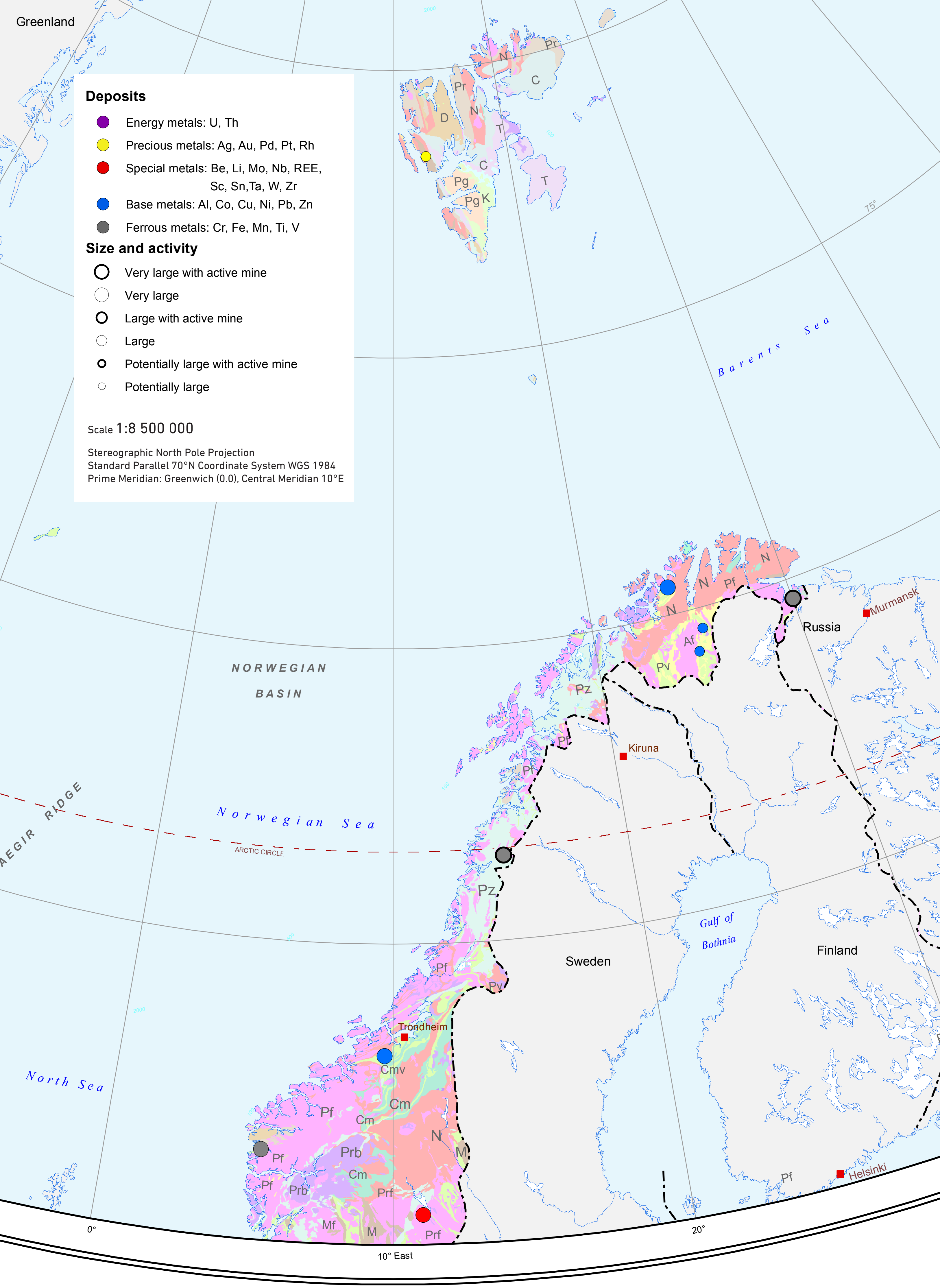
Greenland
Deposits
Energy metals: U, Th
Precious metals: Ag, Au, Pd, Pt, Rh
Special metals: Be, Li, Mo, Nb, REE, Sc, Sn,Ta, W, Zr
Base metals: Al, Co, Cu, Ni, Pb, Zn
Ferrous metals: Cr, Fe, Mn, Ti, V
Size and activity
Very large with active mine
Very large
Large with active mine
Large
Potentially large with active mine
Potentially large
Scale 1:8 500 000
Stereographic North Pole Projection
Standard Parallel 70°N Coordinate System WGS 1984
Prime Meridian: Greenwich (0.0), Central Meridian 10°E
Barents Sea
NORWEGIAN BASIN
Norwegian Sea
AEGIR RIDGE
ARCTIC CIRCLE
North Sea
Russia
Murmansk
Kiruna
Gulf of Bothnia
Sweden
Finland
Trondheim
Helsinki
0°
10° East
20°
75°

CHAPTER 6

NORWAY

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MAINLAND NORWAY INTRODUCTION

Rognvald Boyd

Outline of the geology of Norway

The geology of mainland Norway is dominated by the Caledonide Orogen, which extends, in Norway, over 1500 km from Stavanger in the southwest to the northernmost part of the country (Figure 1). Understanding of the geology of the Caledonides in Scandinavia is in a period of flux following recognition, through the last decade, that a model consisting of four allochthons, Lower, Middle, Upper and Uppermost, all emplaced southeast-wards onto the Baltic Shield, must be revised (Corfu et al., 2014). The four-allochthon model assumed that the Lower and Middle Allochthons were derived from Baltica, with higher allochthons derived outboard of Baltica (from the Iapetus Ocean and related arc complexes) and the highest levels including units derived from the Laurentian side of the Iapetus Ocean (Gee et al., 2008). The recognition that nappe emplacement to the southeast was followed by periods of extensional faulting and large-scale open folding, leading to the development of extensive basement culminations, and that elements in the tectonostratigraphy have been repeated more commonly than earlier recognized, has led to awareness of the need for a more complex model (Corfu et al., 2014).

Much of the coast of southwestern Norway, from Bergen to the region of Namsos, N of Trondheim is dominated by Neo- to Meso-Proterozoic basement rocks, highly deformed and metamorphosed during the Caledonide Orogeny (Corfu et al., 2015): this area is known as the Western Gneiss Complex: it includes a classic eclogite province (Eskola, 1921), one of the first in the world in which micro-diamonds were discovered (Dobrzhinetskaya et al., 1995). The province is also host to dunites which include the world-class Åheim olivine deposit. Southernmost and southeastern Norway is dominated by Mesoproterozoic rocks and by the Permian Oslo Palaeorift. The Mesoproterozoic rocks were deformed and metamorphosed in the Sveconorwegian orogeny (ca. 1140 – 900 Ma) and now form a series of crustal blocks separated by N-S trending deformation belts (Viola et al., 2013). One of the major features in the Sveconorwegian area is the Rogaland Anorthosite Province, S of Stavanger, which includes the world-class Tellnes ilmenite deposit.

The Oslo Palaeorift contains volcanic and intrusive complexes spanning the period from Late Carboniferous to Early Triassic, emplaced into a stacked sequence of Cambro-Silurian sediments which were originally deposited in basins on top of the Sveconorwegian basement, but which were subsequently deformed during the Caledonian Orogeny, and are preserved because of the formation of the Graben.

Archaean and Palaeoproterozoic rocks of the Fennoscandian Shield are exposed west of the Caledonides in northernmost Norway and southeast of the Caledonides along the borders with Sweden, Finland and Russia (Figure 1). The Shield developed by accretion from an Archaean core with banded iron formations in its northeastern regions with, to the west, Palaeoproterozoic granite-greenstone belts (containing gold and copper-nickel-PGE ores) and, even further west, the Mesoproterozoic Transscandinavian Igneous Belt (TIB) which is exposed in windows in the Caledonide nappe sequence along the coast of N Norway: components in the TIB include major granite, pyroxene monzonite (mangerite) and anorthosite intrusions with associated Fe-Ti deposits.

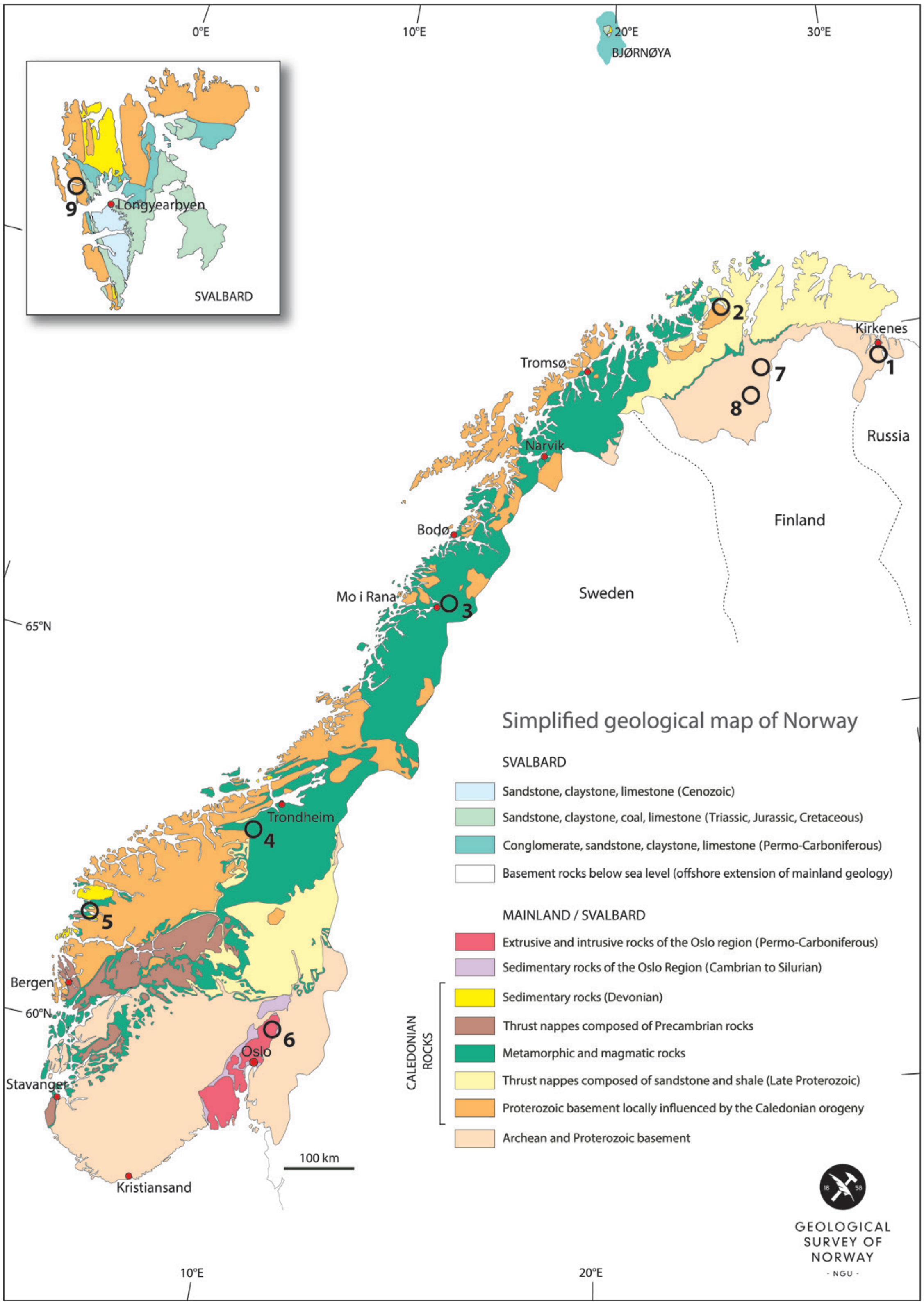

Figure 1. Geological map of Norway.
The numbers refer to the deposits described in the text below.
1: The Bjørnevatn banded iron ore deposit;
2: The Nussir sediment-hosted copper-silver deposit;
3: The Ørtfjell iron deposit;
4: The Løkken volcanogenic copper-zinc deposit;
5: The Engebø eclogite-hosted rutile deposit;
6: The Nordli molybdenum deposit;
7: The Gallujavri nickel-copper-PGE deposit;
8: The Raitevarri copper-gold deposit;
9: The St. Jonsfjorden gold-arsenic deposit.

Norwegian territorial waters extend from the continental shelf, dominated by Mesozoic basins, to include several sections of the Mid-Atlantic Ridge between Iceland and Svalbard (See Chapter 6: Sea-Floor Sulphides). The Centre of Geobiology at the University of Bergen has implemented a long-term research programme to investigate geological and biological processes related to the spreading system, including black smokers and related mineralization. Loki's Castle, a field of five active hydrothermal vents at 73°N degrees on the Mid-Atlantic Ridge at a depth of 2,352 metres was discovered in 2008 by researchers from the Centre (Pedersen et al., 2010).

Figure 2. The open-air mining museum at Skuterud, type locality of skutterudite, where cobalt-copper ores were mined from 1778 to 1898. (Photo: Jan Sverre Sandstad)

History of metal mining in Norway: pre 18th Century

(Based on Boyd. R. in: Eilu et al., 2012)

Bog iron ores were exploited in Norway as early as 400 BC: ^{14}C dating shows that twenty-eight deposits had been exploited in central Norway alone prior to 200 AD (Stenvik, 2005). The oldest record of underground mining (late 12th C) is from the Akersberg silver deposit (of Permian age) in Oslo (Nilsen & Bjørlykke, 1991). Small-scale mining of copper and silver ores began in several parts of the country in the first half of the 16thC (Falck Muus, 1924). A mining law, based on those of Saxony, was introduced in 1538-39: elements of the law are still operative – a system of claims administered by mining inspectors. The Kongsberg silver mine which exploited native silver-arsenide veins of Permian age was opened in 1623 and was in operation, with short breaks, until 1958. Long-term copper mining developed in the following thirty years, at Kvikne (1630), Røros (1644) and Løkken (1654), all massive sulphide deposits in the Caledonides in the region S of Trondheim. Mining at Røros and Løkken continued until 1977 and 1987 respectively. Røros, one of the best-preserved old mining towns in Europe, is a UNESCO World Heritage site. Norway was, for much of the period of rapid development of mining, ruled by Denmark, then a significant military power in need of a ready supply of metals for its weapons industry.

Numerous iron deposits of metasomatic origin, mainly in southernmost Norway, were mined from the 17th C but few survived to the 20th C. One exception, at Ulefoss, was mined from 1650 and finally closed in 1929, though not before it had led to the formation of Ulefos Jernværk (now part of Ulefos Holding) an iron foundry whose products today include a type of stove first produced in 1766.

Metal mining - 18th – 19th Centuries

The established copper mines were joined by another long-term operation, at Folldal, in 1748. New types of metallic ore and minerals were also exploited in addition to the established copper, silver and iron mines. Cobalt arsenide ores of Mesoproterozoic age were discovered at Modum in 1772, leading to development of the Skuterud mines and the establishment of Blaafarveværket as a royal company for the production of the dye

"cobalt blue" (Figure 2). At its peak, in the 1820s and 1830s, the company was Norway's largest industrial concern and produced 80 % of the world's "cobalt blue". Nickel deposits of Mesoproterozoic age were discovered in Espedalen in 1837 and mining operations commenced there in 1846 and at Ertelien in 1849: the first description of the iron-nickel sulphide, later called pentlandite, was in samples from Espedalen (Scheerer, 1845). There followed almost 100 years of semi-continuous nickel mining in Norway, including a period in the early 1870s during which Norway was the world's major supplier (a position supplanted by New Caledonia after the discovery there of nickel laterite ores).

Mining of pyrite from massive sulphides, for use in production of sulphuric acid, began in the mid 19th C at Vigsnes and Stord and, in 1888, at Sulitjelma (also a major copper producer) and other new deposits, as well as from the established copper mines at Røros, Løkken and Folldal (Figure 3). Molybdenum deposits were discovered in the late 1800s, including the Knaben deposit which was mined from 1885 to 1973.

Several new, large deposits of iron ore were discovered before the end of the 19th C. The Neoproterozoic Dunderland deposits (including Ørtfjell), just S of the Arctic Circle near Mo i Rana, were discovered in the 18th C and the Archaean

Figure 3. Winter at the Folldal copper mine, which was in production from 1748 to 1941 (the photograph is used by permission of Stiftelsen Folldal Gruver).

banded iron formations at Bjørnevatn in Sydvaranger in 1865, by Tellef Dahl, the second geologist to be appointed to the Geological Survey of Norway. Foreign investment was important in prospecting and mine development in the late 1800s and early 1900s, especially in northernmost Norway. The most long-lived evidence of this is the town of Longyearbyen on Svalbard, named after the founder of the Arctic Coal Company, established in 1906, the forerunner for Store Norske Spitsbergen Kulkompani which still operates coal mines on Svalbard.

