MINERAL RESOURCES IN THE ARCTIC

AN INTRODUCTION

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GEOLOGICAL SURVEY OF NORWAY SPECIAL PUBLICATION

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Edited by

Rognvald Boyd, Terje Bjerkgård,
Bobo Nordahl and Henrik Schiellerup
Geological Survey of Norway

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INTRODUCTION

This volume summarises the results of cooperation between the geological surveys in the countries in the Arctic region, aimed at compiling information on the most important mineral deposits north of 60°N, in a database, on a map and in descriptive volumes, one for geoscientists and this, briefer volume for general-interest readers[1]. The largest deposits of metals and diamonds on land have been prioritised. This version of the description will be published in English, French and Russian. These products represent the first compilation of information on the most important deposits of the prioritised resource types in the Arctic.

Mankind has used mineral resources since the dawn of civilization. The division (in Europe) of most of the 10,000 year since the end of the last Ice Age into the archaeological periods Stone Age, Iron Age and Bronze Age, bears witness to the importance of mineral-based materials in the development of mankind. This terminology is also commonly applied in the Middle East and Africa: variations used in eastern Asia include periods defined by certain types of pottery – again mineral-based. The earliest uses were related to weapons, tools and the building of dwellings, burial and religious sites, with a gradual development of household articles, pigments and items made for their beauty. The range of metals and minerals used developed relatively slowly (though with clear global variations) until the Industrial Revolution in the 18th - 19th C which saw the invention and large-scale application of equipment at all scales from needles of metal and sewing machines via iron stoves to steam engines and ocean-going ships of iron and steel. A wide range of domestic appliances was developed gradually in the 20th C but more sophisticated items, involving the use of many more raw materials became more common, in many parts of the world, in the second half of the century.

The Electronic Age developed gradually though the 20th C, spurred by research during World War II but with a clear acceleration in the last quarter of the century. This brought computers, of diminishing size and increasing power, televisions sets of increasing sophistication, and especially cell phones (followed by smart phones) into the homes of an increasing proportion of the global population. The number of metals used in everyday household appliances rose dramatically. The 20th C was also a period of dramatic development in communications both in global trade and in travel, both for business and leisure. Modern aircraft technology is based on the use of a wide range of raw materials with special properties – both for the main structures and for special applications such as the engines and landing gear. The economic development of heavily populated countries in Asia and other parts of the globe has led to enormous investments in infrastructure and has brought modern amenities to many hundred million people – elements leading to a dramatic, if not stable, increase in demand for resources. Interruptions and acceleration in the trends towards increased demand (with resulting consequences for commodity prices) have been caused by numerous factors including:

- Wars, leading to increased demand for certain commodities coincident with disruption in supply chains
- Technological development (as noted above)
- Political/economic changes leading to increased well being and development of infrastructure.
- The establishment of cartels and other measures which distort normal development of markets and prices.

[1] The geoscientific description, database and map are accessible at http://www.ngu.no/en/projects/circum-arctic-mapping. The geoscientific description includes a comprehensive reference list, including all those cited in this volume.

Hard-rock mineral resources (i.e. excluding oil and natural gas) can be considered in four groups – metals, industrial minerals, building materials and energy resources (such as coal and uranium). The value/tonne of most industrial minerals and building materials is such that they cannot be transported over long distances. Deposits of most types of these resources are thus of interest only when they are located close to major markets. This publication focuses on the largest known deposits of metals and on one of the few industrial minerals which has a very high unit value, diamonds. The deposits included conform to the categories: Large, Very Large and Potentially Large defined in the Fennoscandian-Russian project: Fennoscandian Ore Deposit Database (see Eilu (ed.), 2012, http://tupa.gtk.fi/julkaisu/tutkimusraportti/tr_168.pdf).

The global distribution of known deposits of metals and diamonds is controlled by their affinity for occurrence in certain types of geological setting. Diamonds occur in kimberlites, narrow pipes of magmatic rock found in units with old continental crust extending to depths of 140–190 km, at which diamonds can be formed from other types of carbon, such as graphite, or in sedimentary units, e.g. placer deposits, derived from kimberlites. Weathering of primary sources of metals can lead to the formation of several types of "placer" deposit along the beds of major rivers or in coastal deposits. The least documented types of deposit are those in the oceans, at mid-oceanic spreading zones and in metal-rich nodules on the deep ocean floor.

Many deposits have one or more metal(s) at a relatively high grade and several potential co-products (e.g. nickel with copper, cobalt and platinum metals, lead and zinc with indium, germanium and silver). The grade and size of the deposits and their numbers dictate the importance they have in relation to the market for the metals which they yield. There are numerous large ("world class") deposits of copper (commonly with molybdenum or cobalt as co-products) and of iron. The number of "world class" deposits/groups of deposit of the platinum metals, however, is much smaller, with the major suppliers located in only two countries (Russia and South Africa).

Definition of the Arctic

The following are among several definitions of the Arctic (see Figure 1):

- The area N of the Arctic Circle, the southernmost latitude in the Northern Hemisphere at which the sun can remain continuously above or below the horizon for 24 hours. Because of changes in the Earth's axial tilt due to tidal forces, the Arctic Circle at the present moves northwards by about 15 m/year.
- The region in which the average temperature for July is below 10°C.
- The northernmost tree line.
- 60°N. This definition includes:
  - Most of Alaska,
  - The Yukon, North West Territories and Nunavut in Canada, the northernmost parts of Québec province and of Labrador.
  - The whole of Greenland, given a slight infringement of the southern limit in order to reach Cape Farewell at 59° 46' 23″ N.
  - Iceland
  - The Faroe Islands
  - The Shetland Islands except for the southernmost 12 km of Mainland.
  - Fennoscandia, approximately N of the capitals, Oslo, Stockholm and Helsinki.
  - Northern Russia, including almost all areas N of the 10°C summer isotherm.

The last of these four definitions is geographically convenient and was adopted in the first of the now five cooperative geoscientific projects implemented in the region.

The Faroe Islands are not known to contain mineral resources of significance and the metallic mineral deposits which are known on the northernmost of the Shetland Islands, ophiolite-hosted chromite and platinum metal deposits, are of very limited tonnage.

Earlier geoscientific cooperation in the region

The first initiative for cooperation on a series of Circum-Arctic geological and geophysical maps was undertaken in 2003 by the Russian Ministry of Natural Resources and Ecology and by the Russian Federal Agency of Mineral Resources (Rosnedra) (Petrov and Smelror, 2014). The

Figure 1. The Arctic, according to the four definitions indicated below. (Map courtesy of the The Perry-Castañeda Library Map Collection, University of Texas Libraries, The University of Texas at Austin)

objective was to produce digital geological and geophysical maps at a scale of 1:5 M for the Arctic region. An agreement was signed, in 2005, by a consortium of national agencies from Canada, Denmark, Finland, Norway, Russia, Sweden and the USA (Petrov & Smelror, 2007). The current project was among the original aims of the participating organizations and is the most recent to be implemented:

- Geological Map of the Arctic (Harrison et al., 2008)
- Magnetic and Gravity Anomaly Maps of the Arctic (Gaina et al., 2011)
- Tectonic Map of the Arctic at scale 1:5M (Petrov et al., in press)
- Mineral Resources in the Arctic (Boyd, Bjerkgård, Nordahl and Schiellerup (editors), 2016)

Compilations of the type provided by these projects are important steps in updating scientific knowledge, in improving knowledge of the development of the Earth's Crust and in providing background information which is relevant in assessment of the potential for mineral resources, not least in relation to energy resources in offshore sedimentary basins.

History of mineral exploration in the Arctic

The Arctic has attracted attention from explorers at least since the three voyages of Willem Barents in the late 16th C. Barents' aim was to search for what we now know as the Northeast Passage or, in Russia, as the Northern Sea Route. Bear Island, Svalbard and Novaya Zemlya were visited by Barents but none of the voyages penetrated the region east of the Kara Sea: Barents died on Novaya Zemlya in 1597. The first commercial exploitation in the High Arctic began early in the following century with the establishment of Dutch and English whaling stations on Svalbard. Whaling expeditions discovered coal on Spitsbergen, the main island in the Svalbard archipelago, as early as 1610 and used the coal on their ships (Dallmann, 2015): serious exploration and long-term exploitation of the coal deposits began approximately three hundred years later. The discovery and use of coal on Svalbard early in the 17th C appears to be the first exploitation of any type of mineral resource in the High Arctic. This project has focussed on the most important mineral deposits on land in the Arctic, not of energy resources such as coal, but of metals and diamonds.

Arctic Russia has a mining history of over 300 years, beginning with a focus on gold and silver in the early 18th C and growing in scale and the range of commodities into a major industry in the latter part of the 19th C. During the 20th C Russia became one of the world's most important sources of a number of metals and of diamonds. Norilsk Nickel which operates mines and processing facilities on the Taimyr Peninsula in Krasnoyarsk oblast (including the original Norilsk and Talnakh deposits) and on the Kola Peninsula in Murmansk oblast, both areas north of the Arctic Circle, is the world's 3rd largest producer of nickel (9.7 % in 2013) and 2nd largest of both platinum (13.4 % in 2013) and palladium (42.4 % in 2013) (data from British Geological Survey, 2015): the company is also an important producer of copper. The mining industry is important in other parts of the Arctic. Sweden and Finland produce over half the metal production of the EU28 (European Union member countries) (Euromines, 2015): both countries also have active exploration industries, which have had some notable successes in recent years.

Metal mining and exploration has been an important industry in Alaska and the Arctic regions of mainland Canada since the discovery of gold in Yukon and some years later in Alaska, late in the 19th C. It has been estimated that over 100,000 prospectors braved rough terrain and extreme winter conditions in their search for gold in the Yukon in the period 1896-99. The discovery of more easily mineable placer gold in the Nome district in Alaska in 1898 led to a new gold rush and to intensive exploitation of the Alaskan deposits for a period of ten years.

Alaska and Arctic Canada still have major mining industries. The Red Dog group of mines in northwestern Alaska is one of the world's largest producers of zinc concentrate (Teck Alaska, 2015) and the Cantung Mine in the Northwest Territories of Canada is, after over fifty years of operation, still one of the world's largest producers of tungsten outside China (North American Tungsten Corporation, 2015). Intensive exploration for diamonds in Canada began in the 1960s:

Figure 2.The Black Angel zinc-lead mine on the W coast of Greenland. (Photo courtesy of Bjørn Thomassen, GEUS).

after 30 years of exploration a mineable deposit, Ekati, was discovered and subsequent exploration has led to further commercial discoveries in the Northwest Territories, Nunavut and Ontario. An advanced development project, the Renard project in Quebec, is expected to achieve full production levels in 2017 (Stornoway Diamonds, 2015).

Greenland has a relatively long mining history (Henriksen, 2008). Coal on Disko Island was exploited from the late 18th C, the cryolite mine at Ivittuut opened in 1854 and was operative until 1987: several mines have been operative for periods after World War II and exploration has resulted in the discovery of numerous major deposits yet to be put into production. Greenland is but one of several regions in which the mineral potential of the Arctic is being confirmed by the ongoing discovery of new deposits, some of them world-class, even in areas which are already geologically well known.

Why consider the mineral potential of the Arctic?

The case for timeliness of the Circum-Arctic Mineral Resource project rests on many factors:

- Heightened national, regional and international focus on the Arctic, including numerous research projects of many kinds.
- National projects on mineral potential in the Arctic regions of a number of countries, including Canada, Greenland and the Nordic countries. These projects involve documentation of mineral potential as part of the basis for assessment of the development potential of the regions covered.
- The continuing discovery of major new deposits, some in known metallogenic provinces but others in regions not previously recognized as having a major mineral potential.
- Concern relating to access to certain critical mineral resources, some of which are known to occur in the Arctic: assessments of critical raw materials in the European Union, the USA and other countries are among the expressions of this concern.
- Improved access due to the more consistent, longer-term opening of sea lanes such as the North-East Passage (also known as the Northern Sea Route), the North-West Passage and the Arctic Bridge (from Churchill to Murmansk), combined with greater access to ice-classified cargo vessels and ice-breakers. The establishment of the Northern Sea Route Administration (http://www.arctic-lio.com/nsr_nsra) with the information and facilities which it provides has had an important role in use of the North-East Passage.

The ready, global availability of metals for construction of infrastructure and consumer items at all scales is the result of decades of exploration for, and investigation of deposits to prove their viability, and continuous improvements in the technology for extraction and processing of the ores they contain. Large areas of the continents are not "prospective" for most of the metals because they are covered by extensive basins of young sedimentary rocks. Deposits in regions with logistical challenges would normally have to be of higher grade/size in order to attract investors willing to risk capital without the guarantee of the safe establishment of a mine and a return on their investment.

Article 7 of the Protocol on Environmental Protection to the Antarctic Treaty (http://www.ats.aq/documents/recatt/att006_e.pdf) which was signed in 1991 bans all mineral resource activities on the continent except those related to scientific research. The Arctic Region is thus, on a global scale, one of the few remaining land regions with extensive areas of "prospective" geology in which knowledge of the mineral potential is limited.

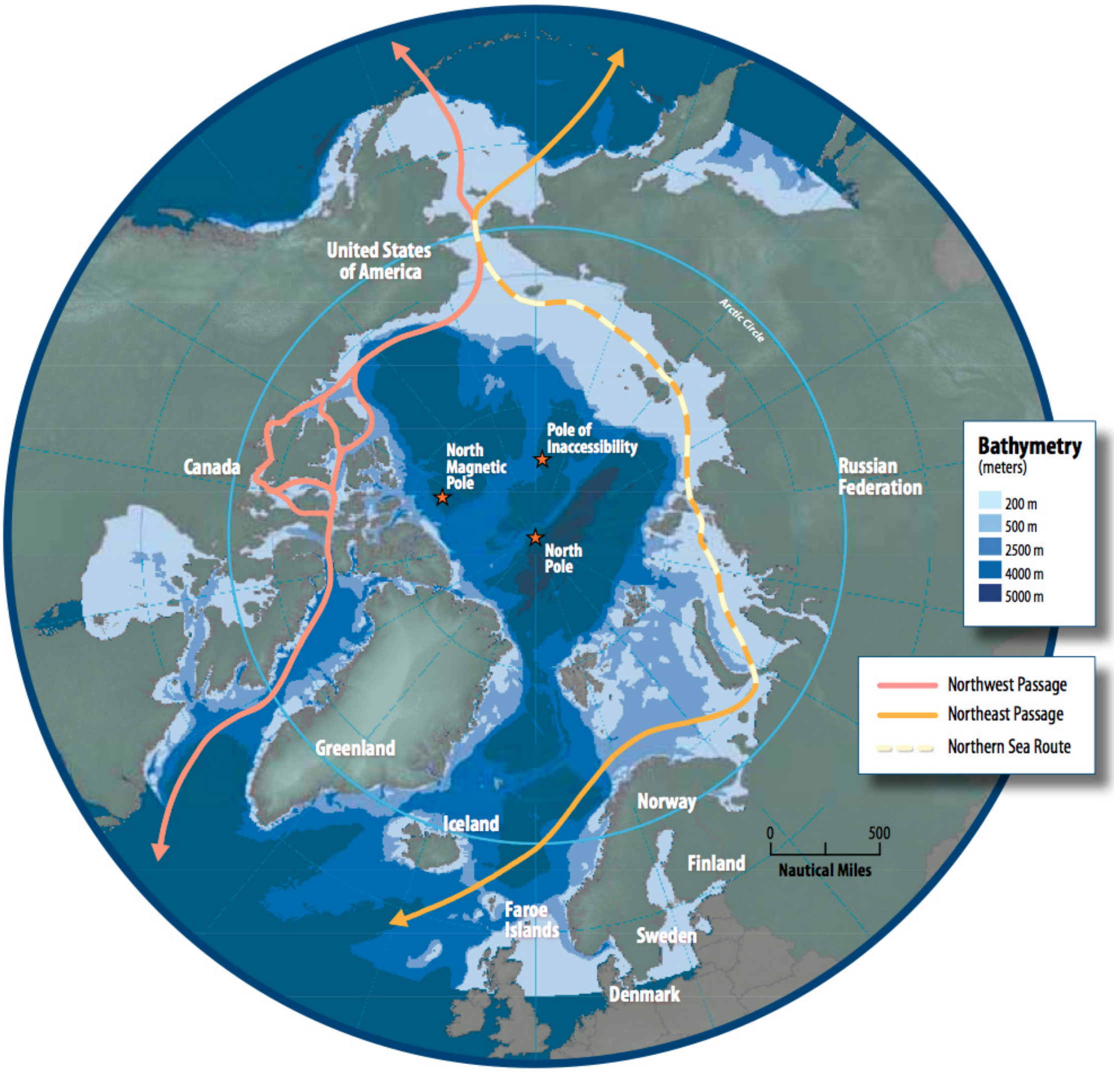


Figure 3. Map of the Arctic showing alternative Northwest Passage routes and the Northeast Passage, including the Northern Sea Route along the coast of Siberia (Arctic Marine Shipping Assessment 2009 Report, Arctic Council, April 2009).

MINERAL DEPOSITS AND METALLOGENY OF ALASKA[2]

Brief Geological Outline

Alaska, the largest State within the United States, and mainly located north of latitude 60°, is an important part of the Circum-Arctic region. Alaska is a richly endowed region with a long and complex geologic history. The mining history is short by world standards but nevertheless there are a number of world-class deposits in Alaska, of which Red Dog and Pebble are among the largest of their respective types in the world.

Alaska is a collection of geologic terranes or regions having distinct histories, most of which were tectonically assembled in the period from 400 million years to 50 million years ago (late Paleozoic through early Tertiary). They now occur as numerous fault-bounded blocks in the northernmost part of the North American Cordillera on the western margin of the Laurentian craton. These terranes are comprised of rocks ranging in age from Paleoproterozoic to Recent.

The east-west trending Brooks Range of northern Alaska is the northernmost segment of the North American Cordilleran orogen. The range is mainly underlain by Neoproterozoic and younger rocks of the Arctic Alaska terrane, which can be divided into a series of subterranes (Figure 1) comprising about 25 % of Alaska. The

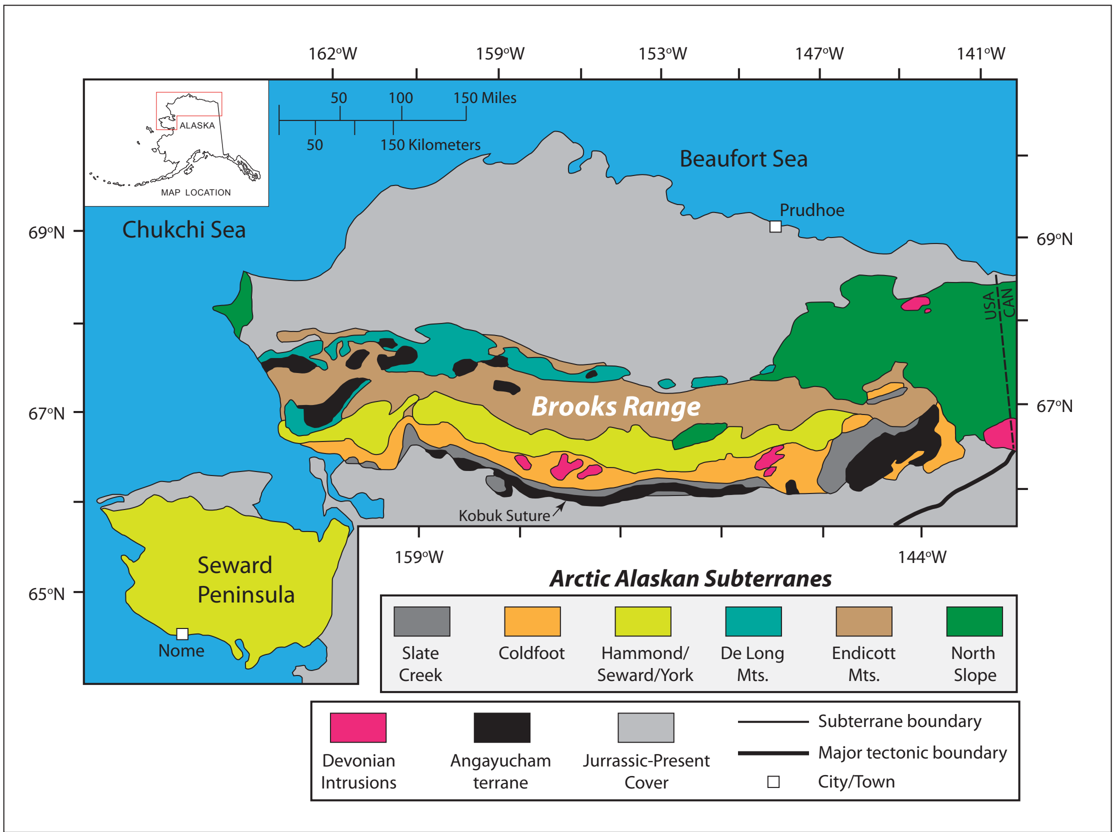


Figure 1. Continental margin subterranes of the Neoproterozoic-early Paleozoic Arctic Alaska terrane, part of the Arctic Alaska-Chukotka microcontinent, which were amalgamated along the Canadian Arctic and now partly form the Brooks Range and buried North Slope basement of northern Alaska. Oceanic rocks of the Angayucham terrane were thrust over the rocks of the Arctic Alaska terrane in Early Cretaceous. After Strauss et al. (2013).

[2] Written by Larry Meinert, US Geological Survey, based on the more detailed information and references in the chapter on Alaska in the geoscientific volume.

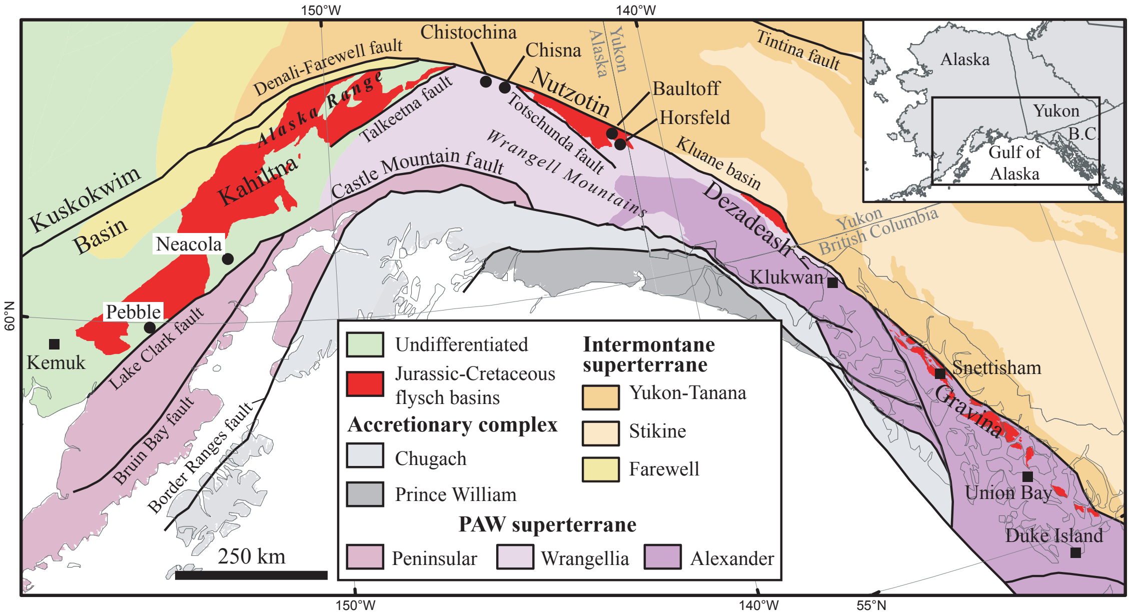


Figure 2. Southern Alaska is dominated by the Wrangellia composite terrane or microcontinent, also referred to as the PAW superterrane. It comprises three distinct oceanic arc terranes (Peninsular, Alexander, and Wrangellia) that were amalgamated in late Paleozoic. The Chugach subduction-accretion complex was added to the seaward margin of the composite terrane when it was located many hundreds of kilometers to the south of its present location. Locations of Pebble and other mid-Cretaceous porphyry deposits (solid circles) and zoned Alaskan-type mafic and ultramafic bodies (solid squares) of southern Alaska are shown. The porphyry deposits are related to igneous rocks that intrude flysch basins on the landward side of the Wrangellia composite terrane. After Goldfarb et al. (2013).

rocks of the Brooks Range consist of a variety of igneous, metamorphic, and sedimentary units that contain volcanogenic massive sulfide and sediment-hosted base metal deposits.

The Seward Peninsula, to the southwest of the Brooks Range (Figure 1) consists of a pre-Carboniferous penetratively deformed continental margin sequence, the Nome Complex, that is correlative with the southern Brooks Range Schist belt. The rocks of the Nome Complex host late Early Cretaceous orogenic gold deposits and economically important associated placers. Large parts of western Alaska, including rocks of the Farewell terrane, are covered by Cretaceous terrigenous rocks of the Koyukuk basin and Early Cretaceous andesitic volcanic rocks of the Koyukuk terrane.

South-central Alaska (Figure 2) mainly comprises the Wrangellia composite terrane and the seaward Chugach terrane that represents a subduction-accretion complex; these terranes are separated by the Border Ranges fault zone with more than 600 km of dextral strike-slip. East-central Alaska is defined by pericratonic rocks of the Yukon-Tanana terrane located between the Denali and Tintina strike-slip fault systems, each with at least 400 km of dextral displacement, and thus between the seaward Wrangellia and Chugach terranes to the south and Arctic Alaska terrane and related rocks to the north. The Yukon-Tanana terrane hosts the giant Fort Knox and Pogo gold deposits. Subduction beneath the Yukon-Tanana terrane is estimated to have occurred from about 220-179 Ma and 115-95 Ma, and is associated with voluminous magmatism.

The 70,000 km² Kuskokwim basin (Figure 2) underlies much of southwestern Alaska. The basin has been interpreted as a strike-slip basin formed in response to the Late Cretaceous faulting along the Denali-Farewell fault system to the south and Iditarod-Nixon Fork fault system to the north. Most sedimentation took place in the period 95 - 77 Ma, when the basin was forming between a series of Middle Jurassic to Early Cretaceous volcanic arc terranes that were approaching the continent from the west and south.

History of Mining

Except for Alaskan Natives' utilization of native copper, Alaska's mining history is relative-

Figure 3. Miners climbing the Chilkoot Pass between Skagway, Alaska and Yukon, Canada, September 1898, during the Klondike gold rush. Image from Per Edward Larss and Joseph Duclos.

Figure 4. Locations of significant placer gold accumulations in Alaska and years of earliest discoveries. Image from Yeend et al. (1998).

1834 Party of Russian-Americans under Malakoff reports finding gold in the Russian River drainage of the Kenai Peninsula.
1867 Alaska purchased from Russia and officially handed over to the United States in a ceremony at Sitka.
1880 Gold discovered near Juneau, both in the Silver Bow Basin and on Douglas Island.
1886 Gold found in the Fortymile River, the first major gold discovery in the interior of Alaska.
1893 Gold discovered on Birch Creek in an area that later became famous as the Circle Mining District.
1896 George Washington Carmack, Skookum Jim, and Tagish Charlie find rich deposits of gold on a tributary of the Klondike River in the Yukon Territory of Canada, starting the Klondike Gold Rush.
1898 Miners from the Klondike continue down the Yukon to Alaska's Seward Peninsula and find god at Nome. Others make finds in other parts of Alaska.
1902 Felix Pedro finds gold on a tributary of the Tanana River at the site what is now the city of Fairbanks.

ly short compared to other Arctic regions of the world. The earliest attempt by a non-native to mine was in 1848 in south-central Alaska by P.P. Doroshin, a Russian mining engineer sent to southern Alaska from St. Petersburg by the Russian-American Company. His two-year effort to mine gold was essentially unsuccessful, but later gold rushes opened up much of the State to mining and development. Early prospectors crossed over Chilkoot Pass from coastal Alaska into the Klondike goldfields in Yukon, Canada (Figure 3), and then eventually into interior Alaska in the 1880s and 1890s. The most spectacular Alaskan gold rush followed announcement in late 1898 of a significant discovery along the beaches of Nome; in 1899 and 1900 as many as 20,000 people flocked to this small town along the coast of the Seward Peninsula in northwestern Alaska. The Nome mining district is the second most important placer district in Alaska, having produced more than 155 tonnes (t) Au, essentially all by placer methods and mostly from complex alluvial deposits or buried beach deposits. Additional Alaskan placer Au discoveries (Figure 4) include the Fairbanks (257 t), Circle (23 t), Fortymile (15 t), Hot Springs (14 t), and Tolovana (16 t) districts in interior eastern Alaska and the Iditarod-Flat (45 t) and Innoko (23 t) districts in southwestern Alaska.

Total historic Alaska gold production is probably more than 1400 t, 54 % of which came from placer deposits. This is undoubtedly a low estimate, as production from small properties often went unreported. In addition, from 1880 through 2013, estimated cumulative Alaskan mining production included about 10,300 t Ag, 1400 t Hg, 5000 t Sb, 3300 t Sn, 2.5 million tonnes (Mt) Pb, 12 Mt Zn, 0.6 Mt Cu, 35,500 t Cr, 600 t U_3O_8, and 21 t Pt .

Base metal deposits were discovered in northwestern Alaska in the late 1960s and exploration took place in the subsequent decades. Iron-oxide staining was first noted along Ferric Creek in the western Brooks Range in 1955. Following up on this occurrence, a USGS geologist sampled stream sediments and rocks along the similar iron-oxide-stained Red Dog Creek (east of Ferric Creek) in 1968 and found >10 % Pb in stream sediments and > 2 % Pb and 1 % Zn in mineralized rock samples. The area was first drilled in 1980 and the second hole intercepted 11.0 m at 48 % Zn and 10 % Pb. Further drilling and ongoing production have established Red Dog as one of the world's largest clastic-dominated Pb-Zn (SEDEX) deposits, accounting for 4 % of the world's and 95 % of U.S. zinc reserves (Athey et al., 2014). Other base metal sulfide deposits are recognized in the Red Dog district and elsewhere in the western Brooks Range, but remain undeveloped.

Additional Alaskan discoveries in the latter half of the 20th century include Quartz Hill in 1974, Greens Creek in 1979, Fort Knox in 1984, Donlin Creek and Pebble (just south of 60°N) in 1988, and Pogo in 1994. At present Alaska has five active lode mines (Fort Knox, Greens Creek, Kensington, Pogo, and Red Dog) in addition to continuing production from numerous placer gold operations throughout the state.

Summary information on the most common deposit types

Gold Deposits

Placer gold deposits eroded from precursor orogenic and reduced intrusion-related gold deposits, were the earliest discoveries in Alaska, have been mined for more than 100 years, and remain economically important. The orogenic gold deposits in the northern part of the State are mostly eroded but one historic (1903-1907) high-grade example on the Seward Peninsula, Big Hurrah, produced from gold-quartz veins, averaging 25 g/t Au, in sheared metasedimentary and metavolcanic rocks. The Seward Peninsula orogenic gold province probably extends into eastern Russia, where large lode deposits such as Mayskoye and Karalveem are hosted by Middle Triassic sedimentary rocks and late Aptian to early Albian granite and granodiorite (Goldfarb et al., 2014).

The placer gold derived from the Seward Peninsula orogenic vein deposits mainly formed alluvial, colluvial, glacial, and particularly marine strandline deposits. Active stream channels, as well as benches with old alluvial or glacial channels high along stream walls, were productive, and in places they yielded large nuggets. However, the majority of the recovered gold was from beach deposits of the Nome area. The marine benches formed in the late Pliocene to Pleistocene as a result of relative sea-level fluctuations. The gold-bearing gravels in the benches were deposited by glaciers on top of the schist bedrock and the fine-grained marine sediments. The gold in the till was then reworked and concentrated by both fluvial and marine processes.

The first gold discovery was on the present-day beaches of Nome, which yielded an estimated 3-4 t of Au along 60 km of coastline. Soon after this initial discovery on the "first beach", it was realized that the bulk of the gold was located slightly inland, within ancient beach deposits, and that these older deposits were responsible for most of the recovered 155 t Au. Six ancient beach marine platforms were located above present sea-level and an equal number were located below present sea-level (Cobb, 1974). The gold within the third beach was located just above bedrock, in beach sands and river gravels at the bottom of 10-15 m deep shafts. The most landward submarine beach was discovered 400-500 m inland and 6-7 m below present sea-level. Metz (1978) estimated reserves of 37 t Au remaining after mining, mainly in the second, third, submarine, and Monroeville beaches. Large-scale mining of the alluvial gold ceased in 1962 but recreational mining of many of the beaches continues today.

In the Fairbanks district, gold has been produced from quartz veins in reduced intrusions, orogenic gold deposits in metasedimentary rocks, and in placer deposits derived from them (Figure 4). Erosion of the widespread auriferous quartz veins in the Fairbanks district has yielded alluvial concentrations responsible for 257 t Au production from placers (Figure 4). Production peaked during the first few years of mining after discovery of alluvial concentrations in 1902 and during a lengthy period of dredging between 1928 and 1963. Most production came from the watersheds of Cleary, Fairbanks, Ester, Dome, and Goldstream Creeks.

The largest orogenic deposit is Pogo (total of past production, current reserves and resources: 220t Au), about 140 km southeast of the city of Fairbanks, where high-grade (avg. 12.5 g/t Au), shear-hosted veins cut Proterozoic to middle Paleozoic biotite-quartz-feldspar orthogneiss and paragneiss of the Yukon-Tanana terrane were discovered in 1996. Underground mining began ten years later. As of 2015, Pogo is the largest gold producing mine in Alaska, producing about 11 t Au/year and with a present production, reserve, and resource total of 220 t Au.

The gold-bearing veins at Pogo, termed the Liese vein system, occur as three individual, laminated, stacked veins that dip shallowly to the northwest. The ductile to brittle veins average 7 m in thickness, although they are locally as thick as 30 m, and have an areal extent of 1.4 x 0.7 km (Smith et al., 1999; Rhys et al., 2003). The largest vein has a down-dip extent of >1.7 km. Sulfide phases, comprising about 3 % of the veins, include arsenopyrite, pyrite, pyrrhotite, loellingite, chalcopyrite, and molybdenite; Bi- and Te-bearing tellurides are also present. Alteration phases include biotite, quartz, sericite, K-feldspar, ferroan dolomite, and chlorite.

Reduced granites and tonalites of the Goodpaster batholith are located a few kilometers north of Pogo. These rocks were intruded ca. 109-103 Ma ago, during the final stages of regional metamorphism and deformation. The temporal association of the intrusions with the gold event has led most workers to define Pogo as an intrusion-related gold system. However, many features of the deposit suggest that it is similar to typical orogenic gold deposits and a genetic relationship to magmatism is far from conclusive (Goldfarb et al., 2005).

The largest reduced intrusion-related deposit in Alaska is the Fort Knox deposit, about 25 km northeast of Fairbanks. At Fort Knox the gold occurs in steeply-dipping, commonly sheeted, quartz-K-feldspar veins, and in planar quartz veins that occur along later gently- to moderately-dipping shear zones cutting the 92.5 Ma variably porphyritic, moderately reduced, monzogranite to granodiorite Vogt stock that intrudes the Proterozoic to middle Paleozoic Fairbanks schist. The reduced nature of the stock is manifest in a low magnetic susceptibility and an Fe_2O_3/FeO ratio of 0.15-0.30 (Hart et al., 2004).

