholmen i Jokkmokk socken. Sveriges geologiska undersökning, prospekteringsrapport, brap83801. 13 p. (in Swedish).
Essuka, O.M., 2011, The Ersmarksberget Gold Mineralisation, Its Mineralogy, Petrography, Setting of Gold and Metallurgical Implications. Master of Science, Luleå Technical University, LTU-EX-2011-32823308. 77 p.
Frietsch, R. 1966. Berggrund och malmer i Svappavaarafältet, norra Sverige. Sveriges geologiska undersökning, serie C 604. 282 p. (in Swedish)
Frietsch, R., 1978, On the magmatic origin of iron ores of the Kiruna type. Economic Geology 73 478-485

Frietsch, R., 1984, On the magmatic origin of iron ores of the Kiruna type - a reply. Economic Geology 79 1949-1951

Frietsch, R., 1985: The Lannavaara iron ores, northern Sweden. Sveriges geologiska undersökning serie C 807, 55 p.

Frietsch R., 1991: Register över Svenska fyndigheter av malmmineral och industriella mineral och bergarter. Forskningsrapport, TULEA 1991:04, Luleå University of Technology, 340 p. (in Swedish)

Frietsch, R., 1997, The Iron Ore Inventory Programme 1963-1972 in Norrbotten County. Sveriges geologiska undersökning. Rapporter & meddelanden 92, 77 p.

Frietsch, R. & Perdahl, J.-A., 1995, Rare earth elements in apatite and magnetite in Kiruna-type iron ores and some other iron ore type. Ore Geology Reviews 9, 489–510.

Gee, D. G. 1979. Projekt alunskiffer. Sammanfattning av undersökningar fram till 1978-12-31. Sveriges geologiska undersökning, prospekteringsrapport, brap79511. 28 p. (in Swedish).

Gee, D. G., Brekke, H., Lahtinen, R., Sigmundsson, F., Sundquist B., Thybo, H. & Weihed, P., 2008a. Nordic geosciences and the 33rd International Geological Congress: Introduction. *In* Gee, D. G., Ladenberg, A. (eds.) Special issue for the 33rd International Geological Congress Oslo, Norway, 6-14 August, 2008, Episodes vol. 31 4-8.

Gee, D. G., Fossen, H., Henriksen, N. & Higgins, A. K., 2008b. From the Early Paleozoic platforms of Baltica and Laurentia to the Caledonide orogen of Scandinavia and Greenland. *In* Gee, D. G., Ladenberg, A. (eds.) Special issue for the 33rd International Geological Congress Oslo, Norway, 6-14 August, 2008, Episodes vol. 31, 44-51.

Gee, D.G., Kumpulainen, R., Thelander, T. 1978, The Tåsjö decollement, central Swedish Caledonides. SGU serie C 742 36P.

Gee, D. G., Snäll, S., 1981, Alunskifferprojektet, undersökningar norr om Storsjön till Tåsjön. Prospekteringsrapport brap 81525, 79p. (in Swedish).

Gee, D. G., Snäll, S., Stejskal, V., 1982a, Alunskifferprojektet, undersökningar mellan Östersund och Svenstavik. Prospekteringsrapport brap 82502, 377p. (in Swedish).

Gee, D. G., Snäll, S., Stejskal, V., 1982b, Alunskifferprojektet, undersökningar mellan Svenstavik och Klövsjö. Prospekteringsrapport brap 82558, 77p. (in Swedish).

Geijer, P., 1910, Igneous rocks a iron ores of Kiirunavaara, Loussavaara a Tuolluvaara. Geologie des Kirunagebiets 2 pp 278

Geijer, P., 1918, Recent developments at Kiruna. SGU C 288 1-22

Geijer, P., 1919, Rapport över undersökningsarbeten å Nokutusvaara malmfält och Rektorsmalmen sommaren 1918. Sveriges geologiska undersökning, prospekteringsrapport, brap00806. 21 p. (in Swedish)

Geijer, P., 1920, Tuolluvaara malmfälts geologi. SGU C 296 1-51

Geijer, P., 1930, Gällivare malmfält. Sveriges geologiska undersökning, serie Ca 22. 115 p. (in Swedish)

Geijer, P. 1936. Norbergs berggrund och malmfyndigheter. Sveriges geologiska undersökning serie Ca 24. 162 p. (in Swedish)

Geijer P. 1961. The geological significance of the cerium mineral occurrences of the Bastnästype in Central Sweden. Arkiv för Mineralogi och Geologi, Bd 3, nr 4. 99-105

Geijer, P. & Magnusson, N.H. 1944: De mellansvenska järnmalmernas geologi. Sveriges geologiska undersökning serie Ca 35. 654 p. (in Swedish).