Metal mining - 20th – 21st Centuries

Mining commenced at three major iron ore deposits within the first decade of the new century – at Sydvaranger (1906), Fosdalen (1906) and Rødsand (Fe-V-Ti) (1910). Operations also began at Dunderland but were sporadic until 1937. The first steps, which led ultimately to Norway's major role as a producer of titanium-oxide pigments, were taken in the early 1900s, with the establishment of a company to exploit a patent for manufacture of "titanium white" pigment from titanium dioxide. Titania A/S opened mining operations on the Neoproterozoic Storgangen deposit in Rogaland in 1916: the company was taken over by National Lead (NL), in 1927, and is now part of the NL subsidiary, Kronos. In 1957 the nearby Tellnes deposit, one of the first discovered in Norway with the aid of aeromagnetic methods, was opened. It is one of the largest ilmenite deposits in the world, currently providing >7% of world production of ilmenite (BGS, 2015). Other new ore types to be exploited in the first half of the century included the SEDEX type Zn-Pb–Cu ores at Mofjell, just S of Mo i Rana, which were mined in the period 1928- 1987.

The Svalbard Treaty, signed in 1920 by 14 countries, granted Norway sovereignty of the archipelago, but gave the right to own property, including mineral rights, to nationals of all the signatory countries. 42 countries have now signed the treaty. The Norwegian company, Store Norske Spitsbergen Kullkompani, was established in 1916 and currently owns three coal mines on Svalbard. The Russian company, Trust Arktikugol, established a coal mine (still in operation) at Barentsburg in 1932. A second Russian mine, at Pyramiden, was operated by Trust Artikugol from 1927 to 1988. Several prospecting campaigns, focused on gold and iron mineralisations, have been implemented but none of these have so far led to the definition of economically viable deposits.

Occupation of Norway during World War II had an important impact on mining in Norway due to the strategic importance of certain types of ore which were not readily obtainable to Germany.

	SIZE CLASS	LATITUDE	LONGITUDE	MAIN METALS	MAIN METAL %	OTHER METALS	TONNAGE MINED (MT)	RESOURCE + RESERVE
Bjørnevatn	Large	69.65	30.03	Fe	32		140	380
Nussir	Large	70.46	24.20	Cu, Ag	1.16/15g/t	Au, PGE		66
Ørtfjell	Large	66.41	14.68	Fe	34		28.7	388
Løkken	Large	63.12	9.70	Cu, Zn, Co	2.3/1.8/0.07	Ag, Au	24	6
Engebø	Large	61.49	5.43	Ti	2.4			400
Nordli	Large	60.48	11.02	Mo	0.09			210
Raitevarri	Potentially large	69.27	24.94	Cu, Au		Mo		Not determined
Gallujavri	Potentially large	69.63	25.38	Ni, Cu, Co, PGE		Au		Not determined
St. Jonsfjorden	Potentially large	78.48	12.89	Au				Not determined

Table 1. Large and potentially large metal deposits in Norway north of 60° N (Sources: FODD database: http://en.gtk.fi/informationservices/databases/fodd/, Nussir ASA, Ojala (2012)

Deposits of several types, especially of nickel and molybdenum, were exploited intensively: the known reserves at two nickel deposits, Hosanger and Flåt, which had been opened early in the century, were exhausted. The period of industrial development following World War II saw the opening of numerous new sulphide mines, in some cases based on known deposits but also on new deposits found on the basis of new geophysical exploration methods and intensive prospecting. These included the Caledonian massive sulphide deposits (year opened in parentheses) Skorovatn (Zn-Cu-pyrite) (1952), Bleikvassli (Zn-Pb–Cu) (1957), Tverrfjell (Cu-Zn) (1968), Joma (Cu-Zn) (1972) and Lergruvbakken, a new deposit in the Røros province (Cu-Zn) (1973) as well as the Bruvann Ni-Cu deposit (1988). Deposits in the Palaeoproterozoic greenstone belts included Bidjovagge (Cu-Au) (1971) and Ulveryggen (Cu) (1972). More exotic ores were mined at Søve in the Neoproterozoic Fen carbonatite where niobium was mined from 1953-65. The Finnish mining giant, Outokumpu, developed an important role in mining in Norway in the 1990s with ownership or part-ownership in operations at Løkken, Tverrfjell, Joma, Bruvann and Bidjovagge. Exhaustion of a number of deposits, erratic metal prices and competition from large, easily-mined deposits in other parts of the world led to the closure of most of the remaining sulphide deposits in the last quarter of the 20th C.

Skills in metallurgy developed during Norway's long mining history, combined with ready access to hydro-electric power and imported mineral raw materials have led Norway to a dominant position in Europe in production of aluminium (29 % of EU production in 2013), ferro-alloys (42.8 %), refined nickel (40.1 %), and silicon metal (44.7 %) (data from BGS, 2015). Norway is a major producer of industrial minerals, being the world's largest producer of olivine and ground calcium carbonate and the largest in Europe of flake graphite and high-purity quartz. At the time of writing there are three metal mines in Norway – the Tellnes ilmenite mine (at 58° 20' N) and the iron mines at Rana (Ørtfjell) and Sydvaranger (Bjørnevatn). Permissions to proceed with development of a rutile mine at the Engebø deposit in West Norway and of a copper-noble metal mine at the Nussir deposit in North Norway (including the proposed plans for tailings deposition) have recently been given. Nine deposits in Norway meet the specifications for deposits considered to be large or potentially large in the FODD classification (Eilu et al., 2007; Table 1): other candidates for the classification "potentially large" have been considered but were excluded because the level of exploration in these was not considered sufficient to confirm their potential. None of the deposits qualifies for the "very large" category.

THE BJØRNEVATN BANDED IRON DEPOSITS

Peter M. Ihlen

The Neoarchaean iron deposits in the Sør-Varanger area are banded iron formations (BIF) interpreted as exhalative sedimentary ores by Bugge (1960b). They constitute characteristic members of the supracrustal sequences of the Sørvaranger–Kola terrane, which is unconformably overlain by the Palaeoproterozoic Polmak and Pasvik Greenstone Belts, being overthrust by the Inari Terrane in the southwest.

The individual lithotectonic units were largely formed and amalgamated into their present position in the period 2.90–2.73 Ga, prior to the intrusion of late orogenic granite plutons,

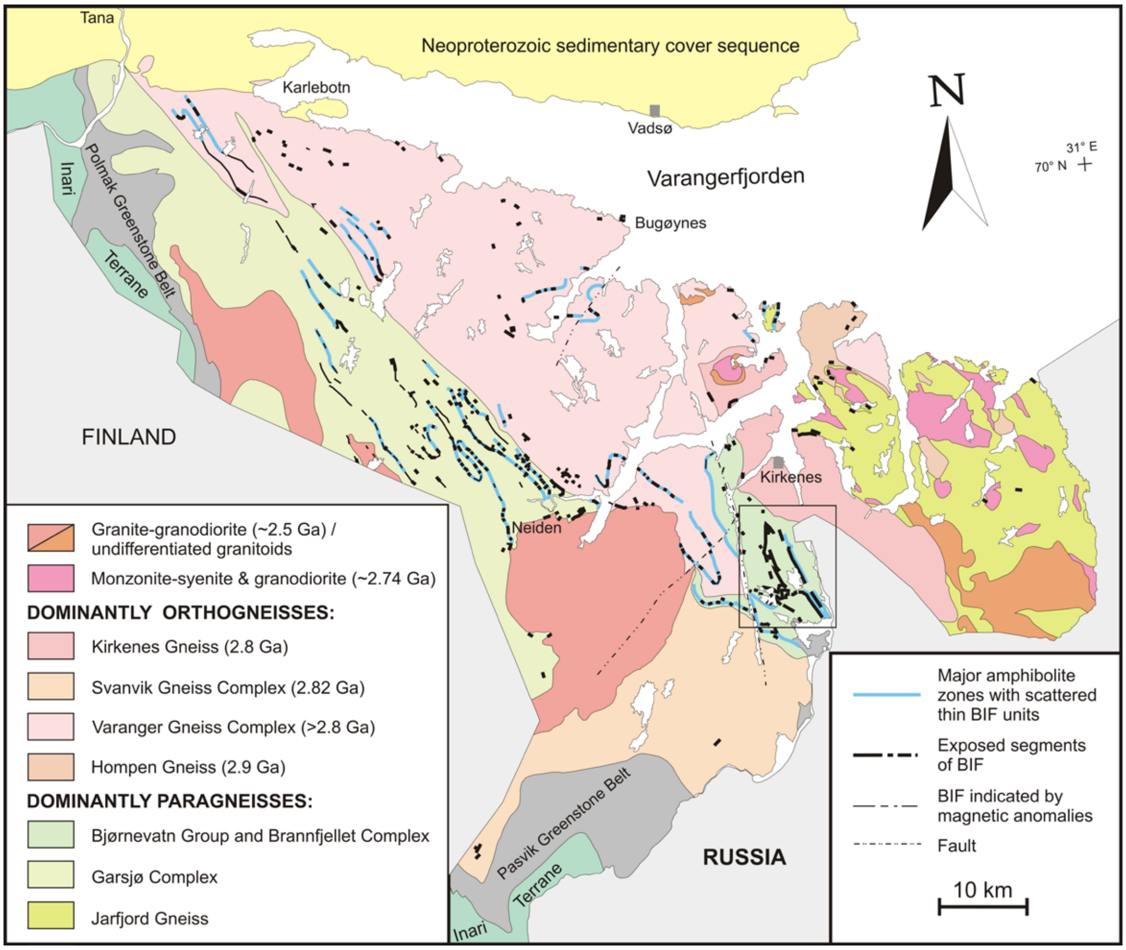

Figure 4 (from Ihlen, in Eilu, P. (ed.) 2012. Geological map of the Sørvaranger province showing the distribution of BIF units. The terminology of the gneiss units is after Dobrzhinetskaya et al. (1995). Compilation of the BIF occurrences is based on Wiik (1966), Iversen and Krill (1990, 1991), Iversen and Nilsson (1991), Nilsson and Iversen (1991), Siedlecka and Roberts (1996) and unpublished field data from Ø. Nordgulen, M. Heim, E., Iversen, and L. P. Nilsson. The rectangle indicates the area shown in Figure 5.

for example the Neiden granite, at ca. 2.5 Ga (Dobrzhinetskaya et al., 1995; Levchenkov et al., 1995). Geochronological data presented by the latter authors indicate that most of the supracrustals and the BIF units were deposited at ca. 2.8 Ga. The supracrustal gneiss complexes hosting the BIF deposits as presented in Figure 4 are predominantly composed of pelitic, semipelitic and psammitic sediments. They generally contain only subordinate sequences of mafic to intermediate metavolcanic rocks, which are, however, important carriers of the BIF units, especially those containing Fe-rich amphibolite members (Siedlecka et al. 1985, Dobrzhinetskaya et al., 1995).

The BIF deposits vary considerably in mineralogy, type of banding (on a mm to dm scale), and size. The individual bands are mainly composed of up to three of the following minerals: magnetite, quartz, hornblende, grünerite-cummingtonite, biotite, and garnet, as well as locally diopside and hypersthene (Wiik, 1966; Siedlecka et al., 1985). They can, according to the type of mineralogical banding, be subdivided into typical oxide-facies BIF composed of alternating bands of quartz and magnetite, which may grade into silicate-facies types containing bands of magnetite and Fe-rich silicates. Although the BIF units are strongly deformed, causing tectonic dismembering and changes in the original thicknesses, they were most probably deposited at different levels in the original volcano-sedimentary sequences. The BIF ores in the Garsjø Group and in the Jarfjord Gneiss frequently comprise silicate-facies ores. They are normally 1-15 m thick and commonly constitute several-kilometre-long trains of lenses with the strike length of the individual ore bodies rarely exceeding a few hundred metres.

The Bjørnevatn area (Figure 5) contains the largest accumulation of BIF ores in the Sør-Varanger metallogenic district. The BIF units of the presently mined ore field were first discovered by the Commissioner of Mines, Tellef Dahll, in 1865 (Dahll 1891), but exploration did not begin until 1906. Full-scale mining by A/S Sydvaranger

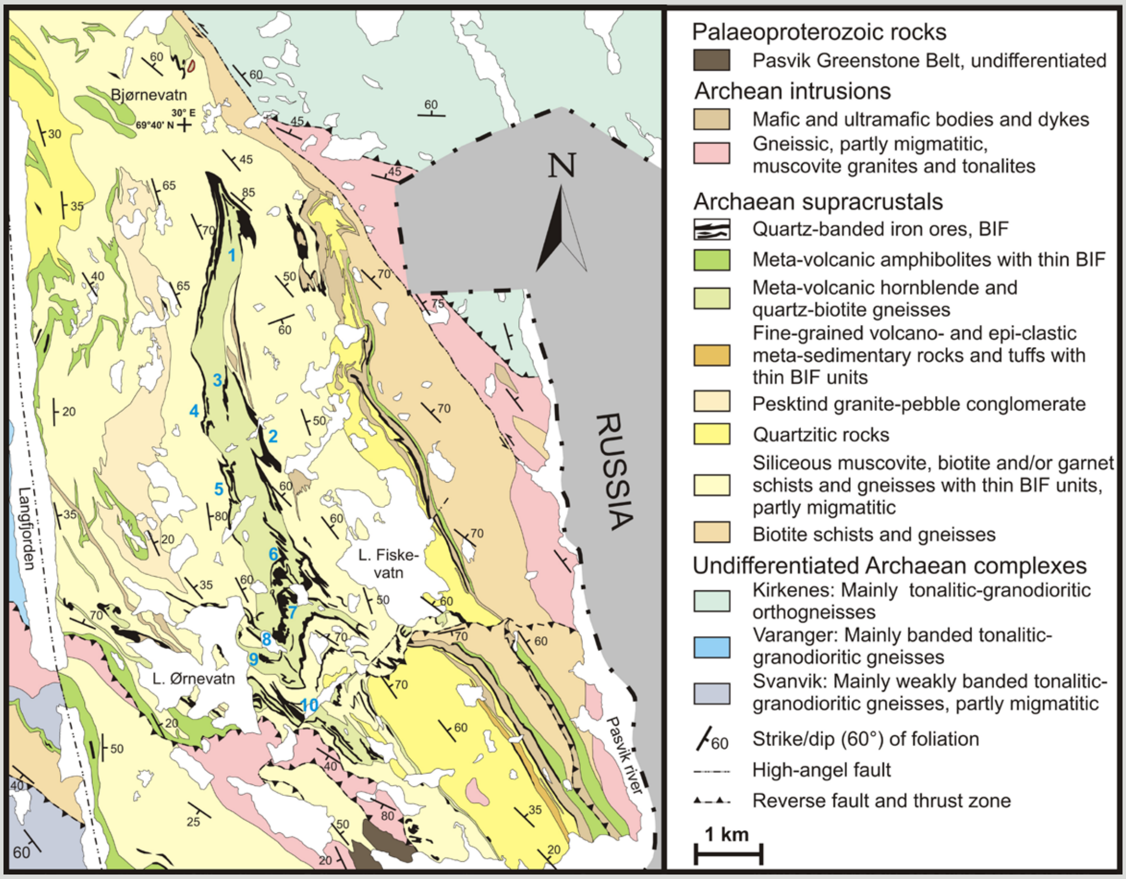

Figure 5 (from Ihlen, in Eilu, P. (ed.) 2012). Geological map of the Bjørnevatn subarea, compiled from Iversen and Krill (1990) and Iversen and Nilsson (1991).

commenced in 1910 and continued until 1997. Open pit and subordinate underground mining gave a total production of >200 Mt of ore with about 30 % Fe (magnetic) in this period. Sydvaranger Gruve AS reopened the deposit in 2009: four of the ore bodies (Bjørnevatn, Kjellmannsåsen, Fisketind and Bjørnfjell) were being mined in 2014: probable ore reserves were 154 Mt containing 30.4 % Fe (total) (Northern Iron, 2015). Total resources (proven+indicated+ inferred) have recently been stated to be 506.6 Mt with 31 % Fe (total) (Northern Iron, 2015).

The ore bodies are part of the Bjørnevatn Group, which comprises formations predominantly composed of quartzite, conglomerate, siliceous mica schist and gneiss, as well as biotite-rich mica schist and mafic to intermediate metavolcanic rocks with major BIF units. The metavolcanic rocks contain two levels of BIF ores that occur interlayered with and separated by sequences of hornblende and quartz-biotite gneisses, as well as magnetite-rich amphibolites, locally with pillow structures. These rocks are interpreted as andesitic, dacitic and basaltic volcanic rocks, respectively (Bugge, 1978b; Siedlecka et al., 1985). The ore zones and their wall rocks are crosscut by late orogenic granite dykes and Mesoproterozoic dolerite dykes (1300–1200 Ma, Siedlecka & Nordgulen, 1996), not shown in Figures 4 and 5. The ore bodies of the upper BIF level have been the main target for open-pit mining. The shape of the ore bodies shown in Figure 5 is the ultimate result of three phases of isoclinal to tight folding. The distribution of the ores in the northern part of the mining field is governed by a synform overturned towards the west and with a moderate plunge to the SE. The ore bodies may reach a thickness of nearly 200 m and a strike length of 1–5 km. The upper BIF usually contains 30–35 % Fe (magnetic) (>50 % magnetite) and the lower BIF 10–30 % Fe (magnetic) (Siedlecka et al., 1985). The ores consist of alternating magnetite- and quartz-dominated bands (2–10 mm thick).