The sheeted veins have clear to gray quartz and K-feldspar grains that were deposited by a magmatic-hydrothermal fluid. The density of the sheeted veins strongly controls the ore grade. The veins generally fill northwest-striking, shallowly to moderately southwest dipping shear zones, and individual veins range in width from 0.3-1.5 m. High fineness gold in the veins

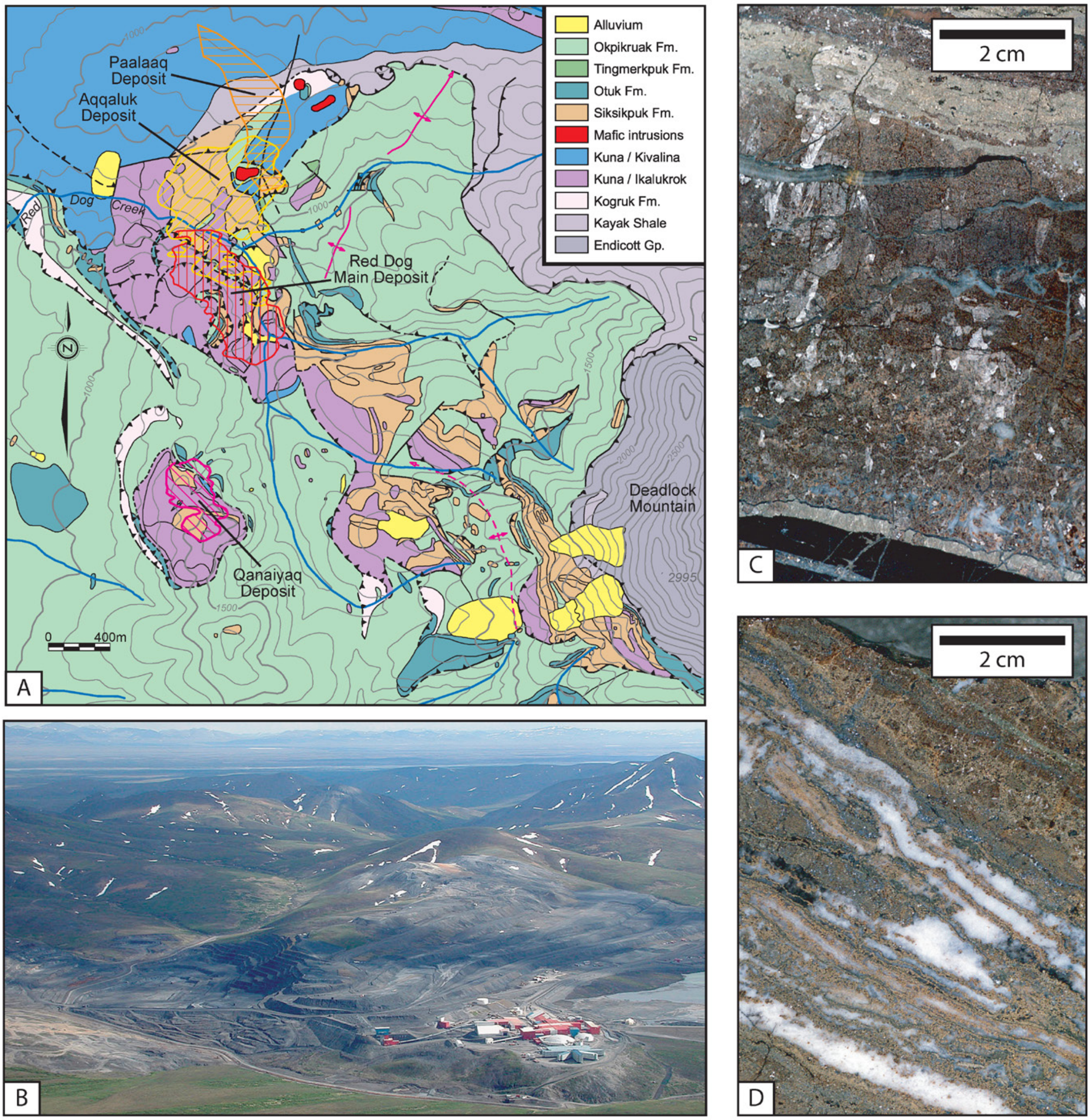


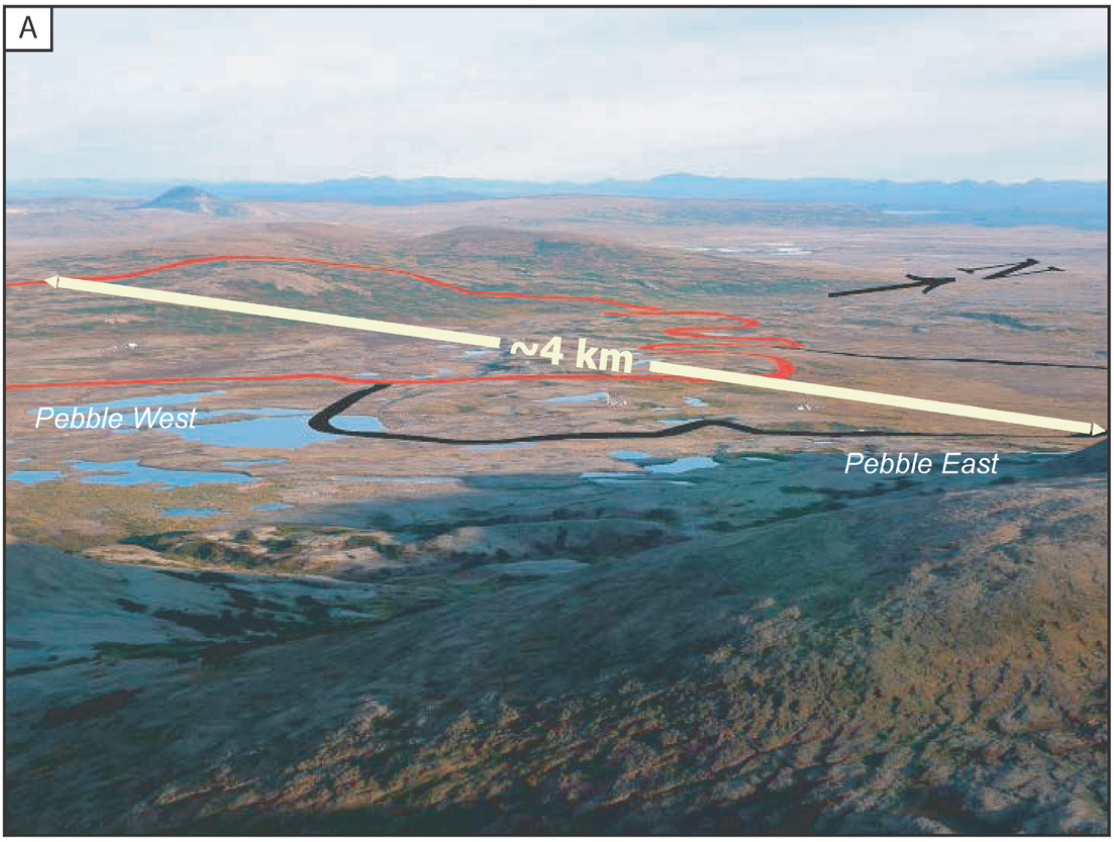
Figure 5. A) Geologic map of the area hosting the Red Dog deposits: Qanaiyaq, Main, Aqqaluk, and Paalaaq. Modified from Kelley and Jennings (2004). B) Aerial photo of Red Dog mine. C) Vein ore at Red Dog. D) Massive sulfide ore at Red Dog. Photos 16C and 16D courtesy of Karen D. Kelley.

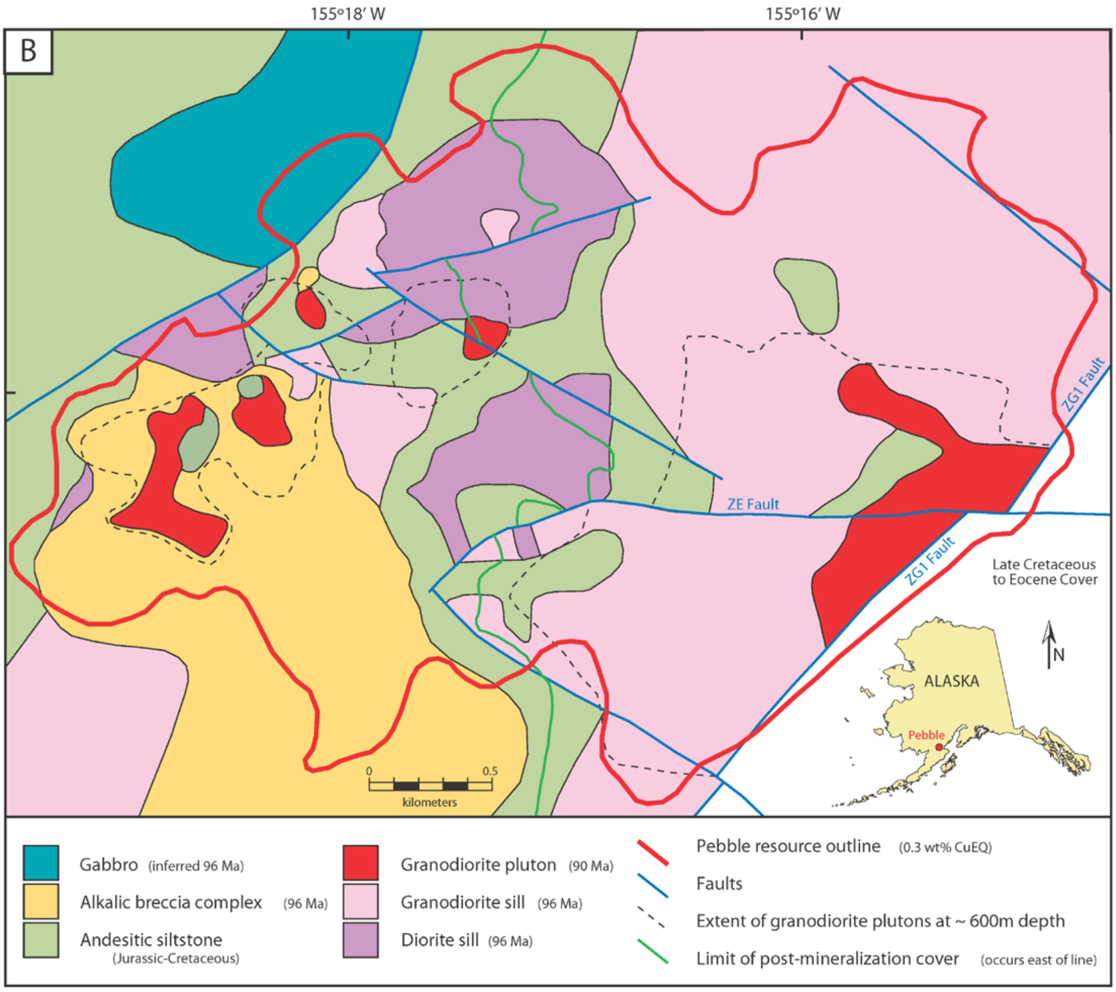
is commonly intergrown with native bismuth, bismuthinite, and tellurobismuth. Total sulfide volume is typically much less than 1 % and bismuthinite is commonly the most abundant sulfide phase in the veins. Other minor sulfides include pyrite, pyrrhotite, arsenopyrite, and molybdenite. Alteration phases include K-feldspar, albite, biotite, sericite, and ankerite; they generally define haloes surrounding veins of only a few centimeters.

Clastic-dominated Pb-Zn (SEDEX) deposits

Red Dog is one of the world's largest clastic-dominated Pb-Zn type deposits. The mine at Red Dog has recovered ore from two orebodies or deposits: the Main deposit (mined out in 2012) and the Aqqaluk deposit (currently being mined). The Qanaiyaq (or Hilltop) and Paalaaq deposits are potential sources of near-term higher-grade ore to supplement the reserves currently being mined from the adjacent Aqqaluk pit (Figures 5A, 5B). The four deposits at Red Dog have a cumulative reserve and resource of

Figure 6. A) The location of the giant Pebble Cu-Au-Mo porphyry deposit, in largely concealed terrain, showing the surface expression of the Pebble West Zone (red outline) and Pebble East Zone (black outline) in southern southwestern Alaska (from Gregory et at., 2013).
B) Geologic map of the ca. 90 Ma Pebble porphyry deposit. Courtesy of Karen Kelley, USGS.





140.6 Mt of 16.6 % Zn and 4.6 % Pb. Also within the broader Red Dog district are important unmined resources of Zn+Pb at Su-Lik and Anarraaq. A recent estimate indicates a combined pre-mining estimate for all district deposits of 171 Mt containing 15.7 % Zn, 4.5 % Pb, and 82.6 g/t Ag (Blevings et al., 2013). Numerous barite bodies, some associated with the Zn-Pb deposit, are scattered throughout the district and include an estimated 1000 Mt of barite at Anarraaq.

The Pb-Zn ores are mainly hosted in non-metamorphosed, fine-grained Mississippian clastic rocks, turbiditic carbonate rocks, and chert at the top of the Kuna Formation within the Lisburne Group. The clastic rocks include black siltstone, and siliceous and carbonaceous mudstone and shale. Deposition occurred in a late Early to Late Mississippian anoxic to euxinic basin isolated from the open ocean with limited siliciclastic input and significant amounts of organic carbon; carbonate turbidites derived from adjacent carbonate platforms are locally present in the Kuna Formation.

Ore minerals in the Zn-Pb-Ag deposits of the Red Dog district include sphalerite, galena, pyrite, and marcasite (Kelley et al., 2004b). Copper-bearing sulfide phases are rare. Barite and quartz are the main gangue phases in the Red Dog ore. Mineralization styles for the base metal sulfides include vein (Figure 5C), massive (Figure 5D), breccia, and disseminated. The Red Dog deposit ores are very coarse-grained and may be brecciated, whereas deposits such as Anaarraq and Lik-Su are predominantly characterized by extremely fine-grained sulfide layers. Due to post-mineralization deformation during the Brookian orogeny, the Red Dog deposits are structurally separated in a series of thrust slices of siliceous shale and chert.

Porphyry Cu deposits

The giant Pebble Cu-Au-Mo, located 320 km southwest of Anchorage and just south of 60°N (59° 53' 50″ N) contains the largest gold endowment of any porphyry deposit in the world (3033 t Au grading 0.35 g/t), and is associated with ca. 90 Ma intrusive bodies of the Kaskanak batholith emplaced into the Jurassic-Cretaceous Kahiltna flysch (Figure 2). It may have been the northernmost of a series of porphyry deposits formed along the landward margin of the Wrangellia composite terrane in the mid-Cretaceous many hundreds of kilometers south of their present latitude (Figure 2); other deposits are exposed in the high elevations of the eastern Alaska Range. The Pebble deposit formed during 10 million years of magmatism, beginning with emplacement of granodiorite and diorite sills, early alkalic intrusions and related breccias, and finally intrusion of the 90 Ma subalkalic granodiorite Kaskanak batholith, with those rocks along the batholith margin hosting the mineralization. Lang et al. (2013) suggest the large size of the deposit, as well as its high-grade hypogene ore, reflect multiple episodes of magmatic-hydrothermal events, an effective synhydrothermal fault zone for fluid focusing, and overlying hornfels zones in the flysch forming an aquitard to the upward fluid movement.

The Pebble deposit is divided into the Pebble East Zone and Pebble West Zone, which define two associated hydrothermal centers with the east zone dropped 600-900 m in a graben (Kelley et al., 2013). Pebble West extends from the near surface to 500 m depth, whereas Pebble East, below 300-600 m of Late Cretaceous to Eocene sedimentary and volcanic rock cover, continues to depths below 1700 m. There is a small zone of supergene mineralization above the West Zone orebody, but generally all ore is hypogene. The chalcopyrite ± bornite, pyrite, free gold, and electrum are associated with potassic and sodic potassic alteration, with a kaolinite and illite alteration event redistributing the metals.

Future potential

Alaska's relatively short history of mineral exploitation, barely more than 100 years, and the reconnaissance nature of geologic knowledge for much of the State allow the possibility of major undiscovered ore deposits. The known very large ore deposits have been discovered relatively recently (since ~1970) and in the case of the Fort Knox gold deposit, represent a new, previously unexpected mineral deposit type. It is likely that other major metallic mineral resources remain to be discovered in this region of extremely complex and prospective geology. The known large deposits north of 60°N are base- and precious metal deposits, as are the vast majority of known mines and prospects. For much of modern history, gold has been an important driver of mineral exploration in Alaska, yet a number of the very large deposits, for example Red Dog, are base metal deposits containing little or no gold.

The major known metallogenic provinces, for example those hosting the polymetallic base metal deposits of the Brooks Range and eastern Alaska, and the more widespread gold and porphyry deposits spread across different parts of Alaska, reflect ores formed in quite different temporal and tectonic environments. The VMS and clastic-dominated lead-zinc provinces reflect largely stratabound Paleozoic mineralization formed in ocean basins that is overprinted in many cases by mid-Cretaceous metamorphism. The gold provinces throughout much of Alaska and porphyry belts in the southern part of the State primarily reflect mid-Cretaceous to Eocene tectonism along active continental margins. Both metamorphism and magmatism may have been significant in the formation of various lode gold deposits; erosion of lodes has led to many large and productive placer gold fields.

Major brownfield and greenfield discoveries are both likely to be part of Alaska's exploration future. Brownfield developments will be highly influenced by socioeconomic issues. The Fort Knox deposit, for example, was explored and developed at the site of a gold occurrence known for almost 100 years, but a favorable infrastructure near the town of Fairbanks and a local population that mainly supported the nearby mining activity were critical for success. Giant mineral deposits are now recognized at Donlin Creek, Money Knob, and Pebble, but issues of infrastructure, metal price, and (or) potential environmental effects are impacting their additional exploration and potential development. The successful model of sustainable resource development in the Red Dog district, with beneficial inclusion of the Native Alaskans in all stages of activity, provides an example that could be followed for future mining of other large tonnage deposits in many parts of the State. Pebble and Pogo represent recent greenfield exploration successes that indicate numerous giant deposits still remain to be discovered throughout Alaska, particularly in the relatively poorly understood areas of extensive young cover. State-of-the-art approaches in exploration geochemistry, remote sensing, and particularly geophysical methods will be required for better defining geology and structure in many of these areas of cover and identifying the most favorable areas for discovery of important resources.

MINERAL DEPOSITS OF ARCTIC CANADA[3]

Geological outline

The following description gives a brief overview of the geological setting for mineral deposits of Arctic Canada, divided into:

- The cratons or granitic and metamorphic roots of the Canadian Shield which contain many of the deposits of gold, copper, nickel, iron, uranium, rare earth elements and diamonds.
- The bounding Mesoproterozoic to Phanerozoic platforms, basins and accreted terrains of the Canadian Cordillera which extend into the High Arctic and contain many of the deposits of zinc, lead, gold, silver, copper, molybdenum and tungsten.

The Canadian Shield contains four Archean cratons (Figure 1):

- The Slave craton (4030-2550 Ma) which lies to the northwest and is bound by Paleoproterozoic mountain belts (orogens), the Thelon-Taltson orogen to the east and the Wopmay orogen to the west. The Slave craton is associated with orogenic gold, volcanogenic massive sulphides (VMS), diamond-rich kimberlites and a large rare earth mineral deposit.
- The Rae craton (3250-2580 Ma) and the Hearne craton (2740-2540 Ma) which lie to the east, underlying most of the remaining parts of the Canadian shield across the Canadian Arctic. The Neoarchean Rae craton includes supracrustal rocks containing important resources of iron, orogenic gold of Paleoproterozoic age, uranium associated with a sub-Paleoproterozoic unconformity, nickel and commercially significant diamondiferous kimberlites. Deposits in the Hearne craton include nickel, copper, platinum group elements (PGE), uranium, VMS and one large orogenic gold deposit (Meliadine).
- The Superior craton is mostly located S of 60°N but is also exposed in the northern extremity of Quebec. It is bound to the north by the Paleoproterozoic Cape Smith belt (1870–1800 Ma), part of the circum-Superior Trans-Hudson orogen. This belt is noted for its magnesium-rich rocks which contain important resources of nickel, copper and platinum group minerals.

The other significant Paleoproterozoic belt is represented by the Wopmay orogen (1890-1840 Ma) which lies west of the Slave Craton. This features an eastern sedimentary belt and, to the west, the plutonic and volcanic rocks of the Great Bear batholith. The latter contains noteworthy resources including iron-oxide copper gold (IOCG), polymetallic veins and vein uranium.

The Precambrian cratons and Paleoproterozic basins are fringed to the north and west by widespread shelf carbonates, deposited in the period from the Mesoproterozoic through the upper Paleozoic. These rocks contain carbonate-hosted zinc-lead deposits. This realm also contains iron deposits, notably the very large Crest deposit in Neoproterozoic strata. The shelf carbonate succession gives way southwestwards to the Cambrian to Devonian deep-water sediments of Selwyn Basin, including shale, chert, carbonate and turbidites. Important resources include shale-hosted zinc-lead mineralizations of which there are three large deposits in the Yukon. The Selwyn Basin also includes two significant VMS copper-zinc deposits.

[3] Written by J. C. Harrison Natural Resources Canada, Geological Survey of Canada (GSC)

Table 1: Overview of the very large and large deposits in Canada, north of 60°

Deposit	Status	Size	Genetic type	Main metals	Total tonnage - Mt (Mined)	Grades
Andrew Lake	Not exploited	Large	Unconformity	U	7.67	0.23 % U3O8
Casino	Not exploited	Very large	Porphyry (Cu, Au,Mo, W, Sn, Ag)	Cu, Mo, Au, Ag	2752.6	0.16 % Cu, 0.02 % Mo
Coffee	Not exploited	Large	Orogenic gold	Au	92.95	1.4 ppm Au
Con Mine	Closed mine	Large	Orogenic gold	Au	10.7 (10.7)	17.1 ppm Au
Courageous Lake	Renewed exploration	Large	Orogenic gold	Au	156.448 (0.17)	2.3 ppm Au
Crest	Not exploited	Very large	Stratiform iron	Fe	3200	43.0 % Fe
Faro Mine	Closed mine	Large	Sedimentary exhalative	Zn, Pb, Ag (Au)	58 (53.186)	5.0 % Zn, 3.4 % Pb, 33 ppm Ag, 0.3 ppm Au
Ferguson Lake	Not exploited	Large	Magmatic Ni-Cu-PGE	Ni, Cu (Co, Pt, Pd)	46	0.7 % Ni, 1 % Cu, 0.06 % Co, 1.3 ppm Pd, 0.2 ppm Pt
Gayna River	Not exploited	Large	MVT to Irish type Pb-Zn	Zn, Pb (Ga, Ge, Ag)	50	4.7 % Zn, 0.3 % Pb
Giant Mine	Closed mine	Large	Orogenic gold	Au	15.5 (15.5)	15.8 ppm Au
Golden Revenue	Not exploited	Large	Epithermal gold, plus porphyry	Au, Ag (Cu, Mo)	231.96	0.08 % Cu, 0.02 % Mo, 2.0 ppm Ag, 0.4 ppm Au
Goose	Not exploited	Large	Orogenic gold	Au	24.76	6.4 ppm Au
Hackett River	Not exploited	Very large	VMS	Zn, Pb, Cu, Ag (Au)	82	3.8 % Zn, 0.5 % Pb, 0.4 % Cu, 144 ppm Ag, 0.23 ppm Au
Hasselberg	Not exploited	Large	VMS	Zn, Pb, Ag	4.1	6.2 % Zn, 1.8 % Pb, 84 ppm Ag
High Lake	Not exploited	Large	VMS	Zn, Cu, Pb (Ag, Au)	14	3.8 % Zn, 0.4 % Pb, 2.5 % Cu, 84 ppm Ag, 0.2 ppm Au
Howards Pass	Not exploited	Large	Sedimentary exhalative	Zn, Pb	388.5	4.9 % Zn, 1.6 % Pb
Izok Lake	Not exploited	Large	VMS	Zn, Cu, Pb (Ag, Au)	14.6	13.1 % Zn, 1.4 % Pb, 2.3 % Cu, 73 ppm Ag, 0.2 ppm Au
Keno Hill Silver	Active mine	Large	Ag-Pb-Zn veins	Ag (Pb, Zn)	7.214 (4.847)	4.4 % Zn, 5.3 % Pb, 1107 ppm Ag
Kudz Ze Kayah	Not exploited	Large	VMS	Zn, Pb, Cu (Ag, Au)	14.55	5.6 % Zn, 1.5 % Pb, 0.9 % Cu, 121 ppm Ag, 1.3 ppm Au
Logtung	Not exploited	Large	Porphyry (Cu, Au,Mo, W, Sn, Ag)	W, Mo	424.6	0.08 % W, 0.03 % Mo
Lupin Mine	Closed mine	Large	Orogenic gold	Au (Ag)	12.83 (11.73)	10 ppm Au
Mactung	Not exploited	Large	Skarn (Zn-Pb-Ag, Cu, Au, Fe, W)	W	44.886	0.73 % W
Mary River 1	Active mine	Large	Algoma-style iron formation	Fe	631	66.5 % Fe
Mary River 2 & 3	Not exploited	Large	Algoma-style iron formation	Fe	362	65.9 % Fe
Meadowbank Mine	Active mine	Large	Orogenic gold	Au	27.407	3.3 ppm Au
Meliadine	Not exploited	Large	Orogenic gold	Au	48.273	6.5 ppm Au
Minto	Active mine	Large	IOCG to porphyry	Cu (Au, Ag)	110.144 (53.72)	1.7 % Cu, 4.9 ppm Ag, 0.6 ppm Au
Nanisivik Mine	Closed mine	Large	MVT to Irish type Pb-Zn	Zn, Pb (Ag)	17.525 (17.524)	9.0 % Zn, 0.7 % Pb, 41 ppm Ag
Nechalacho	Not exploited	Large	Peralkaline rock-associated rare metals	REE	304.63	2335 ppm Nb, 1.18 % REE, 196 ppm Ta, 1.81 % Zr
Nickel King	Not exploited	Large	Magmatic Ni-Cu-PGE	Ni, Cu (Co)	44.172	0.4 % Ni, 0.09 Cu, 0.02 % Co
Nunavik Mine	Active mine	Large	Magmatic Ni-Cu-PGE	Ni, Cu (Co, Pt, Pd)	27.146	0.9 % Ni, 1.1 % Cu, 0.05 % Co, 2.2 ppm Pd, 0.5 ppm Pt
Pine Point	Closed mine	Large	MVT to Irish type Pb-Zn	Zn, Pb	100.96 (64.26)	5.6 % Zn, 2.5 % Pb
Polaris Mine	Closed mine	Large	MVT to Irish type Pb-Zn	Zn, Pb	20.107 (20.107)	13.4 % Zn, 3.6 % Pb
Prairie Creek	Not exploited	Large	MVT to Irish type Pb-Zn	Zn, Pb (Ag)	11.67	12.8 % Zn, 10.9 % Pb, 0.5 % Cu, 197 ppm Ag
Raglan Mine	Active mine	Large	Magmatic Ni-Cu-PGE	Ni, Cu (Pt, Pd)	42.03 (6.89)	3.2 % Ni, 0.9 % Cu
Red Mountain	Not exploited	Large	Porphyry (Cu, Au,Mo, W, Sn, Ag)	Mo	187	0.1 % Mo
Roche Bay C	Not exploited	Large	Algoma-style iron formation	Fe	567.3	26.4 % Fe, 0.09 % P2O5
Tom and Jason	Not exploited	Large	Sedimentary exhalative	Zn, Pb, Ag	30.99	6.6 % Zn, 3.8 % Pb, 39 ppm Ag
Wellgreen	Renewed exploration	Large	Magmatic Ni-Cu-PGE	Ni, Cu, Pt, Pd (Co, Au)	461.28 (0.17)	0.3 % Ni, 0.3 % Cu, 0.02 % Co, 0.3 ppm Pd, 0.4 ppm Pt
West Raglan	Not exploited	Large	Magmatic Ni-Cu-PGE	Ni, Cu (Pt, Pd)	10	2 % Ni
Wolverine Mine	Active mine	Large	VMS	Zn, Cu, Pb, Ag (Au)	6.154	12.2 % Zn, 1.6 % Pb, 1.2 % Cu, 363 ppm Ag, 1.7 ppm Au

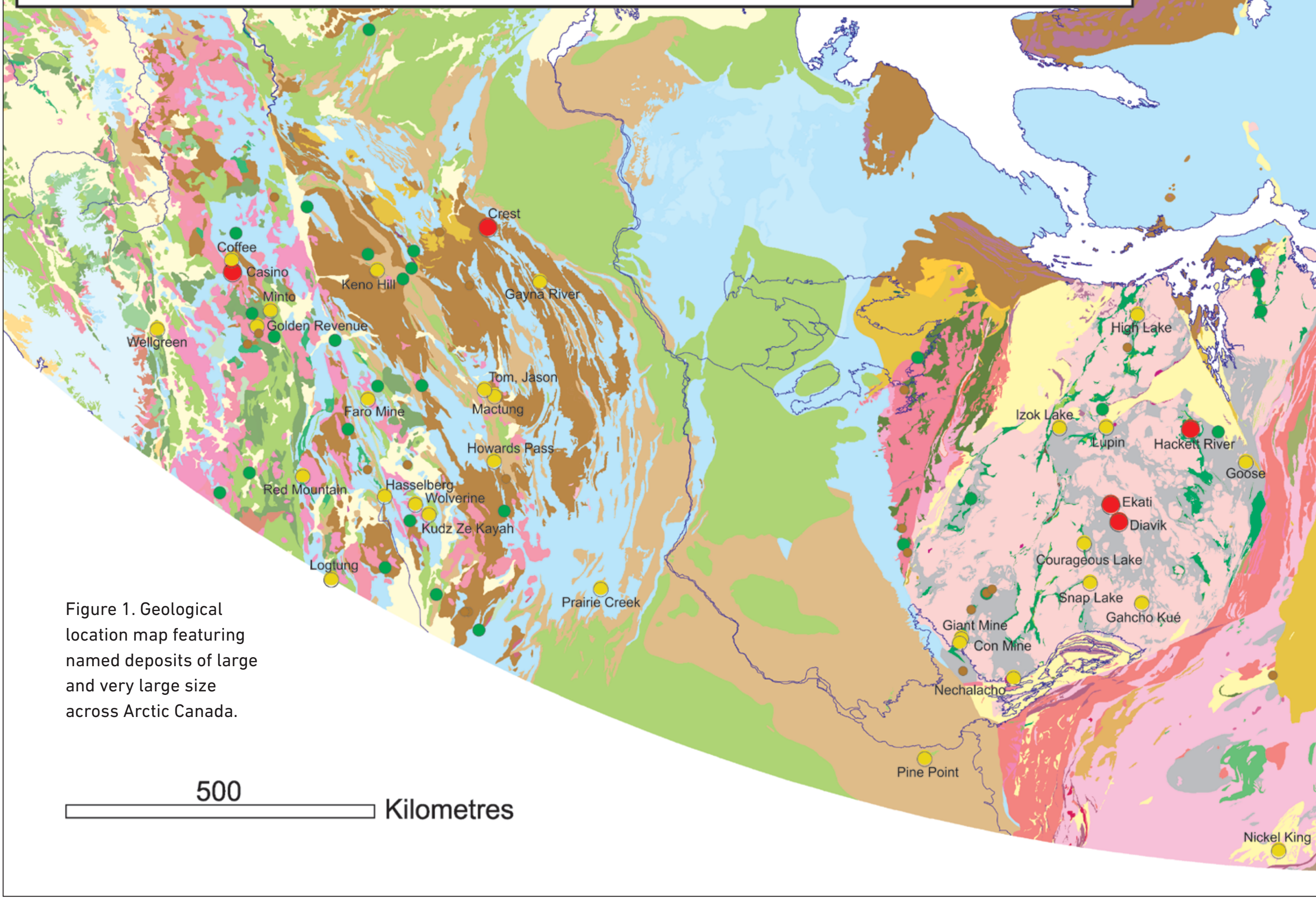
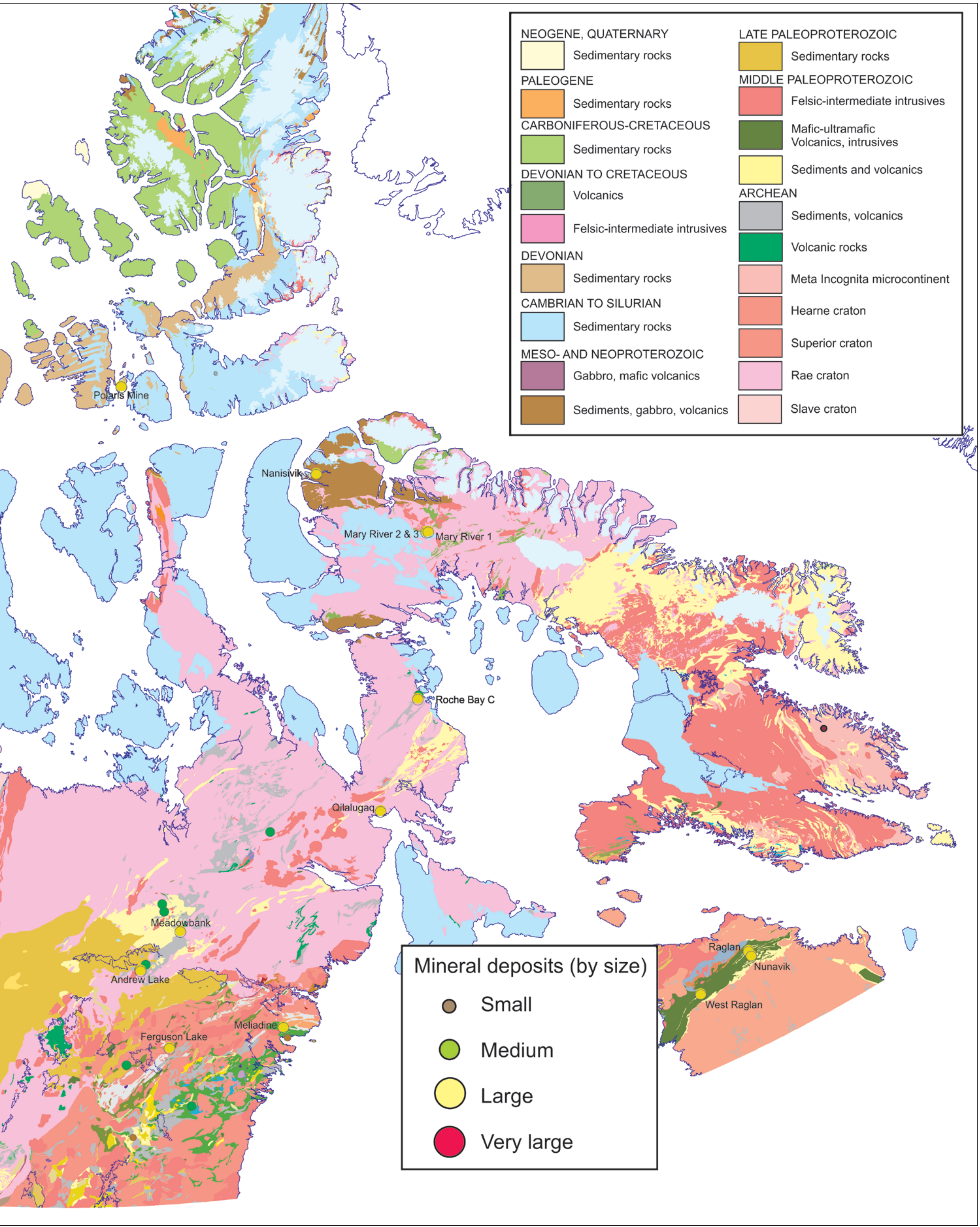


Figure 1. Geological location map featuring named deposits of large and very large size across Arctic Canada.


NEOGENE, QUATERNARY
Sedimentary rocks
PALEOGENE
Sedimentary rocks
CARBONIFEROUS-CRETACEOUS
Sedimentary rocks
DEVONIAN TO CRETACEOUS
Volcanics
Felsic-intermediate intrusives
DEVONIAN
Sedimentary rocks
CAMBRIAN TO SILURIAN
Sedimentary rocks
MESO- AND NEOPROTEROZOIC
Gabbro, mafic volcanics
Sediments, gabbro, volcanics
LATE PALEOPROTEROZOIC
Sedimentary rocks
MIDDLE PALEOPROTEROZOIC
Felsic-intermediate intrusives
Mafic-ultramafic Volcanics, intrusives
Sediments and volcanics
ARCHEAN
Sediments, volcanics
Volcanic rocks
Meta Incognita microcontinent
Hearne craton
Superior craton
Rae craton
Slave craton
Polaris Mine
Nanisivik
Mary River 2 & 3
Mary River 1
Roche Bay C
Qilalugaq
Meadowbank
Andrew Lake
Meliadine
Ferguson Lake
Raglan
Nunavik
West Raglan
Mineral deposits (by size)
Small
Medium
Large
Very large

The western part of the Yukon is dominated by Jurassic and Cretaceous accreted terranes and by associated granitic to intermediate intrusive rocks. This is a key realm for gold, polymetallic silver-lead-zinc veins and nickel-copper-PGE. The Mesozoic intrusives include tungsten and copper skarns, and copper-molybdenum porphyries. The many resources of the Yukon also encompass eleven gold placer districts of which the Klondike is most significant.

History of Mining

The history of mining in Arctic Canada has its beginnings in the search for placer gold in the Yukon. Prospecting revealed gold along the Yukon River as early as 1883, but a report by George Dawson (Geological Survey of Canada; GSC) identified the unglaciated areas of west central Yukon as having the greatest potential. Significant gold was discovered in the river gravels of Bonanza Creek in August 1896. This became widely known and by July 1897 there was a major gold rush into the Klondike from the west coast of the USA and from many parts of Canada. In total 30,000 to 40,000 would-be miners entered the region from 1897 to 1899.

Prospecting for gold led to discoveries of other types of hard-rock deposit. These included copper at Carmacks, Yukon (1887) and silver-lead-zinc at Keno Hill (1901). Further afield there were new indications of nickel mineralization in northern Quebec (1898), gold along the Yellowknife River on the north side of Great Slave Lake (1898), zinc and lead at Pine Point south of Great Slave Lake (1899) and of copper, uranium and cobalt at Port Radium on the east side of Great Bear Lake (1900). The carbonate-hosted deposits at Pine Point were low in silver and thus of limited interest to the mining community at the time of the discovery. The area became commercially viable 66 years later.

The introduction of float planes in the 1920s gave a major boost to exploration, allowing large areas of remote country to be accessed as never before and contributing significantly to the discoveries of the 1930s. This led to the discovery of high grade pitchblende and silver ore in 1930 at what would become the Eldorado mine. Production at Eldorado began in 1933 and continued, with some interruptions, to 1982.

Renewed prospecting, near Yellowknife in the early 1930s, led to the discovery of the Giant and Con gold deposits in 1935 and to the establishment of the town of Yellowknife in 1936. As many as five mines were operating in the late 1930s. The outbreak of World War II brought much of this activity to an end but significant mining began again after the war. Other gold properties, elsewhere within the Slave craton, were established in this period, including Courageous Lake (1944) and Lupin (1960).

The 1950s were an especially active period for nickel exploration across Arctic Canada. Follow-up of discoveries in Ungava, Quebec led to the discovery of the Raglan deposit (1956) and the Nunavik property (1957). West of Hudson Bay new prospects were found at Ferguson Lake (1950), at Nickel King (1952) and in the southwest Yukon at Wellgreen (1952). New discoveries of metasomatic skarn mineralization were also made in this period. Skarn-related copper had been found at Whitehorse as early as 1897. Tungsten skarns were delineated near the Yukon-Northwest Territories border at Cantung in 1954 followed by Mactung in 1962.

Discoveries in the 1960s included iron at Snake River, Yukon (Crest: 1961), at Mary River in northern Baffin Island (1965) and at Roche Bay on Melville Peninsula (1968-1970). This period was also noteworthy for the exploration for porphyry copper-molybdenum in the Yukon. This led to discoveries at Red Mountain (1967) and Casino (1967), which precipitated a staking rush, and later to the discovery of the Logtung tungsten-molybdenum deposit (1976). New properties associated with iron oxide-copper-gold (IOCG) mineralization were discovered at this time, including the Minto deposit (1971), Yukon. Carbonate-hosted zinc-lead deposits also became commercially viable in this period, notably Pine Point (1965), Polaris on Little Cornwallis Island in the Arctic (1970), Gayna River (1974) and Nanisivik on Baffin Island (1976). Also noteworthy were discoveries of shale-hosted (SEDEX) zinc-lead deposits including Anvil (1953, 1965), Tom and Jason (1951, 1974) and especially the large Howard's Pass deposit (1972). This latter announcement precipitated a major staking rush across the central Yukon. Volcanogenic massive sulphides (VMS) were also being discovered in the Yukon: Hasselberg

(1955), and in the Slave craton, notably Hackett River (1966).