Gilmour, P., 1985, On the magmatic origin of iron ores of the Kiruna type - a further discussion

Godin, L. 1976. Viscaria – en ny kopparmineralisering i Kirunagrönstenen. Abstracts, XII Nordiska Geologvintermötet, Göteborg 7–10 januari 1976, Geologiska Institutionen, Chalmers Tekniska Högskola/Göteborgs Universitet, 17–17. (in Swedish).

Grigull, S., Jönberger, J., 2014, Geological and geophysical field work in the Kiruna-Jukkasjärvi and Svappavaara key areas, Norrbotten. SGU-rapport 2014:10 30 p.

Grigull, S., Berggren, R., Jönsson, C., 2014, Background information Käymäjärvi-Ristimella key area. SGU-rapport 2014:30

Grip, E. & Frietsch, R., 1973, Malm i Sverige 2 Norra Sverige. Almqvist & Wiksell. 295 p. (in Swedish)

Gustafsson, B., 1979, Uranuppslag inom Norrbotten och Västerbotten 1979. SGU Berggrundsbyrån brap 79056.

Gustafsson, B. 1990. Sällsynta jordartsmetaller i Sverige. Sveriges geologiska AB, prospekteringsrapport PRAP90024. 36 p. (in Swedish).

Hallberg, A., 2001., Rock classification, magmatic affinity and hydrothermal alteration at Boliden, Skellefte district, Sweden – a desk-top approach to whole rock geochemistry. In: Weihed, P. (ed.) Economic geology research, Volume 1 1999–2000. Sverige geologiska undersökning, serie C 833, 93–131.

Hallberg, A., Rimsa, A. & Hellström, F. 2008. Age of the host-rock to the Grängesberg apatite-iron ore. Sveriges geologiska undersökning, rapport 2008:27, 19–22.

Hübner, H. 1971. Molybdenum and tungsten occurrences in Sweden. Sveriges geologiska undersökning serie Ca 46, 29 p.

Hallgren, U. G., 1970, Sautusvaara järnmalmsfyndighet, Rapport rörande resultaten av SGU:s undersökningar under åren 1961-1967. Sveriges geologiska undersökning, Malmbyrån brap 893 (in Swedish)

Hedberg, N. 1907. Grängesberg. En gruffältsbeskrivning. Jernkontorets Annaler 62, 67–125. (in Swedish)

Hedin, J.-O., 1988, Sjiska granitområde. Slutrapport stödetapp III. LKAB Prospektering AB, prospekteringsrapport K8801. 7 p. (in Swedish)

Henriquez F., Naslund H.R., Nystrom, J.O., Vivallo, W., Aguirre, R., Dobbs, F.M., Lledo. H., 2003, New field evidence bearing on the origin of the El Laco magnetite deposit, northern Chile; discussion. Economic Geology 98 1497-1500.

Hildebrand R.S., 1986, Kiruna-type deposits; their origin and relationship to intermediate subvolcanic plutons in the Great Bear magmatic zone, Northwest Canada. Economic Geology 81 640-659.

Hitzman, M.W., Oreskes, N., Einaudi, M.T., 1992, Geologic characteristics and tectonic setting of Proterozoic iron oxide (Cu-U-Au-REE) deposits. Precambrian Research 58 241-287.

Hübner, H. 1971. Molybdenum and tungsten occurrences in Sweden. Sveriges geologiska undersökning, serie Ca 46. 29 p.

Högbom A., 1937, Skelleftefältet, med angränsande delar av Västerbottens och Norrbottens län, en översikt av berggrund och malmförekomster. SGU C 389. 122 p.