Additional minerals in the BIF include hornblende, grünerite, epidote, biotite and hematite, together with traces of pyrite and chalcopyrite that are mainly confined to the magnetite bands. In some parts of the mining field, the BIF comprises nearly monomineralic bands of hornblende and grünerite. In the southernmost part of the mining field, both the amphibolitic rocks and the ore zones thin out and start to interfinger with arenitic to pelitic metasedimentary rocks locally grading into conglomeratic units with pebbles of BIF and tonalite in a magnetite-rich matrix. These features indicate transformation to shallow-water palaeoconditions.

THE NUSSIR SEDIMENT-HOSTED COPPER-SILVER DEPOSIT

Jan Sverre Sandstad and Espen Torgersen

Several sediment-hosted copper deposits are associated with Paleoproterozoic volcano-sedimentary rocks exposed in tectonic windows within the Scandinavian Caledonides in western Finnmark, North Norway. The most significant of these is the Nussir deposit in the Repparfjord Tectonic Window (RTW) with indicated and inferred resources of 66 Mt of copper ore with average grade of 1.15 % Cu and payable amounts of silver and gold (Nussir ASA, 2015; JORC estimates). Ulveryggen is another major deposit within the RTW with total resources of 7.7 Mt grading ca. 0.8 % Cu. About 3 Mt of ore with an average grade of 0.66 % Cu were mined in the period 1972–1979 from four open pits in this deposit. Nussir ASA is planning to start operating both deposits. Minor, but widespread sediment-hosted copper occurrences and mineralisations are known in neighbouring tectonic windows. Small-scale mines have been opened in several of these mineralisations, e.g. the Raipas deposit in Alta, in the late 19th century (Vokes, 1955; Vik, 1986). All of these sediment-hosted Cu-deposits are characterized by a bornite+chalcopyrite+chalcocite (±neodigenite) ore mineral paragenesis and a noticeable lack of pyrite. They exhibit textural features indicative of syn-diagenetic and epigenetic mineral precipitation and localized structural reworking. They are commonly enriched in Ag and locally have elevated Au, PGE and Co contents (Sandstad et al., 2012).

The Repparfjord Tectonic Window comprises an 8 km thick sequence of Early Palaeoproterozoic volcano-sedimentary rocks (Pharaoh et al., 1983; Torgersen 2015). The sediment-hosted copper deposits are located in the nearly 3 km thick Saltvatn Group (Figure 6) - a sequence of clastic metasediments deformed and metamorphosed at greenschist facies conditions during the Palaeoproterozoic Svecofennian Orogeny. Coarse-grained arkosic sandstones and

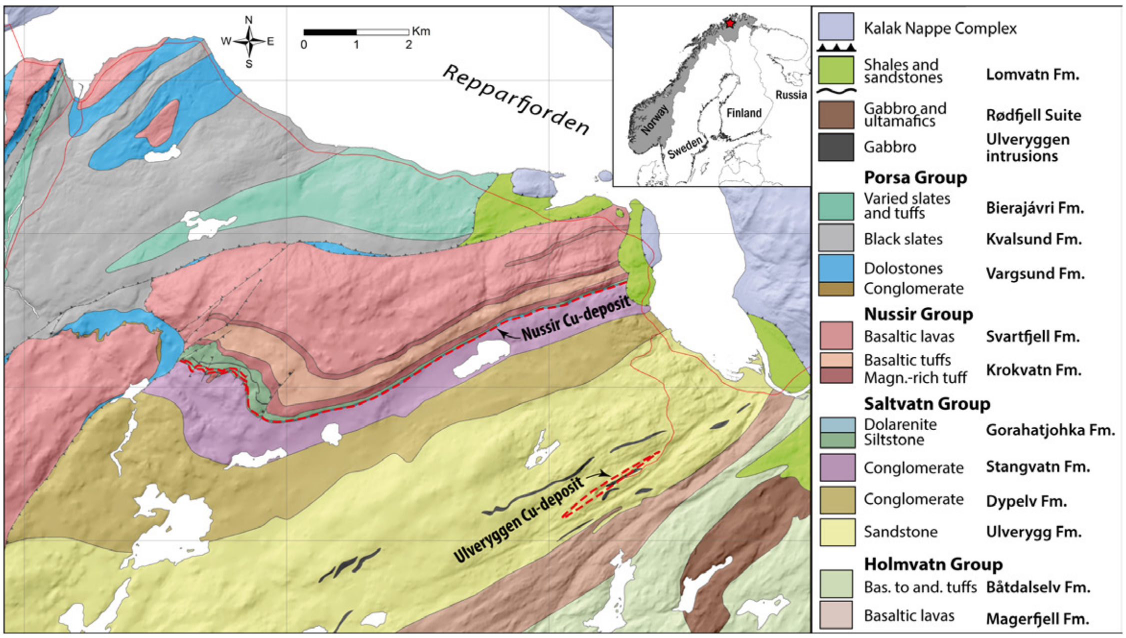

Figure 6. Geological map of the northern part of the Repparfjord Tectonic Window with the Ulveryggen (Repparfjord) and Nussir Cu-deposits marked.

Figure 7. Copper mineralised partly sheared metasandstone at the Ulveryggen copper deposit.

quartz-pebble conglomerates, interpreted as braided river deposits, are the stratigraphically lowermost exposed rocks of this group and host the Ulveryggen Cu-deposit. The sandstone coarsens upward into green polymict conglomerates and purple volcaniclastic conglomerates, interpreted as alluvial fan deposits. The Nussir Cu-deposit is hosted by 3-5 m thick argillic dolostone and dolarenite situated within grey-purple siltstones conformably overlying the conglomerates. The sedimentary rocks are assumed to have been deposited within a rapidly subsiding basin, possibly a fault-controlled half-graben in a continental arc/back-arc setting (Torgersen, 2015).

The sedimentary sequence is conformably overlain by tholeiitic basaltic tuffs, tuffites and lavas of the Nussir Group. U–Pb dating of zircons from a mafic tuffite at the base of the Nussir Group has yielded a maximum formation age of 2073 $^{+23}/_{-12}$ Ma (Perelló et al., 2015). A minimum age of 2069 ± 14 Ma is provided by Re–Os dating of sulphides in carbonate veins cutting the Nussir metabasalts (Torgersen et al. 2015).

Structurally, the Saltvatn Group comprises an open, km-scale NE-SW trending anticline with the Nussir Group metavolcanic rocks on its north-western limb. The metamorphic grade is up to upper greenschist facies in the northwestern part of the RTW and has been dated by K-Ar on amphibole, yielding a Svecofennian age of ca. 1840 Ma (Pharaoh et al., 1982). The area is also affected by later southeast-directed thrusting during the Silurian Caledonian Orogeny (Torgersen & Viola, 2014).

The **Ulveryggen** deposit is situated in coarse-grained quartzitic to feldspathic sandstone and conglomerate (Figure 7) and consists of several saucer-shaped ore bodies that are ≤ 130 m wide and at least 250 m deep, and are discordant to the bedding over a length of c. 2 km (Figure 6). On a local scale, Cu-minerals occur disseminated along bedding as matrix between clastic grains and replacement of detrital feldspar and mica, as well as in quartz veinlets and along cracks. The highest copper grades seem to be confined to a more strongly sheared part of the sequence (Sandstad et al., 2007).

The **Nussir** deposit is located in the upper part of the Saltvatn Group that comprises interbedded grey-purple siltstone and sandstone with three, 3-5 m thick beds of argillitic dolostone, dolarenite and dolostone (Figure 8a). The two lower beds are Cu-mineralised and located in the lowermost 10s of meters of the sequence. Only the upper of these beds extends along the entire exposed length of the sequence (c. 9 km). The Cu-mineralised beds are mainly composed of white to light gray, fine-grained,

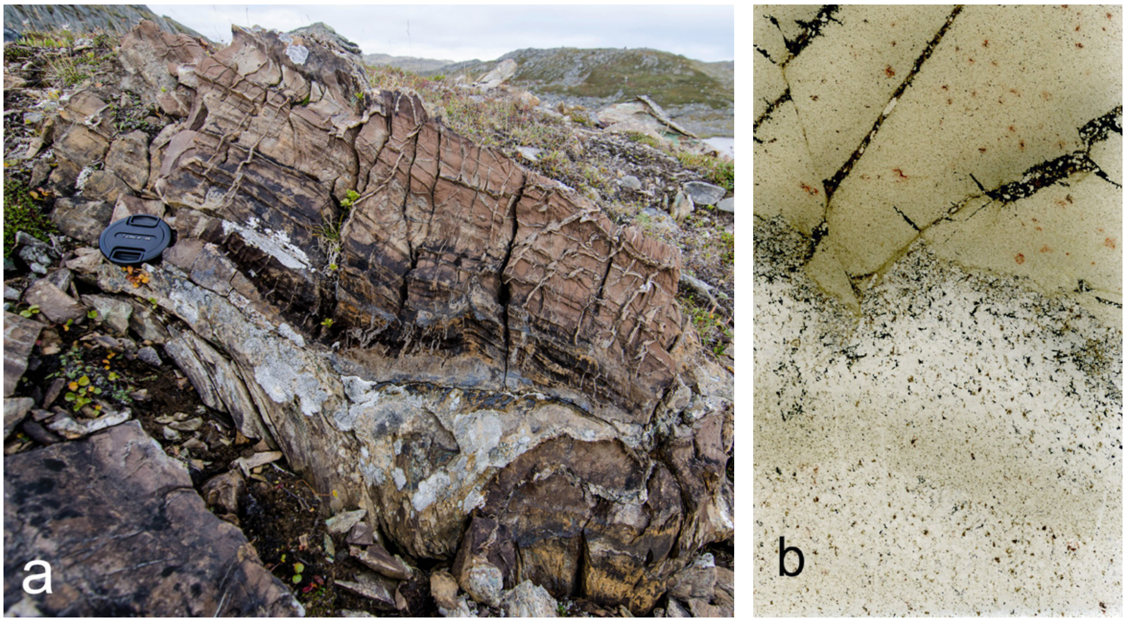

Figure 8. Nussir Cu-deposit. a): Cu-mineralised finely laminated and well bedded dolarenites above strongly foliated argillitic dolostones. b): Scanned image of thin section showing Cu-sulphides, both disseminated and in thin (dark-coloured) veinlets in dolarenite (width of image 18mm).

massive to bedded (<5 cm) dolarenites (Figure 8a). The contacts with the adjacent siltstones are transitional over 1–3 meters and consist of strongly foliated, dark gray, sericite-rich dolostones (Torgersen et al., 2015). The ore minerals, mainly bornite, chalcocite and chalcopyrite (± neodigenite) occur finely dissiminated and commonly comprise interstitial grains and aggregates forming the matrix in the dolarenite, but are also found enriched in irregular quartz-rich veinlets and lenses (Figure 8b). The common grain size, 0.1 - 1 mm, varies according to the size of the clastic grains. Accessory sulphide minerals include covellite, wittichenite, carrolite, pyrite, sphalerite, galena and molybdenite (Sandstad, 2010; Perello et al., 2015). Au and Ag correlate well with copper whereas the distribution of PGE mineralisation deviates in relation to the main copper ore. Platinum minerals occur mainly as microscopic grains of sperrylite, both as clusters of inclusions in bornite and as dissemination in the gangue matrix (Sandstad 2010).

The formation of the sediment-hosted copper mineralisations in the RTW is not fully understood. They resemble the classical sediment-hosted Cu-deposits of the Central-African Copperbelt and Kupferschiefer in terms of host rocks, textures and mineralogy. The tectonic setting, however, differs as an active plate margin is more likely for formation of the rocks of the RTW than the intracontinental rifting setting commonly advocated for sediment-hosted Cu-deposits elsewhere. Perello et al. (2015) argue for a structurally controlled, synorogenic formation of the Cu-deposits in the RTW based on Re-Os dating of molybdenite (model ages 1761±8 Ma and 1768±4 Ma) associated the Cu-mineralisation. Although re-mobilisation during deformation of the host rock is recorded, the major Cu sulphides more commonly comprise interstitial grains and aggregates in the dolarenite matrix. This suggests an initial diagenetic formation of the major copper mineralisation.

THE RANA IRON DEPOSITS

Terje Bjerkgård

Rana iron ores

The stratiform, banded iron ores in the Dunderlandsdal valley N of the town Mo i Rana occur in a strongly deformed unit, the Dunderland formation, comprising various schist and carbonate units with subordinate amphibolites of intrusive origin (Figure 9). This formation belongs to the Ørtfjell Group in the Ramnåli Nappe, which is part of the Uppermost Allochton of the Norwegian Caledonides (Søvegjarto et al., 1988, 1989; Gjelle et al., 1991, Marker et al., 2012). The sequence hosting the iron ores extends from Mosjøen in the south almost to Tromsø in the north, and is thought to have been deposited in Middle Cryogenic times, (730-800 Ma, Melezhik et al., 2014, 2015). There are several ore deposits in the northern part of the area, but none of these are economic at present.

Due to complex folding, the stratigraphy of the Dunderland formation is very uncertain. The main host-rock lithologies comprise different types of amphibolite-facies mica schists grading into calcareous schists or quartz–garnet–mica schists (Figure 9). The schists contain abundant units of dolomite and calcite marble that occur commonly in close proximity to the iron ores (Figure 10). The contact of the ores with the host rocks can be tectonic or conformable. The conformable contacts are characterised by a thin interval of carbonate-mica schist, which is commonly rich in Mn-carbonates and Mn-silicates. The iron ore shows a conformable contact with a diamictite unit in the mine area at Ørtfjellet-Kvannvatnet (Figure 11) in the western part of the Dunderland antiform. The diamictite consists of unevenly distributed, unsorted fragments mainly of fine-grained dolostones suspended in a massive, calcareous, mica-rich schist matrix. Clast sizes range from a few millimetres to a few centimetres and, rarely, up to nearly 1 m.

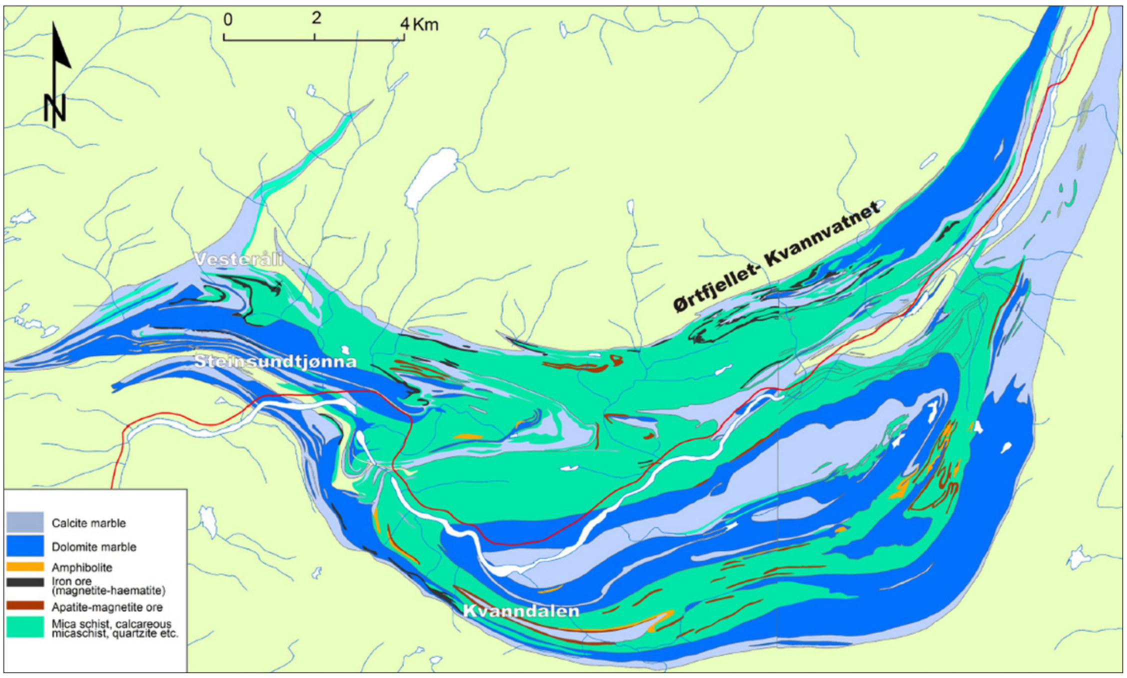

Figure 9. Geology of the iron ore-bearing Dunderland Formation. The names of the main iron deposit areas are shown (modified from Melezhik et al., 2015).

Figure10. The Kvannevann open pit (looking east), showing the ore and surrounding lithologies.

The iron ores occur, in general, as a series of tectonically dismembered and densely spaced segments, rarely exceeding 4 km in length (Figure 9). They occur both as linear units up to 30 m thick and as detached isoclinal folds with ore horizons doubled to tripled in thickness in the hinge zones. The ores are generally fine-grained (<1 mm) and show a banded distribution of Fe-oxides in a carbonate-bearing quartzitic to pelitic matrix (Bugge, 1948).

The ores can, in accordance with their contents of Fe, Mn and P, be separated into a number of sub-types. The two most important ores include low- and high- phosphorus ores. The former, containing 0.4–0.9 wt.% P_2O_5, is generally the most iron-rich type and comprises both specularitic haematite ores and magnetite ores that commonly constitute separate zones in the individual ore bodies. Where haematite is dominant, the gangue minerals are quartz, calcite, epidote and biotite, and where magnetite is dominant, the gangue minerals are quartz, calcite, biotite, hornblende and grunerite (Bugge 1978b). Bands of pyrrhotite up to 1 m thick are present at the margins of the ore zones, whereas minor amounts of pyrite are present in most ore types. The magnetite/haematite weight ratio of the ores currently being mined at Ørtfjellet-Kvannvatnet area is about 1:7 (Anders Bergvik, personal communication, 2014).