The latest significant development in the mining history of Arctic Canada has been the discovery of commercially important diamond-bearing kimberlites. This was the vision of two men, Charles Fipke and Stewart Blusson, who tracked kimberlite indicator minerals extracted from Quaternary glacial river channels (eskers) and in so doing pin-pointed the favourable kimberlite source in bedrock near Lac de Gras in the central Slave craton. This was an endeavor of ten years, ending with drilling of the first diamond-bearing kimberlite in 1991. The announcement of their discovery precipitated one of the biggest staking rushes in Canadian history. As well as the original Ekati property, kimberlite prospects of economic significance were located at Snap Lake (1994), Diavik (1995), Qilalugaq (2000-2005), and Chidliak (2005).

Summary description of major deposits

Neoarchean iron

Two large Neoarchean iron deposits are located in the Rae craton of northeastern Nunavut. The Mary River deposit is located 1000 km NW of Iqaluit on northern Baffin Island. The second major deposit is the Roche Bay iron deposit located 60 km SW of the settlement of Sanirajak on eastern Melville Peninsula.

Iron ore of commercial significance was proven by drilling at Mary River as early as 1965. There was no new interest until 2004 when additional drilling was completed. A revised estimate of the undeveloped resource was made available in 2006 (631 Mt grading 66.5 % Fe; 362 Mt grading 65.9 % Fe). The current owner is Baffinland Iron Mines Corporation. The Mary River group is named for a group of metasedimentary outliers in the northwestern part of Baffin Island. The thickness of the Mary River Group in the vicinity of the iron deposits is considered to be of the order of 2000-4000 m. The greatest thickness of iron formation occurs in the vicinity of the ore bodies: 52-195 m thick and traceable for up to 3.8 km. The nine ore zones are, however, generally lenticular in shape. Mining began in 2015 with production of 18 Mt/a from the No.1 deposit. The ore is sufficiently high grade that no processing is required prior to shipping. At present the mined ore is trucked to the north coast of Baffin Island. However, plans for shipment by rail to the south coast are still considered feasible. Ice-breaking freighters are intended to remove ore from Baffin Island at a frequency of one every two days year-round.

Neoarchean volcanogenic massive sulphide

Three volcanogenic massive sulphide (VMS) deposits are located in the northern part of the Slave craton of western Nunavut. The large Izok Lake deposit (14.6 Mt grading 2.3 % Cu, 13.1 % Zn, 1.4 % Pb, 0.2 ppm Au and 73 ppm Ag) in the northwestern Slave is 265 km S of Coronation Gulf. The Hackett River deposit (82 Mt grading 0.4 % Cu, 3.8 % Zn, 0.5 % Pb, 0.2 ppm Au and 144 ppm Ag) in the Hackett River volcanic belt of the northeastern Slave is 485 km NE of Yellowknife. The large High Lake deposit (14 Mt grading 2.5 % Cu, 3.8 % Zn, 0.4 % Pb, 0.2 ppm Au and 84 ppm Ag) in the High Lake volcanic belt of Nunavut is located in the northern Slave craton 40 km S of Coronation Gulf.

The Hackett River gossans were discovered in 1956 but significant mineralization was not located until 1969. Airborne and ground geophysics, and other ground-based activities by Cominco Ltd. and Sabina Gold and Silver Corp., followed by drilling through to 2012, outlined a resource of 82 Mt containing significant zinc, lead, copper, gold and silver. In total there are four deposits at Hackett River, specifically the Main, Jo, Boot Lake and East Cleaver zones. Host rocks typically include tuff, breccia, and volcaniclastic sediments with sills of dacitic and andesitic composition. Sulphide zones include a conduit facies associated with a funnel-shaped fumarole and overlying volcanogenic massive sulphides containing pyrite, chalcopyrite, pyrrhotite, sphalerite and galena.

The High Lake belt, 70 km in strike length and 5-25 km wide, is divided into a central metasedimentary belt bound to the east and west by volcanic domains. The volcanic domains are dominated by intermediate and felsic volcanic rocks and sandy rocks of volcanic origin with an age range of 2705-2695 Ma. Iron oxide zones (gossans), massive sulphides and gold occurrences are common. The High Lake property features lenses, pods and other deposits farther afield. The largest deposit is the AB zone which measures 200 x 600 m. Mineralization includes massive to semi-massive and stringer zone pyrite, pyrrhotite, chalcopyrite, sphalerite and minor galena. Additional phases include magnetite and minor hematite. Local textures include banded pyrite and cavities lined with drusy quartz, pyrite and chalcopyrite.

Neoarchean orogenic gold

Orogenic gold deposits of Neoarchean age are located in the Slave craton of the Northwest Territories. The Giant mine (15.5 Mt grading 15.8 ppm Au) is located on the west side of Yellowknife Bay on the north shore of Great Slave Lake. It occurs in the northerly-striking Yellowknife volcanic belt. Giant, together with the nearby Con mine (10.7 Mt grading 17.1 ppm Au), are the largest gold deposits of the Slave craton (followed in size by Goose Lake: 24.8 Mt of 6.3 ppm Au, Courageous Lake: 156.5 Mt of 2.3 ppm Au, and Lupin: 12.8 Mt of 10.1 ppm Au). Although separated by faulting, the Giant and Con deposits are generally considered to be parts of a single ore deposit.

Gold was produced from the Giant mine near Yellowknife from 1948 to 2004. Gold-bearing shear zones occur in the Yellowknife Bay Formation (2710-2700 Ma) and in felsic tuffs and porphyries of the Townsite Formation. Lode gold also occurs in the younger Jackson Bay Formation (metasediments) and in the overlying Banting Group (2670-2660 Ma; felsic tuff and mafic volcanics). The Giant mine is bound on three sides by faults and to the east are Banting Group and Jackson Bay Formation. The Giant Mine is classified as a quartz-carbonate, shear-zone hosted vein deposit. The mineralization occurs as: 1) bands of quartz and sulphides alternating with sericite-carbonate schist; 2) sericite-carbonate schist with matrix quartz and sulphides, and; 3) folded and fragmented quartz-carbonate veins.

Figure 2. Lupin: iron formation-hosted stratabound gold. Arsenic-rich gold-bearing sulphide iron formation showing sulphide-arsenide megacrysts distributed along bedding. Scale bar is 1 cm. GSC 1995-201A;

Gold was discovered in the Lupin area by Canadian Nickel Company (Canico) staff in 1960, and was mined underground by Echo Bay Mines Limited from 1984 to 2004. The site is now (as of 2012) being prepared for renewed mining by Elgin Mining Inc. Five ore zones are confined to metamorphosed iron formation and the deposit is identified as iron-formation- hosted lode-gold type. The iron formation includes silicate, sulphide and oxide types. The Lupin iron formation has been traced for 3 km and to a depth of 1500 m. The host rock is hornblende-quartz-chlorite-native gold ± pyrrhotite, arsenopyrite and loellingite in the ore zones (Figure 2). In general, there are 5 – 30 % sulphides in areas of mineralization. Characteristic dimensions of the ore zones are West zone: 220 m long x 2.5 m thick; West zone South: 300 m x 2.0 m; Central zone: 225 m x 5 m thick. The M1 and M2 zones are largely mined out but down-dip potential remains.

Paleoproterozoic rare earth deposit

Uranium claims on the north shore of Great Slave Lake were first registered on the Thor Lake property in 1970. Niobium (Nb) and tantalum (Ta) were subsequently found in 1976 by Highwood Resources Ltd. Property work and drilling from 1976 to 1979 resulted in the discovery of Nb, Ta, Y (yttrium) and rare earth elements (REE). The large Nechalacho deposit (304.6 Mt of 2335 ppm Nb, 196 ppm Ta, 1.2 % REE, 1.8 % Zr), not yet mined, is located in the Blatchford Lake Complex which is intrusive into the Slave craton N of the East Arm of Great Slave Lake. Based on cross-cutting relationships, three distinct late phases of intrusion are documented in the immediate vicinity of the deposits: Grace Lake granite, Thor Lake syenite (2177 Ma), and the Nechalacho layered suite (2164 Ma). The Nechalacho layered suite features nepheline, sodalite, rare mineral phases such as eudialyte (a zirconium silicate) and a so called “basal zone” which hosts the mineral deposits (Figure 3). Ore minerals (4.6 - 9.1 %) represent in part an alter-

Figure 3.
Nechalacho: Eudialyte pseudomorphs in foyaite (Basal Zone) (V. Moeller, McGill University).

ation assemblage and include allanite, monazite, bastnaesite and synchysite (sources of light REE), fergusonite (for Y, heavy REE, Nb, Ta), ferrocolumbite (Nb) and zircon (heavy REE, Nb, Ta, Zr).

Paleoproterozoic gabbro-hosted nickel-copper PGE

Canadian Nickel Company Ltd. (Canico) discovered nickel at Ferguson Lake in 1950. East and West zones were tested by drilling from 1950 to 1955, resulting in the discovery of significant resources to depths of 240 m. Ore zones, not yet exploited, were proven east and west of Ferguson Lake as well as under the lake. The host rocks of the magmatic Ni-Cu-PGE mineralization are gabbro and hornblendite. This same body is 10-600 m thick and traceable over a distance of 12 km. Better grades occur in lenses, pods and stringers (2 - 10s of metres thick) of massive to semi-massive ore consisting of 80-90 % pyrrhotite, lesser chalcopyrite, pyrite and pentlandite (46 Mt of 1 % Cu, 0.7 % Ni, 0.06 % Co, 0.2 ppm Pt, 1.3 ppm Pd). Platinum group minerals including tellurides, bismuthinides, and arsenides have also been found. Other textures include brecciated ores (gabbro clasts in a sulphide matrix), and net-textured ores noted in stringer and fracture-filling zones.

Paleoproterozoic ultramafic-hosted nickel-copper PGE

Large Ni-Cu-PGE deposits of commercial significance are located in Paleoproterozoic ultramafic rocks in the Cape Smith belt of northern Ungava (province of Quebec). The Cape Smith belt (2040 - 1860 Ma) has been interpreted as a stack of southerly transported thrust sheets consisting of quartzite, semipelite, ironstone and gabbro-peridotite in the lower part (Povungnituk Group) and basalt, and gabbro-peridotite in the upper part (Chukotat Group). Nickel-copper-PGE deposits are located primarily in Chukotat peridotite. The Raglan deposit (48.6 Mt of 0.9 % Cu, 3.2 % Ni) is described below. Similar features may be found in the West Raglan and Nunavik ore bodies.

Sporadic exploration has taken place in the Cape Smith belt and Raglan deposit area since the 1930s with the first high-grade showings discovered by prospectors in 1956. The predominant mined mineralization at Raglan is footwall-contact type composed of disseminated, net-textured and massive pyrrhotite, pentlandite and chalcopyrite, this contained in over 140 lenses located from the surface to a depth of 750 m. Lens sizes range from 0.01 - 5.2 Mt, averaging 0.2 Mt. The basal layer in each lens is typically massive, overlain by net-textured ore that grades into dis-

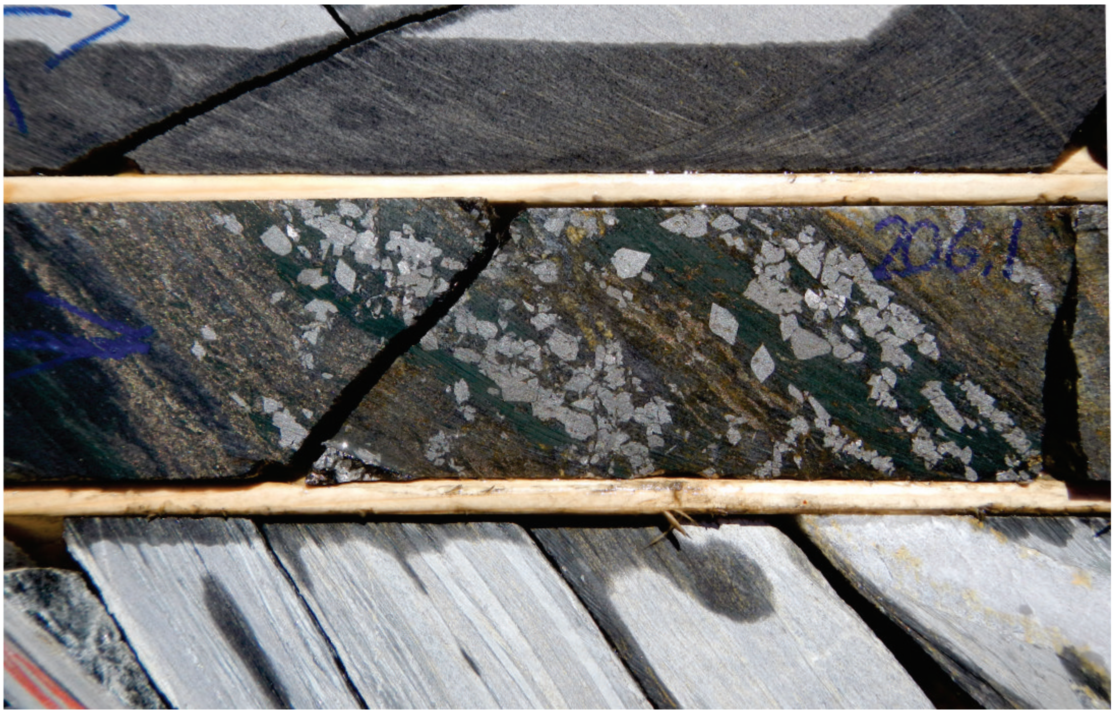


Figure 4. Meliadine: hydrothermally altered oxide facies iron formation adjacent to a cryptic and arseno-pyrite-rich quartz vein. GSC 2015-115.

seminated ore. Massive to semi-massive brecciated ore also occurs and consists of a mixture of footwall sediments and ultramafic rock. Ore lenses typically occur in embayments at the base of ultramafic sheets. Similarly, canoe-shaped intrusions feature keel zone sulphide lenses; size: 10s to 100s of metres in length. Mining began at Raglan in 1997. Mined ore is concentrated on-site and then shipped by freighter and train via Quebec City to the smelter at Sudbury.

Paleoproterozoic orogenic gold

Gold deposits of presumed or established Paleoproterozoic age are hosted in Neoarchean iron formation in the Rae and Hearne cratons of southwestern Nunavut. The large Meadowbank deposit in the Rae craton (27.5 Mt of 3.3 ppm Au) and the large Meliadine deposit (48.3 Mt of 6.5 ppm Au) of the Hearne craton, both located west of Hudson Bay, are described below.

The Meliadine deposit, not yet exploited, was discovered by prospecting and drilling between 1987 and 2004. It is located W of Hudson Bay within the Rankin Inlet volcanic belt, part of the Hearne craton. The gold deposits and showings are closely associated with the Meliadine trend, a WNW-trending belt of supracrustal rocks that includes a major structure, the Pyke break. This is a several kilometres wide high-strain zone that is spatially associated with seven known gold deposits. Ore emplacement is considered to have occurred during a third deformation phase in the Paleoproterozoic. In general, gold mineralization is associated with shearing and quartz veining during the Paleoproterozoic Trans-Hudson orogeny. Gold-hosting quartz occurs as veins several metres thick but these range downwards in size to erratic quartz stringers and stockwork. Typical vein mineralogy includes quartz, and quartz-iron carbonate. Primary sulphides introduced during mineralization occur in iron formation and argillite as wispy discontinuous laminae of pyrrhotite, pyrite, chalcopyrite and arsenopyrite (Figure 4). Sulphides are, however, not a reliable prerequisite for good gold grades.

Paleoproterozoic polymetallic veins

Host rocks for uranium and silver arsenide vein deposits lie within the Great Bear batholith (1870 - 1840 Ma). This is the western domain of the Wopmay orogen, a magmatic and collisional deformation belt that resulted from convergence of the Hottah terrane in the west with the Slave craton in the east. Included in this category of deposits are the Eldorado and Echo Bay mines near Port Radium on Great Bear Lake.

Silver and uranium deposits near Port Radium are located along the eastern shore of Great Bear Lake, Northwest Territories. These include the former Eldorado uranium and silver mine (1.82

Mt grading 0.12 % Cu, 0.01 % Pb, 137 ppm Ag, 0.01 % Ni, 0.1 % Co, 0.34 % U) and the Echo Bay silver deposit. Mining began at Eldorado in 1933 and production followed, more or less continuously, to 1982. Ore-deposit metals are associated with steep northeasterly-striking faults in andesitic deposits of the Great Bear magmatic zone. The earliest mineralizations of sparse chalcopyrite and pitchblende in quartz are seen to heal these brittle faults. These are then cut by 1740 Ma Cleaver diabase dykes. Post-Cleaver fault reactivation led to a total of five phases of mineralization as follows: Stage 1: pitchblende; stage 2: arsenides, nickel sulphides, native silver and native bismuth; stage 3: polymetallic sulphides and silver tellurides; stage 4: carbonates, native bismuth and some native silver; stage 5: native silver and bismuth.

Paleoproterozoic unconformity uranium

The undeveloped Kiggavik deposits are located 80 km W of Baker Lake in the Kivalliq region of Nunavut, in basement, but close to the unconformity under the Paleoproterozoic Thelon Basin. Exploration in the area has been ongoing since the 1970s. The Kiggavik Main Zone (KMZ) and two other deposits were discovered in 1974 by lake/water geochemical methods and by airborne radiometrics. The project now consists of five uranium deposits, three at Kiggavik and two at a separate location. Four of these deposits are to be mined by open pit, and one by underground methods. Other discoveries were subsequently made at Andrew Lake and Endgrid 15-17 km SW of Kiggavik. The deposits lie in basement just outside the Paleoproterozoic Aberdeen Sub-basin of the northeastern Thelon Basin. The host rock at Kiggavik is Neoarchean greywacke with minor iron formation and metapelite, unconformably overlain by 2600 Ma rhyolite (ore host) and early Paleoproterozoic quartzite (barren). The three ore zones discovered to date are the East (EZ), Main (KMZ) and Centre (CZ) zones. The largest is KMZ, hosted by greywacke and granite. Uranium ore minerals are arranged as fine disseminations, veinlets parallel to foliation and fracture fillings.

Iron-oxide copper gold (IOCG) deposits

These include the NICO deposit in the Great Bear batholith and Carmacks and Minto (both large) deposits located in the Canadian Cordillera of central Yukon. The NICO property is located in the vicinity of Mazenod Lake, 160 km NW of Yellowknife. Mineralization was discovered in the area in the 1930s. The first property work on known Co-Bi-Cu arsenide showings was by New Athona Mines Ltd from 1968 to 1970. Drilling uncovered the additional occurrence of gold. New discoveries were made by Fortune Minerals Ltd who acquired NICO in 1994, and recognized favourable analogies with the world-class Olympic Dam deposit in Australia. The host rock at NICO is brecciated clastic sediments and dolomite modified by introduced iron and potassium. These are interpreted as hydrothermal breccia pipes (there are other interpretations). The breccias have sediment and felsite clasts in a matrix of iron oxides, biotite, amphibole, chlorite and K-feldspar. The NICO deposit (30.9 Mt grading 1.12 ppm Au, 0.12 % Co), not yet exploited, is mostly contained within magnetite ironstone, schist and subarkosic wacke containing 3-10 % sulphides.

The Minto deposit (110 Mt grading 1.65 % Cu, 0.58 ppm Au, 5.0 ppm Ag) lies within the Yukon-Tanana terrane of the Canadian Cordillera, host of the Carmacks Copper Belt and several intrusion-related Cu-Au hydrothermal systems. Five mineralized zones are recognized. Primary mineralization consists of chalcopyrite, bornite, chalcocite, and other sulphides. Textures include disseminations and sulphide veinlets parallel to foliation. Grades increase in zones of intense folding. There are also massive and semi-massive sulphide zones which obliterate primary host rock fabrics. In the Minto Main deposit there is a zonation from bornite-rich (up to 8 %) in the west to chalcopyrite-rich but lower grade in the east. Precious metal grades are also higher in the bornite zone.

Stratabound base metal deposits

Stratabound deposits of the Canadian Cordillera of Yukon and Northwest Territories lie in platform and deep-water basin strata of Neoproterozoic to Carboniferous age range. These include iron deposits of Neoproterozoic and Jurassic ages, zinc-lead deposits hosted by Mesoproterozoic to Devonian shelf carbonates, zinc-lead deposits found in deep water sediments of Cambrian to Devonian age, and volcanic-hosted deposits formed in Paleoproterozoic to Mississippian volcanic rocks.

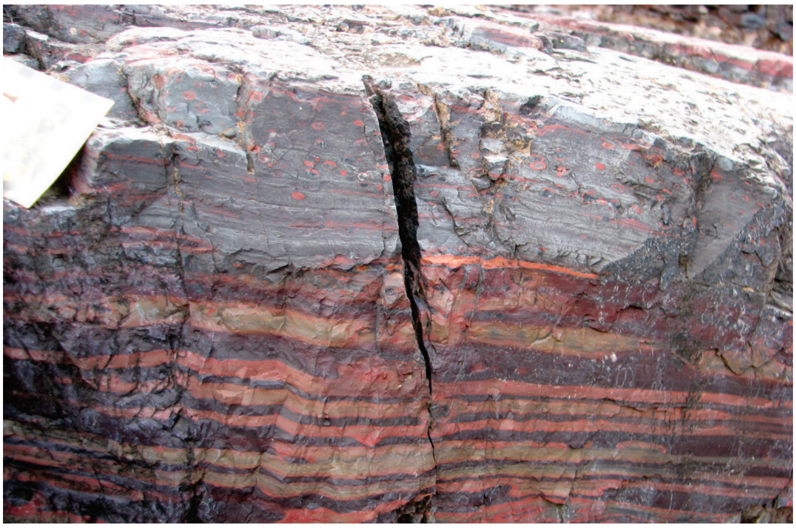


Figure 5. Crest deposit: Boulder of banded jasper and specular hematite. Nodular hematitic layer at the top (Yukon Geological Survey).

• Neoproterozoic and younger iron deposits

The very large Neoproterozoic Crest iron deposit (3200 Mt of 43 % Fe), located in the headwaters area of the Snake and Bonnet Plume rivers of the Mackenzie Mountains, northern Yukon, is described here.

The deposit was discovered in 1961 by Standard Oil Company geologists who identified 10-30 m thick sections of jasper hematite iron formation. Subsequent reconnaissance determined that the deposit might contain 15 billion tons of iron ore. Nevertheless, evaluations by Kaiser Engineers to 1998 have shown that the deposit is sub-economic. The iron formation consists of fine-grained specular hematite with alternating jasper-rich bands (Figure 5). It has been traced for a distance of 51.5 km. Economically significant iron deposits occur up to 305 m above the Neoproterozoic sub-Rapitan contact. This zone attains a maximum thickness of 120 m of which 85 to 105 m is iron formation. Shaly conglomerate is the most significant lithology between iron formation layers. Types of iron formation include nodular, banded, and irregular intergrowths of hematite and jasper. The average iron content is 43 %. The main impurity is apatite.

• Carbonate-hosted deposits

Carbonate hosted zinc-lead deposits are located in the Canadian Arctic Islands (Polaris deposit: 20.1 Mt grading 13.4 % Zn, 3.6 % Pb, and Nanisivik deposit: 17.5 Mt grading 9 % Zn, 0.7 % Pb, 41 ppm Ag), along the northern edge of the Western Canada Sedimentary Basin (Pine Point deposit: 101 Mt grading 5.6 % Zn, 2.4 % Pb) and, in the Mackenzie Mountains, the large undeveloped Gayna River deposit (50 Mt grading 4.7 % Zn, 0.3 % Pb) and undeveloped Prairie Creek deposit (11.7 Mt grading 0.4 % Cu, 12.8 % Zn, 10.9 % Pb, 197 ppm Ag).

The Pine Point deposits are located 800 km N of Edmonton near the south shore of Great Slave Lake. Shipment of high grade ore by Cominco Ltd was initiated in 1965 and continued until mine closure in the late 1980s. In the Middle Devonian, a carbonate barrier (the Presqu'ile Reef) formed along a southwesterly-trending basement ridge with open marine conditions to the north and restricted back reef facies (the Elk Point lagoon) to the south. In total there are 97 known deposits within three northwest ore trends, distributed over a strike length of 68 km and a width of 6 km. Forty-eight of these deposits were mined by Cominco Ltd. before 1990. The deposits have the form of vertical pipes (karst chimneys), and tabular bodies that lie along former subsurface stream channels. Sphalerite occurs in globular colloidal (colloform) masses. Galena is present in a nested form inside sphalerite. Other ore-related phases include marcasite, pyrite, minor pyrrhotite, celestite, barite, gypsum, anhydrite and fluorite. Also present are bitumen and pyro-bitumen, particularly in hydrocarbon trap settings above the ore bodies. Hydrogen sulphide gas has also been reported.

• Shale-hosted (sedimentary-exhalative) deposits

Sedimentary-exhalative (SEDEX) deposits are an important zinc and lead resource in the Yukon. These include the large deposits in the Anvil area (Early Cambrian Faro, DY, Grum, Swim, Vangorda), the potentially very large Howard's Pass (Early Silurian), and large Tom and Jason (Late Devonian) ore bodies.

The Anvil mining camp (Figure 6) is located NE of Whitehorse near the town of Faro. The Faro deposit (53.2 Mt grading 5 % Zn, 3.4 % Pb, 0.3 ppm Au, 33 ppm Ag) is one of five significant deposits discovered between 1953 and 1965 in the Anvil Mining Camp of the central Yukon. Open pit mining began at Faro in 1969 with mining initiated on sever-

Figure 6. Anvil: Faro mine site, Yukon including open pit, tailings piles, mine roads and mine buildings. (Yukon Geological Survey)

al of the other deposits in the early 1990s. All operations ceased in 1997. The five known deposits are associated with a 150 m thick interval that straddles the Lower Cambrian Mount Mye and Cambrian to Ordovician Vangorda formations. The sulphide lenses have been traced laterally into a carbonaceous pelite unit which has been identified as a submarine hydrothermal layer produced through venting of hot metallogenic brines to the sea floor.

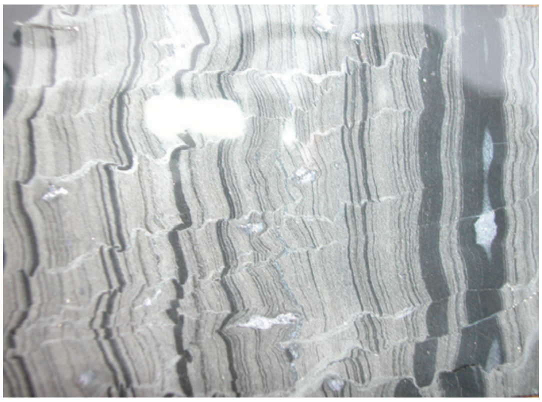


Figure 7. Howard's Pass: fractured high-grade ore from the Selwyn property: deformed finely laminated sulphides (galena and sphalerite) in host black shale (Yukon Geological Survey).

The Howard's Pass property is located along the Yukon-Northwest Territories border with most of the claims located inside the Yukon. The Howard's Pass deposits (388.5 Mt grading 4.9 % Zn, 1.6 % Pb), not yet exploited, were discovered in 1972 during follow up of a 1971 stream sediment reconnaissance program. This led to a significant staking rush. 218 drill holes were drilled from 1973 to 1981 and also in 2000. Bulk testing on the XY deposit occurred in 1980 and 1981. The early Silurian Active Member contains all known zinc and lead mineralization. This ranges from 0 - 60 m in thickness and contains nine intercalated facies, most notably a whitish grey lead- zinc mudstone. This is a laminated cherty unit containing up to 70 % sulphides consisting of quartz, sphalerite, galena and minor pyrite (Figure 7). The Active Member has been identified over a strike length of 37.5 km within which there are 15 deposits. The mineralized horizon is generally 20-30 m thick and is mineralogically consistent over the entire property. However, higher grades and coarser grain sizes have been encountered in the XY, Don and Anniv zones.

The Tom and Jason deposits (31 Mt grading 6.6 % Zn, 3.8 % Pb, 38.6 ppm Ag), not yet developed, are accessible via the Canol Road from Ross River, Yukon. The Tom prospect was first staked by Hudson Bay Exploration Development Company Ltd (HudBay) in 1951. Surface evaluation and some drilling occurred from 1951 to 1953, and again from 1967 to 1968. Underground evaluation began in 1970, including bulk testing and metallurgy. The Tom and Jason deposits are located along the eastern margin of the largely deep water Selwyn Basin. The deposits lie in a structural domain featuring turbidites of the Lower Earn Group. Hydrothermal vent facies include ankerite and quartz veins containing pyrite, chalcopyrite and galena. Sulphide-barite mineralization occurs as laminae within sediment host rocks and collectively is found in stratiform lenses up to 40 m thick and traceable for up to 1200 m along strike. Economic minerals include fine- to coarse-grained sphalerite and galena. Mineralization is separately identified as Grey facies (pink sphalerite, galena, pyrite and grey barite) or as Black facies (black mudstone, cream sphalerite, galena, and pyrite). Collectively these two facies comprise the bulk of the mineralization.

• Devonian-Mississippian volcanogenic massive sulphide (VMS) deposits

Volcanic-hosted deposits of Paleozoic age have been discovered most notably in Devonian and Mississippian strata of the Finlayson Lake area of the central Yukon (the largest, and currently developed for underground mining is Wolverine: 6.2 Mt grading 1.2 % Cu, 12.2 % Zn, 1.6 % Pb, 1.7 ppm Au, 363 ppm Ag) but also at Hasselberg (4.1 Mt grading 6.2 % Zn, 1.8 % Pb, 84 ppm Ag) which has not been exploited.

The Hasselberg (Wolf) property is located southwest of the Tintina Fault in the Pelly Mountains SE of Ross River. The deposit lies in the Late Devonian to Early Mississippian Pelly Mountains volcanic belt, part of the Pelly-Cassiar platform, consisting of volcaniclastic strata, lapilli tuff, argillite and lesser trachyte flows, sills and dykes. Bedded barite and massive sulphides are interbedded with these strata. The Hasselberg deposit consists of two massive sulphide lenses collectively up to 1200 m wide and extending to a depth of 500 m, underlain by andesitic tuff, and overlain by rhyolite tuff and porphyry. The upper part of the deposit features lenticular barite and disseminated pyrite, sphalerite and galena. Drilling in 1997 and 1998 indicated the possibility that the deposit lies on an overturned fold limb: stringer mineralization above and exhalite below. In general the deposit is 3 to 5 m thick and consists of pyrite with banded amber sphalerite and galena, or botryoidal sphalerite and galena in a matrix of Fe-Mg carbonate and lesser barite.

• Triassic ultramafic-hosted nickel-copper-PGE

The large Wellgreen deposit (461 Mt grading 0.3 % Cu, 0.2 ppm Au, 0.3 % Ni, 0.02 % Co, 0.4 ppm Pt, 0.34 ppm Pd), developed for open-pit mining, is located 317 km NW of Whitehorse in the southwest Yukon. The property lies within the Insular Superterrane consisting of the Wrangel and Alexander terranes which were amalgamated at ~320 Ma. The Wellgreen host rock is within the Kluane ultramafic belt which lies within Wrangellia and consists of Triassic flood basalts and related intrusive rocks. The Wellgreen deposit lies along the lower contact of an Upper Triassic sill, locally referred to as the Quill Creek complex. The mineralization occurs at the base of a peridotite body within which there are massive sulphide lenses as well as a skarn zone in calcareous footwall strata. The extent of the mineralization is 1500 m x 700 m wide. Typical ore forming features include nickel-copper sulphides in disseminated, net-textured, semi-massive and massive mineralization.

Mississippian polymetallic silver-lead-zinc

The large Keno Hill district (7.2 Mt grading 4.4 % Zn, 5.3 % Pb, 1107 ppm Ag) is located in the central Yukon 500 km by all-weather road from Whitehorse. Exploration and mining dates back to the early 1900s. Production ended in 1989. The bulk of the mineralization occurs in the Basal Quartzite Member of the Mississippian Keno Hill Quartzite. This unit consists of thin- to thick-bedded quartzite and graphitic phyllite. Silver mineralization is hosted by a series of northeast-striking faulted veins with left lateral and normal displacement. These veins can be up to 30 m wide. The vein mineralogy is complicated by the fact that there have been multiple pulses of hydrothermal activity acting on the system. This has produced vein reactivation and related brecciation. Silver mostly occurs in argentiferous galena and argentiferous tetrahedrite (freibergite).

Cretaceous epithermal gold

The property is 200 km NW of Whitehorse. Lode gold was first discovered on Freegold Mountain in 1930 which precipitated a staking rush through to 1931. Work continued intermittently through the 1950s when interest shifted to porphyry deposits. A soil survey in the 1960s led to the discovery of the Nucleus deposit. Associated with the undeveloped Golden Revenue deposit (232 Mt grading 0.02 % Mo, 0.08 % Cu, 0.43 ppm Au, 2.0 ppm Ag) is the Revenue Breccia. The matrix is quartz feldspar porphyry. The breccia is typically altered to clay and carbonate and also contains pyrite and copper oxides. Mineralization is contained within Revenue breccia and in host granodiorite. Mineralization is typically seen as porphyry veins, stockwork and disseminated sulphides. Minerals of economic interest include native gold, chalcopyrite and silver with lesser molybdenite and scheelite.

Cretaceous porphyry copper and molybdenum

Classic porphyry deposits of the Cordillera in the Yukon variously comprise chalcopyrite, molybdenite, gold and tungsten minerals and include Casino (2753 Mt grading 0.16 % Cu, 0.02 % Mo, 0.2 ppm, Au, 1.5 ppm Ag), Logtung (19.2 Mt grading 0.03 % Mo, 0.08 % W) and Red Mountain (187 Mt grading 0.1 % Mo).

The very large but mostly not exploited Casino deposit is located in the Dawson Range Mountains 300 km NW of Whitehorse in the west central Yukon. Placer claims were first staked in 1911. Silver-rich veins were mined periodically from 1963 to 1980. Porphyry potential was investigated from 1967 onwards. Rocks of the Dawson Range are represented by the Devono-Mississippian Wolverine Creek metamorphic suite and by Cretaceous intrusions in the Dawson Range batholith. Mineralization types include leached cap mineralization; weathered zone oxide mineralization; weathered zone sulphide mineralization; and primary (unaltered) mineralization. The oxide zone is notably copper enriched and is typically 10 m thick. Associated minerals include chalcanthite, malachite, brocanthite and others. The sulphide zone is notably enriched in copper and features digenite, chalcocite, minor covellite, bornite and copper-bearing goethite. Below the weathered zone, unaltered mineralization is typically found in stockwork veins and breccias. This consists of finely disseminated pyrite, chalcopyrite, molybdenite and minor sphalerite and bornite.

The large undeveloped Logtung deposit is located 260 km SE of Whitehorse, Yukon, 130 km southwest of the Tintina Fault in the Yukon-Tanana terrane. The Logtung porphyry tungsten-molybdenum deposit is characterized by a quartz vein stockwork and a sheeted vein set centred on a quartz feldspar intrusion complex, one of several intrusions that are enriched in tungsten, molybdenum and fluorine. While skarn is present, the ore minerals are associated with veins and with open fractures. For this reason Logtung is considered a porphyry deposit rather than skarn mineralization. Nevertheless, the property is underlain by skarn and related metasedimentary rocks. The mineralized zone is 2.5 km x 1.0 km and extends along the northern and western margins of the quartz monzonite stock. Mineralization also extends into the stock and is closely associated with porphyry dykes.

Cretaceous copper and tungsten skarns

Skarn mineralization has developed adjacent to Cretaceous intrusive rocks most notably along the Yukon-Northwest Territories border. In this region are found the Cantung tungsten mine (11 Mt grading 0.8 % W) and other economically significant deposits that include the large but undeveloped Mactung (45 Mt grading 0.7 % W) inside the Yukon.

Mactung was discovered and staked in 1962 with surface geology and geophysics from 1963 to 1967, drilling campaigns beginning in 1968 and underground sampling from 1973 to 2005. The Mactung property is located in the eastern Selwyn Basin, a region of deep-water sediments that persisted from the Neoproterozoic to the Middle Devonian. Five intrusive suites are recognized including the Tungsten Suite dated at 97-92 Ma. The deposit itself has an age of 97.5 Ma which is older than the U-Pb age from the adjacent stock (92.1 Ma). There are two mineralized skarn zones at Mactung separated by 100 m of locally metamorphosed shale and siltstone. Cutting these there are numerous veinlets containing pyrite, pyrrhotite, scheelite and molybdenite. Consisting of nine mappable units, four containing tungsten ores, the entire succession forms a recumbent fold with a shallow-plunging axis.

Figure 8. A bird's-eye view of Dominion Diamond Corporation's Ekati mine in the Northwest Territories (Dominion Diamond Corporation).

<u>Diamond-rich kimberlites</u>

Although hundreds of kimberlite pipes have been discovered in the Archean Slave craton and in Archean portions of the Rae and Hearne cratons, most of these are isolated and small or unproductive. A key to economic significance is close proximity of a number of diamondiferous pipes. The producing Ekati and Diavik mines in the Northwest Territories part of the Slave craton, are described here.

Ekati is located 300 km NE of Yellowknife in the central Slave craton. It includes the Ekati diamond mine, currently held by Dominion Diamond Corporation, 150 kimberlites, 17 containing macrodiamonds and four producing pipes (Figure 8). Elements of the exploration phase included stream-, glaciofluvial- and till-sampling, and magnetic and electromagnetic surveys. These techniques served to pin-point kimberlite targets. Kimberlites have been preferentially emplaced into Archean plutonic rocks, at lineament intersections, along dykes, and at dyke intersections. Thirty kimberlites have ages of 75 to 45 Ma. Most are steep sided and inward tapering cones but there is a spectrum of shapes. Normal size ranges from 0.1 ha to 5.0 ha to a maximum of 20 ha. Although most are single pipes, the Misery complex consists of eight distinct bodies. Syn-depositional winnowing and mass flow-related sorting may contribute to improvement of grade. The diamond content is inversely proportional to diluting materials such as mud and ash. Diamond abundance is closely correlated with the content of olivine and other mantle-derived materials including eclogitic garnet, chromite and chrome diopside. These minerals have also proven useful as diamond indicators during till sampling campaigns.