Jansson, N. F., Allen, R. L., 2011, Timing of volcanism, hydrothermal alteration and ore formation at Garpenberg, Bergslagen, Sweden. Geologiska Föreningen Förhandlingar (GFF) vol. 133 3-18

Jansson, N. F., Allen, R. A., 2015, Multistage ore formation at the Ryllshyttan marble and skarn-hosted Zn–Pb–Ag–(Cu) + magnetite deposit, Bergslagen, Sweden. Ore Geology Reviews vol. 69 pp.217-242

Johansson , H., 1910, Die eisenerzführende Formation in der Gegend von Grängesberg. Geologiska Föreningens i Stockholm Förhandlingar vol. 32 239-410 (in German).

Johansson, R., 1980, Jokkmokksområdets järnmalmer – geofysisk tolkning med malmberäkning. Sveriges geologiska undersökning tolkningsrapport FM 8012, 36p. (in Swedish)

Jonsson, E. & Högdahl, K., 2013: New evidence for the timing of formation of Bastnäs-type REE mineralisation in Bergslagen, Sweden. In E. Jonsson et al. (eds.) Mineral deposit research for a high-tech world, 1724-1727

Kathol, B. & Weihed, P. (eds), 2005. Description of regional geological and geophysical maps of the Skellefte District and surrounding areas. Sveriges geologiska undersökning, serie Ba 57. 197 p.

Kendrick, M.A., Burgess, R., Harrison, D., and Bjorlykke, A., 2005, Noble gas and halogen evidence for the origin of Scandinavian sandstone-hosted Pb-Zn deposits: Geochimica et Cosmochimica Acta, v. 69, p. 109–129.

Kresten, P. 1993. Undersökning av malmer och slagger. Ett tvärsnitt genom Gamla Uppsala sn. Arkeologiska undersökningar inför gång- och cykelvägen mellan Gamla Uppsala och Storvreta. In: Karlenby, L., Kresten, P. & Sigvallius, B. (eds) RAÅ Rapport UV 1993:3. Stockholm. (in Swedish).

Lager, I. 2001. The geology of the Palaeoproterozoic limestone- hosted Dannemora iron deposit, Sweden. Sveriges geologiska undersökning, Rapporter och meddelanden 107. 49 p.

Lasskogen, J. 2010. Volcanological and volcano-sedimentary facies stratigraphical interpretation of the Falun Cu-Zn- Pb-(Ag-Au) sulphide deposit, Bergslagen district, Sweden. Master thesis, Luleå University of Technology, Division of Ore Geology. 104 p.

Lilljequist, R., 1973, Caledonian geology of the Laisvall are, southern Norrbotten, Swedish Lapland. Geological Survey of Sweden, serir C 691 45 p.

Lindroos, H. 1972. PM Angående Kaunisvaara malmstråk. Sveriges geologiska undersökning, brap763. (in Swedish)

Lindroos, H. 1974. The stratigraphy of the Kaunisvaara iron ore district, northern Sweden. Sveriges geologiska undersökning, serie C 695. 18 p.

Lindroos, H., 1989, Gold exploration in the Juktan area 1989, Swedish geological company prap 89536.

Lindroos, H., Nilsson, B., Ros, F., 1992, NSG Gold exploration in Sweden 1984-1991. State Mining Property Commission NSG 92038.

Lindroos, H., Nylund, B. & Johansson, K. I. 1972. Tapuli och Palotieva järnmalmsfyndigheter. Rapport rörande resultaten av SGU:s undersökningar under åren 1963–1969. Sveriges geologiska undersökning, brap764. (in Swedish)

Ljung, S. 1974. Adak-Lindsköld och Brännmyrangruvorna inom Adakfältet. Sveriges geologiska undersökning, serie C 701. 94 p. (in Swedish)

Looström, R., 1929a, Likheter mellan Lapplands- och Grängesbergsmalmerna. Geologiska Föreningen i Stockholm Förhandlingar 51 303-308

Looström, R., 1929b, Nya blottningar i Exportfältet i Grängesberg. Geologiska Föreningen i Stockholm Förhandlingar 51 624-627

Looström, R. 1939. Lönnfallet. Southernmost Part of the Export Field at Grängesberg. Sveriges geologiska undersökning, serie C 428. 30 p.

Lundberg, B. 1967. The Stora Sahavaara iron ore deposit, Kaunisvaara, Northern Sweden. Sveriges geologiska undersökning, serie C 620. 37 p.