The second major type of iron formation is high-P magnetite (Fe–P) ore, which contains > 0.9 wt. % P_2O_5, and < 0.2 wt. % MnO. The Fe–P ore horizons are hosted, almost invariably, by calcareous mica schists, which commonly contain hornblende as an important mafic mineral. Although currently available geological information does not suggest any obvious stratigraphic separation between the different ore types, the lithostratigraphic relationships of the different segments of Fe, Fe–Mn and Fe–P iron ores in the Rana region indicate deposition at several closely spaced levels in the original stratigraphy (Melezhik et al., 2015).

The **Ørtfjell** deposit, by far the largest in the district, includes the Kvannevann mine, which currently produces ca. 2.1 Mt/a. Mining at the present level (Figure 12) will allow production until 2023.

Figure 11. Outcrop of diamictite close to the main Ørtfjellet-Kvannevann deposits

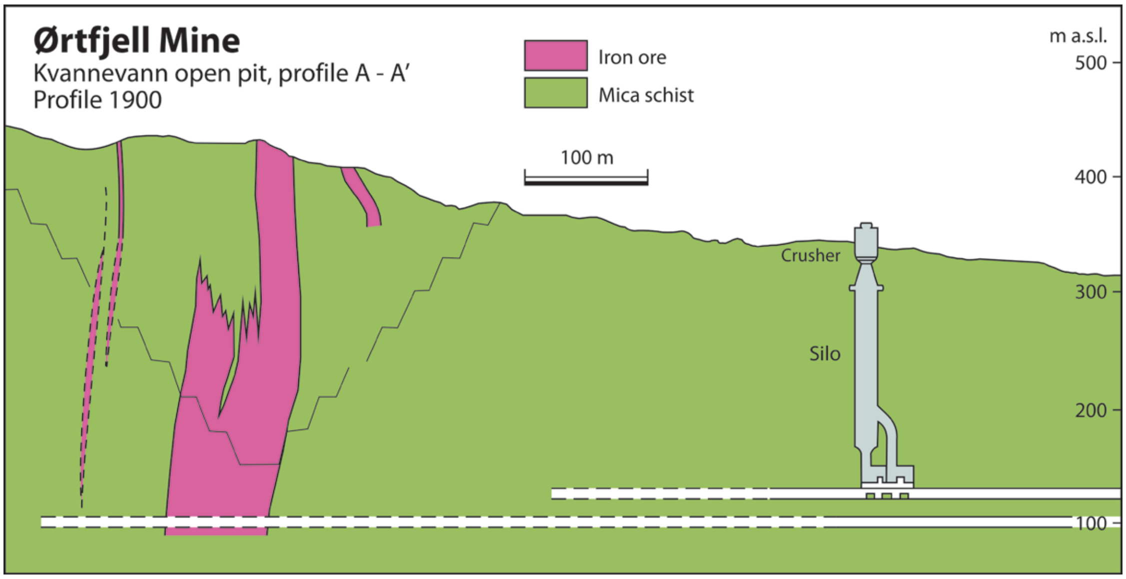

Figure 12. Cross section of the Kvannevann ore body (Rana Gruber, 2015).

THE LØKKEN VOLCANOGENIC COPPER-ZINC DEPOSIT

Terje Bjerkgård

The ophiolite sequence at Løkken has been proved to be a fragment of a supra-subduction-zone (SSZ) ophiolite (Grenne, 1989a). It is a 1–2 km thick volcanic sequence composed of a sheeted dyke complex overlain by three volcanic members (op.cit.). The volcanic rocks comprise N-MORB to IAT basalts with lesser units of hyaloclastites, jasper beds, rhyolitic effusives and iron formations including sulphide, oxide and silicate layers (known as "vasskis") (Grenne, 1989a). The ophiolite unit hosts the significant *Løkken* VMS deposit.

The **Løkken** Cu-Zn deposit was the largest ophiolite-hosted VMS deposit (i.e. Cyprus- type) in the world (Grenne, 1986, Grenne et al., 1999). It contained an original tonnage of about 30 Mt grading 2.3 % Cu, 1.8 % Zn, 0.02 % Pb, 16 g/t Ag and 0.2 g/t Au. About 24 Mt of the ore was mined in a period of 333 years (1654–1987): 6–7 Mt is still left in pillars and walls in the mine.

The massive sulphide ore consists predominantly of pyrite with subordinate chalcopyrite and sphalerite, whereas galena, magnetite, haematite and bornite are minor components locally and fahlore is the most important accessory phase (Grenne, 1989b). Quartz is the main non-sulphide, constituting 12–14 % of the ore.

Due to deformation, the ore body is tectonically disrupted into one major and several smaller bodies (Figure 13). The total length of the ore body is ca. 4 km, its average width is 150–200 m and its thickness ca. 50 m. This morphology can be ascribed to primary features such as subparallel faults at the seafloor, and an extensive, fissure-related hydrothermal vent system (Grenne & Vokes, 1990). An extensive feeder-zone system, found along the entire length of the deposit, is associated with the massive ore body (Grenne, 1989b; Figure 14). This system comprises a network of sulphide veins, from mm to some 10 cm

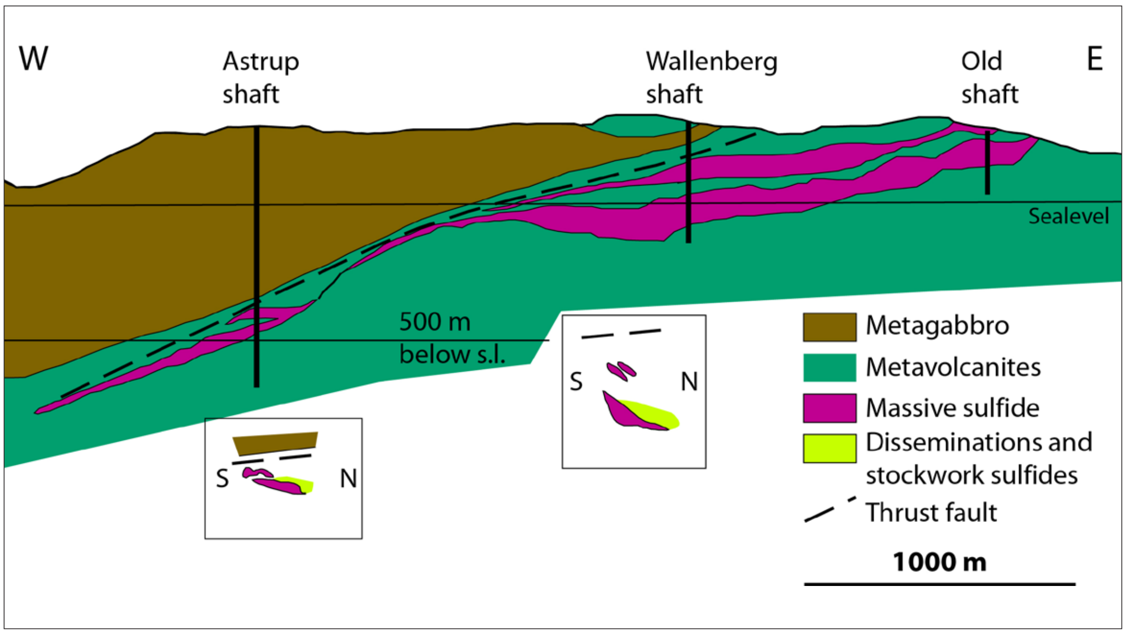

Figure 13. Vertical longitudinal (east-west) and cross sections of the Løkken massive sulphide deposit (modified from Grenne et al., 1980).

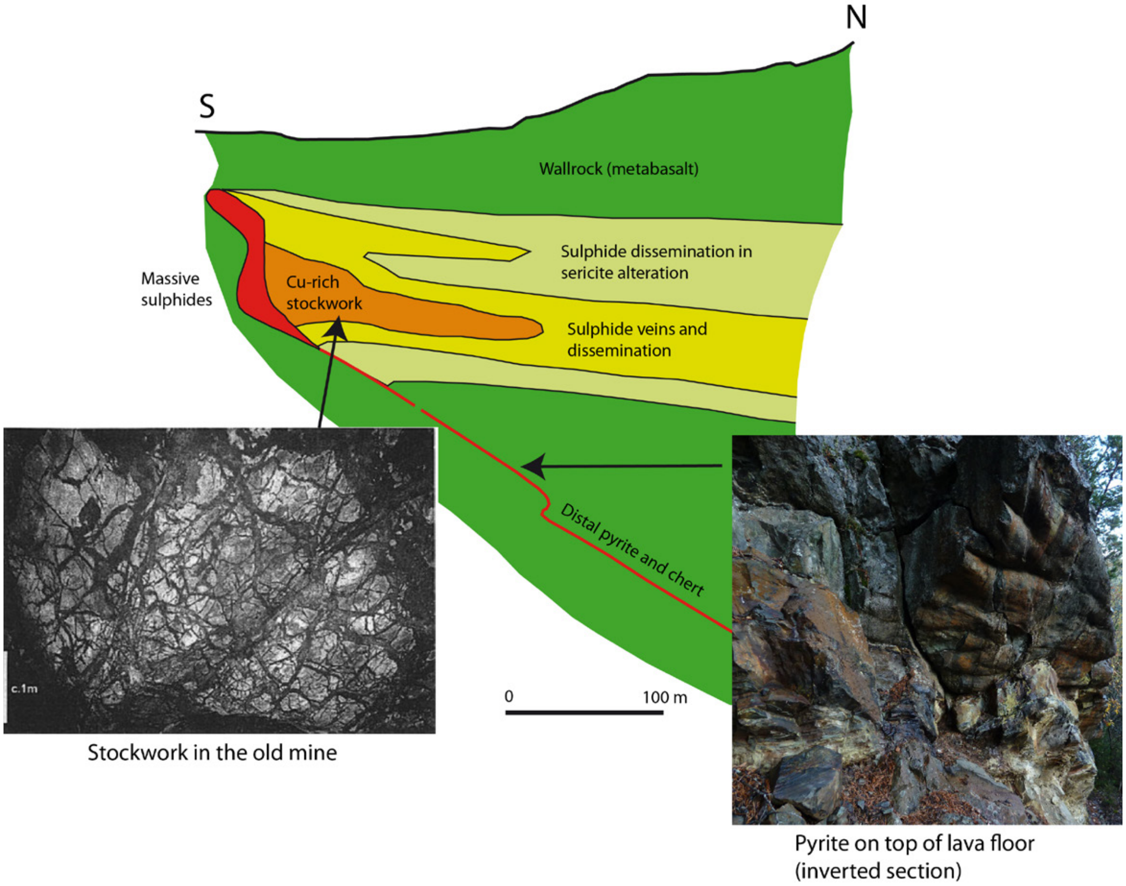

Figure 14. Schematic profile from the eastern part of the Løkken deposit (modified from Grenne, 1989b).

thick. The feeder zone has pyrite, chalcopyrite and quartz as its main constituents, and accessory amounts of sphalerite, magnetite and iron oxides. The total width of the zone is about 100 m. This part of the deposit was, because of its high Cu-content, the first to be mined at Løkken.

The Støren Group, E of Løkken, comprises a several km thick volcanic sequence mainly consisting of metabasalts (greenstones) of submarine origin (Grenne et al., 1999). Ribbon cherts, black shales and tuffitic to cherty metasediments are interlayered with the volcanic rocks. Geochemical data from the metabasalts mainly show MORB- but also WPB affinities (Gale & Roberts, 1974; Grenne & Lagerblad, 1985). Rhyolitic volcanic rocks are locally abundant in the northern part of the Trondheim Region, including a subvolcanic felsic intrusion dated to 495 ± 3 Ma (Roberts & Tucker, 1998). The Løkken and Støren units may be connected: the Løkken unit may, for example, have formed during subduction of parts of the Støren volcanics (the supra-subduction zone). The Støren unit contains the 19 Mt Tverrfjellet VMS deposit, which was closed in 1993 after production of 15 Mt of ore averaging 1.0 % Cu, 1.2 % Zn, 0.2 % Pb and 36 % sulphur. The deposit also contained ca. 4% magnetite, 10 g/t Ag and 0.1 g/t Au.

THE ENGEBØ ECLOGITE-HOSTED RUTILE DEPOSIT

Are Korneliussen

The Engebø rutile deposit (Figure 15) is a 2.5 km long and up to 0.5 km wide E-W trending body of rutile-bearing eclogite on the northern side of Førdefjord in the Sunnfjord region of West Norway. Two types of titanium deposit occur in the region (Korneliussen et al., 2000): magmatic ilmenite-magnetite deposits associated with Mesoproterozoic mafic intrusions, and rutile-bearing Caledonian eclogitic rocks. The rutile-bearing eclogites are mafic intrusions that were transformed into eclogites during Caledonian high-pressure metamorphism at ca. 400 Ma, during the Scandian continent-continent collision stage in the orogeny (see Cuthbert et al., 2000 for an in-depth overview of eclogites in Western Norway). During the eclogitisation process, ilmenite in the protolith broke down, with the Fe entering into garnet and Ti into rutile. Hence, large volumes of ilmenite-bearing mafic rock were transformed into rutile-bearing eclogite. Other eclogite bodies in the Sunnfjord region (e.g. Orkheia) are also known to have significant contents of rutile (Korneliussen et al., 2000; Korneliussen, 2012).

The Engebø deposit is situated in a large E-W trending antiform, and has experienced a complex structural reworking and metamorphic evolution associated with high-pressure eclogite facies metamorphism and subsequent retrograde alteration at amphibolite and greenschist facies conditions (Braathen & Erambert, 2014). The deposit wedges out upwards to the east but continues at depth westwards. The main volume of rutile-rich rocks is at depth in the central and western parts of the deposit. The highest part of the deposit reaches 320 m a.s.l., just east of the profile A-A´ in Figure 15 and it continues at least to 150 m below sea level in the western parts. Ore-type eclogite contains more than 3 wt % TiO_2 and the low-Ti eclogite < 3 wt % TiO_2, with large variations locally.

The major minerals in ore-type eclogite (Figure 16) are garnet (30-40 wt.%), clinopyroxene (omphacite; 30-40 wt.%) and amphibole (barroisite; 5-10 wt.%), whereas the most characteristic minor minerals are rutile, quartz, white mica (phengite) and pyrite; see Kleppe (2013) for detailed

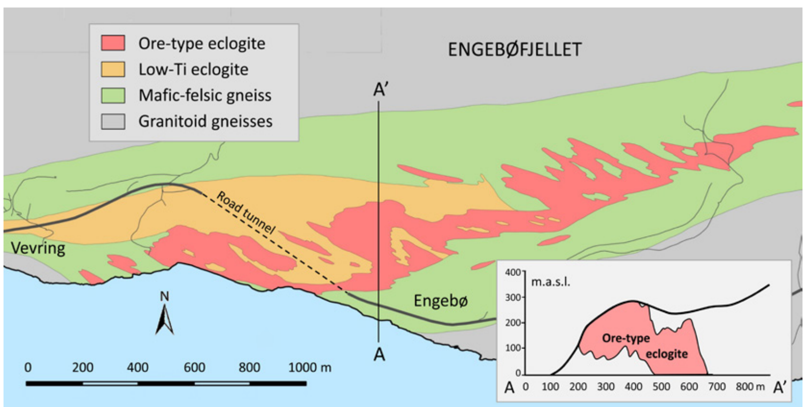

Figure 15. Simplified geological map of the Engebø rutile deposit, modified from Korneliussen (2012; originally based on Korneliussen et al., 1998).

mineralogical information. More than 90 % of the titanium is situated in rutile, as indicated by the majority of samples in Figure 17, plotting close to the TiO_2-rutile 1/1-line. Retrograde alteration tends to alter rutile to ilmenite and occasionally to titanite, and in the TiO_2-rutile diagram such samples tend to plot below the 1/1-line.

There is a continuous variation in TiO_2 content from less than 0.5 wt.% to 5 wt.% (locally higher) as shown in Figure 17. For practical reasons the geological mapping of the deposit (Korneliussen et al. 1998) was based on TiO_2-content by distinguishing low-Ti eclogite with less than 3 % TiO_2 from high-Ti (ore-type) eclogite with more than 3 % TiO_2.

Although rutile-bearing eclogite rocks have been known in the Førdefjord area for a long time, geologist Hans-Peter Geis from the company Elkem was probably the first who realized the economic potential for rutile at Engebø (in 1973). In the following years Engebøfjellet was studied on a reconnaissance basis by NGU as well as by various companies. In 1995-97 an extensive project was carried out by the American titanium pigment producer DuPont and the petroleum company Conoco, at that time a DuPont subsidiary (now ConocoPhillips), in collaboration with NGU. Based on 49 drillholes (total 14,527 m) the company identified an ore resource at 380 Mt with 2.5-4.5 % rutile, sufficient to provide a fairly large amount of rutile concentrate (200.000 t/a) to the company's downstream titanium pigment plants. The deposit was regarded to be mineable as an open-pit operation with mine waste deposition into the fjord nearby. The company, however, closed the project at the end of 1997.