The Diavik mine property, currently held by Dominion Diamond Corporation, is located 295 km NE of Yellowknife in the central Slave craton. The property features four diamondiferous kimberlite pipes located at the lake bed of eastern Lac de Gras. Exploration from 1991 to 1995 resulted in the identification of 52 kimberlite pipes. Four, identified to be commercially significant, were discovered in 1994 and 1995: A21, A154 North, A154 South and A418. The four commercial kimberlites are steep- to vertically-sided pipes that to varying degree narrow downward. Surface areas are mostly less than 2 ha. The A154 South pipe consists of tuff, tuff breccia and alternating pyroclastic and resedimented volcaniclastic kimberlite. This gives way to mudstone xenoliths in the upper part. The A154 North pipe has volcaniclastic kimberlite with an olivine-rich bed in the upper 40 m that increases in grain size with depth. At greater depth (>150 m) there is crystal-rich volcaniclastic kimberlite. A418 is dominated by mudrock fragments which significantly affect diamond grade. Also significant are ash lapilli intervals. A21 has a more pronounced flaring pipe. The dominant components include ash lapilli (as for A418).

Pliocene to Holocene gold placers

The Klondike placers are located in west-central Yukon in an area that has largely escaped glaciation. Initial discoveries in 1896 included gold placers on Quartz Creek, Gold Bottom Creek and on Bonanza Creek. Collectively the Klondike region stands as one of the world's most productive gold placers. The region has been more or less continuously productive for 119 years (1896-2015). Placer gold occurs in four settings: 1) the lower part of the high-level White Channel gravels (5-3 Ma; up to 46 m thick) stratified with and overlain by; 2) glaciofluvial Klondike gravel (Pliocene; up to 53 m thick), 3) intermediate terrace gravels of limited extent (1.4 Ma; up to 9 m thick), and 4) low-level gravels (late Pleistocene-Holocene; up to 20 m thick) that occupy and underlie modern stream and river gravels at 10 to 200 m below the high-level gravels. Gold in the low-level gravels derives from erosion of both the White Channel gravels and primary bedrock sources. The majority of the placer gold is considered to be alluvial in origin. However, some may be introduced by precipitation from water that carries gold in solution. Concerning the bedrock source, one theory is that high grade lode gold source(s) have been largely eroded away to form the present placer gold deposits leaving only lode gold relicts. An alternative is that one or more high grade lode gold sources remain to be discovered.

Future Potential

Conventional wisdom recognizes that future discoveries will be made in the vicinity of existing deposits. This suggests that the most productive areas of Arctic Canada will also yield many of the future new discoveries. This is especially true for gold and diamonds in the Slave craton and for gold, tungsten and base metals in the Yukon. It also follows that future discoveries will be made down-dip in existing mines, below deposits yet to be mined, below Quaternary overburden or on the floor of lakes and shallow seas. Especially favourable is the undeveloped potential for kimberlites in all areas of Archean crust with vast areas of the Rae and Hearne cratons likely to see new commercially viable diamond mines in the coming years. Other areas in which there have been new finds in recent years may yield additional discoveries, for example of gold in the Hope Bay belt (Slave craton), volcanic-hosted deposits in the Hackett River belt (Slave craton) and Finlayson belt (Yukon), of iron-oxide copper gold in the Great Bear magmatic zone and uranium in the vicinity of the Thelon and Baker Lake basins.

GREENLAND[4]

Greenland (Kalaallit Nunaat) is probably more extreme and more isolated than most other regions in the Arctic with its central continental ice cap and its location between North America and Europe. Although the location may be recognized as an advantage for trading routes, Greenland has always been a demanding base for a sustainable society. Raw materials played a major role in the early settlement of the largest island on Earth. The so-called Saqqaq culture people settled in western Greenland between 2500 and 800 BC and used and traded silica-enriched rocks derived from the Disko Bugt area. These rocks could be manufactured into tools. Later cultures used iron from iron meteorites that were discovered on glaciers and locally from native iron in basalt of the Disko Bugt area.

Modern colonization of Greenland started in the 18th C, and shortly after, the cryolite ($Na_3[AlF_6]$) deposit near Ivittuut was discovered in South Greenland (Figure 1). The Ivigtut cryolite deposit was mined for over 130 years from 1854 until 1987 and represents one of the few economic mining successes in Greenland. Cryolite was used first as an aluminium ore and then as a flux in the electrolytic processing of bauxite ore to make aluminium. The Ivigtut cryolite mine was the only mine for this material on Earth until natural cryolite was replaced by synthetic cryolite in the 1960s. Kryolitselskabet Øresund A/S who operated the mine started the first systematic exploration program in the 1950s with helicopter prospecting flights mainly along the west coast, selecting targets for further investigations. At the same time, Nordisk Mineselskab A/S started mineral exploration in eastern Greenland based on discoveries from earlier expeditions. One of these discoveries is the Blyklippen Zn-Pb deposit that was mined between 1956 and 1962 (Figure 1). Other early and less successful mining operations have been the Josva copper mine (1904-1915) and the Amitsoq graphite mine (1915-1924) in South Greenland, and the Qullissat coal mine (1924-1972) on Disko Island in central West Greenland (Figure 1). The discovery of the world-class Black Angel zinc-lead deposit represented a continuation of successful mining in Greenland (Figure 1). Between 1973 and 1990, a zinc-lead concentrate was produced from the deposit in a spectacular operation in which both ore and miners were transported from the adit, at an elevation of 600 m above sea level, by cable car to the opposite side of a fjord. Increased exploration activity in recent decades, supported by the partly state-owned exploration company Nunaoil A/S, the split-off company NunaMinerals A/S, and the geological surveys (the Geological Survey of Greenland and later the Geological Survey of Denmark and Greenland), have led to major improvements in the quality and coverage of geological, geochemical and geophysical data. This has resulted in the discovery of the Nalunaq gold mine (2003-2013) in South Greenland and the Seqi olivine mine (2005-2010) north of Nuuk (Figure 1). With the cessation of gold production in Nalunaq in 2013 and the final closure of the mine in 2014, modern mining activity came to halt in Greenland for the first time in 160 years. In 2015 however, approx. 70 exclusive exploration and 6 exploitation licenses were granted, covering approximately 10 % of Greenland's ice-free area and showing the continued interest in Greenland's raw materials. Exploitation licenses have been granted for the Nalunaq gold deposit, the Black Angel zinc-lead deposit, the Malmbjerg molybdenum deposit, the Isua iron ore deposit, the Aappaluttoq ruby deposit and the White Mountain calcium feldspar deposit (Figure 1). The Aappaluttoq ruby deposit opened production of the corundum (Al_2O_3) gemstone late in 2015.

[4] Written by Jochen Kolb, Geological Survey of Denmark and Greenland

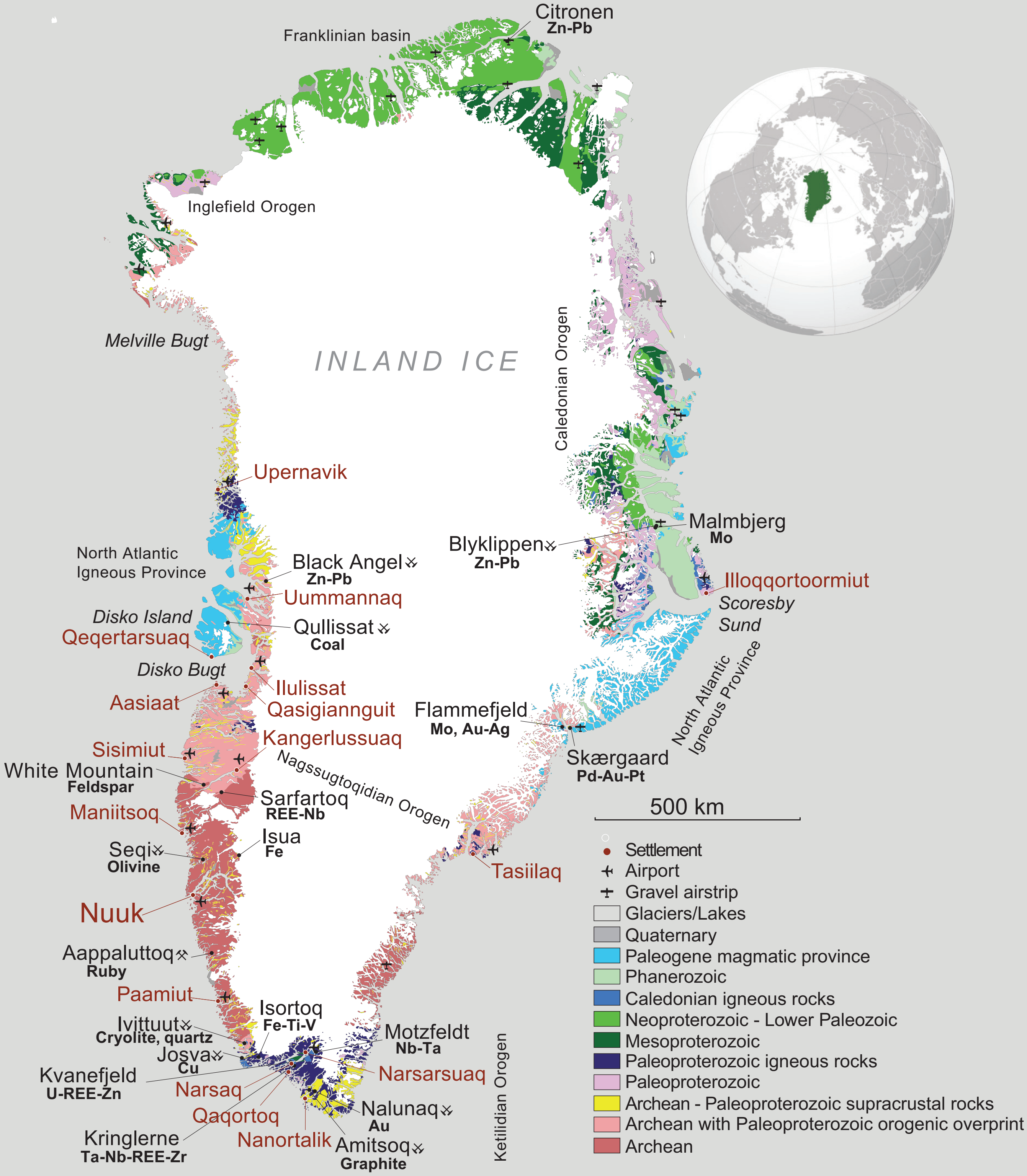


Figure 1. Simplified geological map of Greenland showing the location of the most important mineral deposits currently known.

The Circum Arctic Mineral Deposit Map shows the larger mineral deposits in Greenland and the basic geology within the framework of the other Arctic countries. Greenland is dominated by Archaean rocks that formed 3.9-2.5 billion years ago in particular along the western coast and the eastern coast north to the Scoresby Sund area (Figure 1). The rocks have been metamorphosed and deformed deeper in the crust and are today mostly gneiss and granite. These rocks locally host deposits of gold, nickel, chromium and platinum group elements (PGE). Less metamorphosed and deformed rocks are rare and locally host iron ore in so called banded iron-formation. The Isua iron ore deposit, discovered in 1965 by Kryolitselskabet Øresund A/S 150 km northwest of Nuuk, is one example (Figure 1; Table 1). The Isua banded iron-formation is a tabular body 1.5 km long in outcrop, 200 m thick, which dips 60-70° ESE: it increases in thickness to 450 m with depth, underneath the Inland Ice. Quartz-rich and magnetite-rich bands are 0.5-100 mm thick with magnetite (Fe_3O_4) being the ore mineral. The mineralisation formed 3691 ± 22 million years ago by hydrothermal fluids at the Ocean floor. Since then, the rocks have been metamorphosed and deformed, changing the original geometry and mineralogy of the iron ore.

Two Archaean continents, the northern Rae craton and the southern North Atlantic Craton, are distinguished by their different geological evolution. At the margins of these continents, sedimentary and volcanic rocks were deposited in the Palaeoproterozoic between 2500 and 1600 million years before the present (Figure 1). The continents collided in the younger Palaeoproterozoic, which resulted in the formation of a central Greenlandic mountain belt (Nagssugtoqidian-Rinkian Orogen) and mountain belts in the north (Inglefield Orogen) and in the south (Ketilidian Orogen). The Black Angel deposit at Maarmorilik is situated in the central mountain belt and hosted in deformed and metamorphosed calcium and magnesium carbonates (marble). The deposit produced 11.2 million t of zinc, lead and silver ore (Figure 1; Table 1). The mineralisation formed by hydrothermal fluids that migrated through the sedimentary rocks before metamorphism and deformation. Several similar zinc-lead occurrences are known from the area and are being explored.

The newly formed continent, which had a similar outline to Greenland today, except for the northern part, started to fracture in South Greenland in the later Mesoproterozoic between 1400 and 1100 million years before the present. The thinner crust and large faults gave way to exotic mantle melts that formed numerous intrusions. These intrusions host some of the world's largest deposits of rare metals, namely Kvanefjeld (uranium-rare earth elements (REE)-zinc), Kringlerne (tantalum-niobium-REE-zirconium) and Motzfeldt (niobium-tantalum), but also the Ivigtut cryolite deposit (Figure 1; Table 1). The ore minerals in the deposits are exotic silicates and phosphates and formed by crystallisation during the solidification of the intrusion and later hydrothermal modification. The Ivigtut cryolite deposit, described above has recently been explored for its pure quartz resource. The Isortoq iron-titanium-vanadium mineralisation is hosted by a 16.3 km long and up to 200 m wide near-vertical gabbro dyke (Figure 1; Table 1).

A younger, continental fracture stage affected southern West Greenland and is related to the intrusion of dykes and carbonate-bearing magmatic rocks, carbonatites, at ca. 565 million years before the present. The dykes locally consist of kimberlitic rocks and host diamonds. The Sarfartoq carbonatite complex contains mineralisation in exotic silicates, phosphates and carbonates (Figure 1; Table 1). The mineralisation formed in the late-magmatic stages, from when a volatile phase unmixed from the carbonatite magma and reacted with the surrounding rocks.

In north Greenland and further into Canada, the large Franklinian basin developed at the continental margin reaching an approx. 2000 km E-W extent (Figure 1). The basin contains sedimentary rocks that were deposited in a marine setting transitional from shallow- to deep-water environments towards the north. Several kilometre-thick sedimentary packages mainly of carbonate and sandstone were deposited from ca. 600 to ca. 400 million years before present.

The first indication of mineralisation in the region was reported in 1960 during a helicopter reconnaissance in Peary Land by the U.S. Geological Survey. Several Zn-Pb sulphide occurrences have since been discovered, the most important being the world-class Citronen Zn-

DEPOSIT	TONNAGE [MT]	GRADE	OWNER (STATUS 2016)
Isua	1 107	32.6 % iron	General Nice Development Limited
Black Angel	13.6	12.3 % zinc, 4.0 % lead, 29 g/t silver	Black Angel Mining A/S
Kvanefjeld	673	1.08 % REE oxides, 273 g/t uranium oxide, 0.24 % zinc	Greenland Minerals and Energy A/S
Kringlerne	4 300	0.65 % REE oxides, 0.2 % niobium oxide and 1.8 % zirconium oxide	Tanbreez Mining Greenland A/S
Motzfeldt	340	0.26 % REE oxides, 0.19 % niobium oxide, 0.012 % tantalum oxide, 0.46 % zirconium oxide	Regency Mines Plc.
Isortoq	70.3	38.1 % iron oxide, 10.9 % titanium oxide, 0.144 % vanadium oxide	West Melville Metals Inc.
Sarfartoq	14	1.5 % REE oxides, 3.89 % niobium	Hudson Resources Inc.
Citronen	132	4.0 % zinc, 0.4 % lead	Ironbark Zinc Limited
Skaergaard	202	1.33 g/t palladium, 0.88 g/t gold, 0.11 g/t platinum	Platina Resources Limited
Flammefjeld	200	0.2-0.3 % molybdenum sulphide	21st North
Malmbjerg	329	0.1 % molybdenum	KGHM

Table 1. Tonnage and grade data for mineral deposits in Greenland (sources: Source: company data and information at the Geological Survey of Denmark and Greenland (GEUS).

Pb deposit (Table 1). Four sulphide ore bodies are distinguished and each has a length of 1500 m, a width of 600 m and a thickness of 25 m, with individual sulphide beds being 0.3-2.0 m thick. The ore minerals sphalerite (ZnS) and galena (PbS) formed on the seafloor in a reduced environment from hydrothermal fluids derived from submarine vent sites. Subsequently, the rocks were only slightly metamorphosed and deformed.

East Greenland is characterized by a mountain belt (Caledonian Orogen) of deformed and metamorphosed latest Palaeoproterozoic to Silurian rocks (Figure 1). This mountain belt formed during the collision between two continents, Laurentia and Baltica, with, today, the western part of the belt located on Greenland and the eastern part in Norway, Sweden and the UK. Sedimentary rocks of Devonian to Cretaceous age were deposited in local basins after the formation of the mountain belt. The sedimentary rocks locally host Cu-mineralisation, and Caledonian granites locally contain Cu, W, Sb, U occurrences.

The two continents started to break apart, as recorded by intense magmatism that formed numerous intrusions, massive lava flows and finally the sea-floor of the Atlantic Ocean. This massive magmatism formed a large igneous province (LIP) called the North Atlantic Igneous Province (NAIP; Figure 1). Rocks that formed 63 million years before the present extend for more than 3000 km from Baffin Island across Greenland, Iceland and the Faeroe Islands to Scotland and Ireland and stretch from 63°N to 75°N, covering a distance of more than 1300 km in East Greenland. Basaltic lava flows formed episodically until ca. 13 million years before the present. More than 60 intrusions have been discovered along the eastern coast of Greenland, with 28 in the Kangerlussuaq Fjord area alone, which is also the area with the most numerous, important mineralisations. The layered gabbro-diorite Skaergaard intrusion hosts a major PGE-Au mineralisation (Figure 1; Table 1). The deposit was discovered by Platinova Resources Ltd. in 1986 and has subsequently been explored by various companies. The intrusion is world famous for its spectacular layering and has served as a natural laboratory for studying magma-chamber processes and the differentiation of basaltic liquids. The intrusion measures approximately 7 x 11 km on the surface and formed ca. 56 million years ago. One ca. 60 m thick layer hosts the mineralisation in five main Pd-rich layers and one Au-rich layer. The precious metals are in alloys of palladium, gold and copper with skaergaardite (PdCu), zvyagintsevite (Pd_3Pb) and tetra-auricupride (AuCu) being the most common minerals.

Syenite and monzogranite intrusions host Mo-porphyry ores as well as peripheral Au-rich veins and Zn-Pb vein mineralisation, e.g. at Flammefjeld and Malmbjerg (Figure 1). The Flammefjeld deposit formed 39.6 million years ago in an intrusion at shallow levels and was discovered in 1970 by Nordisk Mineselskab A/S. Hydrothermal fluids derived from the magma formed the mineralisation at approximately 500 m below the present surface, with a modelled diameter of 800 m, a thickness of 200 m (Table 1). Gold and silver-bearing quartz-carbonate veins have been discovered within 5 km of Flammefjeld: they are commonly <1 m wide and generally trend ESE. The Malmbjerg porphyry-molybdenum deposit is located further north, in the Werner Bjerge complex. It was discovered in 1954 by the Danish East Greenland Expeditions and from 1958 to the present more than 30 km have been drilled and adits totalling 1329 m have been excavated (Table 1). The mineralisation formed 25.7 million years ago from a hydrothermal fluid that was derived from the magma. These fluids formed 1 mm to 5 cm thick molybdenum-mineralised veins in an inverted bowl-like structure of approximately 700 x 700 x 150 m.

The long, complex geological evolution of Greenland as well as its numerous deposits, suggest that the few successful mineral exploration and mining examples illustrate a much greater potential. Geological knowledge is still relatively basic for many areas and modern geophysical and geochemical data are commonly only available at a regional scale, which makes knowledge- and mineral system-driven exploration difficult and costly. The mineral deposits shown on the Circum-Arctic Mineral Deposit Map have to be considered as a snap-shot and the difference in deposit density compared to Fennoscandia, for example, indicates the mineral potential which Greenland may have hidden in unexplored ground.

PROSPECTING FOR GOLD IN ICELAND[5]

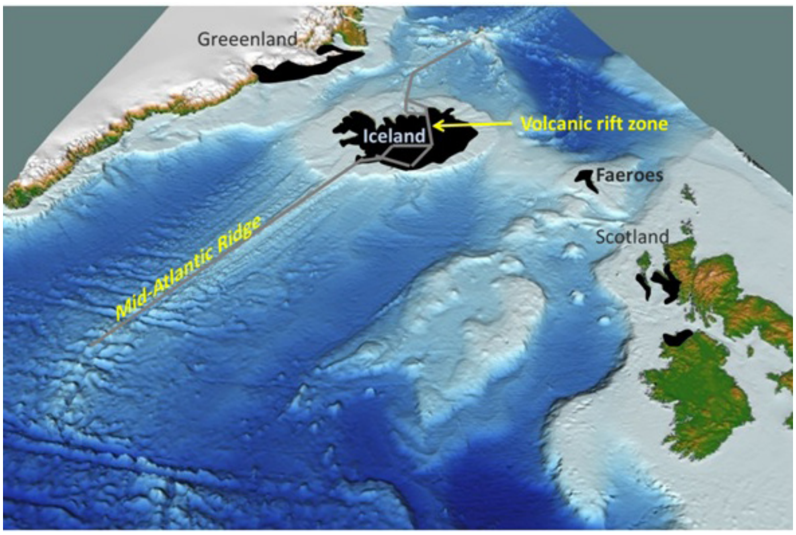
Iceland represents a geological environment very different from the continental crust of Scandinavia, Greenland, Canada, Alaska and Russia. It illustrates, in many ways, the processes that are found within the oceanic crustal environment of the Arctic Ocean. It can also be viewed as a "living" example of the geological environment and processes which, in earlier geological periods, created some of the metallogenic provinces in the continental crust now hosting deposits which are being mined.

For decades, hydrothermal systems related to rifting of the oceanic crust have fascinated scientists, not the least when it was realized that economic deposits were being made there. The problem, though, is the difficulty of reaching these great depths for research, not to mention mining. Iceland is one of the few places on Earth where a mid-oceanic ridge surfaces on land and where structures can easily be viewed and studied. Iceland, however, only partly represents an oceanic ridge as it also is a mantle anomaly called a hotspot. The topography in Figure 1 shows this clearly. We see on one hand the northerly-trending Mid-Atlantic Ridge crossing the country, and on the other the easterly- trending trace of the mantle plume extending from Greenland in the west to the Faeroe Islands and Scotland in the southeast.

The geology of Iceland shows a clear history of rifting, in which the rock formations increase in age away from the volcanic zones, reaching a maximum of some 16 Ma furthest to the east and west. Among the apparent differences between the oceanic and the Icelandic rifts is the more intense volcanic activity and accumulation in Iceland, as well as the development of central volcanic complexes where the maximum uptake of magma into the crust takes place. This, in many instances, results in the production of more evolved magmatic rocks such as rhyolites and minor andesites, and relatively shallow emplacement of larger intrusive bodies. This condition leads to the formation of vigorous high-temperature systems within these volcanic systems. These hydrothermal systems, most of which are far from the ocean, are recharged by fresh groundwater, forming very low-salinity fluids. The magma sources differ in some respects from those in the subduction zones in that they are lower in magmatic gases, suggesting a lower ability to transport metallic oxides within the geothermal systems. These systems gradually drift out of the volcanic zone and become exhumed by repeated glacial erosion. This erosion varies with the age of the rock and is often in the range of 500-2000 m.

The concentration of primary gold in the oceanic crust is low, normally below 1 ppb, but studies have indicated that the gold content increases up to 13-fold along the Reykjanes Ridge towards the Icelandic plume. It is speculated that the gold enrichment owes its origin to the deep upwelling of the mantle material.

Figure 1. A view of the topography of the North Atlantic Ocean showing the trace of the Mid-Atlantic Ridge, Iceland and the E-W trending trace of the Iceland plume (in black).



[5] Written by Franzson, H., Robertsdottir, B.G. and Hardardottir, V.

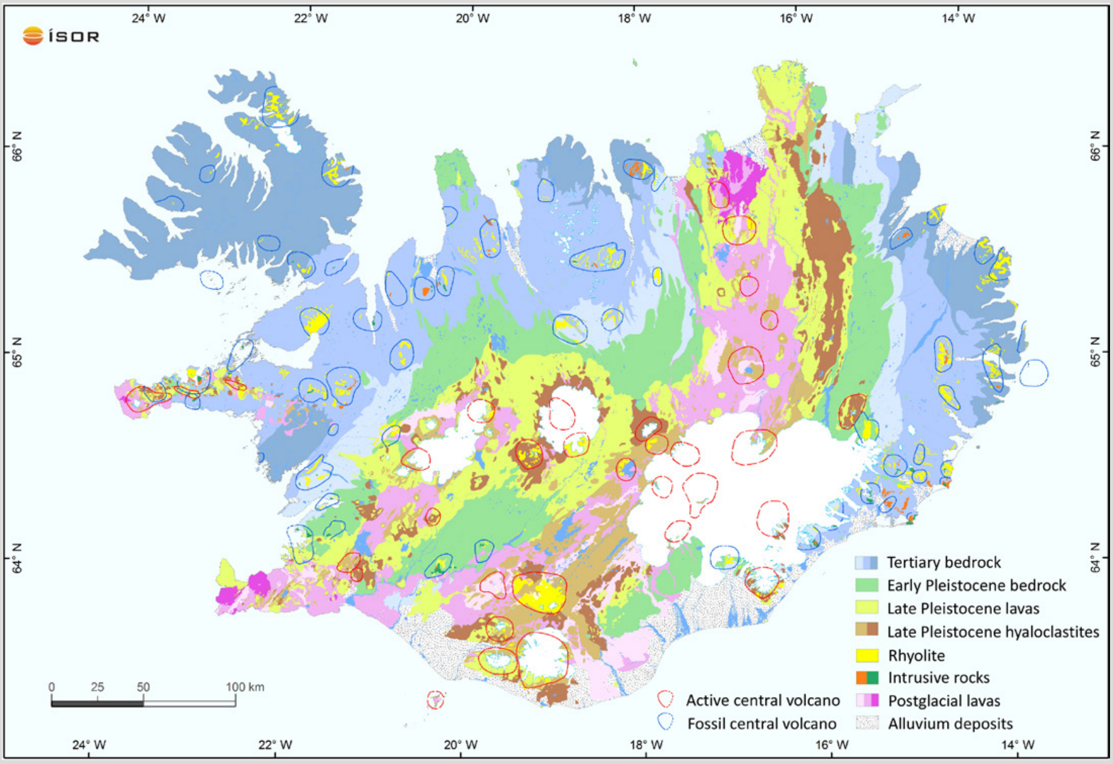


Figure 2. A simplified geological map of Iceland showing the volcanic zones (pink), Plio-Pleistocene (green) and Tertiary formations (blue) representing approximate ages of 0-0.7 Ma, 0.7-3 Ma and 3-16 Ma, respectively. Also shown are prospect areas for gold exploration carried out between 1990 and the present day, along with the locations of the main gold anomalies.

Exploration for gold in Iceland started in the beginning of the twentieth century. It was driven by persons influenced by the gold rush in the New World who recognized gold-rich rocks. These efforts led nearly to mining, but plans were abandoned, partly due to world financial crises and world wars.

The gold exploration effort was resumed in the late 1980s when the relationship between active hydrothermal systems and deposition of gold was established. The exploration started gradually at the end of the century, but has gathered momentum up to the present time. This effort has mainly been carried out under the auspices of the company Melmi ehf., which has served as a center bringing together scientists from Icelandic research institutions, foreign companies, and investors. The exploration has focused on the fossil and partially eroded hydrothermal systems of the volcanic complexes outside the volcanic zone. Figure 2 shows the prospect areas that have been explored to various degrees during the last twenty-five years. The main target of the exploration has been the uppermost 600-1000 m of these fossil hydrothermal systems, where the geothermal upflow is expected to be in a condition of vigorous boiling, and where the optimum probability of gold precipitation occurs. Base metal anomalies are usually not found due to the low salinity of the hydrothermal fluids, except at a location in SE-Iceland probably associated with a rhyolite breccia pipe. The exploration methods used include low- to high-density river sediment sampling combined with float and rock sampling. The main results are shown in Figure 2.

Although the active hydrothermal systems are dominantly of low salinity as mentioned above, exceptions are found near the coast where the rifting environment enters sea. The most famous one is on the Reykjanes Peninsula in the southwest (Figure 2). The peninsula can be viewed as a transition between the oceanic crustal environment and the Icelandic crust. Indeed, the strata of the Reykjanes hydrothermal system, which is situated at the tip of the peninsula, show strong evidence of having been built up from an oceanic environment into a sub-aerial one. The hydrothermal system has a salinity equivalent to that of seawater, albeit of modified composition. Deep fluid aquifers that feed wells extending to more than 3 km depth show compositions very similar to those found at black smokers in deep waters on the Mid-Atlantic Ridge and may thus be viewed as analogues to such systems.

SEA-FLOOR MASSIVE SULPHIDES IN ARCTIC WATERS[6]

The first underwater hot springs were discovered on the sea floor near Galapagos in the SE Pacific in 1977. Black fluids saturated with sulphides, soon to be named black smokers, were venting and forming metal deposits on the sea floor. Around the vents there was a unique ecosystem based on chemosynthesis, i.e. living on breaking down sulphur species. Soon a number of these vent systems were discovered especially along the mid-ocean ridges.

Until quite recently the mid-ocean ridges in the Arctic were some of the least explored parts of the global ridge systems. Systematic mapping of the ridges N of Iceland began in the late 1990s and has resulted in discovery of a number of active and inactive vent systems all the way from Iceland into the so-called Eurasia Basin close to the North Pole (Figure 1). The most important of these are described below.

The southern segment of the Arctic ridge system, the Kolbeinsey Ridge and the southern Mohns Ridge are strongly impacted by the hotspots under Iceland and Jan Mayen, leading to elevated topography and increased volcanic activity. Further north, the magmatic activity and the crustal thickness decrease, and spreading centres and rift valleys become deeper and more pronounced.

The Grimsey Field is situated only 30 km from the island of Grimsey. The field of active venting covers ca. 1 km^2. Intense gas bubble plumes reach more than 300 m above the seafloor due to vigorous boiling of 250°C fluids. The field hosts mounds with 1-3 m tall anhydrite-talc chimneys on top. Sulphides may precipitate at depth, resulting in clear fluids depleted in metals.

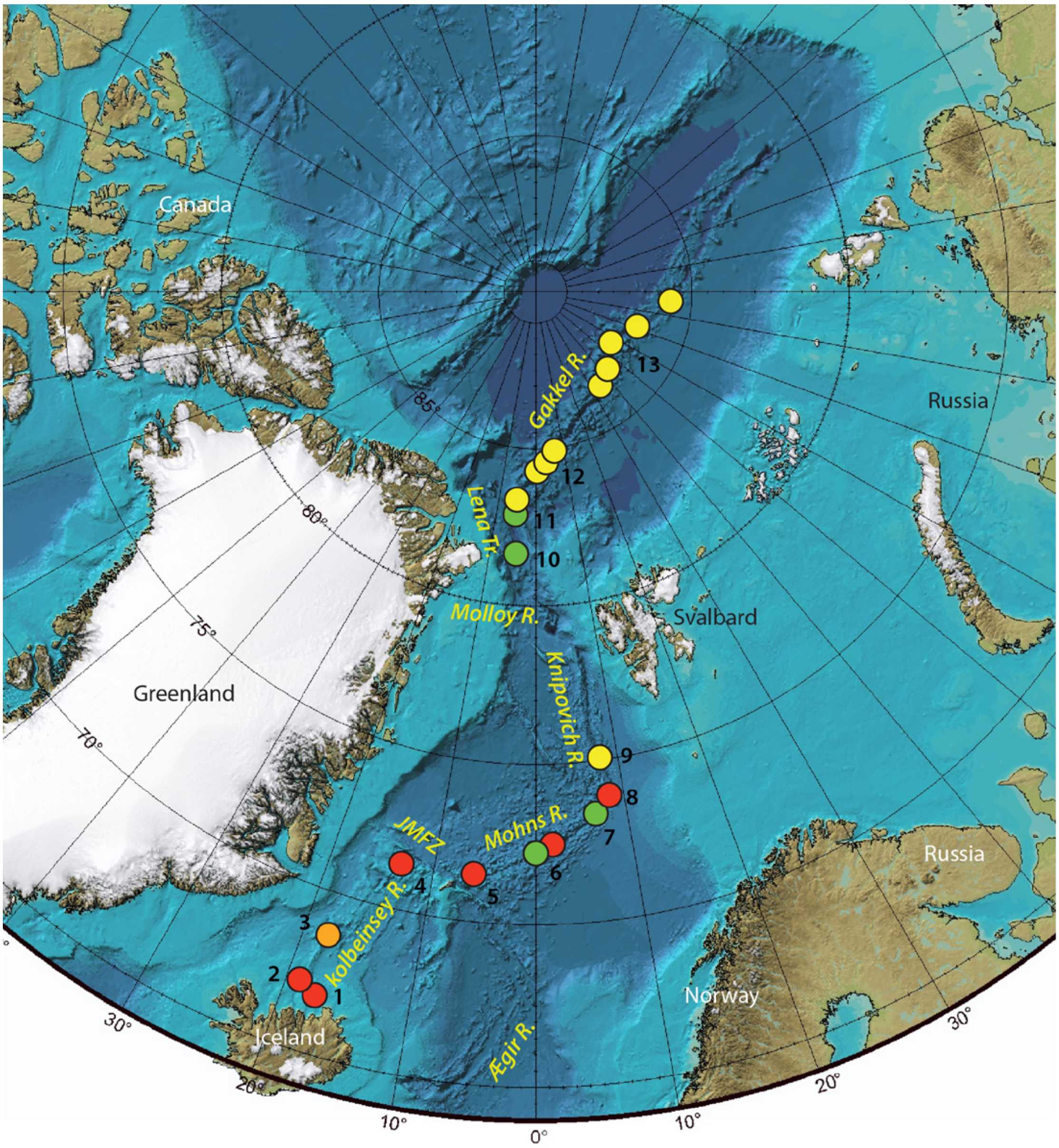
The Squid Forest is an extinct field, which was discovered in 1999. The field is located at 900 m water depth on the plateau of a flat-topped, semi-circular volcano and consists of two sites with clusters of chimney structures, up to 4 m tall. Analyses of a sampled chimney of pyrrhotite, sphalerite, barite and amorphous silica indicate fluid temperatures of 250-300°C.

The Troll Wall, Soria Moria and Perle & Bruse active fields are collectively referred to as the Jan Mayen vent fields. They are all situated at the southernmost segment of the Mohns Ridge, just to the north of the island of Jan Mayen. The fields are characterised by being Zn-rich, emitting fluids with temperatures of 270°C and releasing CO_2-rich gas in extensive bubble plumes. The Troll Wall field comprises at least 10 major sites of venting, each with several 5-10 m high chimneys. The Soria Moria vent field has at least two venting areas 100-200 m or more across, which are underlain by lava flows. In the field are 8-9 m tall sulphide chimneys with spalerite as the main sulfide phase, as well as irregularly shaped areas of edifices 15-20 m across and up to 10 m high, and which emit clear fluids.

The Loki's Castle vent field was discovered in 2008 and was the first black smoker vent field visited at an ultra-slow spreading ridge and in Arctic waters. The field is located at the northern end of the Mohns Ridge, near the summit of a large axial volcanic ridge at 2,400 m depth. Venting occurs at the top of two hydrothermal mounds that are around 20-30 m high and approximately 200 m across. Venting is marked by a plume that rises 3-400 m above seafloor. Low-temperature venting occurs at the flank of the mound and this give rise to a distict field of barite chimneys. Although the vent field is un-

[6] Written by Rolf Birger Pedersen, University of Bergen and Terje Bjerkgård, Geological Survey of Norway

Figure 1. Overview of the active (red) and extinct (orange) vent fields, sulphide deposits (green) and hydrothermal plumes (yellow) found along the Mid-Atlantic Ridge north of Iceland:
1) Grimsey,
2) Kolbeinsey,
3) Squid Forest,
4) Seven Sisters
5) Soria Moria, Troll Wall, Perle & Bruse,
6) Copper Hill, Aegirs Kilde,
7) Mohns Treasure,
8) Loki's Castle,
9) hydrothermal plume,
10) sulphide deposit,
11) sulphide deposit and hot waters,
12) and 13) hydrothermal plumes.



derlain by volcanic rocks, the influence of sediments from the nearby Bear Island sedimentary fan is observed in the fluid chemistry (e.g. very high methane and ammonia values). The Loki's Castle field hosts a unique Arctic vent fauna.

Massive sulphides, alteration products and hydrothermal sediments were recovered in a 30 kg dredge sample from the Lena Trough at 81°N in 1999. Oxidized porous material resembling chimney pieces were also recovered. There were also fragments of ultramafic rocks (serpentinite and harzburgite), indicating an ultramafic host rock. Because the field was found without any other indications before dredging, it was named Lucky B (resembling the finding of the Lucky Strike Field further south on the Atlantic Ridge). Approximately 200 km further north, at nearly 83°N, another dredge recovered massive sulphides in 2002. Here the Lena Trough makes a sharp eastward bend, and transitions into the Gakkel Ridge. The sulphides represent chimney fragments. Furthermore, a camera tow above the site showed shimmering water, indicating some hydrothermal activity.