Lundström, I., Allen, R. L., Persson, P. O. & Ripa, M. 1998. Stratigraphies and depositional ages of Svecofennian, Palaeoproterozoic metavolcanic rocks in E. Svealand and Bergslagen, south central Sweden. GFF 120, 315–320.

Lundström, I., Papunen, H. (eds.), 1996, Mineral deposits of southwestern Finland and the Bergslagen Province, Sweden. SGU Ca 61

Lynch E.P., Jönberger J., Bauer T.E., Sarlus Z. & Martinsson O., 2015, Meta-volcanosedimentary rocks in the Nautanen area, Norrbotten: Preliminary lithological and deformation characteristics. SGU, Report 2015:30, 51 pp.

Magnusson, N. H. 1938. Neue Untersuchungen innerhalb des Grängesberg-feldes. Sveriges geologiska undersökning, serie C 418. 44 p. (in German)

Malmqvist, D. & Parasnis, D. S. 1972. Aitik: geophysical documentation of a third-generation copper deposit in north Sweden. Geoexploration 10, 149–200.

Martinsson, O., 1995: Greenstone and porphyry hosted ore deposits in northern Norrbotten. Report, NUTEK, Project nr. 9200752-3, Division of Applied Geology, Luleå University of Technology.

Martinsson, O., 1997, Tectonic setting and metallogeny of the Kiruna greenstones. PhD thesis 1997:19, Luleå University of Technology. 162 p.

Martinsson, O., Wanhainen, C., 2004, Character of Cu-Au mineralisation and related hydrothermal alteration along the Nautanen deformation zone, Gällivare area, northern Sweden. In R.L. Allen, O. Martinsson & P. Weihed (eds.): Svecofennian ore-forming environments of northern Sweden – volcanic-associated Zn-Cu-Au-Ag, intrusion-associated Cu-Au, sediment-hosted Pb-Zn, and magnetite-apatite deposits in northern Sweden. Society of Economic Geologists, guidebook series 33, 149–160.

Martinsson, O. & Wanhainen, C., 2013, Fe oxide and Cu-Au deposits in the northern Norrbotten ore district. Society of Geology Applied to Mineral Deposits (SGA) excursion guidebook SWE5, 74 pp.

Mattson, B., 1991., Mineralmarknaden Tema: Krom. Sveriges geologiska undersökning, Periodiska Publikationer 1991:1, 32–34. (in Swedish)

Mellqvist, C., Öhlander, B., Skiöld, T. & Wikström, A., 1999: The Archaean-Proterozoic Palaeoboundary in the Luleå area, northern Sweden: field and isotope chemical evidence for a sharp terrane boundary. Precambrian Research 96, 225243.

Mercier-Langevin, P., McNicoll, V., Allen, R.L., Blight, J. H. S., Dubé, B., 2013, The Boliden gold-rich volcanogenic massive sulfide deposit, Skellefte district, Sweden: new U–Pb age constraints and implications at deposit and district scale. Mineralium Deposita vol 48 485-504

Monro, D., 1988, The geology and genesis of the Aitik Cu-Au deposit, arctic Sweden. Ph.D. thesis, University College Cardiff, UK, 386 pp.

Montelius, C., 2005. The genetic relationship between rhyolitic volcanism and Zn-Cu-Au deposits in the Maurliden volcanic centre, Skellefte district, Sweden: Volcanic facies, lithogeochemistry and geochronology. Doctoral Thesis 2005:17, Luleå University of Technol-