In 2006 the Norwegian company Nordic Mining acquired the mineral rights to the prospect and continued its development. In agreement with the local community a compromise was developed to minimize the environmental impact, involving a two-stage mining operation: The ore is first to be mined from an open pit in the central part of the deposit, and thereafter underground. With this alternative, the resource estimate is 150 Mt of mineable rutile ore, which is much less than the DuPont estimate due to the different mining scenarios. Nordic Mining succeeded, in 2015, in achieving a permit for deposition of mineral waste at 300 m depth in the nearby

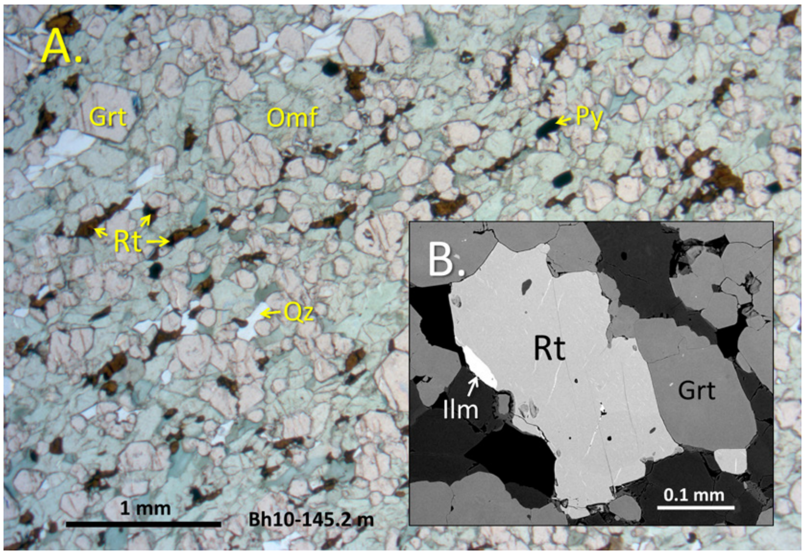

Figure 16. Microphotograph of rutile-rich ore-type eclogite (A) with a SEM back-scattered electron image.
(B) Rt - rutile, Grt - garnet, Omf – omphacite, Amf – amphibole, Qz – quartz, Py – pyrite.

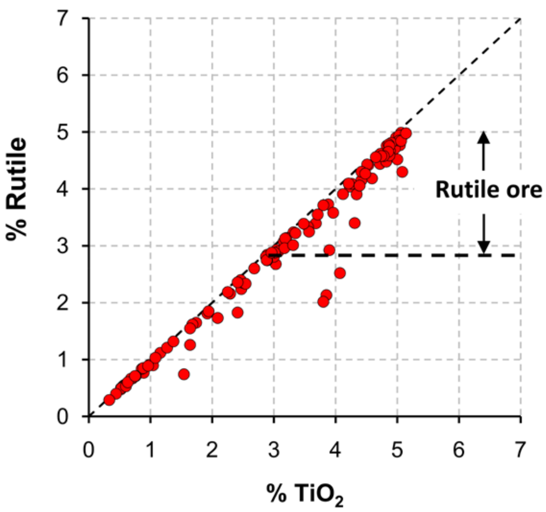

Figure 17. Wt. % TiO_2 vs. wt. % rutile based on analyses of predominantly 10 m cored ore sections (Korneliussen et al. 1998). The indicated range for rutile ore (ore-type eclogite) is in accordance with the geological map in Figure 15.

Førdefjord. The deposit is now being developed further, and an annual production of 80,000 t of rutile concentrate based on the mining of 4 Mt rutile ore is expected to be a reality by 2019-2020.

The Engebø project is the first in the world to be based on extraction of rutile from hard rock such as eclogite. The main challenges relate to CaO-contamination of the rutile concentrate relative to quality criteria set by the TiO_2-pigment industry (Korneliussen et al., 2000).

THE NORDLI MOLYBDENUM DEPOSIT

Peter M. Ihlen

The Permo-Carboniferous Oslo Palaeorift comprises two half grabens containing sedimentary rocks of Cambro-Silurian age, deformed during the Caledonian Orogeny and subsequently overlain by volcanites and truncated by numerous granitic batholith massifs. The volcanites comprise early fissure eruptives of tholeiitic and alkali basaltic composition overlain by thick sequences of trachy-andesitic rhomb porphyry lavas, which gave way to the development of central volcanoes with late-stage cauldron formation. The igneous activity ended in the Permo-Triassic with the emplacement of numerous batholiths dominated by monzonites, syenites and granites (Ihlen, 2012). The metallogeny of the rift is correspondingly varied (Ihlen, 1986), the most important types of deposits being:

- Polymetallic vein deposits along the western margin of the southern half-graben. The most important of these are the calcite veins with native silver and cobalt arsenides cross-cutting Mesoproterozoic sulphidic paragneisses at the town of Kongsberg.
- Skarn deposits of Fe, Cu, Bi, Zn, Pb, Mo and/or W at the contacts of granite intrusions with Cambro-Silurian calcareous units (marbles).
- Special-metal deposits of Nb, REE and Zr found in aphyric trachyte flows, such as that at Sæteråsen in the Vestfold Lava Plateau, in the southern half-graben. These may be of economic interest.

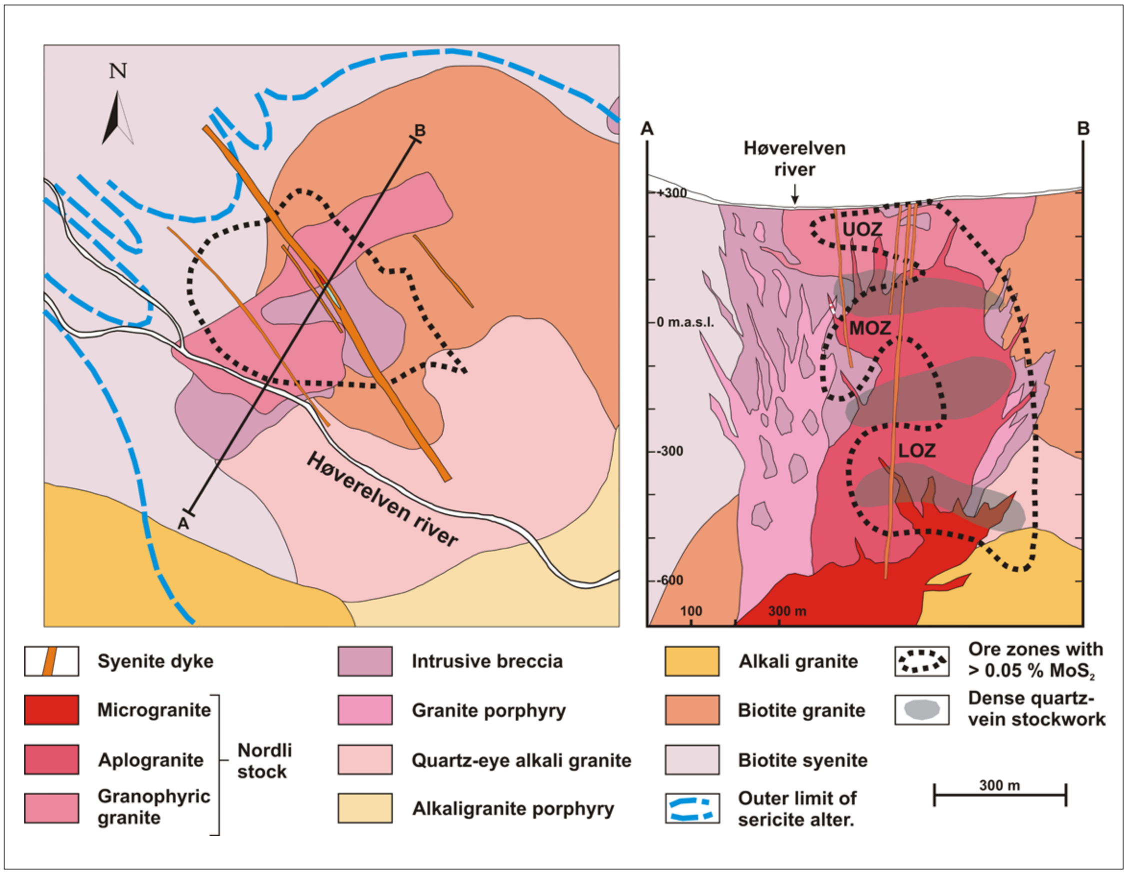

Figure 18 (from Ihlen, 2012). Geology of the Nordli deposit at the surface and in cross section. Abbreviations: UOZ = Upper Ore Zone, MOZ = Middle Ore Zone, LOZ = Lower Ore Zone.

- Apatite-ilmenomagnetite mineralizations occur in most of the monzonitic intrusions inside the Rift. The most important deposits are in the larvikite massif at Kodal in the southernmost part of the exposed plutonic rocks in the Rift.
- Porphyry Mo deposits are the most important type of deposit in economic terms. They are associated with central granite stocks in a number of cauldrons throughout the province, and include the Nordli deposit in the Hurdal Batholith of the northern half-graben.

Comprehensive overviews of the metallogeny of the Oslo Rift can be found in Ihlen & Vokes (1978), Olerud & Ihlen (1986) and in Bjørlykke, Ihlen & Olerud (1990).

The Hurdal batholith, located in the northernmost part of the Rift, and its contact zones contain a range of types of molybdenum mineralizations (Ihlen, 2012), but by far the most important is the Nordli deposit, a stockwork porphyry mineralization discovered by Norsk Hydro in 1978 and intensively explored up to 1983.

A drilling programme led to definition of a tonnage of 200 Mt grading 0.14 % MoS_2 (cut-off 0.05 % MoS_2), which is thought to be the largest Mo deposit in Europe. Further drilling, carried out by Intex in 2006-2008, led to a minor adjustment of the reserve estimate to 210 Mt grading 0.13 % MoS2 (cut-off 0.07 % MoS_2) (Intex Resources, 2015). Intex Resources has an exploitation licence valid to 2018, which confers exclusive rights to development of a mining operation, subject to other statutory requirements.

The deposit formed in the root zone of a deeply eroded and nested system of calderas in the northern part of the Hurdal batholith (Ihlen, 2012). The molybdenite stockworks are related to the emplacement and crystallisation of the composite Nordli alkali-granite stock, which postdates the major caldera-forming processes and which represents the final derivates of a large alkali granite pluton in the area (Pedersen, 1986) (Figure 18). The ore zones form discs 150–250 m thick and 200-300 m across: they are stacked over a vertical distance of ca. 900 m. The zones were formed by the expulsion of molybdenum-bearing magmatic fluids generating hydraulic fractures in the apical parts of the host intrusions, which include early granophyric granite (top), intermediate aplogranite and late microgranite in the lower part of the Nordli stock.

GALLUJAVRI AND RAITEVARRI – POTENTIALLY LARGE DEPOSITS IN THE KARASJOK GREENSTONE BELT

Lars-Petter Nilsson, Peter M. Ihlen, Morten Often, Jon Are Skaar, Rognvald Boyd

The Palaeoproterozoic Karasjok Greenstone Belt (KGB, Figure 19) is a north-trending continuation of the Central Lapland Greenstone Belt (CLGB) in Finland, extending parallel to the Norwegian-Finnish border on the eastern part of the Finnmark plateau. The CLGB hosts important ore bodies of several types, including iron, gold, and copper-nickel (Pohjolainen, 2012; Eilu et al., 2012), some of which also occur on the Norwegian side of the border. The KGB extends across a plateau covered by Arctic tundra at levels of 200-600 m. a.s.l.: outcrop is sparse but the region attracted gold panners and prospecting companies in several periods in the 20th C. The two most important targets have been the Gallujavri Ni-Cu-PGE deposit and the Raitevarri Cu-Au deposit.

The **Gallujavri** ultramafic intrusion (Figure 20) is located 20 km NNW of the town of Karasjok and is hosted by easterly dipping psammitic rocks belonging to the Early Proterozoic Iddjajav'ri Group (Siedlecka et al., 1985; Siedlecka & Roberts, 1996). The intrusion is considered to be at least 500 m thick, striking approximately N-S with a length of at least 5 km. Much of the northwestern part of the intrusion lies under the lake, Gallu'javri, with most of the exposures along the eastern bank of the lake. The intrusion was studied successively by A/S Sydvaranger (1976-82), Tertiary Minerals plc (2002-2003), Anglo American (2006-2010) and Store Norske Gull (2011-2013): the claims are now held by Nussir ASA.

The earlier investigations included ground geophysics, geological mapping, geochemical sampling and shallow drilling. Eleven shallow holes have been drilled - 8 by Sydvaranger and 3 by Tertiary Minerals, the deepest to 180 m below the surface. Outcrop and core logs indicate that the intrusion is dominated by olivine-pyroxene cumulates, at least partially recrystallized at amphibolite facies. Nilsson and Often (2005) describe different models proposed for the distribution of ultramafic components and mineralization in the body, suggesting that the base of the intrusion coincide with its western contact. Outcrops show the presence of up to ca. 4 % disseminated sulphides with grades of up to 0.42 % Ni and 0.42 % Cu in four separate areas of mineralization, one of which is exposed along a strike length of 500 m. Recorded noble metals grades range up to 2.45 g/t Pt+Pd+Au. Available data thus suggest quite high metal-in-sulphide tenors. Ore petrographic studies have revealed the presence of pentlandite, pyrrhotite and chalcopyrite but not discrete platinum-group minerals (Hagen and Nilsson, unpublished data).

High-resolution aeromagnetic (and radiometric) data were acquired for the whole of Finnmark county in the period 2007-2014, partly by industry but mainly by the Geological Survey of Norway (NGU). The northern part of the Karasjok Greenstone Belt was mapped in 2011 for Airborne Gravity Gradient (the first area in Norway to be covered using this technology). The availability of high quality aeromagnetic and gravity data allowed creation of a 3D interpretation of the shape of major metavolcanic units and of Gallujavri and other intrusions in the area (Skaar, 2014). The interpretation indicates that the exposed part of the Gallujav'ri intrusion is

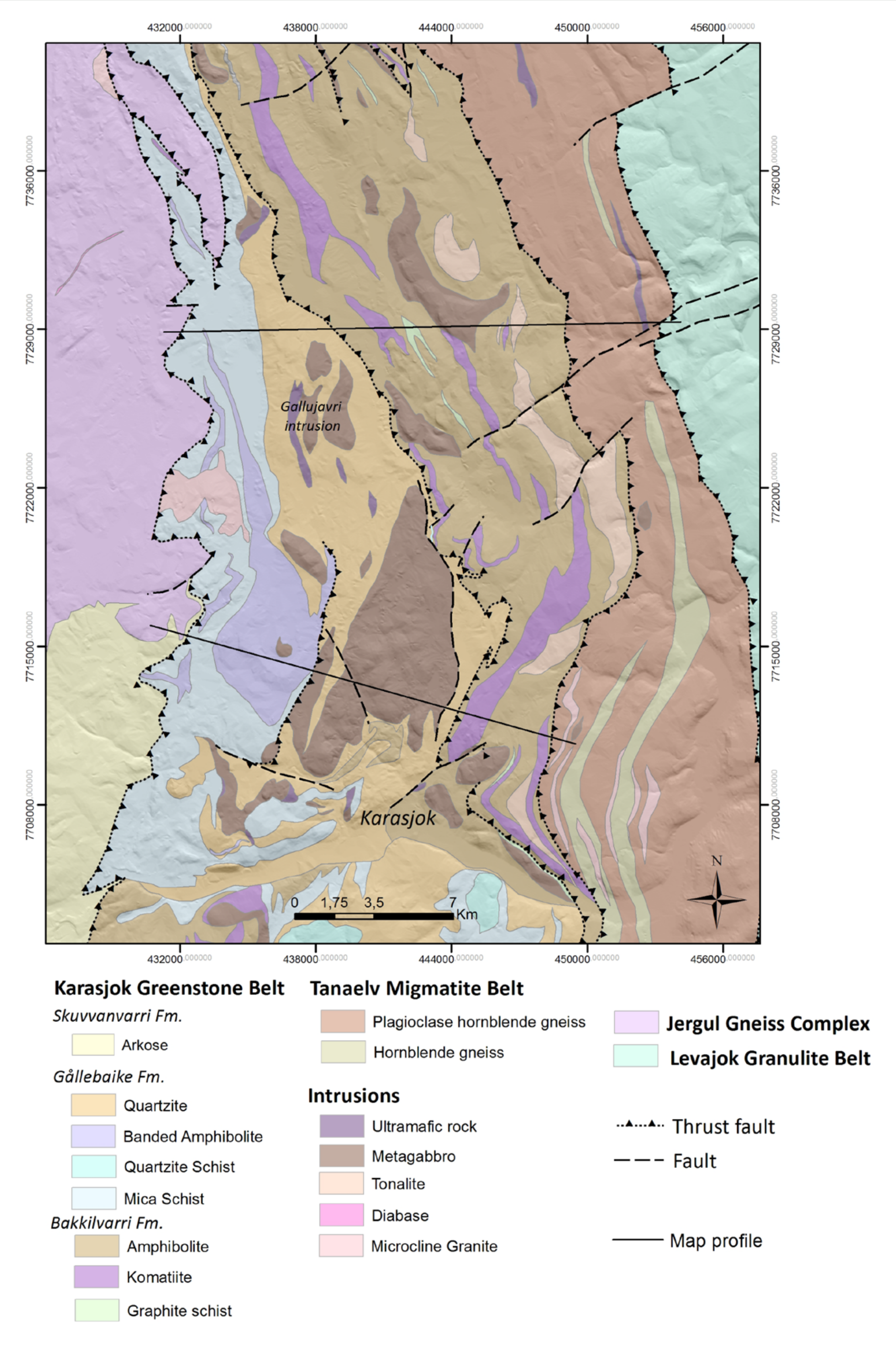

Figure 19. Geological map of part of the Karasjok Greenstone Belt (from Skaar 2014), based on Henriksen (1986) and Nilsen (1986). The Raitevarri deposit is just to the south of the map border.