A number of hydrothermal plumes has been detected along the 1100 km long Gakkel Ridge segment of the Arctic. No sulphides have been recovered or observed. Of the nine potential vent sites, a plume at 85°E was the most active found so far, the plume being 1400 m high and centred 1000 m above the seafloor. Bacterial mats were observed at the seafloor, supported by slightly warm and reduced fluid seeps through cracks in the fresh volcanic rocks.

NORWAY[7]

Outline of the geology of Norway

The geology of mainland Norway is dominated by the Caledonide mountain belt, which extends, in Norway, over 1500 km from Stavanger in the southwest to the northernmost part of the country (Figure 1): the mountain chain which we see today has experienced several cycles of erosion and uplift since its formation in the Palaeozoic Era over 400 My ago.

Much older rocks belonging to 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 from an Archaean core (older than 2500 Ma) with banded iron formations in its northeastern regions with, to the west, Palaeoproterozoic granite-greenstone belts containing gold and copper-nickel-PGE ores formed in the period 1800-2500 Ma.

The Oslo Palaeorift contains volcanic and intrusive complexes spanning the period from Late Carboniferous to Early Triassic, emplaced into a stacked sequence of mainly Cambrian to Silurian sediments (formed in the period 540–420 Ma) which were originally deposited in basins on top of the older basement rocks, but which were subsequently deformed during the Caledonian Orogeny, and are preserved due to the formation of the Rift.

History of metal mining in Norway

Pre 18th Century

The oldest record of underground mining (late 12th C) is from the Akersberg silver deposit in Oslo. Small-scale mining of copper and silver ores began in the first half of the 16th C. The Kongsberg silver mine, which exploited native silver veins 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.

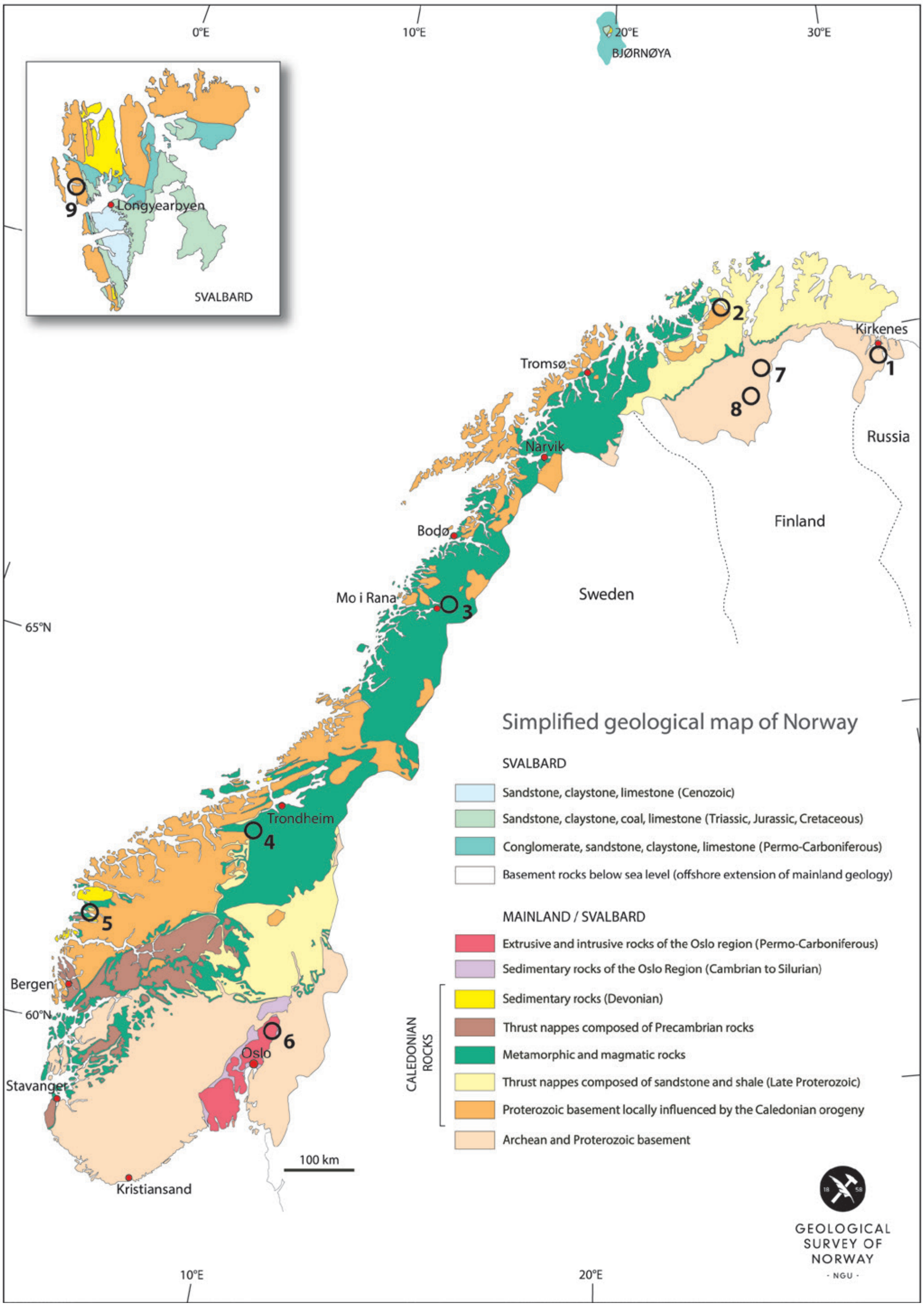
18th – 19th Centuries

A new copper mine was established at Folldal, in 1748. New types of ore were also exploited, in addition to the established copper, silver and iron mines. Cobalt arsenide ores 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". Nickel deposits were discovered in 1837 at Espedalen, where mining commenced in 1846, and at Ertelien in 1849. By the early 1870s mining of pyrite from massive sulphides, for use in production of sulphuric acid, began at several deposits in the mid 19th C and, in 1888, at Sulitjelma (also a major copper producer), as well as from the established copper mines at Røros, Løkken and Folldal. 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 Dunderlandsdalen deposits (including Ørtfjell), just S of the Arctic Circle, were discovered in the 18th C and the Archaean banded iron formations at Bjørnevatn in 1865. Foreign investment was important in mine development in the late 1800s and early 1900s, especially in northernmost Norway. The most long-lived ev-

[7] Summary compiled by Rognvald Boyd, Geological Survey of Norway

Figure 1. Geological map of Norway. The numbers refer to the sequence of deposits listed in Table 1:
1 Bjørnevatn,
2 Nussir,
3 Ørtfjell,
4 Løkken,
5 Engebø,
6 Nordli,
7 Gallujav'ri
8 Rai'tevarri
9 St. Jonsfjorden



	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	1.16/15 g/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/).

idence of this is the town of Longyearbyen on Svalbard, named after the founder of the Arctic Coal Company, established in 1906.

Metal mining - 20th – 21st Centuries

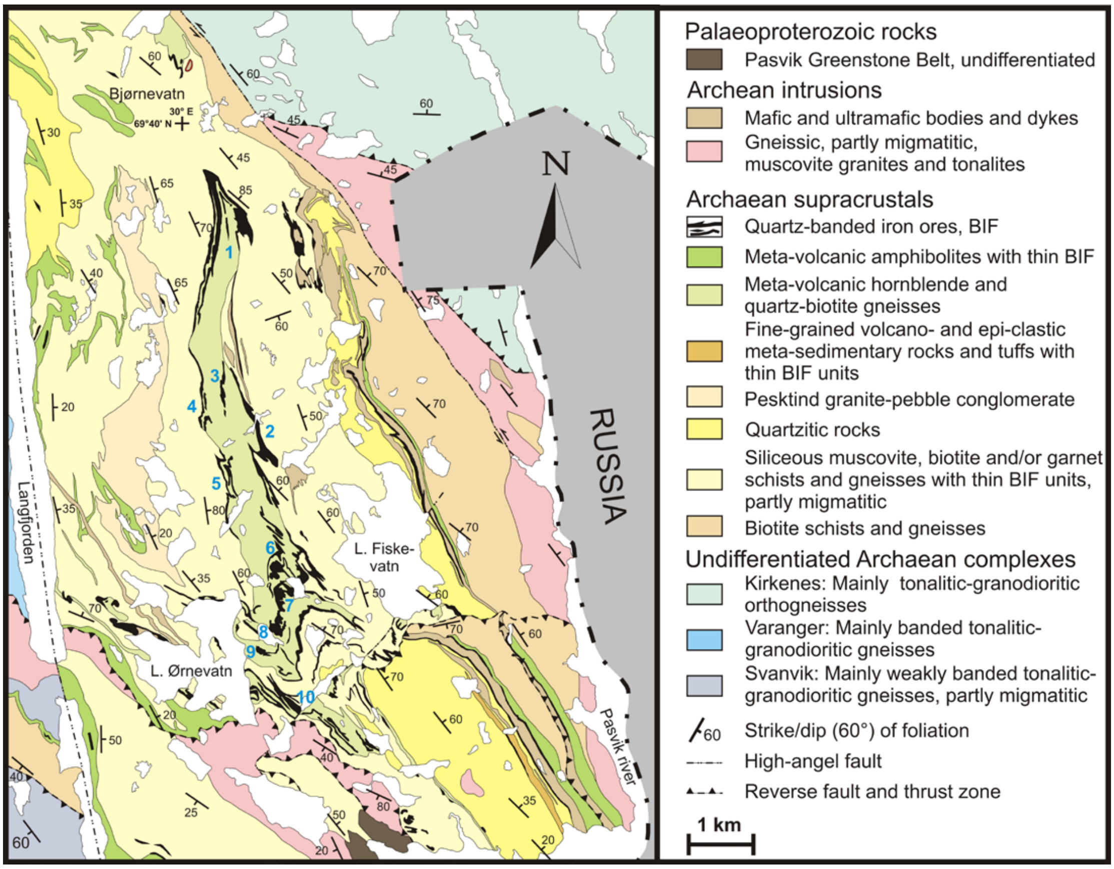
Mining commenced at three major iron ore deposits early in the 20th C – at Sydvaranger (1906), Fosdalen (1906) and Rødsand (Fe-V-Ti) (1910). The first steps, which led to Norway's major role as a producer of titanium-oxide pigments, were taken in the early 1900s, with the establishment of a company to 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 is now part of the National Lead subsidiary, Kronos. In 1957 the nearby Tellnes deposit was opened. It is one of the largest ilmenite deposits in the world, providing >7 % of world production of ilmenite in 2014.

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. Forty-two countries have now signed the treaty. The Norwegian company, Store Norske Spitsbergen Kullkompani, was established in 1916 and currently owns three coal mines (though only one in operation) on Svalbard. The Russian company, Trust Arktikugol, established a coal mine (still in operation) at Barentsburg in 1932.

The period of industrial development following World War II saw the opening of numerous new sulphide mines. These included the Caledonian massive sulphide deposits (year opened in parentheses): Mofjellet Zn-Pb-Cu (1928), Skorovatn Zn-Cu-pyrite (1952), Bleikvassli Zn-Pb–Cu (1957), Tverrfjellet Cu-Zn (1968), Joma Cu-Zn (1972) and Lergruvbakken, a new deposit in the Røros province (mainly 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. 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.

There are, at the present, three metal mines in Norway – the Tellnes ilmenite mine (at 58° 20' N) and the iron mines at Rana (Ørtfjell) and Sydvaranger (Bjørnevatn – currently (April 1916) on care and maintenance). 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 and Ulveryggen deposits in North Norway have recently been given. Nine deposits in Norway meet the specifications for deposits considered to be large or potentially large.

Figure 2. Geological map of the Bjørnevatn area.



Summary description of the major deposits

Bjørnevatn iron ore deposits

The Neoarchaean iron deposits in the Sør-Varanger metallogenic area are banded iron formations (BIF) deposited at ca. 2.8 Ga. The gneiss complexes hosting the BIF deposits (Figure 2) are predominantly pelitic, semipelitic and psammitic metasediments with subordinate sequences of metavolcanic rock, which are important hosts of the BIF units. The ores are normally 1–15 m thick and form several-kilometre-long trains of lenses with each ore body rarely more than a few hundred metres long. The Bjørnevatn ore field was discovered by Tellef Dahll, in 1865, but exploration did not begin until 1906. Full-scale mining by A/S Sydvaranger commenced in 1910 and continued until 1997. Open-pit and subordinate underground mining yielded a total of >200 Mt of ore with about 30 % Fe in this period. Sydvaranger Gruve AS reopened the deposit in 2009: four ore bodies (Bjørnevatn, Kjellmannsåsen, Fisketind and Bjørnfjell) were being mined in 2014: probable ore reserves were 154 Mt containing 30.4 % Fe_{tot}. Total resources (proven+indicated+ inferred) were stated in 2015 to be 506.6 Mt with 31 % Fe_{tot}.

Nussir copper-silver deposit

Several sediment-hosted copper deposits are associated with Palaeoproterozoic volcano-sedimentary rocks exposed in tectonic windows within the Scandinavian Caledonides in western Finnmark, North Norway. The most significant 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 (www.nussir.no). The nearby Ulveryggen deposit (also in the RTW) has resources of 7.7 Mt grading ca. 0.8 % Cu. About 3 Mt of ore grading 0.66 % Cu were mined from this deposit in the period 1972 – 1979. Nussir ASA plans to start operating both deposits.

The Nussir deposit is located in the upper part of the Saltvatn Group (Figure 3). The two lower beds are Cu-mineralised: the uppermost bed extends along the entire exposed length of the sequence (ca. 9 km). Au and Ag correlate well with copper whereas PGE mineralisation devi-

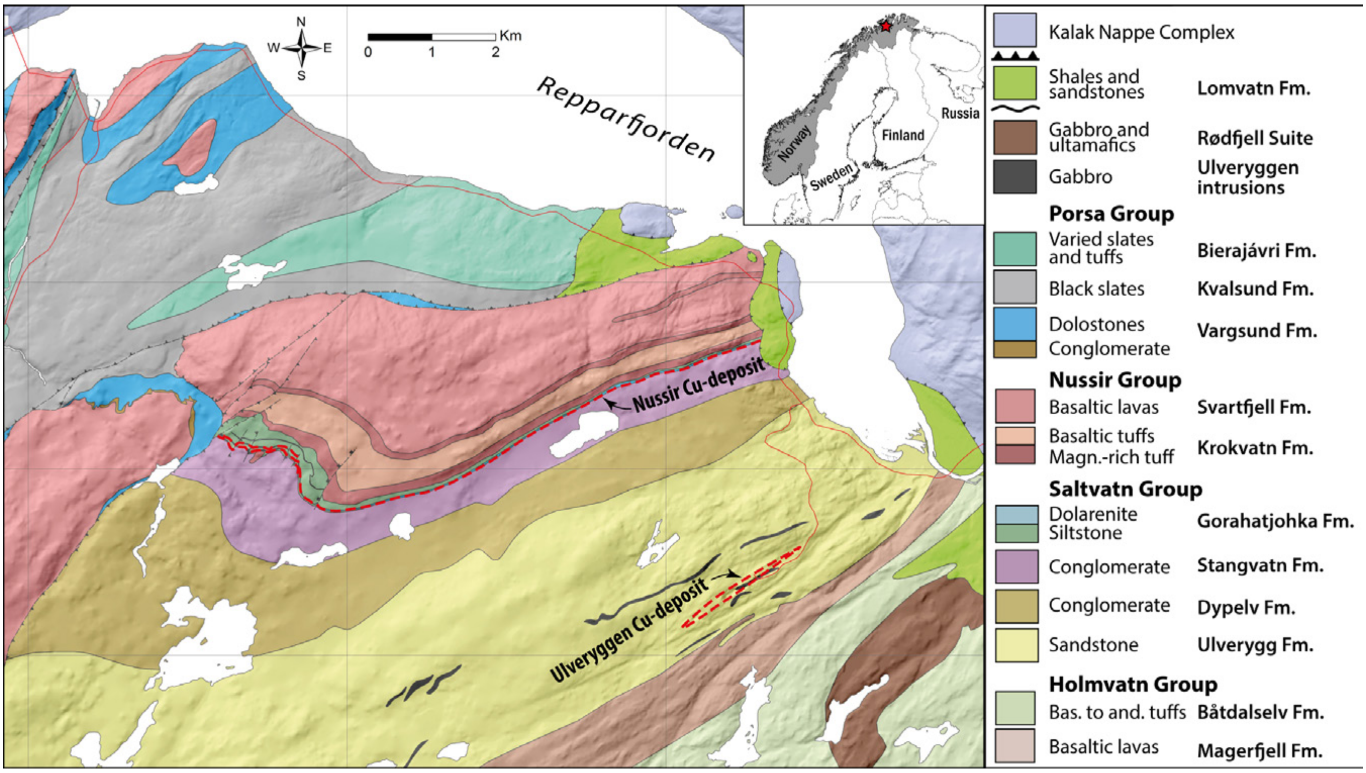


Figure 3. Geological map of the northern part of the Repparfjord Tectonic Window with the Ulveryggen (Repparfjord) and Nussir Cu-deposits marked.

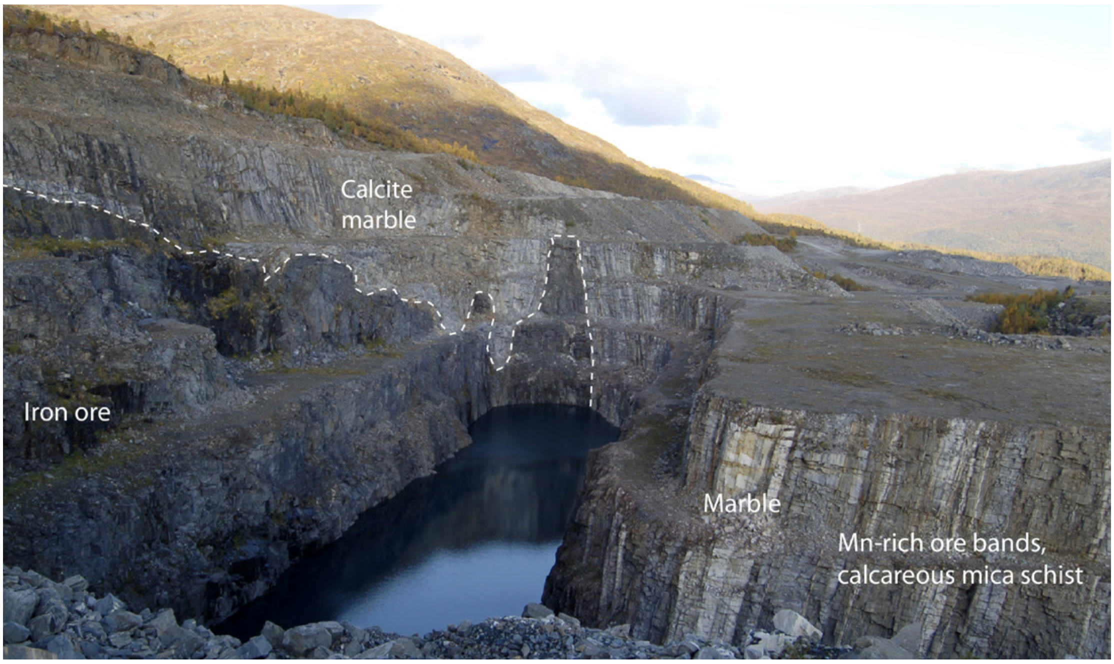


Figure 4. The Kvannevann open pit (looking east), showing the ore and its host rocks.

ates relative to the main copper ore. The copper mineralisations in the RTW have geological similarities to the important Cu deposits of the Central-African Copperbelt and the Kupferschiefer in Poland.

The Rana iron deposits (Ørtfjell)

The stratiform, banded iron ores in the Dunderlandsdal valley N of the town Mo i Rana occur in the Dunderland formation, comprising various schist and carbonate units with subordinate amphibolites. The sequence hosting the iron ores extends from Mosjøen in the south almost to Tromsø in the north, and is thought to have an age of 730-800 Ma. There are numerous ore deposits in the northern part of the area, but none are economic at present.

The iron ores occur as a series of dismembered and densely spaced segments, rarely exceeding 4 km in length. 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. The ores can be separated into several sub-types, the two most important being 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 constituting separate zones in the ore bodies. The magnetite/haematite weight ratio of the ores currently being mined is ca. 1:7. The high-phosphorus magnetite ore contains >0.9 % P_2O_5, and < 0.2 % MnO. The Ørtfjell deposit, the largest in the district, includes the Kvannevann mine, which currently produces ca. 2.1 Mt/a. Mining at the present level will allow production until 2023.

Løkken copper-zinc deposit

The Løkken Cu-Zn deposit is hosted by a fragment of an ophiolite complex (a slice of ancient oceanic crust). The deposit was the largest ophiolite-hosted volcanogenic massive sulphide deposit in the world. 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 the period 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 local, minor components and fahlore is the most important accessory phase. Quartz is the main non-sulphide, constituting 12–14 % of the ore.

Engebø eclogite-hosted rutile deposit

The Engebø rutile deposit (Figure 5) is a 2.5 km long, up to 0.5 km wide, E-W trending body of rutile-bearing eclogite on the N side of Førdefjord in the Sunnfjord region of West Norway. Two types of titanium deposit occur in the region: magmatic ilmenite-magnetite deposits associated with Mesoproterozoic mafic intrusions, and rutile-bearing Caledonian eclogites. The 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. Other eclogite bodies in the region (e.g. Orkheia) are also known to have significant contents of rutile.

The Engebø deposit wedges out upwards to the east but continues westwards at depth. 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 5 and it continues at least to 150 m below sea level in the west. Ore-type eclogite contains > 3 wt % TiO_2 and the low-Ti eclogite < 3 wt % TiO_2, with large variations locally.

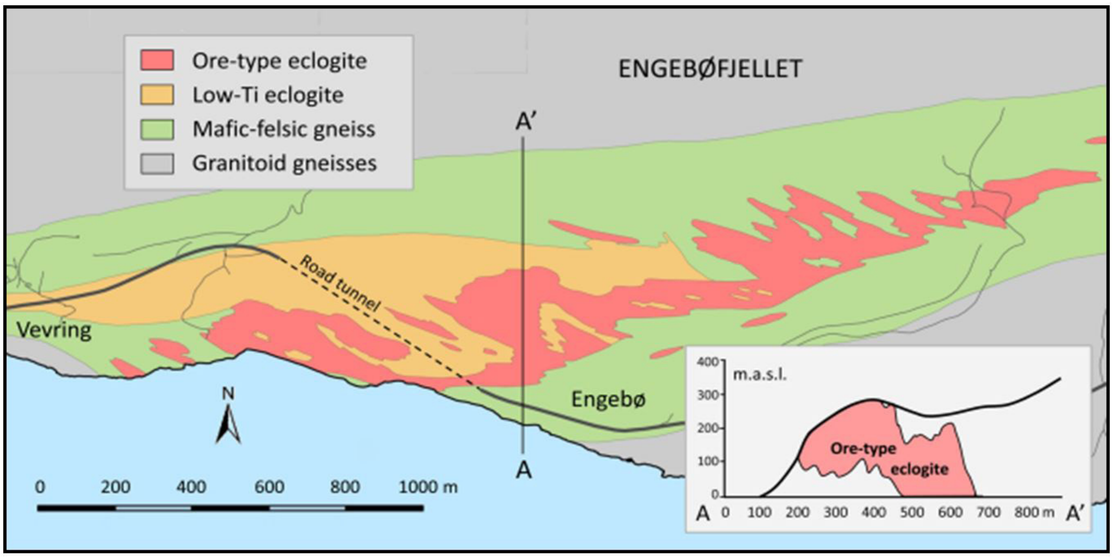


Figure 5. Geological map of the Engebø rutile deposit

Geologist Hans-Peter Geis from the company Elkem was probably the first who realized the economic potential for rutile at Engebø (in 1973). Engebøfjellet was thereafter studied on a reconnaissance basis by NGU as well as by various companies. In 2006 the Norwegian company, Nordic Mining acquired the mineral rights to the prospect and continued its development. The company succeeded, in 2015, in achieving a permit for deposition of mineral waste at 300 m depth in the nearby 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.

<u>The Nordli molybdenum deposit</u>

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 Hurdal granitic intrusion, in the northernmost part of the Rift, and its contact zones contain several types of molybdenum mineralization: the most important is the Nordli 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, by Intex in 2006-2008, led to a minor adjustment of the reserve estimate to 210 Mt grading 0.13 % MoS_2 (cut-off 0.07 % MoS_2) (Intex, 2015). Intex has an exploitation licence, valid to 2018, which confers exclusive rights to development of a mining operation.

<u>The Gallujav'ri (nickel-copper-PGE) and Rai'tevarri (copper-gold) deposits</u>

The Palaeoproterozoic Karasjok Greenstone Belt (KGB, Figure 6) is a 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, 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 prospecting companies in several periods in the 20th C. The two most important targets have been the Gallu'javri Ni-Cu-PGE deposit and the Raite'varri Cu-Au deposit.

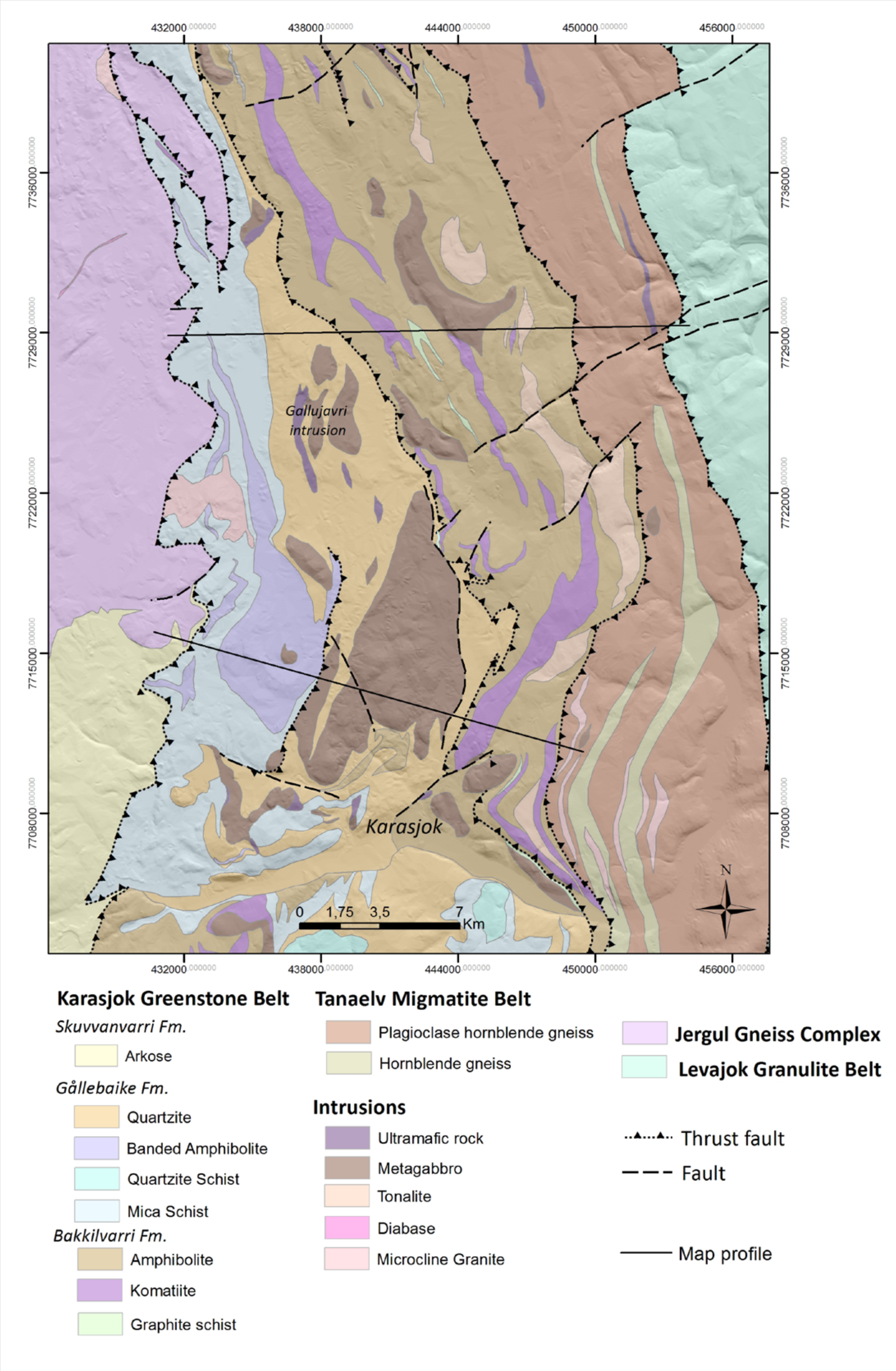
The Gallujav'ri ultramafic intrusion is located 20 km NNW of the town of Karasjok: it is considered to be > 500 m thick and at least 5 km long. The intrusion was studied successively by A/S Sydvaranger (1976-82), Tertiary Minerals plc (2002-2003), Anglo American (2006-2010) and Store Norske Gull (2011-2013): the claims are now held by Nussir ASA. 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-metal grades range up to 2.45 g/t Pt+Pd+Au. Available data thus suggest quite high metal-in-sulphide tenors.

Acquisition of high-quality aeromagnetic and gravity data during the period 2007-2014 allowed creation of a 3D interpretation of the form of major metavolcanic units and of Gallujav'ri and other intrusions in the area. The interpretation indicates that the exposed part of the Gallujav'ri intrusion is 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 Rai'tevarri mineralization is hosted by a more than 25 km-long, sporadically exposed unit of quartz-hornblende-plagioclase-bioitite gneiss (the Rai'tevarri Gneiss) ca. 30 km SW of Karasjok. The attraction for the prospecting industry has been the surface expression of the mineralization, of the order of 10 km^2. 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 NE flank of the complex
- Mineralisation along fault zones. 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

Figure 6. Geological map of part of the Karasjok Greenstone Belt (from Skaar 2014). (The Rai'tevarri deposit is just to the south of the map border.)



maximum values of 0.9 g/t Au, 0.76 % Cu, and 0.24 % Zn.

Holes drilled by RTZ show great variation in content of sulphides: one core 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 10m thick with elevated sulphide contents (up to 4 %). Grades are stated to be low, invariably <0.8 % Cu in 1 m sections, with gold rarely exceeding 0.5 g/t.

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.

Svalbard

The metallogeny of Svalbard is poorly known: detailed information about individual deposits is mainly found in unpublished company reports written in Russian or Norwegian. These suggest that the ore occurrences are dominated by epigenetic sulphide mineralisation, mostly on the main island, Spitsbergen. Occurrences of other types 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 7). Few of these 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 in the western parts of the West Spitsbergen Fold Belt where they are associated with breccias and deformation zones. The St. Jonsfjorden prospect area in western Spitsbergen (Figure 8) is known for its sulphide mineralisation, as reflected in the place name "Copper Camp" on the southern shore of the fjord (Figure 8). This location also marks the northern margin of the Holmeslettfjella gold prospect area.

Scree geochemical surveys carried out in the 1980s by the Geological Survey of Norway (NGU), Store Norske Spitsbergen Kulkompani AS (SNSK) and Norsk Hydro in cooperation led to the discovery of the Svansen Au-As deposit N of Kongsfjorden (Figure 7) and a system of Cu-Au-bearing quartz veins W of Woodfjord. The presence of gold and arsenopyrite in the Svansen deposit was confirmed by subsequent bedrock mapping and sampling.

<u>St. Jonsfjorden Au-As mineralization</u>
Store Norske Gull AS (SNG), established as a subsidiary of SNSK in 2003, carried out a geochemical prospecting campaign in Oscar II Land and Haakon VII Land (Figure 7) and started exploratory activities for gold in the St. Jonsfjorden area in 2009. A mineralised zone characterized by pyrite and arsenopyrite and containing up to 55 g/t gold was found in a thrust zone at Holmeslettfjella. Exploration, including a drilling programme, continued in 2010, but all activity was terminated 2013 when SNG was sold. The claims to the mineralized areas S of St. Jonsfjorden were, however, transferred to SNSK.

Scree and bedrock samples show a wide range of gold contents, up to 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. The map (Figure 8) reveals a clear spatial association between gold mineralisation and several thrust zones, particularly along the roof and floor thrusts of the thrust sheet containing the folded Bullbreen Group. 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". The structural control of the mineralisation inferred from surface relationships is confirmed by the drilling results.

<u>Svansen Au-As mineralization</u>
The Svansen Au-As mineralization N of Kongsfjorden (Figure 7) is hosted by banded metasandstone and quartzite of assumed Proterozoic age. Numerous, mainly concordant quartz veins,

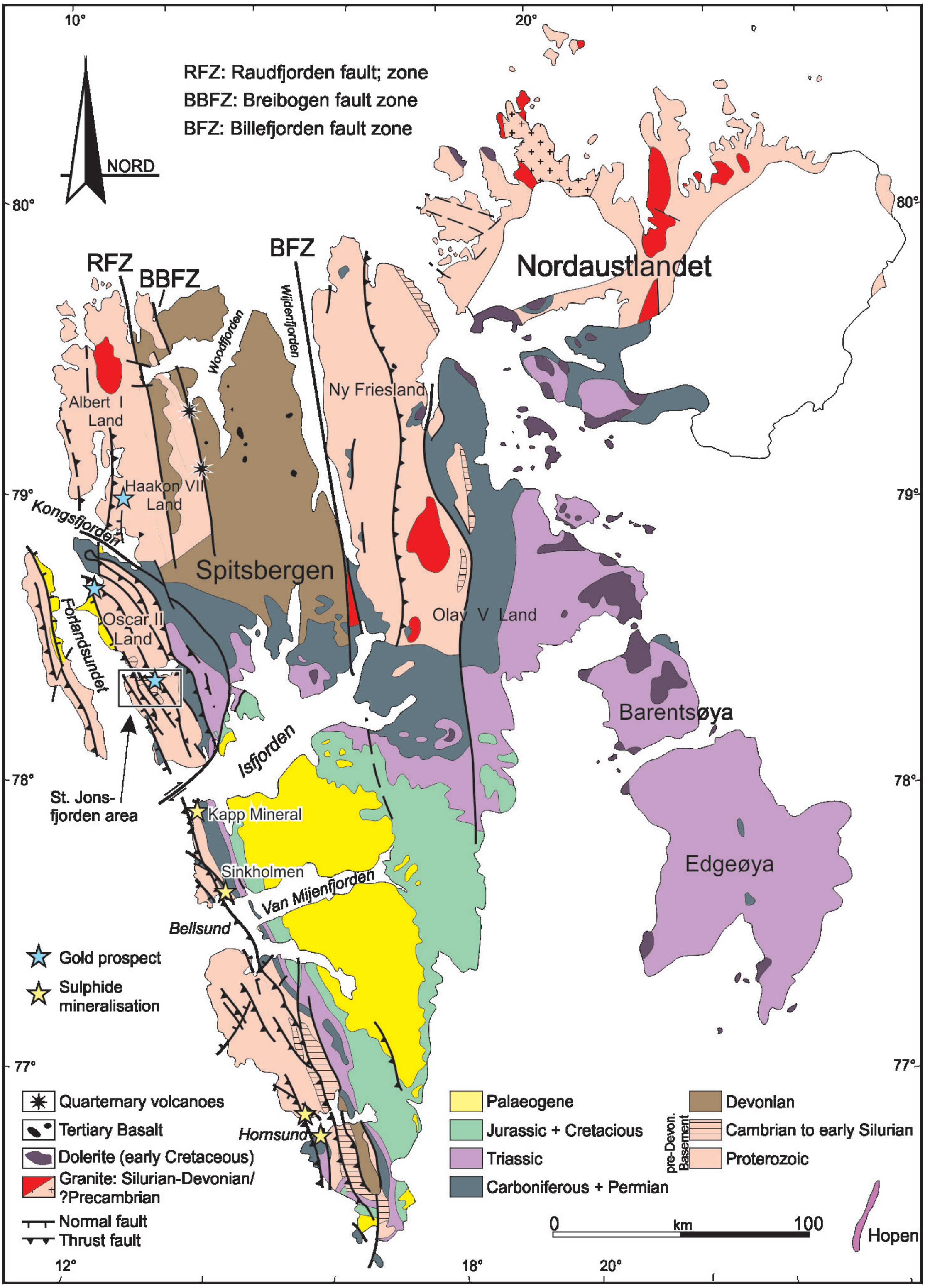


Figure 7. Geological map of Svalbard. The map also shows the location of gold prospect areas in western Spitsbergen (Store Norske Gull AS) and the location of the St. Jonsfjorden prospect area.

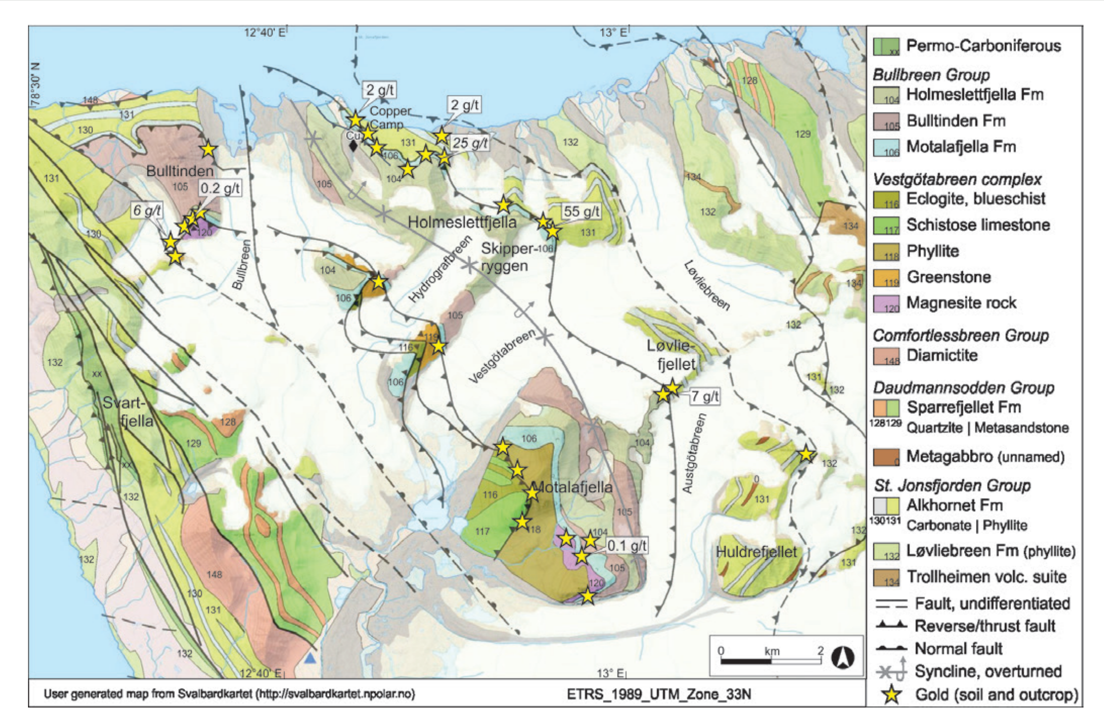


Figure 8. Geological map of the St. Jonsfjorden prospect area (modified after Bergh et al., 2003) showing gold values (g/t) from selected scree sample sites and from bedrock samples (italics = boulders) (Ojala, 2012).

pods and veinlets at cm- to dm-scales occur in the metasediments, but metre-wide quartz layers are rare. 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. The gold values of grab and channel samples vary from a few ppb to ca. 80 ppm. The 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.