ogy, Sweden.
Montelius, C., Allen, R.L., Svensson, S., Å., 2004, Polymetallic Massive and Network Sulfide Deposits Hosted by a Crystal-Rich Rhyolite Pumice Deposit, Maurliden, Skellefte District, Sweden. Society of Economic Geologists Guidebook Series, Volume 33, p. 95–109
Montelius , C., Allen , R. L., Svenson, S. Å., & Weihed, P., 2007 Facies architecture of the Palaeoproterozoic VMS-bearing Maurliden volcanic centre, Skellefte district, Sweden, GFF, 129:3, 177-196
New Boliden (2014). Annual report 2014, www.boliden.com
Nyström, J.O., Henriquez, F., 1994, Magmatic features of iron ores of the Kiruna type in Chile and Sweden: Ore textures and magnetite geochemistry. Economic Geology 89 820-839.
Nyström, J.O., Henriquez, F., 1995, Magmatic features of iron ores of the Kiruna type in Chile and Sweden: Ore textures and magnetite geochemistry - a reply. Economic Geology 90 473-475.
Nystuen, J. P., Andresen, A., Kumpulainen, R. A. & Siedlecka, A. 2008. Neoproterozoic basin evolution in Fennoscandia, East Greenland and Svalbard. Episodes 31, 35–43.
Ohlsson, L.-G. 1979. Tungsten occurrences in Sweden. Economic Geology 74, 1012-1034.
Ohlsson, L.-G. 1980. Turn around at Yxsjöberg. Mining Magazine 142, 518-531.
Padget, P., 1970. Beskrivning till berggrundskartbladen Tärendö NV, NO, SV, SO. Sveriges geologiska undersökning serie Af 5–8, 95 p. (in Swedish)
Panno, S.V., Hood, W.C., 1983, Volcanic stratigraphy of the Pilot Knob iron deposit, Iron County, Missouri. Economic Geology 78 972-982.
Parak, T., 1969, Nya undersökningar inom Kirunafältets norra del. Geologiska Föreningen i Stockholm, Förhandlingar (GFF) 91, 34–51. (in Swedish).
Parak, T., 1975a, The origin of the Kiruna iron ores. SGU C 709 .
Parak, T., 1975b, Kiruna Iron Ores Are Not "Intrusive-Magmatic Ores of the Kiruna Type". Economic Geology 70 1242-1258.
Persson, G.,1981, Kobolt-kopparfyndigheten vid Kiskamavaara, del 1 tonnage of haltberäkning. Sveriges geologiska undersökning, brap 81552 (in Swedish)
Rickard D. (ed.), 1986, The Skellefte Field. Sveriges geologiska undersökning, serie Ca 62. 54 p.
Rickard, D., Coleman, M., Swainbank, I., 1981,Lead and sulfur isotopic compositions of galena from the Laisvall sandstone lead-zinc deposit, Sweden. Economic Geology vol. 76 2042-2046.
Rickard, D. T., Willden, M. Y., Marinder, N. E. & Donnelly, T. H. 1979. Studies on the genesis of the Laisvall sandstone lead-zinc deposit, Sweden. Economic Geology 74, 1255–1285.
Romer, R. L., Öhlander, B., 1994, **U-Pb age of the Yxsjoberg tungsten-skarn deposit, Sweden.** G F F, Vol. 116, No. 3, p. 161-166
Romer, R.L. & Öhlander, B., 1994: U-Pb age of the Yxsjöberg tungsten-skarn deposit, Sweden. GFF, Vol. 116 (Pt. 3, September), pp. 161–166. Stockholm. ISSN 1103–5897.
Romer, R.L. & Öhlander, B., 1995: Tectonic implications of an 1846 }1 Ma old migmatitic granite in south-central Sweden. GFF 117, 69-74.
Ros, F., Nylund, B. & Oldeberg, H. 1980. Pellivuoma Järnmalmsfyndighet, Rapport rörande resultaten av SGU:s undersökningar under åren 1964–1971. Sveriges geologiska undersökning, brap80011. (in Swedish)
Rydberg, S. 1979. Stora Kopparberg – 1000 years of an industrial activity. Gullers International AB. 95p.
Saintilan, N.J.D., Spangenberg J.E., Fontboté L., Samankassou E., Stephens M.B., 2014, The Laisvall and Vassbo sandstone-hosted Pb-Zn deposits along the eastern front of the Scandinavian Caledonides: An example of phosphorous-rich sulphide-mineralized Cambro-Ordovician sour gas reservoirs. In: 37th Annual Meeting Mineral Deposit Studies Group. Laurence Robb & Nick Gardiner, 2014. p. 70
Saintilan, N.J.D., Schneider, J.C., Stephens, M., Chiaradia, M., Kouzmanov, K., Wälle, M., Fontboté, L., 2015, A middle Ordovician age for the Laisvall sandstone-hosted Pb-Zn deposit, Sweden: A response to early Caledonian orogenic activity. *Economic Geology and the Bulletin of the Society of Economic Geologists*, vol. 110, no. 7, pp. 1779-1801.
Sammelin M., 2011, The nature of gold in the Aitik Cu-Au deposit. Implications for mineral processing and mine planning. Licentiate thesis, Luleå Technical University, Luleå, Sweden, 67 pp.
Sammelin (Kontturi) M., Wanhainen C., Martinsson O., 2011, Gold mineralogy at the Aitik Cu-Au-Ag deposit, Gällivare area, northern Sweden. GFF, 133, 1-2, 19-30.
Sillitoe R.H., Burrows D.R., 2002, New field evidence bearing on the origin of the El Laco magnetite deposit, northern Chile. Economic Geology 97, 1101-1109.
Smith, M., Coppard, J., Herrington, R. & Stein, H., 2007, The Geology of the Rakkurijärvi Cu-(Au) Prospect, Norrbotten: A New Iron Oxide-Copper-Gold Deposit in Northern Sweden. Economic Geology 102, 393–414.
Smith, M.P., Storey, C.D., Jefferies, T.E. & Ryan, C., 2009, In situ U–Pb and trace element analysis of accessory minerals in the Kiruna district, Norrbotten, Sweden: New constraints on the timing and origin of mineralisation. Journal of Petrology 50, 2063–2094.
Stephens, M. B., Ripa, M., Lundström, I., Persson, L., Bergman, T., Ahl, M., Wahlgren, C.-H., Persson, P.-O. & Wickström, L., 2009. Synthesis of the bedrock geology in the Bergslagen region, Fennoscandian Shield, southcentral Sweden. Sveriges geologiska undersökning, serie Ba 58. 259 p.
Stephens, M.B. & Weihed, P., 2013: Tectonic evolution and mineral resources in the Fennoscandian Shield, Sweden. 12th biennial SGA meeting, excursion guidebooks SWE 1–7.
Sundberg, S., Persson, G., Niva, B., 1980, Kopparmineraliseringen vid Iekelvare. Sveriges geologiska undersökning brap 80013 (in Swedish)
Tegengren, F. 1924. Sveriges ädlare malmer och bergverk. Sveriges geologiska undersökning, serie Ca 17. 406 p. (in Swedish).
Wanhainen C., 2005, On the Origin and evolution of the Palaeoproterozoic Aitik Cu-Au-Ag deposit, northern Sweden. A porphyry copper-gold ore, modified by multistage metamorphic-deformational, magmatic-hydrothermal, and IOCG-mineralizing events. Ph.D thesis, Luleå Technical University, Luleå, Sweden, 148 pp.
Wanhainen, C., Billström, K., Stein, H., Martinsson, O. & Nordin, R., 2005. 160 Ma of magmatic/hydrothermal and metamorphic activity in the Gällivare area: Re-Os dating of molybdenite and U–Pb dating of titanite from the Aitik Cu-Au-Ag deposit, northern Sweden. Mineralium Deposita 40, 435–447.
Wanhainen, C., Billström, K. & Martinsson, O., 2006, Age, petrology and geochemistry of the porphyritic Aitik intrusion, and its relation to the disseminated Aitik Cu-