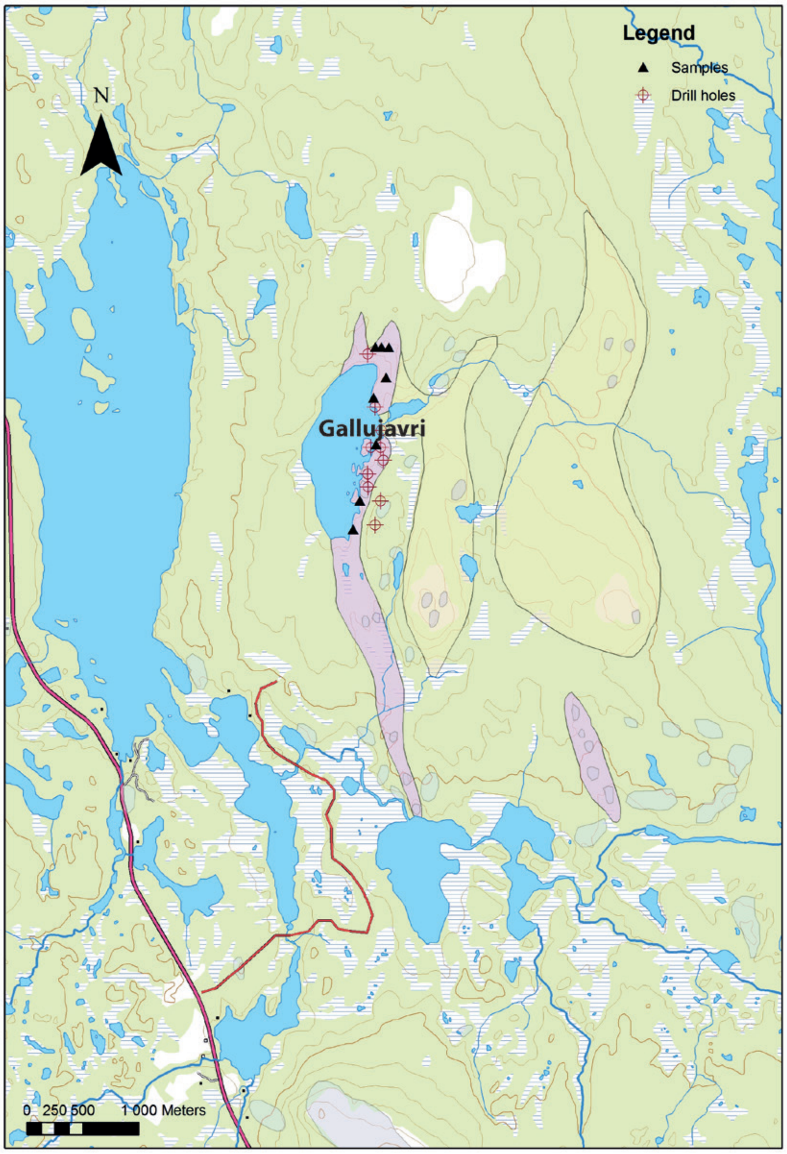

Figure 20. Sketch map of the surface expression of the Gallujavri intrusion (Nilsson & Often, 2005). Ultramafic intrusives are shown in pale purple and gabbroic bodies in pale brown: the country rock is metapsammite.

part of the northern extension of an intrusion which may be ca. 30 km long, plunging at a shallow angle to the SE where it reaches a depth of ca. 1 km.

The **Raitevarri** mineralization is hosted by a more than 25 km-long, sporadically exposed unit of quartz-hornblende-plagioclase-biotite gneiss (the Raitevarri Gneiss of Siedlecka & Roberts, 1996) approximately 30 km SW of the town of Karasjok. The gneiss unit contains widespread garnetiferous zones and sheets of irregularly formed amphibolites and garben-textured hornblendites, as well as biotite-chlorite-muscovite and quartz-kyanite-muscovite-pyrite schists. The latter schists are typical for areas showing ductile shearing. A/S Sydvaranger discovered the mineralization in 1969, and drilled 8 holes in the period up to 1976. ARCO (in the early 1980s) and RTZ have also held claims to the area, RTZ drilling 9 holes in 1994. The Geological Survey of Norway (NGU) carried out extensive geophysical, geochemical and geological investigations in the period 1988-90 (Dalsegg & Ihlen, 1991). The claims were held by Store Norske Gull from 2008-2014. The attraction for the prospecting industry has been the surface expression of the mineralization, said to be in the order of 10 km^2 (Ihlen, 2012b).

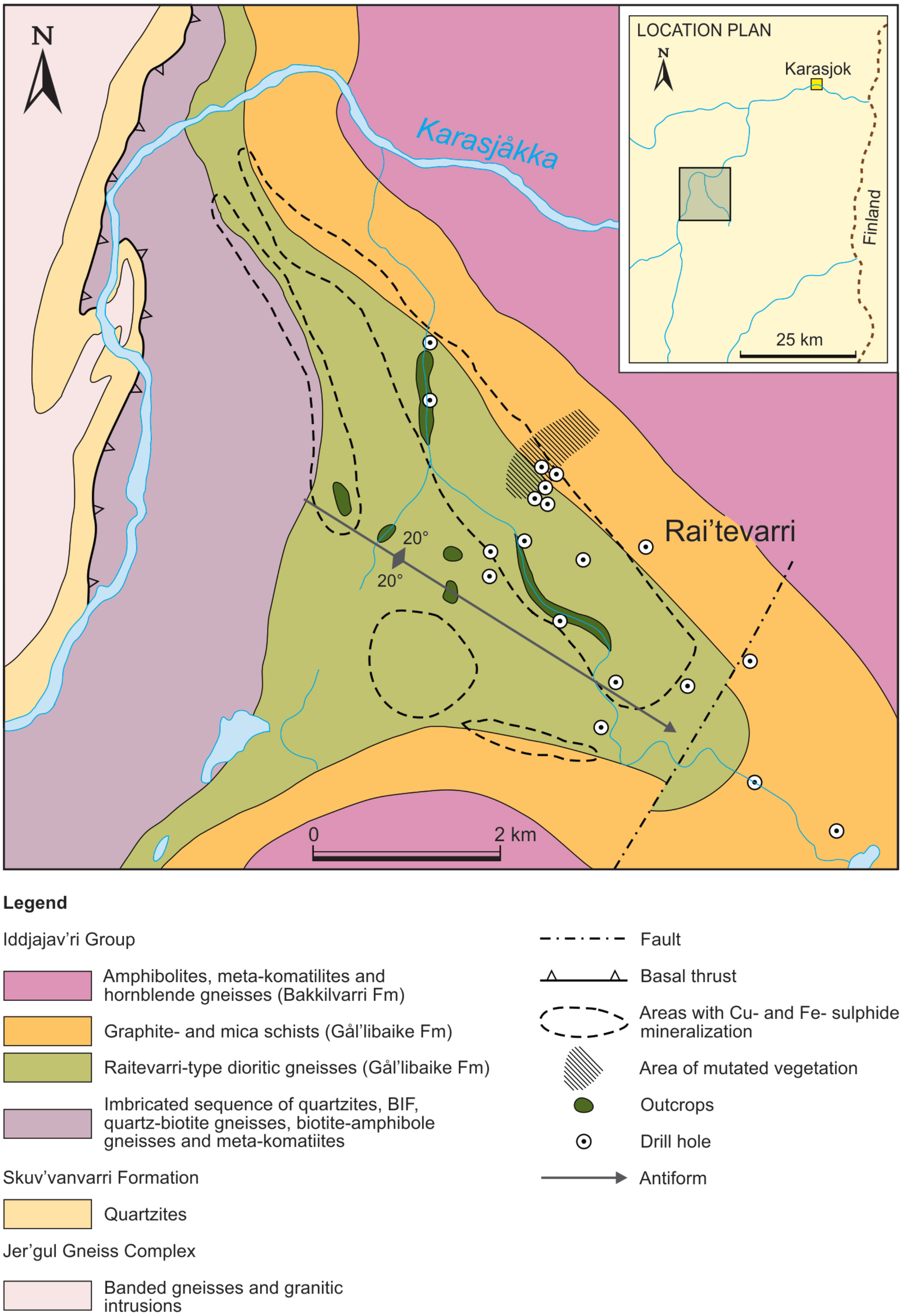

Figure 21. Map of the Raitevarri mineralisation and its environs (after Coppard, 1994).

The mineralisation is located in dioritic gneiss in the Gallibaike Formation, within an antiformal structure which plunges 10° – 20° to the SE (Figure 21). Dalsegg & Ihlen (1991) demonstrated that the mineralisation has three components:

- a generally weak dissemination of pyrrhotite, pyrite, chalcopyrite and/or sphalerite,
- foliation-parallel enrichment of the sulphides close to the northeastern flank of the complex and
- mineralisation along fault zones (revealed by IP measurements). At least part of the mineralisation is in contact with a unit of sulphidic graphite schist along the NE contact of the complex. 170 rock samples yielded maximum values of 0.9 g/t Au, 0.76 % Cu, and 0.24 % Zn.

The holes drilled by RTZ (Coppard, 1994) show great variation in content of sulphides: one hole contains an almost consistent sulphide content of 2–2.5 % from the bedrock surface down to a depth of 120 m. In certain cores the level is almost consistent at 0.5 % sulphide and in others the 0.5 % level includes sections up to 10 m thick with elevated sulphide contents (up to 4 %) (Coppard, 1994). The dominant sulphides are pyrrhotite, pyrite and chalcopyrite but the mineralization also includes a wide range of accessory and trace minerals including sphalerite, galena, molybdenite, native gold and lead and bismuth tellurides. Grades are stated to be low, invariably <0.8 % Cu in 1 m sections, with gold rarely exceeding 0.5 g/t (Coppard, 1994).

Store Norske Gull carried out an extensive programme of till sampling in 2009, and, in 2008-2009, a drilling programme of 28 holes totalling 3,443 m. The new data showed that the main mineralized zone had a NW-SE extent of 700 m and a width of 300 m: the drilling confirmed the relative continuity of this zone but also revealed the presence of a previously unknown mineralized body (Ojala, 2009; Jasberg et al. 2013). Eilu & Ojala (2011) suggest that the original mineralisation shows the following concentric pattern of geochemical zones from the core outwards: Au-Bi-Te, Cu(-Ag), Sn, Mo±As and Zn-Cd-Mo-Tl. They believe that the host gneiss is a metamorphosed calc-alkaline intrusive and that a range of factors indicate that the mineralisation formed as a porphyry-Cu-Au system. Ihlen et al. (1993) and Ihlen (2005), however, argue that the hornblende gneisses may represent deformed equivalents of sea-floor and sub-seafloor hydrothermally altered greenstones. The mineralisation is suggested to have formed both during the volcanic activity and during subsequent episodes of deformation (Braathen & Davidsen, 2000). This model gives a better explanation for both the location of the mineralised zones and the large strike length of the sheet-like body of hornblende gneisses.

THE GEOLOGY OF SVALBARD

Kerstin Saalmann

The Svalbard archipelago, located on the northwestern corner of the Barents Sea Shelf, was positioned north of Northeast Greenland prior to the Palaeogene opening of the Norwegian-Greenland Sea. It comprises rocks ranging in age from Proterozoic to Neogene, which can be broadly separated into pre-Devonian crystalline basement and post-Devonian cover rocks. The latter can be further subdivided into Devonian sedimentary rocks, Permo-Carboniferous sedimentary successions, Mesozoic sedimentary sequences and volcanic rocks, and Cenozoic sedimentary and volcanic rocks.

Pre-Devonian crystalline basement

The pre-Devonian crystalline rocks have traditionally been called the "Hecla Hoek" (Nordenskiöld, 1863). Modern geochronology has, however, shown that the basement units record a complex evolution comprising a number of tectono-thermal events, ranging in age from Late Archaean to Silurian, of which the Grenvillian/Sveconorwegian and particularly the Caledonian orogenies show the largest imprints (Peucat et al., 1989; Gee et al., 1995; Teben'kov et al., 2002; Johansson et al., 2005).

The Caledonian rocks have been divided, based on contrasts in pre-Devonian geological history, into different provinces separated by N-S to NNW-SSE-trending lineaments. It has been proposed that these tectonostratigraphic domains represent independent terranes that were amalgamated during the Caledonian orogeny (e.g. Harland 1969; Harland 1997; Gee and Page 1994). The definition of these provinces and the location of their boundaries are, however, debated. Harland (1997) distinguishes eastern, central and western terranes while others advocate eastern, northwestern and southwestern terranes (Gee and Page 1994; Gee and Teben'kov, 2004). Nordaustlandet, Ny Friesland, and northwestern Spitsbergen share a similar late-Mesoproterozoic to Caledonian evolution with units in East Greenland (Gee and Teben'kov, 2004; Johansson et al. 2005), whereas pre-Devonian rocks along the west coast of Spitsbergen, south of Kongsfjorden, record a different tectonothermal history (Gee and Teben'kov, 2004; Labrousse et al., 2008). Several units in the southwestern province, including the subduction zone-related Ordovician Vestgötabreen Complex at St. Jonsfjorden, have, on the basis of lithology, stratigraphy and tectonic evolution, been correlated with the Pearya Terrane in Arctic Canada (Ohta et al., 1989; Harland, 1997 and ref. therein; Gee and Teben'kov, 2004; Labrousse et al., 2008). This correlation has, however, been questioned by other authors (e.g. Petterson et al., 2010; Gasser and Andresen, 2013).

The pre-Caledonian position of the terranes, and the timing and mode of their juxtaposition, are debated, including the existence and importance of large-scale, strike-slip movements in the range of many hundreds of kilometres (e.g. Harland, 1969, 1997; Gee and Page, 1994; Gee and Teben'kov, 2004; Labrousse et al., 2008; Petterson et al., 2010; Gasser and Andresen, 2013).

Caledonian orogeny

The main collision between Laurentia and Baltica-Avalonia corresponds to the Scandian event (c. 440-400 Ma) for which there is clear evidence in Nordaustlandet and northwestern Spitsbergen (Harland, 1997; Johansson et al., 2005). Intrusion of late- to post-tectonic granites, e.g. the 414 Ma Hornemanntoppen granite in northwestern Spitsbergen (Hjelle 1979) and the 420-400 Ma cooling ages of comparable granite intrusions in the northwestern and northeastern tectonic provinces (Dallmeyer et al., 1990a) indicate the waning stages of Caledonian tectonism.

An earlier, Ordovician, tectono-metamorphic event (ca. 475 Ma) is recorded in the high-pressure rocks of the Vestgötabreen Complex of Motalafjella, S of St. Jonsfjorden (Dallmeyer et al., 1990b; Bernard-Griffiths et al., 1993) (Eidembreen event, Harland, 1997). Comparable rocks of the Richarddalen complex of Biskayahalvøya in NW Spitsbergen (Figure 22) overlap in time. These high-pressure metamorphic complexes are related to subduction- zone environments (i.a. Horsfield, 1972; Ohta et al., 1983; Hirajima et al., 1988; Agard et al., 2005): fragments of the complexes were later obducted during the main collisional event.