SWEDEN[8]

History of Mining - Earliest times

The mining history of Sweden began in the Bergslagen district, south-central Sweden, two thousand years ago, as revealed by archaeological investigations. The Bergslagen district is an intensely mineralized region made up of volcanic and sedimentary rocks that have been metamorphosed, deformed and intruded by several generations of plutonic rocks. Bergslagen is one of several ore-bearing districts in Sweden that were formed and affected by the Svecokarelian orogeny (2.0-1.8 Ga).

Evidence of early mining is found N of Uppsala where fragments of iron ore occur close to bloomer furnaces dated to the period 0–400 AD. Pollen analysis and dating of charcoal shows that the Falun copper mine was in operation in early Viking time, 400–800 AD. The deposit was worked continuously thereafter until the closure of the mine in 1992, with a peak in copper production in the mid-17th C. Archeological investigations of the Lapphyttan blast furnace in the Norberg area, central Bergslagen, show that pig-iron was produced with modern techniques during the 13th C.

Early written documents on mining activity date back to the 13th C. The first document mentioning the Falu mine is from 1288 (Figure 1) and deals with shares in the mining operations, thus making the Falu mine one of the oldest, if not the oldest, limited company in the world. The current incarnation of the company is the Swedish-Finnish forestry company Stora Enso. The mine site was registered as a World Heritage site in 2001.

The deposits of iron, copper and silver, metals that have had the greatest importance in Bergslagen, are hosted, in most cases, by volcanic and sedimentary rocks dated to 1.91-1.88 Ga. Replacement of carbonate rocks, intercalated in both the volcanic and sedimentary rocks, formed skarn deposits, a common type of ore in Bergslagen.

17th century

During the end of the 16th C and the beginning of the 17th C, the demand for iron and steel increased and paved the way for technological improvements in the mines, blast furnaces and smelters in Bergslagen. At the same time, the de-

Figure 1. Panoramic view of the open pit at the Falun copper mine.

[8] Written by Anders Hallberg, Geological Survey of Sweden

mand and production of copper and other base metals increased rapidly. The mines, smelters and blast furnaces, originally small-scale operations established by local farmers, became larger industrial units.

The industrial revolution

The industrial revolution, which started in the early 19^{th} C on the European continent but which developed in Scandinavia somewhat later, brought new manufacturing processes and increased, at the same time, the demand for metals, especially iron. Steam engines, efficient pumps, railways, explosives, methods for processing phosphorus-rich (apatite-bearing) iron ore and the use of coal instead of charcoal in the blast furnaces are some of the innovations that upgraded the mining industry. The changes completely altered the industrial landscape of Sweden, and the development of a Swedish railway network made it possible to start large-scale mining of ores outside the Bergslagen district.

A new industrial era had begun and many foreign companies and entrepreneurs, mostly from Britain, helped with funding and technical assistance to the expansion of infrastructure and industry. Parallel to, and in interaction with, the expansion of the exploration and mining industry, there was a tremendous development of the Swedish engineering industry that supplied exploration, mining and mineral processing equipment during the late 19^{th} and 20^{th} centuries. Examples are Sandvik, Atlas Copco and ASEA (today ABB). Sandvik was founded in 1862 and was, from the very start, a company that delivered rock-drilling equipment to the exploration and mining industries. Through mergers and acquisitions the Swedish and Finnish engineering industries have amalgamated to form multinational companies that today are market leaders as suppliers to the world's exploration and mining industries. Atlas Copco was established in 1873 with the objective to manufacture and sell equipment for railway construction and operation. Today tools from Atlas Copco are found in mines around the world. In 1893, ASEA built Sweden's first three-phase electrical power transmission system for the Grängesberg iron mine.

The iron ores in Norrbotten county, northernmost Sweden, discovered already in the 17^{th} C, became mineable with the arrival of the railway: the railway between Malmberget and the Baltic Sea coast was completed in 1888. Production at the Malmberget iron deposit then rose from 60 t/a to 600 000 t/a within a few years. Fifteen years later, the railway reached Narvik in Norway, opening a link between the Baltic Sea and the Atlantic Ocean: the railway passes several of the large iron deposits in northern Sweden, including Kirunavaara. Production from the ores in Malmberget and Kirunavaara made up more than 50 % of all iron ore produced in Sweden in 1903. The mines in the north have held a leading position ever since. Today most of the iron ore produced in Sweden and in the European Union comes from these two mines. The giant Kirunavaara and Malmberget deposits and several similar but smaller iron deposits are so-called apatite-iron ores formed at 1.91-1.88 Ga during the Svecokarelian orogeny.

The Svecokarelian orogeny also affected older rocks found in the Norrbotten area. The northernmost part consists of Archaean metamorphosed granitic rocks, with minor gneissic rocks of supracrustal origin with ages up to 2.7 Ga. In Palaeoproterozoic time, c. 2.3 Ga ago, the Archaean rocks were rifted and intruded by igneous rocks, followed by deposition of sedimentary, volcanic and carbonate rocks in a rift-related tectonic setting. These so-called Karelian supracrustal rocks make up the oldest ore-bearing formation in Sweden with important iron and copper deposits, i.e. skarn iron ore deposits in the Pajala area (Tapuli, Stora Sahavaara etc.) and the Viscaria copper deposit close to the town of Kiruna.

During the Svecokarelian orogeny, the older rocks were deformed and metamorphosed, and extensive igneous activity resulted in volcanic rocks of different compositions, which, together with sedimentary rocks, were deposited on top of the older rocks. Coevally with these supracrustal rocks, the Kirunavaara and Malmberget apatite-iron deposits were formed and also the large Aitik copper deposit.

The 1920s – a new ore district

During the first decades of the 20th century, several small holding companies called "emissionsbolag" were created by Swedish banks. One of these was Centralgruppens Emissionsbolag with the mission to acquire stocks in new mining companies and to develop mines. It was thus a form of early junior exploration company. In 1924, at a time when the company was nearly bankrupt, the Boliden gold-copper-arsenic deposit was discovered. It was put into production two years later. During the following years, with the aid of newly developed geophysical instruments, several new massive sulphide deposits were found west of Boliden. Today these deposits, and their host rocks, form the Skellefte district, one of the most important ore regions in Europe, currently with five operating mines and two concentrators.

The ore-bearing rocks in the Skellefte district are volcanic rocks deposited in volcanic arc environments, and associated sedimentary rocks. Together with layered sandstone-schist units and coarse-grained sedimentary rocks to the south, they constitute the Bothnia-Skellefteå area, one of the districts formed during the Svecokarelian orogeny. The Boliden gold-copper deposit, the Kristineberg zinc-copper deposit, several other massive sulphide deposits in the Skellefte district and also the Tallberg porphyry copper deposit were formed in association with the volcanic activity. Some gold deposits located in the vicinity of the Skellefte district were probably formed during the later stages of the orogeny.

Discoveries are still being made in the Skellefte district. The Björkdal gold deposit was found 1985 using geochemical methods (till-sampling), went into production in 1988 and is still (2016) in production. The Åkerberg gold deposit was found in 1988 and was in production from 1989 to 2001. One of the most zinc- and copper-rich deposits ever found in the district, the Storliden deposit, was discovered in 1997 and was in production from 2002 to 2008. With the opening of the Kankberg gold-tellurium deposit in 2012, a new commodity, tellurium, was added to the list of metals produced in the district.

The Caledonides

The Caledonian nappe units (the Caledonides) constitute another important mineralized region, the metal potential of which has been known for a long time. Although the lack of infrastructure and, more recently, environmental protection policies, have limited exploration and exploitation, several attempts to develop deposits have been made over the years.

During the Caledonian orogeny, rocks formed in Neoproterozoic to Palaeozoic time, including island-arc and sedimentary rocks, together with older crust were thrust eastwards on pre-existing Fennoscandian crust. Important ore-bearing units are the Köli Nappe Complex, hosting massive sulphide deposits formed in an island-arc setting, and the Seve Nappe Complex with, what is believed to be, sediment-hosted copper deposits.

One of the oldest mining operations took place during the mid 17th C at the Nasafjäll silver deposit close to the Norwegian border. The Fröå copper deposit, hosted by the Seve Nappe Complex, was found in the mid-18th century and mined intermittently, the latest period from 1910 to 1919. Exploration by the Geological Survey of Sweden in the Caledonides led to the discovery of several massive sulphide deposits hosted by the Köli Nappe Complex. The only deposit that has been in production though is Stekenjokk, which was mined for copper and zinc between 1976 and 1988.

The base of the Caledonian nappes consists of platform cover sedimentary rocks of Neoproterozoic to Palaeozoic age. These locally contain sandstone-hosted lead-zinc deposits of so-called Laisvall-type and uranium mineralisations in alum shale (black shale). These rocks also occur as nappes in the Caledonides.

Galena-bearing sandstone boulders found in 1938 led to the discovery of the Laisvall lead-zinc deposit. Exploitation started in 1943, mainly as a measure to secure domestic supplies of lead during World War II but the deposit was economic in a longer term and mining lasted until 2001. Exploration for sandstone-hosted lead-zinc deposits led to several discoveries of similar mineralisations along the Caledonian front, and the Vassbo and Guttusjö deposits 500 km SSW of Laisvall have also been in production.

More discoveries

Improved infrastructure also opened the Nordic region for exploration for other commodities. Boulders from what was discovered to be the large Aitik copper-deposit were found in 1930. Decades of exploration and development eventually led to the opening of a mine in 1968. Initial production was 2 Mt/a: after several phases of expansion, the most recent of which was approved in 2010, plans for an annual production of 36 Mt per year by 2015 were made. This goal was achieved and surpassed already in 2014, when 39.09 Mt @ 0.2 % copper, 0.09 g/t gold and 2.14 g/t silver were produced and milled.

In 1973, a copper-mineralized area was discovered 4 km W of the Kiruna iron ore deposit (Godin 1976). The initial exploration method was the recognition of the "copper flower", *Viscaria alpina*, and the mine, which was named Viscaria for the flower, was in production from 1982 to 1997. Today there are advanced plans to re-open the mine.

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

Status late 2015

There are currently 13 operating metal mines in Sweden (see Figure 2 for the location of the actively mined deposits named in this section). The oldest one still in operation is the Garpenberg mine which, according to documents, was in production in 1402 but probably had been in production long before. Garpenberg is a zinc-lead-copper deposit with a significant silver content. Recent near-mine exploration and investments have increased the production of the mine drastically. Currently (2015) the annual production is 2.367 Mt with 5 % zinc, 2.2 % lead, and 156 g/t silver plus some copper and gold. In the Zinkgruvan mine, zinc- and lead-ore have been mined on a large scale since 1857. In recent years a copper-rich part of the ore has also been exploited. In 2015, the mine produced 1.126 Mt of ore grading 8.3 % zinc and 3.8 % lead as well as 0.139 Mt of ore grading 1.7 % copper, in total 1.265 Mt of ore.

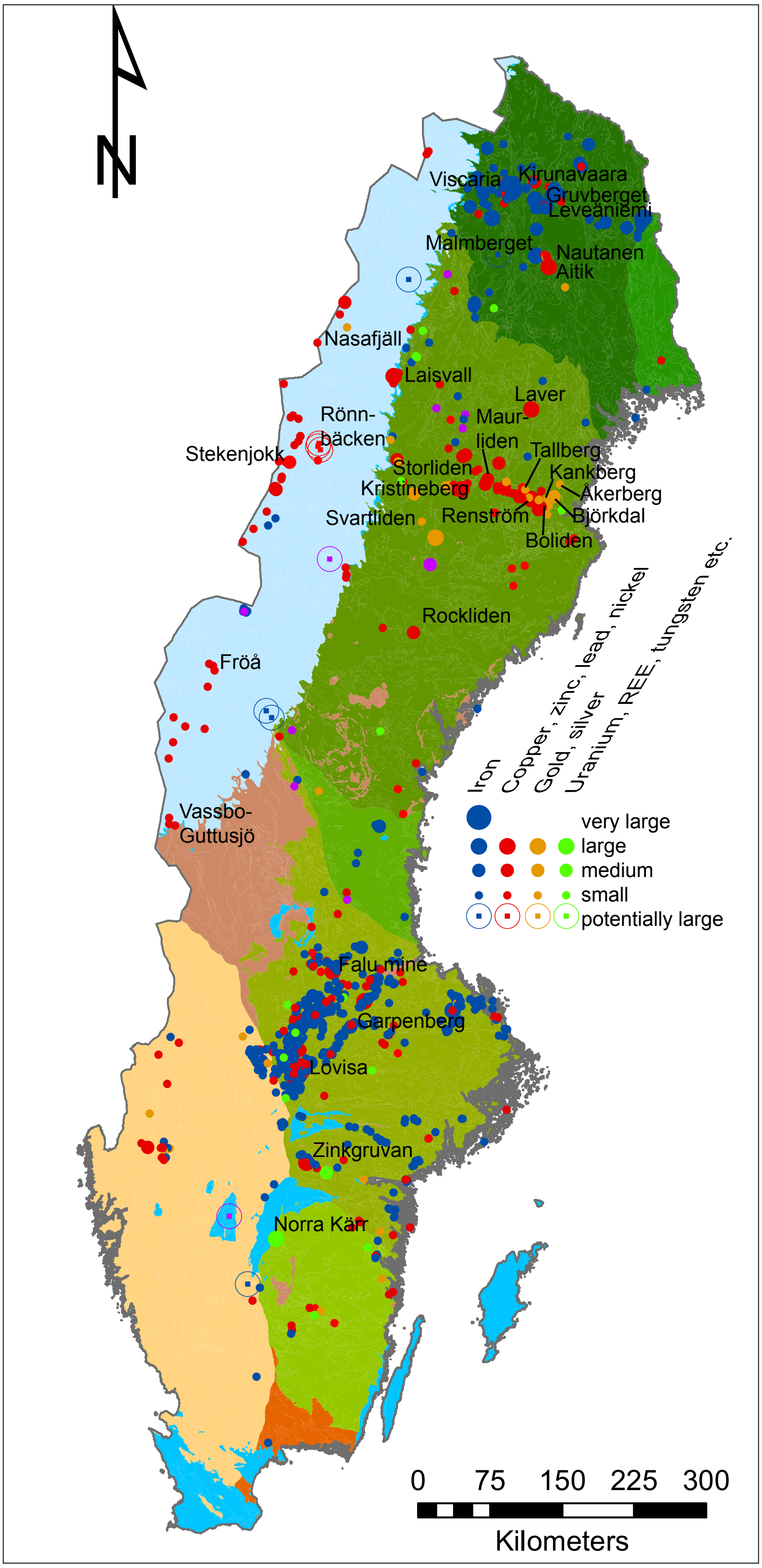


Figure 2. Metal deposits in Sweden, classified according to the criteria for the Fennoscandian Ore Deposit Database (FODD) project (Eilu et al., 2007).

Four mines are in operation in the Skellefte district. The Kristineberg and the Renström mines have been in operation since 1935 and 1948, respectively. Copper-lead-zinc ore with some gold is produced at both deposits and transported to the concentrator at the small town, Boliden. The Maurliden mine is an open-pit operation, in production since 2000, which produces a similar type of ore to those described above. The Kankberg mine, however, produces gold and tellurium from an underground operation. The four mines in the Skellefte district delivered 1.879 Mt of ore to the concentrator in 2015.

Gold ore is mined from an open pit and underground at Björkdal: the deposit produced 1.302 Mt of ore with 1.22 g/t gold in 2015.

The giant Aitik mine is a porphyry-copper deposit in which fine-grained chalcopyrite is disseminated in the host rocks. Efficiency and a high degree of automation make the open-pit mine profitable at low grades. In 2015, the mine produced 36.361 Mt of ore with 0.21 % copper and 0.14 g/t gold.

Iron ore is produced at Kirunavaara, Malmberget, Leveäniemi and Gruvberget. The four apatite-iron deposits produced 30.6 Mt of ore with an iron content of c. 45 % in 2014.

The future

The concepts “brown-field” and “green-field” exploration are in common use by miners and mineral explorers: future mining and exploration operations in Sweden may also be described using those terms. Results from both brown- and green-field exploration indicate a great potential for future mining in Sweden. Brown-field exploration means exploring for new ore close to existing deposits.

Some examples:

- Laver, Norrbotten (in operation 1934–1946): New exploration shows that the mineralized area is much larger than previously believed and contains a very large resource at low copper grade.
- Rävliden (in operation 1936–1991): New resources identified in the vicinity of the closed mine.
- Nautanen (1902–1907, 1915, 1918): New resources identified at the historic mine site.
- Leveäniemi (in production 1964–1982, restarted in 2014): Increased resources.
- Viscaria (in production 1982–1997): New copper and iron resources have been identified.
- Green-field exploration in areas where no mines have been in operation in the past.
- Rockliden: New discovery made in the 1980s. Revised resource estimates indicate significant amounts of ore.
- Norra Kärr: REE deposit known since 1906 and now identified as a significant REE resource.
- Rönnbäcken: Previously considered to be a talc resource, now identified as a potentially important, large nickel resource.

FINLAND[9]

Brief geological outline

The bedrock of Finland is composed almost entirely of Precambrian rocks that are part of the Fennoscandian shield. The bulk of the Finnish bedrock evolved during four time periods. The oldest part consists of 3200-2700 Ma Archean basement and overlying 2500-1920 Ma Paleoproterozoic volcano-sedimentary cover rocks (Figure 1). The southern part of the Finnish bedrock was formed during the 1930-1770 Ma Svecofennian orogen and subsequent 1640-1460 Ma Mesoproterozoic rapakivi magmatism. Younger, Neoproterozoic and Paleozoic sedimentary and carbonatitic and alkali intrusions are known, but they constitute only a minute part of the bedrock in Finland.

Each of the above-mentioned main stages resulted in different metallogenic characteristics and zones. Economically interesting Au, Au-Ag, Ni-Cu, and Mo deposits were formed during the Archean period. In addition, one of the most significant phosphate deposits currently being exploited was formed during the Archean period. Rifting of the Archean supercontinent at ca. 2440 Ma resulted in voluminous magmatism and formation of significant Cr, Fe-Ti-V, PGE, and Ni-Cu-PGE deposits. Subsequent rifting of the Archean basement at ca. 2050 Ma resulted in magmatism which produced Ni-Cu deposits. Sedimentation in the rift basins led to formation of black-shale-hosted Ni-Zn-Cu deposits. Continental break-up was followed by formation of new oceanic crust and by ocean-floor-related ore-forming processes. As a result, significant Cu-Co-Ni deposits were formed. The most prolific metallogenic period in Finland took place during the composite Svecofennian orogen in 1930-1770 Ma. During this time several different types of Ni-Cu, Cu-Zn, Au, Au-Ag and Li deposits were formed along convergent plate boundaries and magmatic and metamorphic terranes. So far no significant metal deposits related to 1640-1460 Ma rapakivi magmatism have been discovered, but the potential of rapakivi intrusions for hosting high-tech. metals including Rare Earth Elements (REE) is under inves-

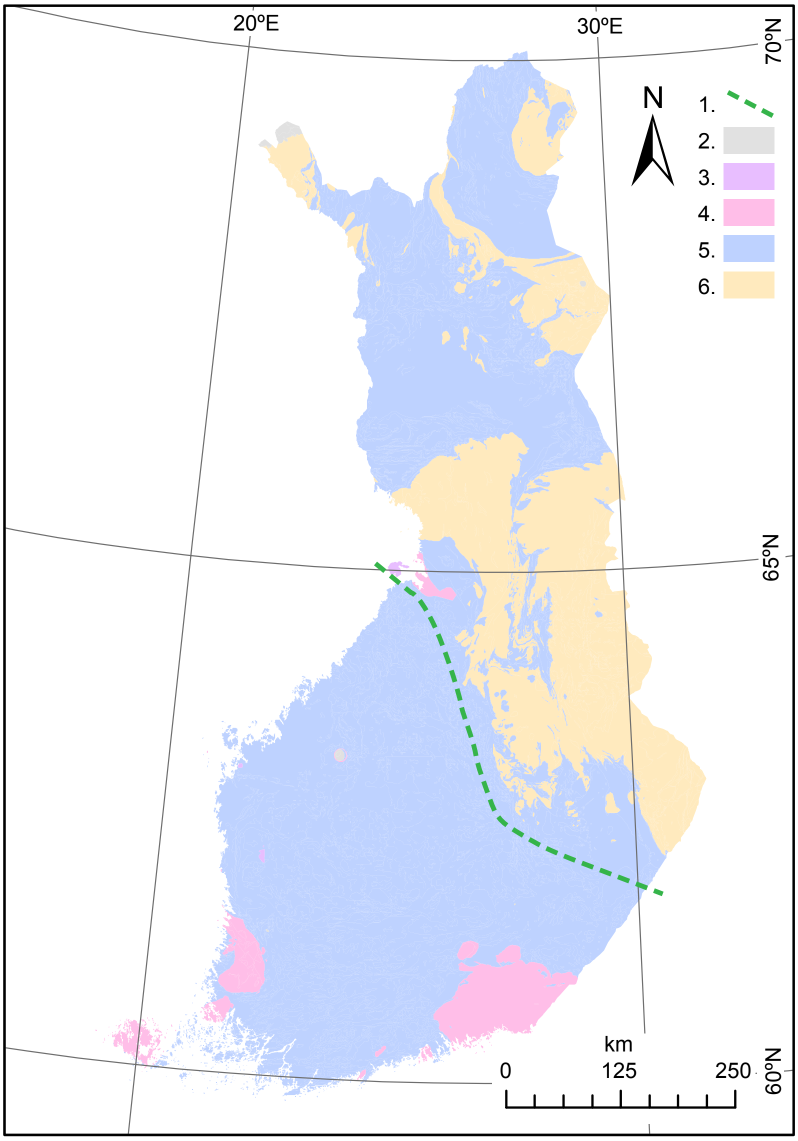


Figure 1. Main geological units of Finland. 1. Southernmost extent of Archean crust, 2. Paleozoic rocks, 3. Neoproterozoic rocks, 4. Mesoproterozoic rocks, 5. Paleoproterozoic rocks, 6. Archean rocks.

[9] Written by Tero Niiranen and Pasi Eilu, Geological Survey of Finland (GTK)

tigation. Diamondiferous kimberlite pipes from ca. 600 and ca. 1200 Ma have been discovered in the eastern part of the country. Phosphorus deposits are known in 420-360 Ma Devonian alkaline and carbonatitic intrusions and their REE potential is also currently under investigation.

History of mining: 16th – 19th Century

The Ojamo iron ore mine, at which production started in 1530, is regarded as the first metal mine in Finland. Following this, over 350 metal mines had been in operation before World War II. The scale of production in these mines was modest, although mining played an important role in the slowly developing society. Before the 1920s, the mines mainly produced iron ore for iron works in southern Finland. Sulphide ore production was mostly from one mine, Orijärvi (Cu-Zn) in SW Finland. From 1530 until the end of the 19^{th} C, metal ore production totalled 1.4 Mt, of which ore from sulphide mines comprised 1.0 Mt (most of which was produced after 1850) and from the iron mines 0.4 Mt

20th Century

The modern mining industry in Finland started to develop along with the Outokumpu mine. The deposit was discovered in 1910 and in 1928 it become the largest sulphide ore mine in the country. Small-scale production started immediately in 1910, production gradually increased in the 1920s and 1930s and total ore output was almost 6 Mt between 1930 and 1945. During its lifetime, 1910–1989, about 28 Mt of ore was mined and 1 Mt copper produced. The Petsamo (Pechenga) nickel deposit was found in 1921, in the then northeasternmost corner of Finland. The development of a mine at Petsamo was complicated, but eventually, in the period 1936–1944, about 0.5 Mt of ore was mined, first as a Finnish-Canadian cooperation, and later, during World War II, by German interests. The war between Finland and the Soviet Union ended in September 1944, and the Petsamo region was subsequently ceded to the Soviet Union.

Soon after the war, in the late 1940s, the Aijala (Cu) and Otanmäki (Fe-Ti-V) mines were opened. Otanmäki gradually developed into a globally significant vanadium mine, responsible for about 10 % of the world's vanadium production during the 1960s and 1970s. Seven metal mines were opened in the 1950s, including the Vihanti (Zn) and Kotalahti (Ni) mines. The most active mine development period thus far in Finland was 1960–1980, when more than twenty metal mines started production. The most important were the still operating Kemi Cr and Pyhäsalmi Zn-Cu mines. As a consequence, total metal ore output peaked in 1979 at slightly over 10 Mt. A few small mines were opened in the 1980s, but a number of major mines were closed in the same period, and total production gradually declined to about 3 Mt in the first years after 2000.

Before the opening of the Talvivaara and Kevitsa mines in 2008 and 2012, respectively, the largest sulphide mine in Finland was Pyhäsalmi. The deposit was discovered in 1958 when a local farmer dug a well through the overburden till into a subcrop of the massive ore. By the end of 2014, over 53 Mt of ore had been mined and the remaining ore has secured a further 5 years of production.

The Kemi chromite deposit was found 1959 by a local layman. Open-pit chromite mining began in 1966 and ferrochrome production in 1967 at nearby Tornio, at the far northern end of the Gulf of Bothnia. Stainless steel production at Tornio commenced in 1976. In 2006, the underground mine became the sole source of ore. Its current design capacity is 2.7 Mt/y of ore. The known ore reserves will enable mining to continue for several decades, and a recent seismic reflection survey suggests that the ore possibly extends beyond a depth of 2 km.

Currently, there is a new era in Finnish mining history. Two major mines, Kittilä Suurikuusikko (gold) and Talvivaara (nickel), were opened in 2008, and the Kevitsa Ni-Cu-PGE mine in 2012. These three mines have multiplied Finnish metal ore output to about 14 Mt/y in 2014. In addition to these major deposits, a number of smaller projects have recently started; these include the Jokisivu mine which produced its first gold in 2008, and the Pampalo gold and Kylylahti Outokumpu-type Cu-Co-Ni-Zn mines which opened in 2011. The Laiva (Laivakangas) gold mine in western Finland also went into production in 2011, but is presently in care and maintenance.

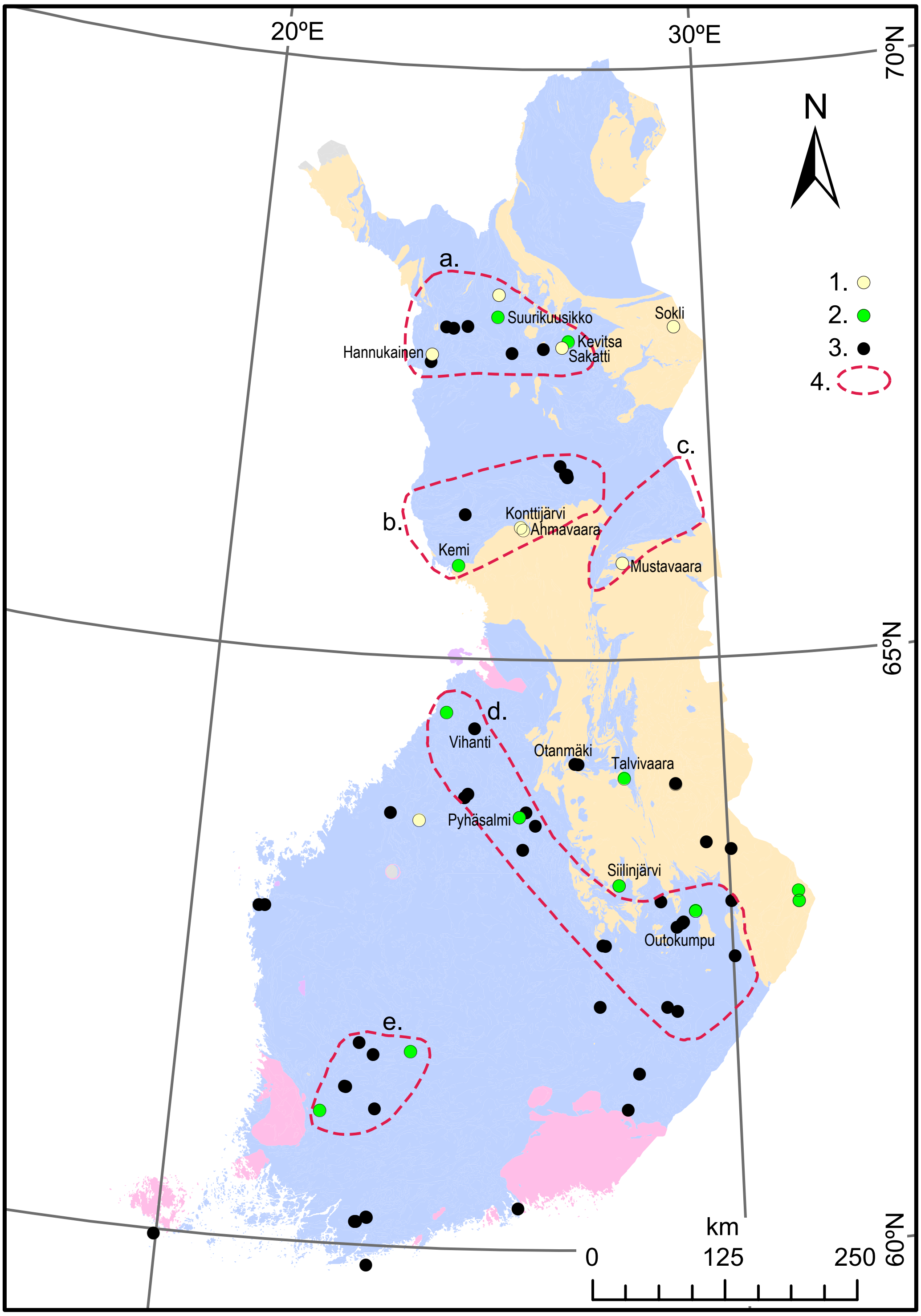


Figure 2. Location of metallic and phosphorus mines and the most important mineral provinces in Finland. 1. Mine under development, 2. Active mine, 3. Closed mine, 4. Boundary of mineral provinces: a. Central Lapland greenstone belt, b. Peräpohja schist belt, c. Kuusamo schist belt, d. Raahe-Ladoga Zone, e. Tampere-Häme belt. Background geology as in Figure 1.

Summary information on the most important provinces and deposits

The five most important ore provinces of Finland are shown in Figure 2. They are (from north to south): Central Lapland greenstone belt (CLGB), Peräpohja schist belt (PSB), Kuusamo schist belt (KSB), Raahe-Ladoga zone (RLZ) and Tampere-Häme belt (THB). Significant and economically interesting deposits also occur outside these main provinces.

The Central Lapland greenstone belt (CLGB) is one of the most prospective belts: several significant deposits of different types are known within the belt. It is highly prospective for gold, not least for hosting the world-class Suurikuusikko deposit and several smaller past-producing Au and Au-Cu deposits. The Suurikuusikko deposit is currently the largest gold deposit in Europe. At the end of 2014, the total pre-mining gold resources were 57.6 Mt @ 4.38 g/t Au, yielding 252.3 tonnes of Au. The deposit is hydrothermal in origin and hosted by a major shear zone. It extends 4 km along the strike of the shear zone and is known to extend to at least 1.5 km in depth. It has been in operation since June 2006. In addition to gold deposits, several Ni-Cu, Ni-Cu-PGE, Cr, Fe, Fe-Cu-Au, Cu-Zn and Fe-Ti-V deposits are known within the CLGB. The most significant of these are the Kevitsa and Sakatti Ni-Cu-PGE, Hannukainen Fe-Cu-Au, and Koitelainen Cr deposits. The Kevitsa Ni-Cu-PGE deposit is a magmatic mafic intrusion-related sulphide deposit. The ore body consists of disseminated sulphides hosted by a 2060 Ma-old mafic intrusion. The mineralization extends roughly 1200 m x 1500 m in horizontal dimensions and reaches a depth of 400 m. The known mineral resources in 2012 were 240 Mt at 0.3 % Ni, 0.41 % Cu, 0.21 g/t Pt, 0.15 g/t, Pd, and 0.11 g/t Au. Production at Kevitsa commenced in 2012 and 7 Mt of ore was processed in 2014. The Sakatti Ni-Cu-PGE deposit was discovered in 2009 and although no official tonnages or grades have been published the data available indicate that it is probably a word-class discovery. The deposit consists of three sulphide ore bodies hosted by mafic intrusions. The Hannukainen Fe-Cu-Au deposit is located in the western part of the CLGB. It consists of five elongated, gently dipping iron oxide ore bodies with local, economically interesting Cu and Au grades. It was mined from two open pits in the period 1978-1990, total production being 4.5 Mt. Recently further investigations aimed at reopening the deposit, were carried out. The total resources at Hannukainen in 2014 were 91.9 Mt at 32.2 % Fe, 0.19 % Cu and 0.09 g/t Au. The Koitelainen Cr deposit is a mafic intrusion-hosted, sulphide-free Cr-oxide deposit. The deposit consists of two, locally over 2 m thick subhorizontal Cr-mineralised reefs which extend across the whole of the 26 km x 29 km intrusion. No resource estimate has been made of the deposit, but the Cr_2O_3 grade ranges between 10.6 % and 32.2 % within drilled sections of the deposit.

The Peräpohja schist belt (PSB) hosts significant Cr, Ni-Cu-PGE and PGE deposits. In addition small but economically interesting Au, Au-Cu, Mo, Fe, and Fe-Cu-Co-Au deposits have been discovered in the area. Recently, a cluster of Au-U deposits, with locally very high Au and U grades, were discovered in the central parts of the area. The single most significant deposit in the belt is the Kemi Cr deposit which was discovered in 1959 and has been in operation continuously since 1968. The Kemi deposit is a mafic layered intrusion-hosted chromite deposit. The mineralization consists of several, steeply dipping chromite horizons. The thickness of the mineralization averages 40 m but varies from a few meters up to 160 m. The length of the mined part is 1.5 km and it is estimated, using geophysical methods, to reach a depth of 2 km. The current mineral reserves are 50 Mt at 26.0 % Cr_2O_3 with an additional 97.8 Mt of mineral resources at 29.4 % Cr_2O_3. A total of 44 Mt of ore had been mined by the end of 2014. The same 2440 Ma mafic layered intrusion complex which hosts the Kemi deposit also hosts Ni-Cu-PGE and PGE deposits. The most significant of these are the Konttijärvi and Ahmavaara Ni-Cu-PGE deposits. The Konttijärvi PGE-enriched base-metal disseminated sulphide deposit consists of a 10-30 thick mineralized zone and a set of plate-like massive, 0.2-20 thick sulphide mineralizations comprises the Ahmavaara Ni-Cu-PGE deposit. The known mineral resources in 2007 were 75.3 Mt at 0.95 g/t Pd, 0.27 g/t Pt, 0.1 % Cu, 0.05 % Ni and 0.07 g/t Au and 187.8 Mt at 0.82 g/t Pd, 0.17 g/t Pt, 0.17 % Cu, 0.08 % Ni and 0.08 g/t Au for Konttijärvi and Ahmavaara, respectively.

The Kuusamo schist belt (KSB) hosts only one deposit (Mustavaara) which has previously been mined: there are, however, about 15 known, somewhat enigmatic, hydrothermal Au-Co-Cu-U-REE deposits in the central part of the belt. The economic viability of the largest ones is currently under investigation. The Mustavaara Fe-Ti-V deposit was mined in the period 1976-1985, the total production being 13.45 Mt of ore. During this time, the deposit produced 6-9 % of global vanadium demand. The deposit is a mafic intrusion-hosted oxide deposit and mineralization consisting of V- and Ti-bearing iron oxide (ilmenomagnetite). Recently, the deposit has been under further investigation and reopening of the mine is planned. According to the most recent data, the resources at Mustavaara are 99 Mt of oxide ore grading 14 wt % ilmenomagnetite with 0.91 % vanadium.

The Raahe-Ladoga Zone (RLZ) is historically the most significant base metal province in Finland. Several past-producing and currently active Cu-Co-Zn, Ni-Cu and Cu-Zn deposits occur within the province. In addition to base metals, economically interesting Au deposits have been discovered and one of these is being mined. Perhaps the most important of the deposits is the Outokumpu Cu-Co-Zn deposit discovery, exploitation of which paved the way to modern mining in Finland. The initial discovery was made in 1910 and the mine was operated from 1910 to 1984. The deposit contained ca. 30 Mt ore at grades of 3.8 % Cu, 0.24 % Co, 1.07 % Zn 0.12 % Ni, 0.8 g/t Au, and 8.9 g/t Ag. The Outokumpu mineralization consisted of tabular massive sulfide ore bodies. The mineralization was originally formed by sea-floor hydrothermal processes and was metamorphosed and deformed into its final shape and position during the Svecofennian orogenic events. A number of similar deposits, referred as Outokumpu-type, were discovered in adjacent areas and one, Kylylahti, is currently being mined. The Pyhäsalmi Cu-Zn deposit is a volcanogenic massive sulphide (VMS) deposit which was originally formed in a seafloor hydrothermal system and was subsequently metamorphosed and deformed into its current shape. The mineralization consists of a stretched diapir-shaped body which extends to a depth of 1400 m. The total production since the beginning of mining in 1959 is 50 Mt at grades of 0.92 % Cu, 2.47 % Zn, 0.4 g/t Au, and 14 g/t Ag. The known remaining resources are expected to be mined out in 2019 at the current average production rate of ca. 1.4 Mt/a. The Vihanti Zn-Pb-Ag deposit is genetically similar to Pyhäsalmi, albeit having a different metal association. The deposit consists of about 20 separate ore bodies with variable size and grades. The deposit was mined in the period 1954-1992 with total production being 28.1 Mt of ore with grades of 4 % Zn, 0.4 % Cu, 0.36 % Pb, 25 g/t Ag and 0.44 g/t Au.