Au-Ag deposit, northern Sweden. GFF 128, 273–286.
Weihed, P., 1992a, Geology and genesis of the Early Proterozoic Tallberg porphyry type deposit, Skellefte district, northern Sweden. Geologiska Institutionen, Chalmers Tekniska Högskola – Göteborgs Universitet vol. A 72, 1–147.
Weihed, P., 1992b, Lithogeochemistry, metal and alteration zoning in the Proterozoic Tallberg porphyry-type deposit, northern Sweden. Journal of Geochemical Exploration 42, 301–325.
Weihed, P., 2001, A review of Palaeoproterozoic intrusive hosted Cu-Au-Fe-oxide deposits in northern Sweden. In: Weihed. P. (ed.) Economic Geology Research 1, 1999– 2000. Sveriges geologiska undersökning, serie C 833, 4–32.
Weihed, P., Bergman Weihed, J. & Sorjonen-Ward, P. 2003, Structural evolution of the Björkdal gold deposit, Skellefte district, northern Sweden: Implications for Early Proterozoic mesothermal gold in the late stage of the Svecokarelian orogen. Economic Geology 98, 1291–1309.
Wik, N-. G.,Stephens, M. B., Sundberg, A., 2006, Malmer, industriella mineral och bergarter i Uppsala län, (Ores, industrial minerals and rocks in the county of Uppsala, with summary in English), SGU Rapporter och meddelanden 124, 225 pp.
Willdén, M., 2004, The Laisvall sandstone-hosted Pb-Zn deposit: Geological overview, in Society of Economic Geologists Guidebook Series, eds. Allen, R. L., Martinsson, O., Weihed, P., vol. 33 115-127.
Witschard, F., 1996, Berggrundskartan 28K Gällivare NO, NV, SO, SV. 1:50 000-scale map. Sveriges geologiska undersökning Ai 98–101.
Wright, S.F., 1986, On the magmatic origin of iron ores of the Kiruna type - an additional discussion. Economic Geology 81 192-194.
Zweifel, H., 1976, Aitik. Geological documentation of a disseminated copper deposit. Sveriges geologiska undersökning C 720, 80 pp.
Årebäck, H., Barrett, T. J., Abrahamsson, S. & Fagerström, P., 2005, The Palaeoproterozoic Kristineberg VMS deposit, Skellefte district, northern Sweden, part I: geology. Mineralium Deposita 40, 351–367.