Devonian basin development and Svalbardian deformation

The Caledonian orogeny was followed by deposition of a thick succession of Late Silurian and Devonian, mainly continental sandstone and shale (Old Red Sandstone) (Friend, 1961; Friend et al. 1997). These deposits are preserved mainly in NW Spitsbergen (Figure 22); isolated outcrops are also found N of Kongsfjorden. Deposition took place in a tectonically active basin characterized by extensional block faulting (Manby and Lyberis, 1992; Piepjohn, 2000 and references therein) or sinistral strike-slip movements (Friend et al., 1997; McCann, 2000) and was interrupted by intervening episodes of shortening (McCann, 2000). Basin inversion led to west-directed folding and thrust faulting of the Old Red Sandstone succession and locally also involved slivers of the pre-Devonian basement (Piepjohn, 2000). This event, known as the Svalbardian deformation (Vogt, 1928), was generally thought

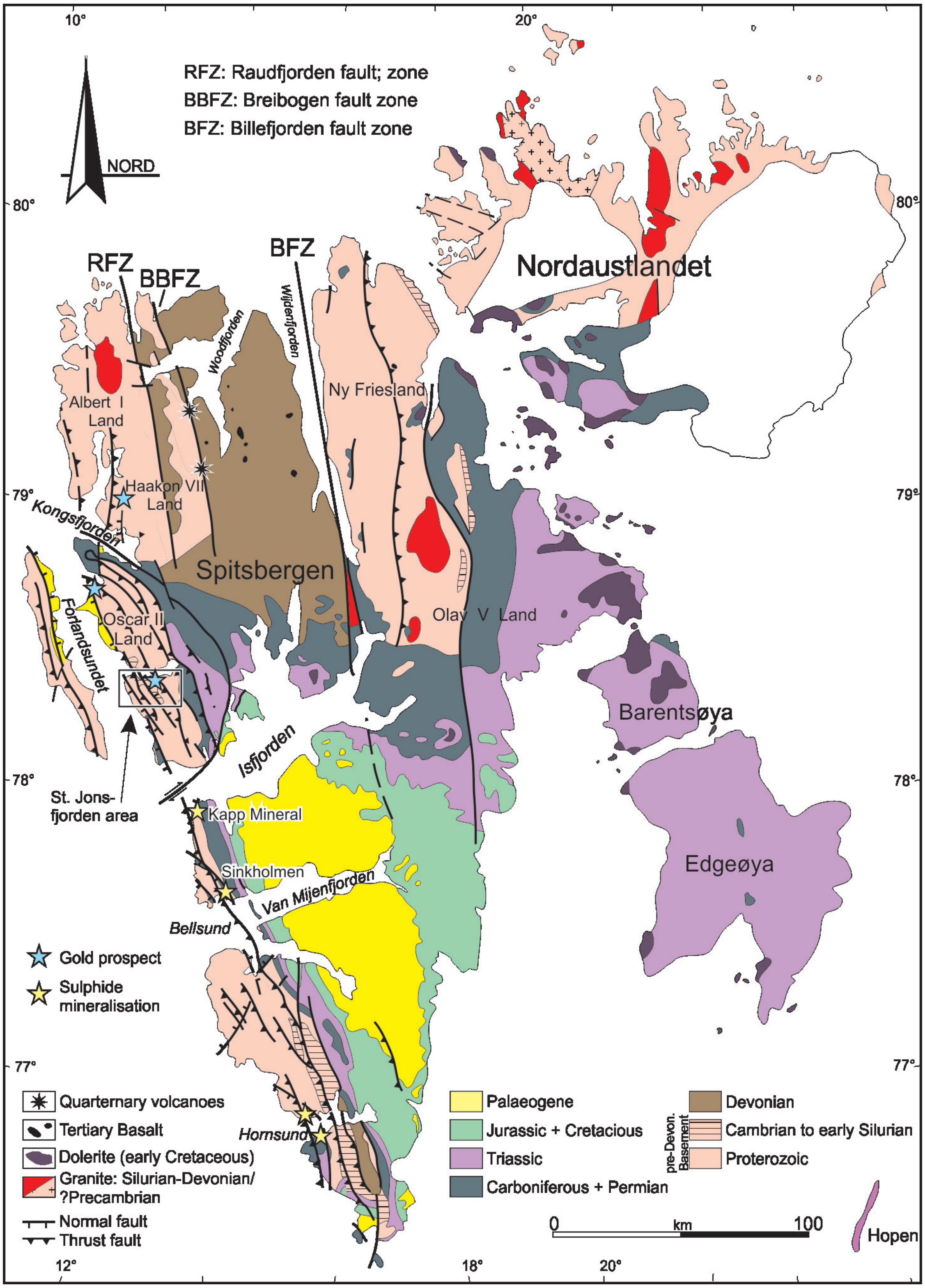

Figure 22. Geological map of Svalbard (modified after Hjelle, 1993). The map also shows the location of gold prospect areas in western Spitsbergen (Store Norske Gull AS) and the location of the St. Jonsfjorden prospect area.

to be late Devonian in age. However, Piepjohn et al. (2000) provided evidence from Dickson Land that contractional deformation took place after the Late Famennian and before Late Tournaisian time. The view regarding the Svalbardian deformation as a major strike-slip event (Harland et al., 1974) has been questioned on structural and sedimentological grounds (Lamar et al., 1986; Manby and Lyberis, 1992) in favour of (sub-)orthogonal E-W to WNW-ESE shortening (Manby et al., 1994; Piepjohn 2000).

Late Palaeozoic and Mesozoic depositional environments and evolution

Svalbard was located N of Greenland after the Svalbardian deformation. Sedimentation during the Lower and Middle Carboniferous was still strongly influenced by extensional tectonics along reactivated, mainly N-S- to NW-SE-trending lineaments controlling the deposition of the infill of several narrow half-grabens and troughs (Cutbill & Challinor 1965; Gjelberg & Steel 1981; Steel & Worsley 1984) with the main rift pulse occurring in the Middle Carboniferous (Bashkirian to Moscovian) (Gjelberg & Steel, 1981; Gudlaugsson et al., 1998). Svalbard and North-Greenland belong to an extensive rift system between Greenland and Norway; rift basin systems in the southwestern Barents Sea could be connected with contemporaneous, approximately N-S-trending, fault-bounded basins in the Arctic (Gudlaugsson et al., 1998). Lower to Middle Carboniferous sedimentation occurred in three main N-S- to NW-SE-oriented half-graben systems, the Billefjorden Trough along the Billefjorden Fault Zone, the Inner Hornsund Trough in southern Spitsbergen, and the St. Jonsfjorden Trough in Oscar II Land between Kongsfjorden and Isfjorden (Steel & Worsley 1984; Dallmann et al., 1999a). Lower Carboniferous siliciclastic sediments containing coal beds are followed by a change from humid to arid climate in the Middle Carboniferous and deposition of fluvial to marginal-marine siliciclastic red beds which, towards the top, intercalate inceasingly with, and finally pass into carbonates (Cutbill & Challinor 1965; Steel & Worsley 1984; Dallmann et al., 1999a).

Tectonic activity waned in late Carboniferous times giving rise to stable platform conditions and deposition of shallow marine carbonate and evaporitic sequences in a restricted- to open-marine, warm-water, tropical, semi-arid environment in late Carboniferous and Permian times. Increased subsidence during late Permian times resulted in a transgression and chert sedimentation on a deeper shelf environment (Steel & Worsley 1984). The strata are characterized by spiculitic cherts with intercalated black shales and silicified limestones passing to glauconitic sandstones (Steel & Worsley 1984; Blomeier et al., 2011)

Stable platform conditions continued during the early Mesozoic (Steel & Worsley 1984; Mørk et al., 1982). Changing facies and lithology distinguish Triassic rocks from underlying Permian strata which they overly with a distinct disconformity (Harland, 1997; Mørk et al., 1999). Mesozoic sedimentation is characterized by siliciclastic coastal and deltaic progradations into a wide shelf basin. Triassic to Early Jurassic strata consist of deltaic, coastal and shallow marine deposits, followed by the establishment of deeper shelf environments during the Middle Jurassic to Early Cretaceous (Mørk et al., 1982). The dark Triassic marine shales sparked interest in phosphorite (Harland, 1997), and their high organic content make them favourable as source rocks for hydrocarbons (Leith et al. 1993; Spencer et al., 2011). Other important source rocks for hydrocarbons are Late Jurassic shales (Golonka, 2011; Spencer et al., 2011).

A return to shallow shelf, fluvial and deltaic sedimentary systems in the Early Cretaceous (Gjelberg & Steel 1995) has been attributed to processes linked to advanced rifting in the North Atlantic and Arctic Basin and the break-up of Laurentia and Europe (Worsley, 2008), finally leading to uplift of the whole northern margin in the late Cretaceous (Worsley, 2008) and, accordingly, to a lack of deposits of this age in Svalbard as well as erosion and removal of Palaeozoic-Mesozoic strata, particularly in the northern parts of the archipelago (Steel & Worsley 1984). Late Jurassic and Early Cretaceous lava flows and intrusion of dolerites, common in eastern Svalbard and Kong Karl Land, are also related to the initial break-up of Pangaea. This mafic magmatism has been linked to the High Arctic Large Igneous Province (HALIP) (Tarduno et al., 1998; Maher, 2001). The age of mafic magmatism in

Svalbard is poorly constrained because of the wide spread of Ar/Ar and K/Ar ages; more recent data may, however, suggest a shorter event at around 124 Ma (Senger et al., 2014).

Development during the Cenozoic plate tectonic reconfiguration of the Arctic

Plate tectonic reconfiguration leading to the opening of the Arctic and North Atlantic oceans during the Palaeogene caused a tectonic overprint and reactivation of pre-existing structures and formation of the NNW-trending West Spitsbergen Fold and Thrust Belt which extends over 300 km along from Sørkapp in the south to Kongsfjorden in the north (Birkenmajer, 1981; Dallmann et al., 1993). The tectonic framework strongly influenced the deposition of Palaeogene and Neogene sediments. The Palaeogene sediments comprise a coal-bearing succession of conglomerates, sandstones and shales deposited in several individual, probably isolated basins (Livšic 1974; Manum & Throndsen 1986; Atkinson, 1963; Dallmann et al., 1999b) with the Forlandsundet Graben and Central Basin being the largest. Smaller outliers of Palaeogene strata occur south of Kongsfjorden (Ny Ålesund), south of Bellsund (Renardodden), and at Sørkapp (Øyrlandet). The present geometry of the Central Basin, as exposed in southern and central Spitsbergen, is a NNW-SSE-striking asymmetric synclinorium which has a steep western limb and is separated from the underlying lower Cretaceous strata by a décollement thrust (Dallmann et al., 1993; Paech, 2001). Its Paleocene to Upper Eocene strata are interpreted to have been deposited in a foreland basin position with respect to the West Spitsbergen Fold and Thrust Belt (Kellogg, 1975; Steel et al., 1981; Steel & Worsley,1984; Helland-Hansen, 1990). Correlation of Palaeogene sediments within the other, smaller basins with the Central Basin succession is, however, difficult.

Palaeogene coal is being mined at Longyearbyen (Gruve 7) by Store Norske Spitsbergen Grubekompani (SNSG) and at Barentsburg (Trust Artikugol). SNSG operated mines at Svea Nord and Lunckefjell until 2015 when the mines were put on care-and-maintenance due to the low prices of coal (Store Norske Spitsbergen Kulkompani, 2015).

Opening of the Greenland-Norwegian Sea and the Eurasian Basin initiated the separation of Svalbard and Greenland by means of dextral movements along the DeGeer Fracture Zone and Hornsund Fault Zone acting as transform structures between two ridge segments (Talwani & Eldholm, 1977; Srivastava, 1985; Harland, 1969; Harland & Horsfield, 1974; Mosar et al., 2002a). The West Spitsbergen Fold and Thrust Belt formed parallel to these fracture zones and has been described as a typical transpressive belt (Harland, 1969; Lowell, 1972; Harland & Horsfield, 1974; Steel et al. 1985), but its origin is still debated and different models have been proposed (e.g. Maher & Craddock, 1988; Nøttvedt et al., 1988; Dallmann et al., 1993; Lyberis & Manby, 1993a; CASE Team, 2001; Saalmann & Thiedig, 2002). The Caledonian basement is involved in thrust belt tectonics and is predominantly exposed in the western, "thick-skinned style" part of the thrust stack. The eastern and northeastern parts of the fold belt, closer to the foreland, are characterized by a "thin-skinned" tectonic style with typical structures of fold and thrust belts (Bergh & Andresen, 1990; Welbon & Maher, 1992; Dallmann et al., 1993; Braathen & Bergh, 1995; Bergh et al., 1997; von Gosen & Piepjohn, 2001; Saalmann & Thiedig, 2002).

The Forlandsundet Graben shows a complex, multiple-stage tectonic evolution which probably commenced already during the formation of the West Spitsbergen Fold Belt and developed mainly in Eocene-Oligocene times (Lepvrier, 1990; Gabrielsen et al., 1992; Kleinspehn & Teyssier, 1992). The latest tectonic developments, represented by E-W extension, are related to post-Eocene passive continental margin development to the west when Svalbard was separated from Greenland. Young magmatic activity is expressed by Miocene to Pliocene plateau basalts in northern Spitsbergen (Burov & Zagruzina, 1976; Prestvik, 1978) and Quaternary alkali basalt volcanic centres in the Bockfjorden area of northwest Spitsbergen (Gjelsvik 1963; Skjelkvåle et al. 1989).

METALLOGENY OF SVALBARD

Kerstin Saalmann

The metallogeny of Svalbard is poorly known and detailed information about the individual deposits is mainly found in unpublished company reports written in Russian or Norwegian. These reports suggest, as does the review by Flood (1969) that the ore occurrences are dominated by epigenetic sulphide mineralisation, almost all of them on the main island, Spitsbergen. Occurrences of magnetite skarn, banded iron formation, gneisses with stratabound dissemination of Fe-sulphides and ores of orthomagmatic Ni-Cu and Fe-Ti-V occurring locally in the Pre-Devonian basement rocks are, on current knowledge, of minor importance. Well-known examples of epigenetic ores include the Zn-Pb mineralisations at St. Jonsfjorden, Kapp Mineral, Hornsund and Sinkholmen (Figure 22). The latter two, occurring in brecciated dolostones, are regarded by some prospectors as Mississippi Valley Type deposits. Few of these mineralisations are considered to have any economic potential. They comprise fracture-bound mineralisations of sphalerite and galena, locally accompanied by copper-bearing minerals and arsenopyrite in a gangue of carbonate and/or quartz. The mineralisations are concentrated in mainly pre-Devonian basement rocks exposed in the western parts of the West Spitsbergen Fold Belt (Flood, 1969; Harland, 1997 and references therein) where they are associated with breccias and deformation zones (Dallmann, 2015). The St. Jonsfjorden prospect area in western Spitsbergen (Figure 22) is known for its sulphide mineralisation, as reflected in the place name "Copper Camp" on

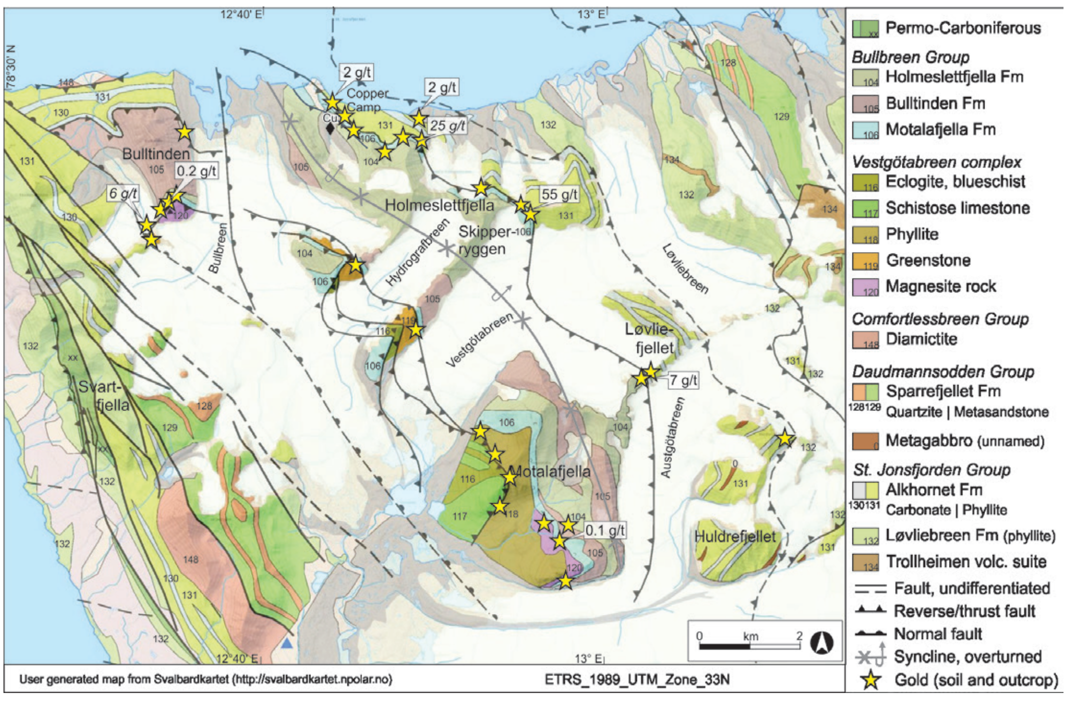

Figure 23. Geological map of the St. Jonsfjorden prospect area (modified after Bergh et al., 2003) showing gold values (g/t) from selected scree sample sites and from bedrock samples (italics = boulders) (Ojala, 2012). Ore grade samples occur at Holmeslettfjella, Løvliebreen and Bulltinden as well as along the thrust zone between Holmeslettfjella and Copper Camp.

the southern shore of the fjord (Figure 23). This location also marks the northern margin of the Holmeslettfjella gold prospect area.

Scree geochemical surveys were carried out in the 1980s by the Geological Survey of Norway (NGU), Store Norske Spitsbergen Kulkompani AS (SNSK) and Norsk Hydro in cooperation leading to the discovery of the Svansen Au-As deposit north of Kongsfjorden and a system of quartz veins, some with high Cu- and/or Au-grades, in the Devonian immediately west of Woodfjord (Ihlen & Lindahl, 1988). The presence of gold and arsenopyrite in the Svansen deposit was confirmed by subsequent bedrock mapping and sampling.