The southernmost of the most important provinces in Finland is the Tampere-Häme belt (THB) which consists geologically of three adjacent belts; the Tampere and Häme greenstone belts and the Pirkanmaa schist belt. A number of Au, Au-Cu, and Ni-Cu deposits of different types have been discovered. Four of these have previously been in production and two deposits are currently being mined. In addition to previously mentioned metals, indications of Cu-Mo-W mineralizations have been discovered in the area.

Several important deposits are known outside the provinces described above:

- The Siilinjärvi phosphorus deposit is by far the largest industrial mineral mine in Finland, and currently the only operating phosphorus mine in the European Union. By the end of 2014 a total of 271 Mt of apatite ore had been mined since the start of the mining operation in 1980. The reported remaining resources in the deposit in 2014 were 1617 Mt at 3.8 % P_2O_5 grade. The mineralization is hosted by an Archean carbonatite intrusion (2610 Ma).
- Talvivaara is a large, low grade Ni-Zn-Cu-Co-U black-shale-hosted sedimentary deposit. It was initially discovered in 1977, but at the time considered uneconomic using conventional extraction methods. Developments in bio-heap leaching techniques led to new interest in the deposit: mining was started in 2007 and the mine produced its first metals in autumn 2008. The total resources of the Talvivaara deposit are 2100 Mt at 0.22 % Ni, 0.50 % Zn, 0.13 % Cu and 0.02 % Co, and 16 g/t recoverable U. Talvivaara has the potential to become a globally significant producer, especially for nickel. However, the bio-heap leach process, a global first for a Ni mine, and the complete metal extraction process, have had

a number of complications, and the mine has yet to reach the expected production levels.
- The Otanmäki Fe-Ti-V deposit is a mafic intrusion-hosted iron oxide deposit. Geologically the Otanmäki deposit bears similarities to the Mustavaara deposit. The deposit in Otanmäki consists of Ti-V-enriched irregular shaped iron oxide mineralizations. The Otanmäki mine was operated from 1953 to 1985. A total of 30 Mt of ore was mined at grades of 32-34 % Fe, 5.5-7.7 % Ti and 0.26 % V.
- The Sokli P deposit is hosted by a Devonian (ca. 360-380), funnel-shaped carbonatite intrusion ca. 5 km in diameter. The main phosphate mineralization consists of a ca. 26 m thick regolith zone on top of the intrusion and contains economically interesting grades of Nb, Ta, Zr, and U in addition to P. The total resources of the regolith ore are 190.6 Mt at 11.2 % P. It has been estimated that there is potentially up to 12 210 Mt of hard-rock P-Nb-Ta ore in addition to the regolith ore. The deposit has so far not been exploited, but there have been recent investigations on opening an operation at Sokli.

Future potential

The modern mining industry in Finland can be considered as having started after the discovery and exploitation of the Outokumpu deposit about 100 years ago. About the same time the Petchenga Ni-Cu deposit was discovered. These discoveries increased awareness of the mineral potential of the country and led to a further increase in the exploration activity which initially focused on base metals and iron. Despite more than 100 years of exploration activity in the country, only a fraction of the ground can be said to have been well explored or "brown field". In some deposit types and metals, the exploration history is considerably shorter and focused on limited areas. Gold exploration, for example, was almost non-existent in the northern part of the country until the first gold deposit was discovered during base-metal exploration in 1985. A number of gold prospects and deposits including the world-class Suurikuusikko deposit have subsequently been discovered in the area.

The extent and sophistication of geophysical and geological mapping of the bedrock, as well as geological understanding, have increased together with exploration activity in the country. The whole of Finland was covered with low-altitude geophysics by 2008 and current data sets comprise huge amounts of geological data. Completely new mineral provinces have been recognized due to a better understanding of the geology in the country. Although the "easy" deposits have probably been discovered, much of the country remains underexplored or "green field". This is best illustrated by the discovery of the world-class Sakatti Ni-Cu deposit in 2007. Sakatti was discovered using the latest geological data and new insight in a region where base metal and gold exploration had been carried out by various organizations for 30 years. The fact that world-class deposits like Outokumpu, Sakatti and Suurikuusikko exist, and are still being found in the country, suggests that its mineral potential remains high. In addition, development and adaptation of new mineral extraction techniques may turn old, previously uneconomic discoveries into profitable operations. Technological development in several fields has resulted in a demand for metals for which there was previously only a very limited market or none at all. These include e.g. high-tech metals such as Rare Earth Elements (REE), Be, Bi, Ga, Ge, In, Li, Nb, Ta, Sb, and W. Exploration for deposits with these commodities was initiated in Finland about ten years ago and some potential for these is now known.

The Geological Survey of Finland (GTK) has carried out assessments of undiscovered mineral resources since 2008. The aim is to provide estimates of "where" and "how much" undiscovered mineral resources exist in the country. The assessment focuses on deposit types which are considered to be among the most important for containing significant undiscovered metal resources in the country. The assessment is done using a three-part quantitative method created by the U.S. Geological Survey (USGS). It is an expertise-driven, statistical method and estimation is done down to 1 km depth. Combined data for nine metals in seven different deposit types in the country are shown in Table 1. The table shows discovered, indentified, and estimated tonnages of the indicated amount of resources in the whole country at 90 %, 50 %, and 10 % probabilities.

			At least the indicated amount at the probability of		
	Discovered	Identified	90%	50%	10%
Ag (t)	2 738	1 174	64	2 108	28 550
Au (t)	431.6	331.4	193.3	1 356.8	8 677.3
Co (t)	139 628	41 188	7 600	86 000	304 000
Cu (t)	3 154 473	1 087 859	1 036 000	13 619 000	54 280 000
Mo (t)	0	0	1 300	100 000	1 100 000
Ni (t)	778 087	438 404	934 000	5 001 000	16 000 000
Pd (t)	255 335	122 031	6 969	158 500	1 984 100
Pt (t)	52	52	660	5 330	27 900
Zn (t)	4 125 755	828 345	100 100	1 810 000	15 890 000

Discovered: total amount of identified resources and cumulative past production. Identified: remaining identified resources as of 31.12.2013. All values in metric tonnes of respective metal. The deposit types included in the assessment: Orogenic Au, Intrusive Ni-Cu, Komatiitic Ni-Cu, Porphyry Cu, Outokumpu-type, VMS, Contact-type PGE, Reef-type PGE.

Table 2. The known and estimated undiscovered metal resources for different deposit types in Finland.

RUSSIA[10]

Outline of the geology of Russia north of 60°N

The Murmansk and Karelia regions

The north-westernmost part of Russia consists mainly of Archaean and Proterozoic rocks, divided into three main provinces – the Kola, Belomorian and Karelian provinces (Figure 1): the Rybachy Peninsula, on the north coast of the Kola Peninsula, consists of a sedimentary sequence deformed during the Neoproterozoic Timanide Orogen which has its continuation W of the northern Urals.

The Kola Province is dominated by Archaean granitic and dioritic rocks with more limited sedimentary units and belts of volcanic and intrusive rocks, including the Pechenga suite, which is host to important nickel-copper ores. The youngest, major geological features in the Kola Province are the Devonian alkaline intrusive complexes, Khibiny and Lovozero, which

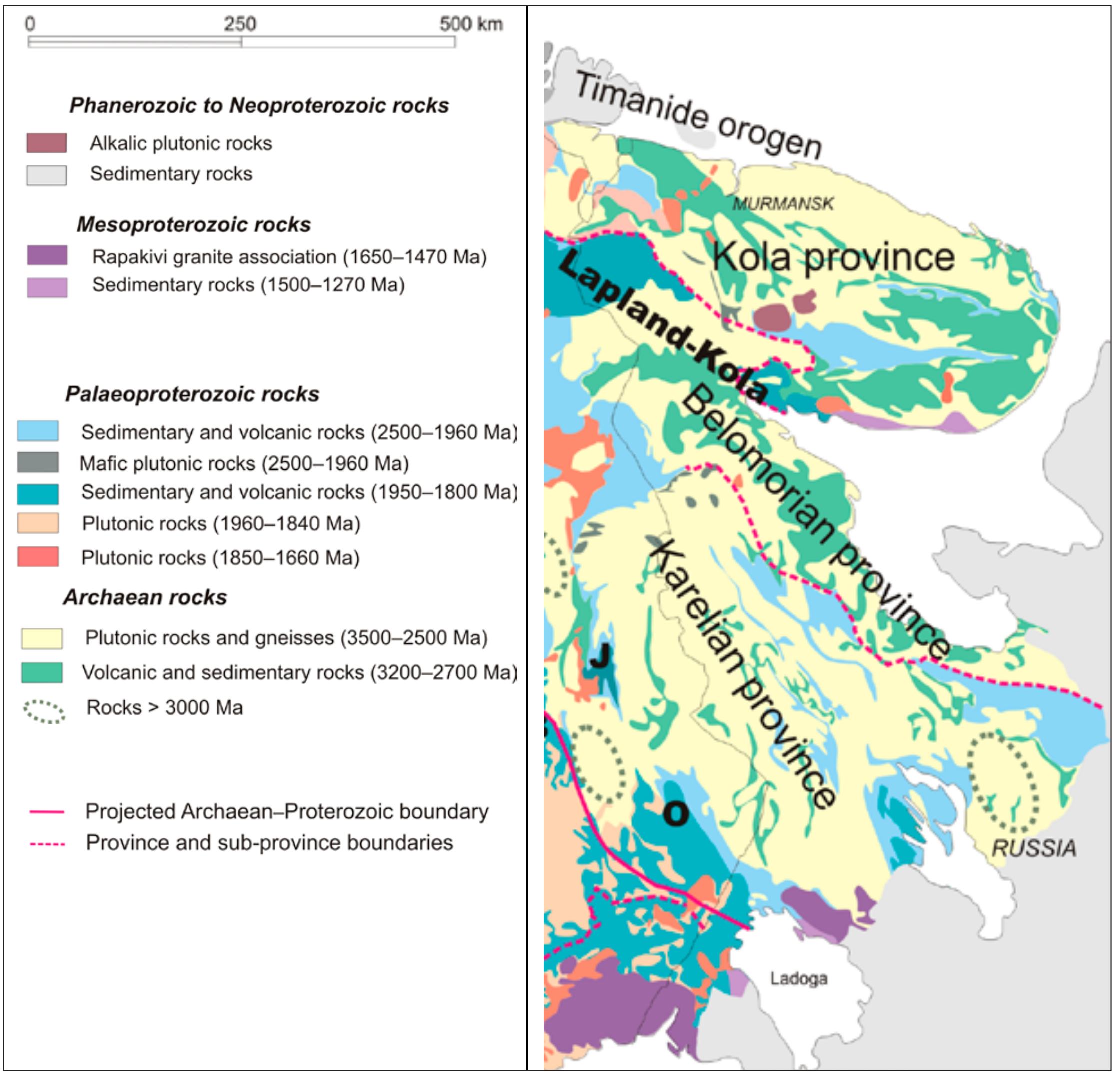


Figure 1. Northwest Russia - the Eastern part of the Fennoscandian Shield (part of Figure 1 in Lahtinen, 2012). International borders are shown in grey.

[10] Written by Petrov O.V., Morozov A.F., Shatov V.V., Molchanov A.V., Terekhov A.V., Lukyanova L.I., Artem'ev D.S., Belova V.N., Khalenev V.O.,

are two of the largest alkaline complexes in the world and contain rich and very large resources of special metals. The Belomorian Province consists mainly of Archaean greenstones and gneisses, deformed and metamorphosed in late Archaean and Palaeoproterozoic orogenic events.

The Karelian Province consists of three terranes:

- The Western Karelian Terrane is dominated by gneisses and amphibolites, ranging in age from Palaeo- to Neoarchaean. It also contains Mesoarchaean greenstone belts, including the Kostomuksha belt which hosts important banded iron formations.
- The Central Karelian Terrane contains intrusions with a wide range of composition, as well as several greenstone (volcanic) belts. These rocks are exclusively Neoarchaean.
- The Vodlozero Terrane in the southeastern part of the Province has a core of Palaeoarchaean granitoids and gneisses, intruded by Mesoarchaean granites and mafic complexes, and surrounded by three generations of greenstone belts, ranging in age from Meso- to Neoarchaean.

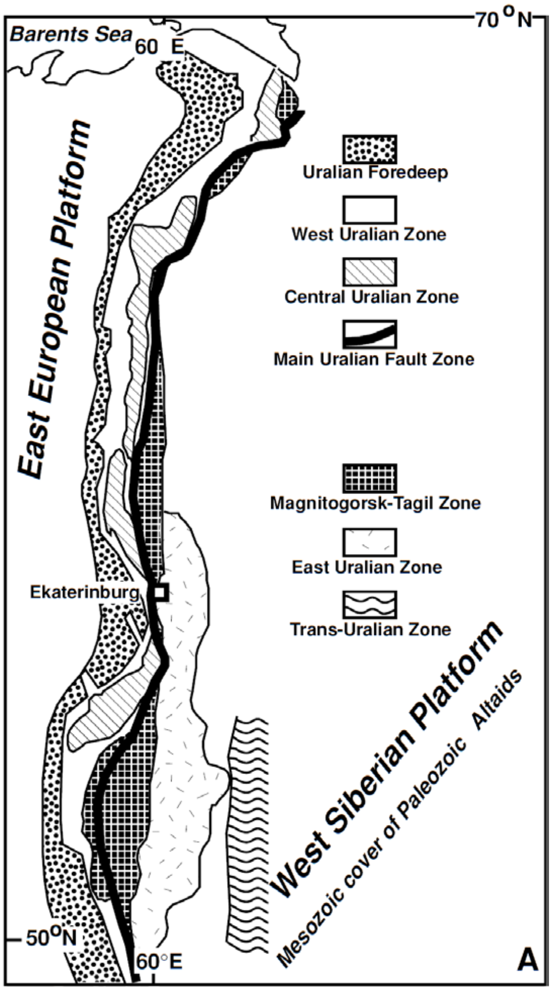


Figure 2. Tectonic zones of the Urals (after Puchkov (1997) in Sazonov et al., 2001.

The East European Platform

The whole northern coastline of European Russia, from the Kanin Peninsula, east of the White Sea, to the Ural Foredeep (see next section) consists of rocks of the Timanide Orogen, which form a wedge-shaped exposure, the southwest margin of which meets the western margin of the Ural Foredeep at ca. 60°N. South of the Timanides the platform cover is represented by two different complexes (www.rusnature.info):

- Riphean to lower Vendian sediments deposited mostly in deep basins (grabens, rifts or aulacogens) and consisting of terrigenous sandy-clayey rocks up to 5 km thick, locally with units of basaltic rocks.
- Late Vendian to Phanerozoic sediments forming vast synclines and basins with a thickness varying from tens of metres to 20-22 km in the deepest basins.

The Ural Mountain Chain

The Urals extend for ca. 2500 km from the Aral Sea in the south to the Barents Sea in the north, with a continuation on Novaya Zemlya north of the Kara Strait. The province is a fold-and-thrust belt including the Pre-Uralide sub-province to the west and the main Ural sub-province: the Urals are bounded to the west by the East-European Platform (overlain by the Timan-Pechora Basin) and to the east by the West Siberian Platform and overlying Mesozoic-Cainozoic sediments.

The geotectonic development of the belt includes: subduction-island-arc, collisional, platform and rift-related settings, each with particular, though not equally important metallogenic characteristics. The longitudinal zoning of the province, from west to east is, as shown in Figure 2:

- Uralian Foredeep: Permian molasse.
- West Uralian Zone: W-directed nappes of Palaeozoic sedimentary sequences.
- Central Uralian Zone: exhumed Precambrian complexes.
- Main Uralian Fault Zone.
- Magnitogorsk-Tagil Synclinorium (MTS): Palaeozoic ophiolite and island-arc complexes.

- East Uralian Upland: as MTS but also includes Precambrian complexes.
- Trans-Uralian Zone: pre-Carboniferous complexes, overlain by Lower Carboniferous volcanic rocks.

The longitudinal tectonic zones are cut by northwesterly trending transverse structures which split the belt into four mega-blocks (Southern, Middle, North and Polar Urals) characterized by specific geological, tectonic and metallogenic features. The main resource-types found in the metallogenically most important zones are:

- West Uralian Zone: barytes, sediment-hosted Cu-Zn.
- Central Uralian Upland: titanomagnetite, iron, chromite, gold, VMS deposits, Mo-W in granite and others.
- Magnitogorsk-Tagil Synclinorium: VMS deposits, Cu and Au-Cu porphyry, platinum metals.

Siberia

Siberia incorporates several large tectonic terranes:

- The Siberian craton.
- The Western Siberian Lowland.
- Neoproterozoic–Palaeozoic orogenic belts north and south of the craton.
- Late Palaeozoic–Mesozoic orogenic belts east of the craton.
- The Cretaceous–Tertiary Okhotsk–Chukotka volcanic belt which overprints easterly orogenic belts.

The following description is based on that of Seltmann et al. (2010), focusing on the area north of 60°N.

Siberian craton

The Siberian craton extends from the R. Yenisei in the west to the R. Lena in the east. The Archaean basement of the craton is exposed in the Anabar and Aldan Shields and in smaller uplifted blocks along the margins of the craton. The platform cover on the craton includes sedimentary and volcanic sequences of Mesoproterozoic, Vendian–Cambrian, Palaeozoic, Mesozoic and Cainozoic age. The cover sequences are intruded by several igneous suites, including the voluminous Siberian traps and related mafic/ultramafic intrusives, ultramafic–alkaline rocks, carbonatites and kimberlites.

The Anabar and Aldan Shields are the largest uplifts of ancient basement within the Siberian craton (Figure 3). The Anabar Shield is composed of Archaean and Proterozoic granulites overthrust by Early Proterozoic granite–greenstone terranes. The Aldan Shield is also composed

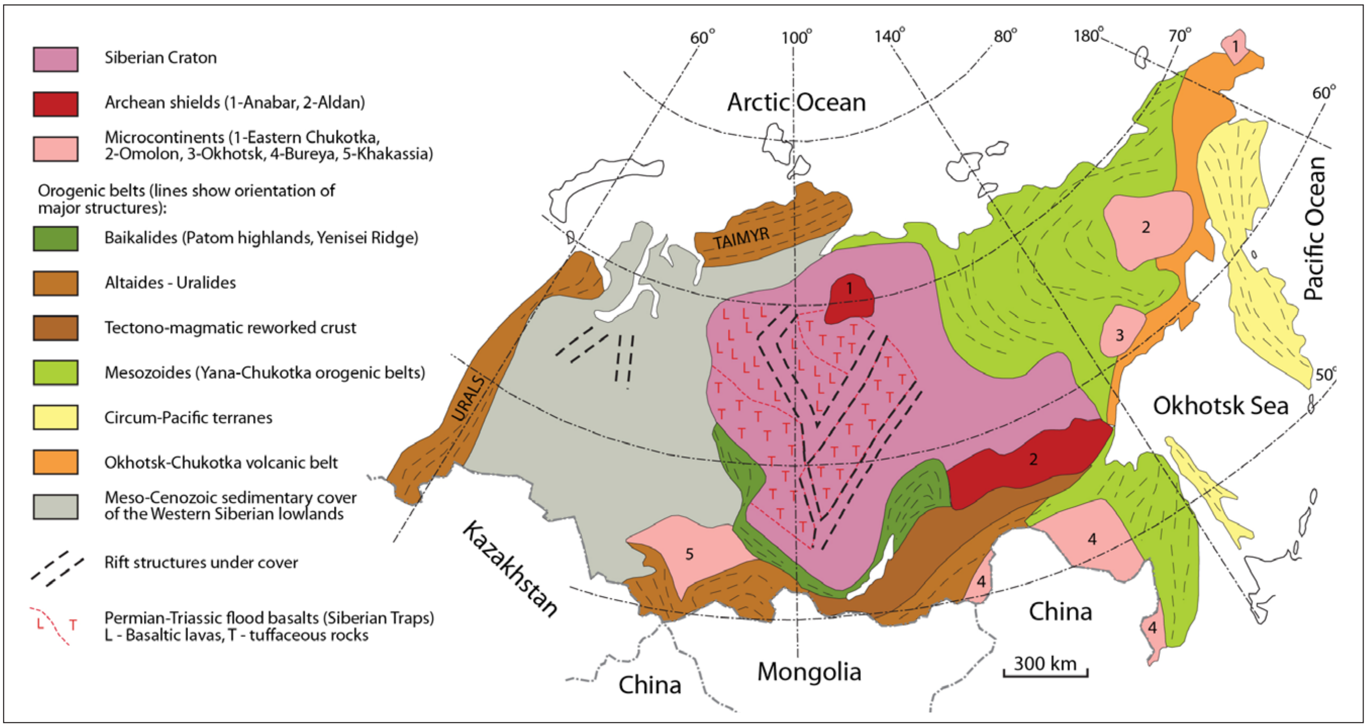


Figure 3. Geology of Siberia (based on Figure 1 in Seltmann et al., 2010)

of Archaean and Proterozoic metamorphic sequences, including major granitoid intrusives, greenstone belts and sedimentary sequences. The Archaean and Proterozoic rocks are overlain by Mesoproterozoic–Vendian (750–550 Ma) and Cambrian carbonate sequences that represent cratonic cover.

Proterozoic terranes of the Yenisei Ridge and Patom Highlands

These two orogenic belts, adjoin the western (south-western) and southern (southeastern) edges of Siberian craton, respectively (Baikalides in Figure 3). They include Archaean terranes (crystalline schists, granulites, gneisses) and predominating thick Mesoproterozoic–Neoproterozoic sedimentary sequences.

Western Siberian Lowland

The Western Siberian Lowland (Figure 3) is comparable in size to the Siberian craton and underlies most of Siberia west of the craton and is bordered by the R. Yenisei to the east and the Urals to the west. A large orogenic system referred to as the Yenisei Ridge separates southern parts of the Western Siberian Lowland from the Siberian craton. The basement of the Western Siberian Lowland E of the Urals consists of Precambrian and Palaeozoic folded structures of the Altai–Sayan orogenic belts. The basement is overlain, in most of Western Siberia, by 4–6 km of terrigenous Mesozoic-Cainozoic sediments.

Neoproterozoic–Palaeozoic orogenic belts of Northern Siberia

The Taimyr–Novaya Zemlya orogenic belt adjoins the Siberian craton in northwestern Siberia. This terrane is separated from the craton by the Yenisei–Khatanga trough which is composed of Triassic–Oligocene sedimentary rocks, and has a Baikalian (Neoproterozoic–Mesoproterozoic) metamorphic basement, which contains blocks of Archaean age (micro-continents). This basement is bordered to the north by Mesoproterozoic–Devonian terrigenous–carbonate rocks and to the south by Ordovician–Triassic terrigenous-carbonate rocks with minor basalts. Orogenic belts in Southern Siberia are part of the Central Asian Orogenic Belt or the Altaid orogenic collage.

Yana–Chukotka orogenic belt

This Mesozoic orogenic belt extends from the northeastern margin of the craton to the Pacific Ocean (Mesozoides in Figure 3). It consists of several terranes/ orogenic belts, including:

- The Verkhoyansk terrane immediately east of the craton.
- The Yana–Kolyma thrust and fold belt.
- The Kolyma and Omolon microcontinents.
- The Oloy and Chukotka terranes.

Formation of this superbelt began on the eastern passive continental margin of the Siberian craton in the Mesoproterozoic and culminated in the Permian–Early Jurassic with deposition of thick sandstone–shale sequences. In the Late Jurassic–Cretaceous, this succession was folded, faulted and intruded by granitic batholiths. These rocks now form the Verkhoyansk and Yana–Kolyma terranes. The Kolyma microcontinent separates the Yana–Kolyma thrust and fold belt from the Oloy and Chukotka terranes: it consists of Archaean and Proterozoic rocks surrounded by Ordovician–Carboniferous sequences, mainly consisting of carbonate rocks.

Okhotsk–Chukotka volcanic belt

This Mesozoic–Cainozoic volcanic belt overlies the eastern part of the Yana–Chukotka orogenic superbelt and thus separates the latter from the Cainozoic Koryak–Kamchatka orogen to the east (Figure 3). The Okhotsk–Chukotka volcanic belt thus has a Mesozoic basement of Upper Triassic to Lower Cretaceous sedimentary and volcanic sequences and is unconformably overlain by Lower Cretaceous to Palaeocene volcanic sequences, locally 45 km thick. The latter include rhyolite (ignimbrite), andesite and basalt.

Intraplate (or intracontinental) tectonic and magmatic activity

The Siberian terranes have experienced several intense intraplate anorogenic tectono-thermal events. These include the intrusion of igneous suites such as the Siberian traps, alkaline and ultramafic-alkaline complexes, carbonatites, kimberlites and lamproites. The Siberian traps have an extent of ca. 7100 km^2, including continental low-Ti tholeiitic flood-basalts, their possible feeders and comagmatic sill-like intrusions. The giant Noril'sk and Talnakh nickel–copper–PGM deposits are hosted in mafic sills associated with the traps. Intraplate tectonic and magmatic processes also resulted in emplacement of kimberlites in Yakutia, many of them diamondiferous, between the Devonian and the Mesozoic.

History of mining

18th – 19th Centuries

Tsar Peter the Great (1672 - 1725), was responsible for numerous initiatives in Russia, also in the search for and exploitation of mineral resources (http://goldminershq.com/vlad.htm). One of the first important mines was at the Nerchinsk silver deposit, southeast of Lake Baikal, which was discovered in 1702: the mines in the district were in operation from 1704 to 1854, yielding 11,540,000 oz (358,934 kg) of silver. Placer gold was discovered in the area in 1830 and was an important product for the last period of operation. Primary gold mineralizations were discovered on the north coast of the White Sea in 1937 and in the eastern Urals in 1745, the latter leading to a mining operation from 1748: the number of discoveries in the latter area by 1800 reached ca. 140, several of them in production as part of a state monopoly. The state monopoly was disbanded in 1812, leading to a dramatic increase in exploration activity and alluvial gold mining, especially in the Urals, and, in the second half of the 19^{th} C in eastern Siberia: Russia, has, thereafter, been one of the world's major producers of gold.

Numerous discoveries were made and mines established in Karelia in the first half of the 18^{th} C, among the most important being Voitskoe (Cu) and Pitkäranta (Cu-Sn-Fe). The mining industry had, by the late 19^{th} C, evolved dramatically, to include major production of Au, Ag, Pt, Cu and Fe in the Urals, Fe and Mn in southern Russia (now the Ukraine), Pb-Zn, Ag and Cu in the Caucasus and Au and Ag in Siberia (https://en.wikipedia.org/wiki/Russian_Empire).

20th Century

The mining industry continued its expansion until the period prior to World War I and the Revolution. The "World War, the civil struggles and foreign invasions" caused a dramatic decline in industrial production in general in the period 1913 – 1921-22 (https://www.marxists.org/history/ussr/government/1928/sufds/ch05.htm). Production of certain metals fell to below 10 % of pre-World War I levels and did not recover until the period of dramatic expansion of the mining industry in the 1930s, which continued for decades after World War II. The following sub-chapters indicate implicitly, in the descriptions of numerous major deposits, the efforts made in exploration for and documentation of new deposits of many commodities, several of which are among the largest of their kind in the world. Exact data on the reserves documented, and on production levels, both at the deposit and commodity levels are not publicly available for past discoveries. Current practice, however, allows publication of data on reserves and resources and their grades for deposits of most commodities. Russia was, in 2014, the world's most important producer of diamonds and palladium and one of the three largest producers of antimony, gold, nickel, platinum, tungsten and vanadium.

Summary information on the most important provinces and deposits: Gold, silver

Russia is currently one of the world's three most important producers of gold. There are numerous deposits, of several types, in the southern part of the Urals, but over 80 % of the known gold resources and most of the important gold mines are found in Siberia, in southern Siberia, E of Novosibirsk and in the Russian Far East, including important deposits in the Khabarovsk, Magadan and Chukotka regions. Russia is also an important producer of silver, also primarily from mines in Siberia. The most important deposits N of 60°N include the Nezhdaninskoye, Kubaka and Kupol gold deposits and the Dukat and Prognoz silver deposits:

Nezhdaninskoye (Au-Ag)

This deposit is located in the valley of the R. Tyra, in the Verkhoyansk Mountains ca. 450 km E of the regional capital, Yakutsk. The deposit encompasses ca. 80 steeply oriented ore bodies, of which ten are major. The richest mineralization is found in tabular quartz veins, some which can be traced downwards to a depth of more than 550 m. The zones are 270-3,500 m long and 3.9-11 m thick. Over 90 % of the deposit reserves lie in ore zone No. 1 which is 3,500 m long and has an average thickness of 11 m. The ore contains 6 % sulphides, including arsenopyrite, pyrite, sphalerite and galena in a host rock consisting mainly of quartz and feldspar minerals. Only gold and silver are of commercial value. Gold occurs in the native state and associated with sulphides and quartz. Gold grades vary from 2 to >5 g/t. The companies Polymetal and Polyus Gold currently have a joint venture for development of the deposit, see: (http://www.polymetalinternational.com/investors-and-media/news/2015/2015-12-24.aspx?sc_lang=en)

Kubaka (Au-Ag)
This deposit is located at almost 160°E, close to the R. Omolon, NE of Magadan. The deposit was discovered in 1979 and investigated in detail in the period 1979-92. The known ore bodies of the mine are concentrated in a block of about 8 km^2 in an area which is elongated in a northwesterly direction. The ore-bearing unit is composed of stratified volcanics of the Kedon Group. The mineralization is associated with veinlet-vein zones which can be followed to depths of 500-700 m: the content of ore minerals does not exceed 0.5 % and the gold grade is approximately 8 g/t. Eighty-five percent of the main gold reserves are concentrated in the Central zone, 10 % in the Socle zone and 5 % in the Northern zone. The deposit, which has been on care and maintenance since 2006, is currently owned by Polymetal.

Kupol (Au-Ag)
The Kupol gold-silver deposit is located in the Chukotka Autonomous Region approximately 300 km SSE of Bilibino and approximately equidistant from the East Siberian and Bering Seas. Sixteen ore bodies have been identified in the deposit. They consist of quartz veins and, to a much lesser extent, of breccias with quartz cement. The ore body is 2-32 m thick and 50-2300 m long. The gold and silver distribution in the ore bodies is extremely uneven. The gold content in the ores varies from 0.01 to 100.0 g/t (rarely to 2622.1 g/t), the deposit average being 21.5 g/t. Silver contents are 0.5-500 g/t (even higher values occur, but rarely, the maximum being 32,417.3 g/t): the deposit average is 266.6 g/t. The highest gold and silver contents are confined to quartz and carbonate-quartz breccias. The gold occurs in the ores as nuggets. The gold-silver ratio in the deposit varies from 1:1.6 to 1:50, with 1:10-1:11 on average: the average silver grade is ca. 250 g/t. The mine is operated by Kinross Gold (http://kinross.com/operations/operation-kupol-russia.aspx): reserves are quoted as 7,616 Mt grading 9.94 g/t gold.

Dukat (Ag)
The Dukat mine is located in the Omsukchan district of the Magadan Region, 31 km from Omsukchan, just over 100 km from the coast on the innermost part of the Sea of Okhotsk and 595 km NE of Magadan. The deposit was discovered in 1968 and is the largest silver deposit in Russia and among the largest in the world. The Dukat ore field is dissected by a series of northeasterly- and northwesterly-trending faults divide the ore field into several blocks with varying mineral potential. Two types of ore body have been identified: mineralized zones and veins. The mineralized zones are complex formations controlled by the largest faults. They include one or more stem-like veins with a breccia structure, blocks of mineralized pre-ore injection breccias and veinlet-disseminated mineralization in the host rocks. The mineralized zones that fill structures which dip gently to the northwest are simpler. There are large (3-5 m) stem-like quartz-rhodonite veins with veinlet-disseminated mineralization of the host rocks (1-3 m). The veins are confined to tectonic fissures of approximately north-south and northeasterly strike. The contact zones are sharp, curvaceous and 1-2 m thick. The mine is operated by Polymetal (http://www.polymetal.ru/operations-landing/dukat-hub/overview.aspx?sc_lang=en): reserves are quoted as 9.45 Mt grading 0,9 g/t gold and 418 g/t silver.

Prognoz (Ag)
The Prognoz deposit is located in the north-east of Yakutia, within the Yana-Adycha ore district in the transpolar part of the Verkhoyansk Range on the divide of the Rivers Sartang and Nelgese which flow southwards to the R. Aldan, a tributary of the Lena. The deposit is hosted by Middle and Upper Triassic sandstones that are overlain by unconsolidated Quaternary sediments 2-10 m thick. The ore bodies are cross-cutting in relation to their host rocks; they are mineralized cataclasite zones without clear boundaries. Their central parts include breccias, brecciated sandstones, quartz-carbonate-sulphide (sulphosalt) veins and their peripheral parts consist of cleaved rocks with quartz-carbonate-sulphide veinlets.

The Glavnoye ore body contains over 50 % of the reserves and resources of silver. It is 4000 m long and has a maximum commercial depth of 250-270 m and is up to 18 m thick (average: 4 m). The content of silver is 10-28 kg/t, of lead, <10 %-52 %, and of zinc <10-15 %. The Boloto ore body, 500-800 m S of Glavnoye, is the second-most productive ore body and includes 21 % of the reserves and forecast resources of silver. It is 2300 m long, extends down dip for 260 m and is up to 7 m thick (average: 2 m). The content of silver is up to 17.7 kg/t, of lead up to 25 % and of Zn, up to 21.5 %. A further 9 ore bodies have been discovered in the deposit. The deposit is held by Nordgold: resources are quoted as 4.9 Mt. (http://www.nordgold.com/operations/development-projects/prognoz/).

Placer gold deposits

Approximately two-thirds of Russia's gold production is from Siberia and the Russian Far East: the proportion of production from placer operations was ca. 80 % in 1996 but declined to under 50 % by 2002 as production from hard-rock mines increased. (Union of Gold Producers of Russia, 2015: http://www.ey.com/Publication/vwLUAssets/EY-gold-mining-industry-in-russia-2015-eng/$FILE/EY-gold-mining-industry-in-russia-2015-eng.pdf).

Base metal deposits and associated PGE ores

This sub-chapter includes descriptions of several nickel-copper-platinum metal deposits, two lead-zinc deposits and of a porphyry copper-gold-molybdenum deposit. Russia is the world's second most important producer of nickel, the most important producer of palladium and the second most important producer of platinum. The major producers of copper, nickel and platinum metals in Russia are the mines in the Norilsk district east of the R. Yenisei in northwestern Siberia. The nickel-copper mines on the Kola Peninsula are also important producers.

Norilsk 1 and 2 (Ni-Cu-PGE)

The first data on the Norilsk 1 deposit is related to merchant K. P. Sotnikov who, in 1865-1868, melted 3275 kg of crude copper out of chalcopyrite-rich sediments and sulphide veins cross-cutting them at the base of the northern slope of Mount Rudnaya. Intense prospecting in the Norilsk district, related to the search for coal for the Northern Sea Route, began in 1919–1920. In 1920, geologist N. N. Urvantsev found primary sulphide ores and in 1922 N. K. Vysotsky found platinum in copper-nickel ores. The largest commercial deposits are located along the Norilsk-Khatanga deep-seated fault. The Norilsk and Talnakh ore clusters are located in this district. Two types of ore are known in the deposits of the Norilsk ore district: platinum metal-copper-nickel-sulphide ores and low-sulphide platinum metal ores: these deposits are the richest of their kind in the world.

The Norilsk 1 deposit is located in a 1 km long, sheet-like intrusion elongated NE-SW with a length of ca. 12 km (Figure 4). The intrusion's thickness varies from 30 to 350 m, the average being ca. 130 m. The copper-nickel sulphide mineralization is related to the lower ultramafic horizons of the intrusion, and includes both veinlet-impregnation and massive ore types. This deposit was the only mine operated in the province for the first 27 years of operation. Remaining reserves and resources of disseminated ore, according to Norilsk Nickel, exceed 124 Mt.

The Norilsk 2 low-sulphide platinum metal deposit is located 7 km from Norilsk and is considered as a non-commercial deposit. Other deposits, both of them S of Norilsk, are Chernogorskoye and Maslov: the latter was discovered as recently as 2009.

Talnakh (Ni-Cu-PGE)

The Talnakh ore "cluster" is located 25 km NE of Norilsk and contains two deposits, Oktyabrskoye and Talnakh. The Talnakh deposits were discovered in 1960 and the first mine, Mayak, started operation in 1965. The Talnakh deposit is currently being mined underground at the Komsomolsky mine and there are two mines in the Oktyabrskoye deposit (Norilsk Nickel, 2015). The Oktyabrskoye deposit is notable for its high grades of copper and platinum metals, especially palladium. Total remaining reserves and resources in the Talnakh ore "cluster", according to Norilsk Nickel, exceed 2,200 Mt.