SELECTED REFERENCES ON THE GEOLOGY OF SWEDEN

Allen, R. L., Lundström, I., Ripa, M., Simeonov, A. & Christofferson, H., 1996. Regional volcanic facies interpretation of 1.9 Ga metasediment- and metavolcanic-hosted Zn-Pb-Ag(-Cu-Au) sulfide and Fe oxide ores, Bergslagen region, Sweden. Economic Geology 91, 979–1008.
Bergman, S., Kübler, L. & Martinsson, O., 2001. Description of regional geological and geophysical maps of northern Norrbotten County (east of the Caledonian orogen). Sveriges geologiska undersökning, serie Ba 56. 110 p.
Bingen, B., Andersson, J., Söderlund, U. & Möller, C., 2008. The Mesoproterozoic in the Nordic countries. *In* Gee, D. G., Ladenberg, A. (eds.) Special issue for the 33rd International Geological Congress Oslo, Norway, 6-14 August, 2008, Episodes vol. 31 29-34.
Gee, D. G., Brekke, H., Lahtinen, R., Sigmundsson, F., Sundquist B., Thybo, H. & Weihed, P., 2008a. Nordic geosciences and the 33rd International Geological Congress: Introduction. *In* Gee, D. G., Ladenberg, A. (eds.) Special issue for the 33rd International Geological Congress Oslo, Norway, 6-14 August, 2008, Episodes vol. 31 4-8.
Gee, D. G., Fossen, H., Henriksen, N. & Higgins, A. K., 2008b. From the Early Paleozoic platforms of Baltica and Laurentia to the Caledonide orogen of Scandinavia and Greenland. *In* Gee, D. G., Ladenberg, A. (eds.) Special issue for the 33rd International Geological Congress Oslo, Norway, 6-14 August, 2008, Episodes vol. 31, 44-51.
Kathol, B. & Weihed, P. (eds), 2005. Description of regional geological and geophysical maps of the Skellefte District and surrounding areas. Sveriges geologiska undersökning, serie Ba 57. 197 p.
Mellqvist, C., Öhlander, B., Skiöld, T. & Wikström, A., 1999: The Archaean-Proterozoic Palaeoboundary in the Luleå area, northern Sweden: field and isotope chemical evidence for a sharp terrane boundary. Precambrian Research 96, 225243.
Stephens, M. B., Ripa, M., Lundström, I., Persson, L., Bergman, T., Ahl, M., Wahlgren, C.-H., Persson, P.-O. & Wickström, L., 2009. Synthesis of the bedrock geology in the Bergslagen region, Fennoscandian Shield, southcentral Sweden. Sveriges geologiska undersökning, serie Ba 58. 259 p.
Stephens, M.B. & Weihed, P., 2013: Tectonic evolution and mineral resources in the Fennoscandian Shield, Sweden. 12th biennial SGA meeting, excursion guidebooks SWE 1–7.