St. Jonsfjorden

Store Norske Gull AS (SNG) was established as a subsidiary of SNSK in 2003 to carry out metal exploration on Svalbard and in the northern part of mainland Norway. SNG carried out a geochemical prospecting campaign in Oscar II Land and Haakon VII Land (Figure 22) and started exploratory activities for gold in 2009 when they revisited and resampled the St. Jonsfjorden area. A mineralised zone characterized by pyrite and arsenopyrite and containing up to 55 g/t gold was found in a thrust zone at Holmeslettfjella (Ojala, 2012). Exploration, including a drilling programme, continued in 2010, but all activity was terminated in the summer of 2013 when SNG was sold. The claims to the mineralized areas S of St. Jonsfjorden were, however, transferred to SNSK.

The geology of the St. Jonsfjorden area comprises Proterozoic to early Palaeozoic metamorphic basement rocks which are unconformably overlain by unmetamorphosed late Palaeozoic to Mesozoic sedimentary rocks. The overall structural architecture of the area is basically defined by the Caledonian orogeny and by Palaeogene brittle deformation related to the formation of the West Spitsbergen Fold Belt. The prospect area is located in the western part of the fold belt where the basement was actively involved in Palaeogene thrusting (Welbon & Maher, 1992; Ohta et al., 2000; Tessensohn et al., 2001; Manby & Lyberis, 2001).

The stratigraphy of the St. Jonsfjorden region is two-fold, consisting of metamorphosed pre-Devonian basement units and unmetamorphosed late Palaeozoic and early Mesozoic sedimentary rocks. The latter do not crop out in the prospect area and are therefore not described in detail: a stratigraphic overview is presented in Figure 24. Original stratigraphic relationships are difficult to reconstruct due to the polyphase tectono-metamorphic history of the basement rocks, further complicated by Palaeogene thrusting. Several, partly conflicting, stratigraphic schemes have been proposed by different working groups using inconsistent nomenclature. Many questions regarding the age and tectonostratigraphic position of distinct units are therefor still controversial and unresolved: no consensus exists on the regional tectonostratigraphy. Nonetheless, the presence of regional marker horizons aids the task of subdivision and correlation of large parts of the basement rock column. Such marker horizons include intercalated diamictites that are interpreted as glaciogenic deposits and metatillites related to the Ediacaran Marinoan glaciation (Kanat & Morris,1988; Harland et al., 1993; Harland, 1997).

In Oscar II Land, including the St. Jonsfjorden area, the pre-Devonian rocks comprise the dominantly Neoproterozoic successions of the St. Jonsfjorden and Daudmannsodden Groups which are followed by metasedimentary rocks of the Comfortlessbreen Group (Figure 24). The latter contains glaciogenic diamictites and overlying carbonates and thus has a Neoproterozoic age. The St. Jonsfjorden Group consists of low-grade metamorphic carbonates, quartzites and phyllites with intercalated greenstones and metabasites. In the gold prospect area, calcareous sandstones and graphite-bearing marble in the lower portions of a drill core at Holmeslettfjella have been assigned to this group (Simonsen, 2012). Pelitic phyllites and carbonates of the Daudmannsodden Group do not crop out in the actual prospect zone but are exposed farther east and west (Figure 23). This also applies to the diamictite-bearing units of the Comfortlessbreen Group.

The Vestgötabreen Complex is an exotic tectonic of blueschist- to eclogite-facies metamorphic rocks thrust on top of the St. Jonsfjorden Group (Horsfield, 1972; Ohta et al., 1983; Ohta et al., 1995; Hirajima et al., 1988; Agard et al., 2005;

Group	Formation/unit	Lithology
Bullbreen Group	Holmeslettfjella Formation	sandstone, shale
	Bulltinden Formation	conglomerate
	Motalafjella Formation	carbonate rocks
Vestgötabreen Complex	Upper unit (eclogite facies)	eclogite (metabasite), glaucophane-epidote schist, garnet-chloritoid schist
	Lower unit (Blueschist facies)	carpholite-bearing phyllite, calc-schist; boudins of serpentinite, metabasalt and metacarbonate
Comforlessbreen Group		Quartzite Carbonate rocks phyllite, greenschist Schistose diamictite
Daudmannsodden Group	Konowfjellet Formation	marble, calcareous phyllite
	Sparrefjellet Formation	quartzite, metasandstone
St. Jonsfjorden Group	Alkhornet Formation	carbonate rocks, calcareous phyllite, phyllite
	Løvliebreen Formation	phyllite, psammitic phyllite, quartzite
	Trollheimen Volcanic Suite	basic metavolcanites

tectonic contact unconformity

	Group	Formation/unit	Lithology
Triassic	Sassendalen Group	Bravaisberget Formation	dark shale, siltstone, sandstone
		Tvillingodden Formation	sandstone, siltstone, shale
		Vardebukta Formation	sandstone, siltstone, shale
Permian	Tempelfjorden Group	Kapp Starostin Formation	silicified carbonates, chert, sandstone
	Gipsdalen Group	Gipshuken Formation	dolomite, limestone
		Wordiekammen Formation	dolomite, limestone
Carboniferous		Tårnkanten Formation	multicoloured sandstone, shale
		Brøggertinden Formation	polymict conglomerate, sandstone
	Billefjorden Group	Orustdalen Formation	sandstone, conglomerate

Figure 24. Stratigraphic tables of the pre-Devonian crystalline basement (top) and post-Devonian cover sedimentary rocks(bottom) of the southern St. Jonsforden area. The latter are exposed east of the gold prospect. Basement lithologies are from Hirajima et al. (1988), Harland et al. (1993), Agard et al. (2005) and Dallmann (2015). Post-Devonian cover stratigraphy is after Dallmann (2015).

Labrousse et al., 2008). The Complex consists of two structural units (Ohta et al., 1986) (Figure 24): the structurally upper unit consists of epidote-, garnet and glaucophane-bearing schists with lenses of ultramafic rocks and metabasite that have been metamorphosed at eclogite facies conditions of approximately 580-640°C and 18-24 kbar (Hirajima et al., 1988). The structurally lower unit is composed of Fe-Mg carpholite-bearing phyllites and calc-schists and containing serpentinite, metabasalt, and metacarbonate boudins; the carpholite schists indicate ca. 15-16 kbar and 380-400 °C suggesting a subduction zone setting (Agard et al., 2005).

Gasser & Andresen (2013), based on detrital zircon patterns, suggest that the Vestgötabreen Complex comprises mainly Neoproterozoic metasedimentary rocks. The origin of the metabasalts and gabbroic rocks is unresolved, but they show oceanic geochemical signatures (Bernard-Griffiths et al., 1993). The timing of high-pressure metamorphism is poorly constrained between 490 and 450 Ma (ca. 475 Ma U-Pb zircon lower intercept age, Bernard-Griffiths et al., 1993; 470-460 Ma $^{40}Ar/^{39}Ar$ white mica and 485-445 Ma Rb-Sr white mica and whole rock ages, Dallmeyer et al., 1990).

The Vestgötabreen Complex is unconformably overlain by the Bullbreen Group (Ohta et al., 1995, Harland, 1997) which shows a marked contrast in metamorphic grade and comprises three formations (Figure 24). The Motalafjella Formation is composed of limestones and dolomites and is overlain by the Bulltinden Formation consisting of conglomerates that contain clasts derived from the underlying limestones as well as from the Vestgötabreen Complex (Kanat & Morris, 1988). The Holmeslettfjella Formation on top is made up of turbiditic sandstones and slates (Kanat & Morris, 1988; Harland, 1997). In the gold prospect area, drilled graphitic schists and shales have been assigned to this formation and are interpreted as layers that have been hydrothermally altered by an organic-rich fluid (Simonsen, 2012). Conodonts from the limestones as well as fossils in some limestone clasts in the Bulltinden conglomerate indicate an early to middle Silurian age (Scrutton et al., 1976; Armstrong et al., 1986). The Vestgötabreen Complex has been interpreted as a tectonic mélange or strongly deformed metasedimentary sequence of mainly Neoproterozoic age with interleaved basaltic rocks of unknown origin that has been subducted, metamorphosed and thrust onto the Proterozoic successions in Ordovician times (Gasser & Andresen, 2013; Bernard-Griffiths et al., 1993). The pebble content in the overlying conglomerates indicates exhumation of the high-pressure rocks during sediment deposition which is consistent with a reconstructed nearly isothermal exhumation path (Agard et al., 2005) and rapid cooling (Dallmeyer et al., 1990).

Structural architecture

Besides the specific subduction zone-related deformation in the Vestgötabreen Complex, the pre-Devonian rocks in the St. Jonsfjorden area have been affected by several phases of folding. While there is general agreement on a Caledonian age of metamorphism and associated foliation development, the style, extent and degree of Palaeogene deformation in the basement related to West Spitsbergen Fold Belt are controversial: these are issues which affect the interpretation of the timing and origin of the gold mineralisation. Michalski et al. (2014), for instance, identify three fold generations (F1-F3), of which the first two are attributed to the Caledonian orogeny. Their F2 generation also includes the major NW–SE-trending and SE-plunging synform which is overturned to the NE and which can be traced from the southern shoreline of St. Jonsfjorden west of the Copper Camp to the SE along Holmeslettfjella and further towards the eastern slope of Motalafjella (Figure 24). This fold has been interpreted as a Palaeogene structure by other authors (Morris 1988; Manby & Lyberis 2001). Likewise, cleavage development in the Bullbreen Group has been attributed to east-vergent folding during Palaeogene thrusting based on the dominant deformation mechanism by pressure-solution which clearly post-dates peak metamorphism (Manby & Lyberis 2001). However, Michalski et al. (2014) recognize flattened and sheared clasts in the Bulltinden conglomerate in the hanging wall of a Palaeogene thrust fault indicating a west-directed sense of shear, opposite to movements along the Palaeogene thrust, and came to the conclusion that the zone represents a west-directed Caledonian thrust that has been reactivated during Palaeogene fold-belt formation. Caledonian deformation in the Bullbreen Group, in turn, implies the possible existence of a Silurian Caledonian event also in Oscar II Land, diverging from the view of solely Ordovician metamorphism in western Svalbard (e.g. Harland, 1997). A late-Caledonian event is corroborated by conodont studies in the Bullbreen Group indicating temperatures above 300°C (Conodont Alteration Index) (Armstrong et al., 1986).

The Palaeogene overprint of the basement rocks, related to development of the West Spitsbergen fold-and-thrust belt, is often difficult to identify with certainty; one distinct difference is that Palaeogene deformation was not accompanied by metamorphism. The late Palaeozoic-Mesozoic sedimentary successions in the inner parts of St. Jonsfjorden show typical structures of foreland-propagating fold-and-thrust belts with out-of-sequence and back thrusting complicating the overall picture (Welbon & Maher, 1992; Manby & Lyberis, 2001). Such sedimentary rocks are absent in the gold prospect area. However, in western Oscar II Land, mainly along the eastern border of Forlandsundet, basement thrust sheets are interleaved with slices of Permo-Carboniferous rocks (Hjelle et al., 1999; Ohta et al., 2000; Saalmann & Thiedig, 2002; Tessensohn et al., 2001), demonstrating that the basement was actively involved in Palaeogene thrusting. These interleaved late Palaeozoic rocks show a strong internal deformation (Tessensohn et al., 2001). The geometry in the western parts of the fold belt suggests a series of basement-rooted floor thrusts that involved the whole sequence and cut up-section into the cover rocks (Manby & Lyberis, 2001). The major thrust faults in the prospect area are interpreted as Palaeogene structures and are examples of such basement-dominated thrust sheets. A number of prominent N/NW-S/SE striking thrust zones can be mapped out, each thrust sheet containing a distinct pre-Devonian stratigraphic unit (Figure 23). A major thrust runs from Bulltinden at the St. Jonsfjorden coastline towards Motalafjella to the SE and carries the high-pressure metamorphic rocks of the Vestgötabreen Complex onto the overturned western limb of the above-mentioned synform (F2) of the Bullbreen Group. The thrust splits into two splay faults leading to further imbrication of the complex. The floor thrust of the Bullbreen Group thrust sheet separates the Holmeslettfjella Formation on the eastern synform limb from structurally lower limestones and phyllites of the Alkhornet Formation (St. Jonsfjorden Group) which, farther east, are in turn thrust onto the Løvliebreen Formation (Figure 23). Regarding the internal deformation of the basement thrust sheets, kink- to box-type folds as well as west-dipping, small-scale reverse faults in the pre-Devonian basement are spatially associated with the major thrust faults and are thus interpreted to be related to the West Spitsbergen fold-and-thrust belt (Michalski et al., 2014). The thrusts are dissected and displaced by normal faults which are partly parallel to the thrust faults (Figure 23). Such strike-parallel, late-tectonic normal faults are common features in the West Spitsbergen fold-and-thrust belt (e.g. Braathen & Bergh, 1995; Bergh et al., 1997; Maher et al. 1997; Saalmann & Thiedig, 2002).

St. Jonsfjorden Au-As mineralization

Scree and bedrock samples show a wide range of gold contents with the highest values of 55 g/t (in outcrops along the thrust NE of Skipperryggen), some boulders showing up to 25 g/t (northern Holmeslettfjella) and most gold values ranging from 0.1-0.2 g/t to values between 2 g/t and 6-7 g/t (Ojala, 2012). The map (Figure 23) reveals a clear spatial association between gold mineralisation and the Palaeogene thrust zones, particularly along the roof and floor thrusts of the thrust sheet containing the folded Bullbreen Group. The floor thrust carries mafic rocks and high-pressure schists of the Vestgötabreen Complex in the hanging wall onto the inverted limb of the Bullbreen Group syncline; the floor thrust also transports schists and phyllites of the Holmeslettfjella Formation and carbonates of the Motalafjella Formation onto calcareous phyllites of the St. Jonsfjorden Group. In addition to a structural control by thrust faults, elevated gold values also occur along a post-thrusting normal fault west of Bulltinden (Ojala, 2012) (Figure 23). The presence of elevated gold values over strike lengths of several kilometres in two, and possibly three structurally defined zones clearly qualifies the St. Jonsfjorden mineralization as "potentially large" (See Table 1). 3263 m of diamond drill core was drilled in three target areas, Holmeslettfjella, Copper Camp and Bulltinden. The holes reached the mineralised zone, but with a maximum of 1.8 g/t Au over 0.25 m did not reflect the high gold values of the surface samples and apparently did not intersect the high-grade shoot (Ojala, pers. commun. 2015). The structural control of the Au-As mineralisation inferred from surface relationships is confirmed by the drilling results. The gold is refractory and occurs in arsenopyrite (Ojala, 2012, 2013), explaining the observed strong correlation between gold and arsenic even at low concentrations (Simonsen, 2012). In addition to gold, the mineralised zones in the Holmeslettfjella Formation and Vestgötabreen Complex are enriched in As, Se, Cu, Hg, Tl, Sb and Te (Ojala, 2012) as well as V, Mo, Zn, which Simonsen (2012) attributes to organic rich fluid that migrated through the rocks, causing their alteration. He further suggests that the sources of the fluids are so-called VAMSNAZ shales, i.e. carbonacous black shales enriched in e. g. V, As, Mo, Se, Ni, Ag and Zn (Large et al., 2011), in which the Au and As have been previously enriched during diagenesis, for instance by adsorption onto organic matter and incorporation into diagenetic pyrite.

The Ordovician Vestgötabreen Complex and the Silurian rocks of the Bullbreen Group are affected by hydrothermal alteration setting a maximum age for this event. The age of the gold mineralisation has not been defined. According to Simonsen (2012) the VAMSNAZ shales have been deposited in Ordovician-Silurian times and alteration took place coeval to Silurian low-grade metamorphism, folding and thrusting of the Bullbreen Group and Vestgötabreen Complex. At the same time the ultramafic rocks of the Vestgötabreen Complex have been altered to listwanites (Simonsen, 2012; Ojala, 2012). A late-Caledonian age for the original gold mineralisation is supported by the apparent restriction of alteration and mineralisation to these rock units whereas other Palaeogene thrust zones lack significant gold mineralisation (Figure 24). Thrusting and local reactivation of older structures during development of the West Spitsbergen Fold Belt may well have remobilized gold from a pre-existing deposit, leading to secondary enrichment along Palaeogene thrust zones (Simonsen, 2012) and the present-day configuration.

SVANSEN AU-AS MINERALIZATION

Jan Sverre Sandstad

The Svansen Au-As mineralization is hosted by banded metasandstone and quartzite of assumed Proterozoic age. Numerous, mainly concordant quartz veins, pods and veinlets in cm- to dm-scales occur in the metasediments, but metre-wide quartz reefs are rare (Sandstad, 1989). Both the host rocks and the quartz bodies are strongly deformed and folded. The gold shows a spatial relationship to the quartz veins/reefs and also to strongly boudinaged portions of the metasediments (Sandstad & Furuhaug, 1990). The gold values of grab and channel samples vary from a few ppb to ca. 80 ppm. Gold has a strong positive correlation to As and S, and occurs mainly as free gold with grains up to 0.3 mm, although grain sizes under 50 µm are common. The wall rock alteration is generally weak with minor sericitization, chloritization and sulphidization (Sandstad & Furuhaug, 1990).

On a mesoscopic scale there is an apparent spatial relationship between hydrothermal quartz, gold and fold structures, and the mineralization shows a number of similarities to turbidite-hosted gold deposits. However, the linear extent of the mineralized zone, greater than 11 km, may indicate a relationship to major vertical shear zones.

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