Pechenga (Ni-Cu)

The Sputnik, Verkhneye, Zhdanov, Tundra and other deposits constitute the Pechenga group of nickel-copper deposits and are located in the

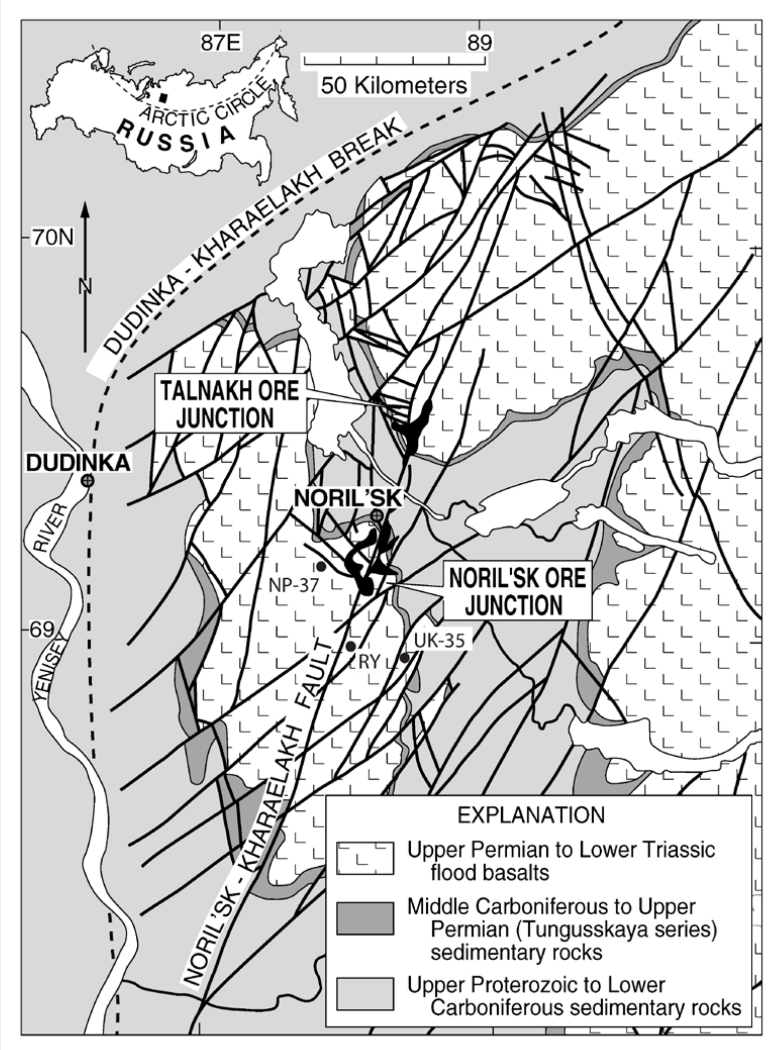


Figure 4. Simplified geologic map of the Noril'sk-Talnakh district, showing major structural features and subsurface outlines of the Noril'sk-type, ore-bearing intrusions (black, true scale). The Kharaelakh and Noril'sk depressions are the ovoid areas, astride the Noril'sk-Kharaelakh fault and defined by the outcrop areas of basalt, which extend, respectively, north from the Talnakh ore junction and south from the Noril'sk ore junction. (Figure from Czamanske et al. (1995)).

Eastern ore cluster of the Pechenga ore district in Murmansk region close to the border with Norway. The largest deposit, Zhdanov, was discovered and investigated by Finnish geologists in the period 1929-34 but was put into production first in 1959: it is currently being operated by the underground, Severny mine. The main ore body has a strike length of 1800 m and is up to 100 m thick. The mineralization is disseminated nickel-copper mineralization. Total remaining reserves and resources in the Pechenga group of deposits, according to Norilsk Nickel, exceed 500 Mt.

Sardana (Pb-Zn)

The Sardana stratiform lead-zinc deposit is located close to the R. Aldan in the south-eastern part of the Yakutia region and just N of 60°N. The deposit was discovered in 1971. The deposit has a documented tonnage of 18.3 Mt grading 10.5 % zinc and 3.23 % lead. It also has high grades of a number of accessory components, including 20-1150 g/t germanium (one of the important but less common "critical" metals) and 1-234 g/t silver. A development license is currently held by Siberian Nonferrous Metals LLC (a member of the Summa Group) who plan to commence development of the deposit in 2017. The company reports that a road is being built from the deposits to the port of Ayan on the Sea of Okhotsk.

Pavlovsk (Pb-Zn)

The Pavlovsk deposit, which was discovered in 1990-1995, is located on the NW coast of South Island, Novaya Zemlya. The deposit consists of five extensive (>600 m), banded, sheet-like layers from 3-5 to 50 m thick. The distribution of the main commodities (zinc, lead, and silver) within the ore bodies is relatively uniform. The ore bodies, which have a total tonnage of over 37 Mt, plunge from the west (where they outcrop) to the south-east, to depths of 200-350 m. The ores include massive, veined and veined/impregnated types (40-90 %) and also massive ore with sphalerite and galena of various generations. The lead grade varies from 1.0-2.9 %, zinc from 1.6-20.8 % and the grade of silver averages 14.5 g/t. A license to develop the deposit is reported to have been granted to Pervaya Gornorudnaya Kompanya which plans to commence production in 2019.

Peschanka (Cu-Au-Mo)
The Peschanka deposit is situated in the central part of the Chukotka Peninsula, close to the western margin of the Okhotsk–Chukotka volcanic–plutonic belt, where this belt is superimposed on the Omolon microcontinent. The belt contains several granite intrusions, located within the Baym metallogenic zone, which forms a linear structure traceable for over 200 km and hosts a number of porphyry deposits. The most widespread mineralization consists of chalcopyrite and pyrite, but the higher-grade ores are associated with a bornite–chalcopyrite–tennantite assemblage. The resources of the deposit are reported as 1,350 Mt of ore grading 0.61 % Cu, 0.015 % Mo, 0.32 g/t Au and 3.7 g/t Ag

Ferrous metals

This sub-chapter includes descriptions of the selected deposits of ores of alumina/aluminium, iron, titanium, vanadium and manganese in Russia. Russia is one of the world's most important producers of aluminium and is a major producer of iron ore.

Vezhayu-Vorykva (bauxite)
The first bauxite stratum was found in the Vychegda River in the Middle Timan in 1949: this led to detailed prospecting leading, in 1970, to discovery of the economically viable Vezhayu-Vorykva bauxite deposit. Later prospecting revealed new deposits and occurrences (Upper Schugor, Eastern, Zaostrovskoye, Volodinskoye and Sventlinskoye), which made Middle Timan the leading bauxite district in Russia. The Vezhayu-Vorykva bauxite deposit is the largest in the whole Timan district. It contains 56.4 % of the bauxite reserves of the Vorykva ore cluster, and nearly 12 % of Russia's commercial reserves. The deposit includes three beds: Central, Western, and Upper Vorykva whose parameters are shown in Table 1.

Keiv Deposits (kyanite)
The use of kyanite and other aluminosilicate minerals as a potential source of alumina was developed in the Soviet Union prior to World War II due to the low grade of then known domestic bauxite resources. Major resources of high-alumina (kyanite-rich) rocks are located in the eastern part of the Kola Peninsula, in the 200 km long, northwesterly-striking Keiv ridge. The ridge comprises Lower Proterozoic Keiv series metasediments, including important units of kyanite-rich schist. The kyanite deposits were discovered in 1928 and exploration has ultimately revealed 29 kyanite deposits of which the largest are Shuururta, Bezymyannoye, Tyapysh-Manyuk, Vorgelurta, Novaya Shuururta, Chervurta and Bolshoi Rov. The form and textures of these deposits vary considerably: their proven reserves exceed 3 billion tons.

One of the largest deposits is Novaya Shuururta, which is located 225 km E of Apatity in the central part of the Kola Peninsula. The ore is large-concretion kyanite schist and was discovered in 1952 and explored in single trenches. The average thickness of the deposit is 148 m and its kyanite content is 42 %.

Ore bed or field	Length, m.	Width, m.	Ore body thickness, m.	Depth of occurrence, m.	
				limits	average
Western	2200	200-1300	1.5-24.4	0.6-66.7	33.2
Upper Vorykva	2200	100-600	1.5-21.0	0.2-57.0	18.6
Central, ore body 1	2100	2200	1.5-27.5	0.6-50.0	24.4
Low-iron bauxite area	460	180-350	0.6-3.6	18.4-41.9	30.7

Table 1. Parameters of the Vezhayu-Vorykva deposit bauxite ores.

Kostomuksha (iron): The Kostumuksha deposit was discovered in 1946 as a result of an airborne magnetic survey. It is located 12 km N of the city of Kostomuksha which was built to support the mine and ore-processing operation: full-scale mining and pellet production began in July 1982. The total reserves approved in advance of mining were in excess of 1,300 Mt grading 26.45 % Fe (magnetic): the deposit also contained > 1,000 Mt of resources then regarded as non-commercial.

The deposit, which consists of iron quartzite, is subdivided into three units, the Northern, Central, and Southern, all of which are currently being mined. Up to 70 % of the reserves are in the Main layer, which consists of three steeply dipping sheet-like ore bodies, 10-330 m thick, which have been traced for 3.3-14 km in an approximately N-S direction. The ore bodies are separated by thin layers of schist. In the central part of the deposit, the Main layer is folded in such a way that it becomes sub-horizontal. The maximum thickness of the layer in the folded area reaches 1750 m while on the fold flanks, its width is 13 -100 m. In the central part of the deposit, at a depth of 400 m, the thickness of the Main ore layer is 250-350 m, which decreases to 120 m at greater depths. Close to its extremities the ore quality drops because of increasing contents of grunerite. Currently approved data for the deposit are 838 Mt of reserves grading 32 % Fe and > 1,000 Mt of resources.

Yarega (titanium)
The Yarega titanium-heavy oil deposit is located in the Republic of Komi, in the Timan-Pechora oil and gas province 25 km SW of Ukhta. The deposit, which is hosted in Middle Devonian sandstone, was discovered in 1932 and has been investigated for its titanium potential since 1958. The Upper and Middle Devonian sediments in the area are commercially oil-bearing, with reservoirs in quartz sandstones.

The unique feature of the deposit is that, apart from the large oil resources, it also contains high concentrations of the titanium mineral leucoxene (an alteration product of the iron-titanium oxide ilmenite). The productive stratum is 30-100 m thick and is divided into two layers which contain three placer deposits:

1) A lower, sheet-like placer, 14.5-21.4 m thick, which contains 11.2 % TiO_2 on average;
2) A middle placer, 0.4-13 m thick, containing 3.0–10.4 % TiO_2;
3) An upper placer, on average 3 m thick, containing a few percent of TiO_2, but locally up to 21.9 %.

The lower lithological horizon consists of coarse-grained quartz sandstones with siltstone and argillite layers, while the upper horizon, contains polymict conglomerates and consertal quartz sandstones containing up to 30 % leucoxene (average composition: TiO_2: 58.5-71.9 %; SiO_2: 20-37.8 %). The deposit resulted from erosion of the weathering crust of the Riphean slates and is enriched in niobium and tantalum in addition to the titanium mineralization.

Yarega is the largest titanium deposit in Russia with calculated reserves of about 640 Mt of titanium ore. The oil in the reservoir has been produced since 1939 by a unique shaft technique. Work is currently underway to set up a pilot facility to produce titanium coagulant, which has important applications in purification of water.

Rare Earth Elements and Special Metals

Deputatsky (tin)
The Deputatsky deposit is located in Yakutia, close to 140°E and approximately 250 km from the coast of the Laptev Sea. Mines were in operation in the area from 1951 to 2009. Only one small block of granitoid crops out on the surface in the ore district; another intrusion bulge was penetrated at a depth of 377 m by a structural drillhole under the central part of the Deputatsky deposit. The area of the subsurface granite bulge within the Deputatsky ore cluster has been assessed by geophysical data to be ca. 50 km^2 at depths of 300-1200 m. In all, there are about 150 ore bodies in the deposit. They are classified in three types: veins, linear elongated stockwork-like zones, and mineralized cataclasite zones traceable for many hundreds of meters, with thicknesses of up to 10 m and more; combinations of two or all three types are common. Most of the ore bodies are represented by thick, extended mineralized shear zones, within which a central fissure vein generally shows up as the most persistent one in lateral extent and

down-plunge, accompanied by a series of parallel apophyses, zones of crushed and mineralized rocks, en echelon fractures of tear and shear, also consisting of ore material. Four main types of ore body, in terms of mineralogy, are found: 1) quartz-tourmaline veins with cassiterite; 2) cassiterite-sulphide-quartz veins with tourmaline and fluorspar; 3) cassiterite-chlorite-sulphide mineralized cataclasite zones and veins; 4) quartz-carbonate veins with sphalerite and galena; weakly tin-bearing greisen formations are also found. Ore bodies of the second and third types, formed in several phases, have had the greatest economic importance.

The remaining reserves are ca. 25 Mt grading 1.15 %. These figures show that the deposit, even after over 50 years of operation, is the largest tin deposit in Russia. As of 2014, the license for its development was held by Deputatsky Mining & Concentration Works JSC. There has been no ore production at the deposit in recent years.

One of the largest placer tin (-wolfram) deposits in Russia, Tirekhtyakh, is located in the same region. Its resources total over 150 million m^3 of tin-bearing sands, of which certain parts are enriched in tungsten.

Tomtor (REE, Nb)

The Tomtor syenite-carbonatite intrusive is located in the northwestern part of Yakutia, W of the R. Lena and ca. 400 km S of the Laptev Sea. It was discovered in 1959: the complex and its mineralizations were investigated in subsequent decades but the remote location and lack of infrastructure have delayed development of the undoubted economic potential of the area. The intrusive has an almost circular surface expression with a core consisting of several types of carbonatite and a broad, peripheral zone of syenite. There are (at least) three types of mineralization – primary mineralization in the carbonatite, "in situ" weathered material in paleoregolith which have an average thickness of 110 m and redistributed weathering products accumulated in depressions in the rock surface which may be up to 300 m thick. (Seltmann et al., 2010). The Tomtor intrusion includes several major deposits of which the Burannyi deposit is the best documented: the reserves of the Burannyi field are 42.7 Mt grading 6.71 % Nb_2O_5, 0.595 % Y_2O_3; 0.048 % Sc_2O_3 and 9.53 % REE_2O_3. Other deposits are known to contain even higher grades of niobium and REE. The mining rights are held by ICT-Rostec who are in the process of developing the deposit for production.

Lovozero (Ta, Nb)

The Lovozero alkali massif was first described by W. Ramsay in 1887. The massif's surface area is 650 km^2 and it is the world's largest agpaite intrusion. The massif is located, in the central part of the Kola Peninsula, between Lovozero and Umbozero. It consists of three successive phases (Kalinkin, 1974):

- A stratified series of loparite-bearing lujavrite/foyaite/urtite, nepheline and cancrinite-nepheline syenites, with alkali syenites in the marginal zone.
- The largest, central part of the massif, consisting of lujavrite and murmanite. Both of these phases are accompanied by veins of alkali pegmatites and rare-metal metasomatites.
- The third phase - dikes, veins and volcanic pipes of alkali lamprophyre. The massif's rare-metal deposits are related to the rocks of the first two phases.

The Lovozero massif contains twelve ore deposits, of which those currently developed (Karnasurt, Kedykvyrpakhk and Umbozero) account for 75 % of the reserves, amounting to > 200 Mt. The operating underground mines have reserves for at least 55 - 100 years. The reserve base consists of eudialyte-loparite ore with high contents of tantalum (up to 1 %) and niobium (up to 10-12 %). The Lovozero mining and concentration mill comprises an ore dressing mill with an annual capacity of up to 1.5 million tons of ore.

Kolmozero (Li, Ta, Nb, Be)

The Kolmozero rare-metal pegmatite deposit was discovered in 1947. The deposit is located in Murmansk Oblast, 80 km E of Lovozero settlement, in an unpopulated and undeveloped area. The deposit consists of 12 veins of albite-spodumene pegmatites localized in a complex of metagabbro and anorthosite. The reserves are 74 Mt grading 1.14 % Li_2O, 0.009 % Ta_2O_5, 0.011 % Nb_2O_5 and 0.037 % BeO.

Placer tin deposits

There are numerous placer tin deposits in Siberia, one of the largest being Tirekhtyakh which

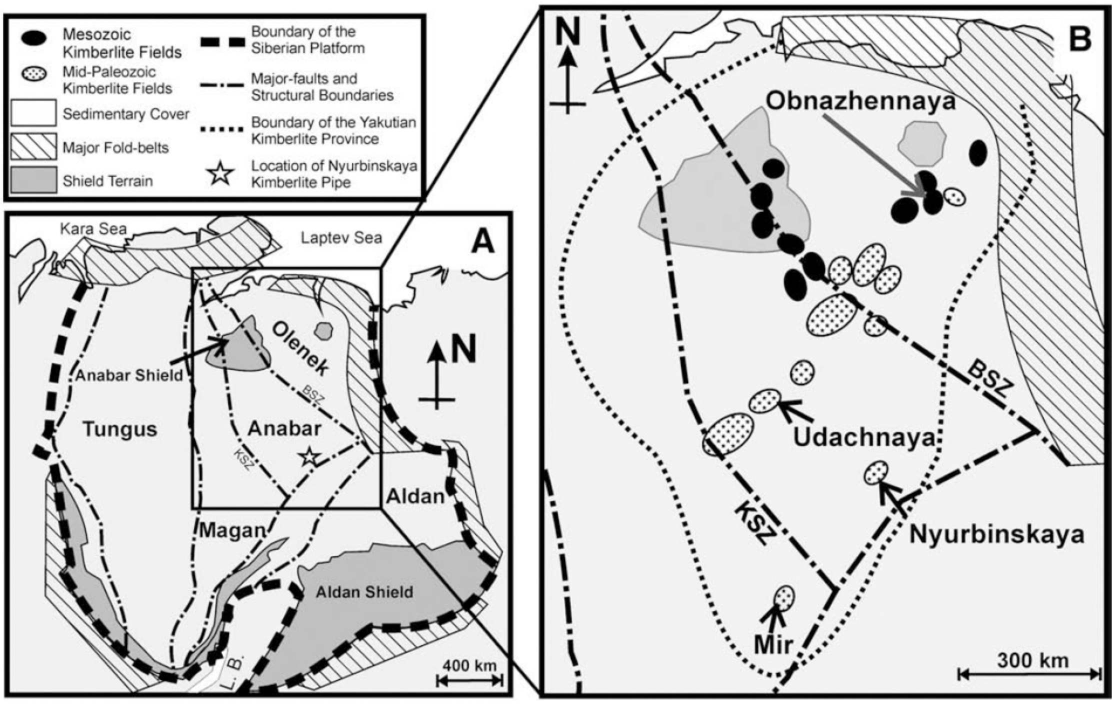


Figure 5. Location and map of the East Siberian (Yakutian) kimberlite province (Riches et al., 2010).

is located 60 km SW of the town of Deputatsky. The defined commercial reserves total over 90 million m³ and contain <74,000 t of tin. The ores also contain tungsten, indium, scandium and niobium.

Diamonds

Numerous large diamond deposits in Russia are found in kimberlite pipes in the East Siberian minerogenic province, within which several kimberlite fields are distinguished The main fields are: Daldyn-Alakit, Lesser Botuoba, and Middle Markha, where kimberlite bodies of different ages form extensive fields (Figure 5). The oldest of them, small dykes and pipes of Precambrian age, are in the southwestern part of the province and contain few diamonds. All primary deposits of economic interest in the province were formed during the period of the Palaeozoic tectonic and magmatic activity.

The first kimberlite pipe to be discovered in the USSR (Russia) was the "Zarnitsa" pipe in the East Siberian diamondiferous province. It was found in bedrock in 1954 as a result of a panning survey focussing on pyrope garnet, led by VSEGEI employees L.A. Popugaeva and N.N. Sarsadskikh, who were the pioneers in this field. In subsequent years, a large number of diamondiferous kimberlite pipes, containing rich diamond deposits were discovered (in several parts of the world) using this method.

Udachnaya

The "Udachnaya" deposit is unique due to its size and average diamond grade. The kimberlite pipe was discovered in 1955 as a result of panning prospecting, including the use of indicator minerals developed by L. A. Popugaeva and her colleagues.

The "Udachnaya" pipe is one of the largest pipes explored in the Republic of Sakha (Yakutia). Since 1971, the deposit has been mined in the "Udachny" open pit; the current surface

Figure 6. Udachnaya pipe open pit.

dimensions of which are 2.0 × 1.5 km (Figure 6). The deposit has been exploited to a depth of more than 600 m in the pit. It is currently being mined from the "Udachny" underground mine. The mine is predicted to reach a maximum production capacity of 4 Mt/a by 2019. The "Udachnaya" pipe breaks through the Vendian-Palaeozoic terrigenous-carbonate rocks of the sedimentary cover. It is confined to the intersection of a near-E-W trending fault system with a NW-trending fault, and can be traced as a consistent ore body from the surface to a depth of 250 m. Below this level the pipe splits into two independent ore bodies, the Eastern and Western ore bodies, separated by a block of the surrounding Upper Cambrian sediments. The distance between the ore bodies increases significantly with depth, from about 100 m at the level of the bottom of the existing open pit (-320 m) to 325 m at -1,080 m elevation.

The composition of the kimberlites and the grain size, and grade of the "Udachnaya" pipe diamonds have been studied in detail, based on data from the mined horizons in the upper part of the deposit. The price of 1 carat diamond of +0.5 mm class from the "Udachnaya" pipe deposit amounted in 2012 to US $ 65.5/carat. Open pit mining is being carried out; an underground mine is being constructed. The largest diamonds found in the deposit are "Alexander Pushkin" – 320 carats, "The Power of the Soviets" – 196.6 carats, "60 years of the Yakut ASSR" – 173.7 carats, "Academician Sakharov" – 172.5 carats.

Mir

The "Mir" kimberlite pipe which was discovered in 1955, is steeply plunging, pipe-shaped, but conical to a depth of 300 m: in the depth interval of 300-900 m it becomes cylindrical. The body becomes markedly narrower in the depth range of 900-1,000 m and evolves into a feeder, a subvertical kimberlite dyke, about 300 m long and 25-30 m thick. The "Mir" pipe is composed of kimberlitic rocks formed as a result of a three-phase kimberlite magma intrusion.

Diamond recovery at the field began in 1957 by open-pit mining and continued for 44 years. The open pit in the "Mir" pipe field is 525 m deep and 1.2 km in diameter. Open-pit mining of the diamondiferous kimberlite ceased in June 2001. According to exploration results, the depth of

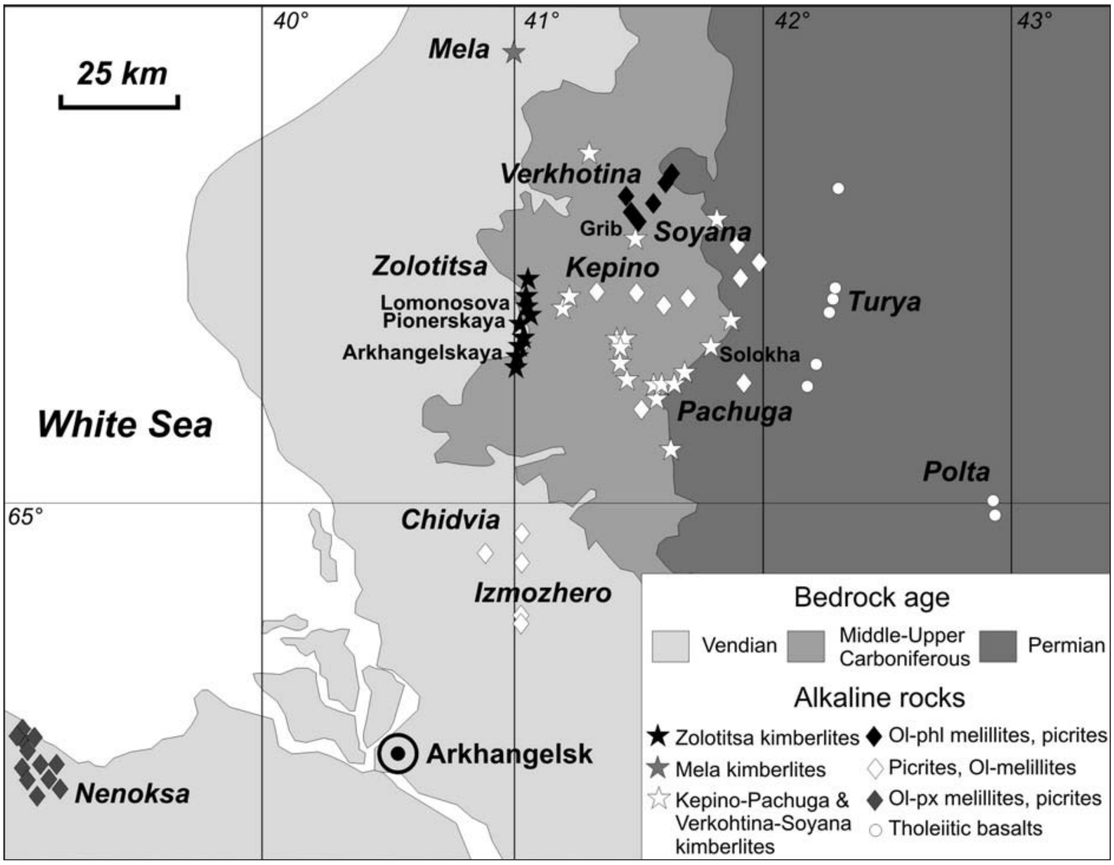


Figure 7. Distribution of kimberlites and other alkaline complexes in the Arkhangelsk diamond province (Lehtonen et al., 2009).

Kimberlite pipe	JORC Code Category	Ore weight (Kt)	Diamond Grade +3 nominal sieve class (ct/t)	Contained Diamonds +3 nominal sieve class (Kct)
Arkhangelskaya	Probable	57, 087	0.76	43,189
Karpinsky -1	Probable	18,438	1.13	20,918
Total probable reserves		75,525	0.85	64,107

Table 2. Ore reserves of the Lomonosov field (Report: "Micon International Co Limited", 2013).

diamondiferous kimberlites in the field is more than a kilometer. “Alrosa” started underground diamond recovery in 2009. The diamond content of the “Mir” pipe is high, averaging above 3 ct/t. The diamonds are noted for their fairly high quality. The diamonds include octahedra (61 %), rhombic dodecahedra (10 %), combinational forms (30 %), and cubes. Colourless stones are most common but brownish, bluish-green, smoky gray, and purple varieties also occur. Studies of the diamond content in the pipe area and to a depth of 1,000 m have not shown any regular variations in their distribution in kimberlite ore. The largest diamond, “XXIV Congress of the CPSU” recovered at the “Mir” mine in 1980 weighed 342.5 carats. The reserves of the “Mir” pipe deposit in A+B+C1 grade are 139,558.9 Kct, in C2 grade, 3,338.5 Kct.

Lomonosov diamond field

The discovery in the early 1980s of a new diamondiferous kimberlite subprovince in the north of the European part of Russia (100 km NE of Arkhangelsk) was the result of a systematic study of the geological structure of the region, started by Arkhangelsk geologists in the early 1960s. In 1978, an airborne magnetic survey was conducted, promising anomalies were distinguished and test drilling penetrated a large number of diamond pipes, including commercial ones, forming individual fields (Figure 7).

Each pipe consists of a supply channel, which, in the case of the “Arkhangelskaya”, “Karpinsky-1”, and “Pionerskaya” pipes. is overlapped by crater facies. The “Arkhangelskaya”, “Karpinsky-1”, and “Lomonosov” pipes are almost circular in plan view, while the “Karpinsky-2” and “Pionerskaya” pipes are elliptical.

The diamond crystals are usually gray or with a gray flash (42 %); the proportion of colourless diamonds is 39 %. Coloured (black, yellow, green-gray, brown) crystals and those with different shades account for 19 %. More than 50 % of the crystals are transparent. The proportion of opaque diamonds is 15 %, of splices 21.5 %, of crystal fragments 11.8 % and of twinned crystals 10 %. Forty percent of the crystals are fractured. The proportion of isometric crystals is 35 % and 25 % are deformed.

Lomonosov GOK, the production enterprise of the Open Joint Stock Company “Severalmaz”, is currently developing the “Arkhangelskaya” and “Karpinsky-1” pipes. Open pit mining was initiated on the “Arkhangelskaya” pipe in 2005. The surface dimensions of the quarry are 1.16 km × 1.12 km, and its depth is currently 110 m. Stripping operations began at the “Karpinsky-1” pipe field in 2010. Currently, the quarry depth is 90 m; its surface dimensions are 830 m × 500 m. The “Karpinsky-1” quarry is scheduled for full production capacity (2 Mt/a) in 2015.

Impact Diamond Deposits

Popigai

The Popigai impact structure (diameter 100 km) formed as a result of an asteroid impact 35.7 million years ago: the structure is located ca. 200 km SE of the Khatanga Gulf (which is located in the SW corner of the Laptev Sea). Rocks of the basement (various gneisses and schists) and the cover of Late Proterozoic – Mesozoic age with total thickness of about 1 km, including graphite-bearing horizons, became the target. The internal astrobleme structure is characterized by the presence of a central depression, a circular elevation of the crystalline basement, and a ring trench surrounded by a zone of deformed rocks. The depression and trench are filled with different impact breccias and impactites originating in impact transformations and in movements of crushed and melted local rocks. Impact breccias and impactites are also developed in small areas outside the crater.

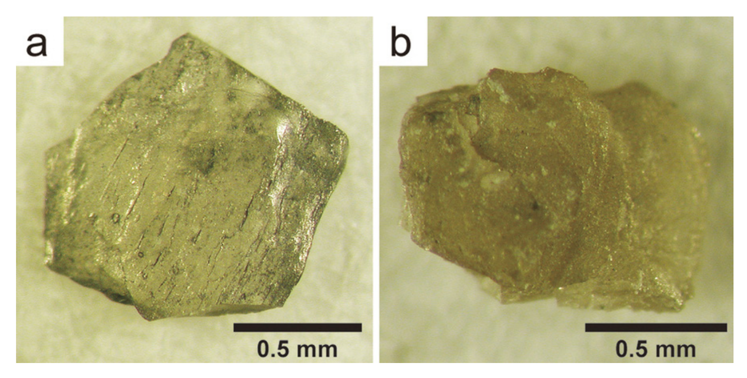


Figure 8. Impact diamonds from the Popigai impact structure

Graphite in the impact area was transformed to diamond in minute fractions of a second, the speed of the transformation being such that normal rates of crystal development were not physically possible: the Popigai diamonds are, relative to gem quality diamonds from the kimberlites described above, small (Figure 8) and extremely hard. Diamondiferous impactites are exposed on the surface within an area of approximately 1,140 km^2; the total area of their development is approximately 3,500 km^2: diamonds are ubiquitous in this area. True diamond impactites occur as thick (up to 600 m), extensive (up to 10-15 km^2) sub-horizontal and lenticular bodies; smaller irregular bodies tens of metres thick are also present.

Proven reserves and inferred resources of impact diamonds in bedrock in a total area of approximately 120 km^2 at Popigai amount to 212 Gct. The total number of diamonds in an impactite layer 50 m thick in the rest of the area (about 1,020 km^2), in addition to the deposit areas and prospects, are assessed to be about 150 Gct. Reserves and resources of placer impact diamonds are also very significant. The diamond reserves of the Popigai astrobleme exceed the diamond reserves of all other diamondiferous provinces in the world.

Future potential related to development of mineral resources in Arctic Russia

Much attention is given to the major resources of hydrocarbons in Arctic Russia. The resources of numerous metals are, however, also very large: these include deposits of iron ore, titanium, vanadium, zirconium, copper, nickel, cobalt, gold, platinum group metals, diamonds and many others. The region is one of the world's most important sources of nickel and platinum metals.

The mineral resource sector occupies a key position in the economies of the Arctic regions of most of the countries concerned: this makes the status and quality of the Mineral Resource Base (MRB) and the dynamics of its development highly important. In a global perspective, there is a steady trend of development of the strategic metal resources in the Circum-Arctic region. The Russian Arctic is a region of exceptional importance for the economy, national security and international relations of the Russian Federation. The development of the Northern Sea Route is one illustration of the national priority given to the region, a priority which has had, and will continue to have particular importance for the development of mineral resources in the northernmost Arctic region.

The Russian government took, in 2015, a decision concerning development of the unique Tomtor iron-aluminophosphate-rare metal deposits. The deposits contain extremely high contents of REE, niobium and other commodities: the creation of the necessary infrastructure will create, in Tomtor, a new source for the production of ferroniobium alloys, yttrium, scandium, aluminophosphates and other highly valued products. Integrated development of Tomtor will create a new centre for the production of strategically important raw materials.

REGION	MAIN TYPES OF MINERAL RESOURCE
Kola Peninsula	PGE, Cu, Ni, Ti, Ta, Nb, REE, Fe, P, Fl, Cr, Mn, Au
Taimyr-Norilsk	Ni, Cu, Co, PGE
Tomtor	REE, Nb, Fe, Al, P
Yakutia-Anabar	Diamonds, Sn, Fe, special metals
Maimecha-Kotui Udzhinskoyw	P, Fe, Nb, PGE, diamonds
Taimyr-Severnaya	Au, Mo, W, Cr, V, base metals
Yaana-Chukotka	Sn, Au, Hg, W, Cu, Mo, Ag,PGE, base metals

Table 3. Summary of the main types of mineral resource found in selected regions and provinces of Arctic Russia

The Arctic regions (Kola Peninsula, Arkhangelsk, Norilsk, Taimyr, Yakutia and Chukotka) contain the following percentages of Russia's reserves of a number of key commodities:, apatite concentrate (90 %), nickel (85 %), copper (60 %), PGE (> 98 %), tungsten (50 %), rare earths (> 95 %), tin (>75 % of proven reserves), gold (ca. 40 %), silver (ca. 90 %) and diamonds (> 99 % in Yakutia, in the Arkhangelsk region and in the Taimyr Autonomous District). There are also major deposits of mercury in the Yana-Chukotka province, and on the Taimyr Peninsula.

Numerous major deposits are, so far, classified less precisely, as resources. Among the most important are deposits of: manganese (on Novaya Zemlya), chromium (in the Yamalo-Nenets Autonomous District and in Murmansk region) and titanium (on the Kola Peninsula). Explored and predicted resources on the Arctic shelf and in the Arctic archipelago include: alluvial tin, gold, diamonds, manganese, base metals, silver, fluorite, precious stones and various gems.

There is every reason to anticipate that further major discoveries will be made in Arctic Russia and that the mineral industry will continue to be of vital importance for the foreseeable future.

WORD LIST – DEFINITIONS FOR SELECTED TERMS

Alkaline rock: magmatic rock enriched in sodium and/or potassium

Alluvial: material transported in suspension and deposited by rivers

Anticlinorium: a composite of several, parallel folds which are, collectively, convex upwards and which contains older rocks in its core.

Base metal: a group of common, chemically active metals, normally cobalt, copper, lead, nickel and zinc.

Botryoidal: Mineral growth with a surface showing coalescing spherical forms.

Carbonatite: a magmatic rock enriched in carbonate minerals

Cratons: Continental areas not deformed or metamorphosed for a prolonged period

Eclogite: a body of rock, usually magnesium-iron rich, which has been metamorphosed at the pressures of the lower crust or mantle and which then consists predominantly of garnet and pyroxene

Esker: stratified fluvial sand and gravel deposited glacially

Exhalite: A sedimentary deposit formed from the fallout of minerals associated with hydrothermal activity on the sea floor

Foreland. A stable area marginal to an orogenic belt

Ga: Billion years

Gossan: iron-bearing weathering products overlying sulphide deposits

Granite: A plutonic rock containing quartz, alkali feldspar and plagioclase, commonly also small amounts of mica.

Kimberlite: magmatic rock formed in the Earth's mantle and penetrating the crust explosively in pipe-formed channels

Mafic: A plutonic rock with a major component of dark, ferromagnesian minerals.

Molasse: A thick, highly variable sedimentary sequence, partly marine, partly continentally derived.

Mt: Million tons

Ophiolite: a slice of ancient oceanic crust, thrust up onto a continent

Orogen: a large-scale linear or arcuate mobile belt that has been subjected to folding and deformation

Orogeny: Mountain building process, generally during continent-continent collisions.

Placer: a river or beach sediment in which valuable minerals, derived from weathering of a hard-rock source, have been concentrated by natural processes

Rapakivi: rock, most commonly of granitic composition, in which crystals have grown to form an orbicular texture

Skarn: Mainly rocks formed at the contact between a magmatic intrusive rock and carbonate-bearing rocks due to fluids derived from the intrusion, country rocks or meteoric water. The fluids may be enriched in silica, aluminum, iron, magnesium, etc. Sometimes mineable for copper, zinc, lead, silver, gold etc

Supracrustal rocks: Rocks formed at the surface, e.g. sandstone, shale, carbonate, volcanic rocks

Terrane: a discrete allochthonous (transported) fragment of oceanic or continental material with a distinct tectonic history

Tonalite: A plutonic rock with quartz and plagioclase as important components.

Turbidite: A sediment deposited from a turbidity current, commonly showing graded bedding.

Ultramafic: An igneous rock in which $\geq$ 90% of the content consists of dark magnesium-iron-rich minerals.

For other terms: http://geology.com/geology-dictionary.shtml

Geological Timescale: http://www.geosociety.org/science/timescale/timescl.pdf

MINERAL RESOURCES IN THE ARCTIC

The geological surveys active in the Arctic region have compiled information on the most important mineral deposits north of 60°N - in a database, on a map and in user-appropriate descriptions (for geoscientists and in a briefer version for general-interest readers in this volume). The largest deposits of metals and diamonds on land have been given priority. The briefer version of the description is published in English, French and Russian.

These products represent the first compilation of information on the most important deposits of the prioritized resource types in the Arctic. The compilation illustrates the importance which the mineral industry has had in the Arctic regions for over a hundred years, but also the priority given to exploration for mineral resources in the region in more recent times. The mineral industry is very important for the northernmost regions of most of the Arctic nations and several deposits north of 70°N (in Canada, Greenland, Norway and Russia) are being mined or developed with a view to mining. Production of certain commodities from mines in the Arctic represents a major part of world production. The results of exploration in both established mining provinces and in new, prospective areas show that there is a considerable potential for new, important discoveries.

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