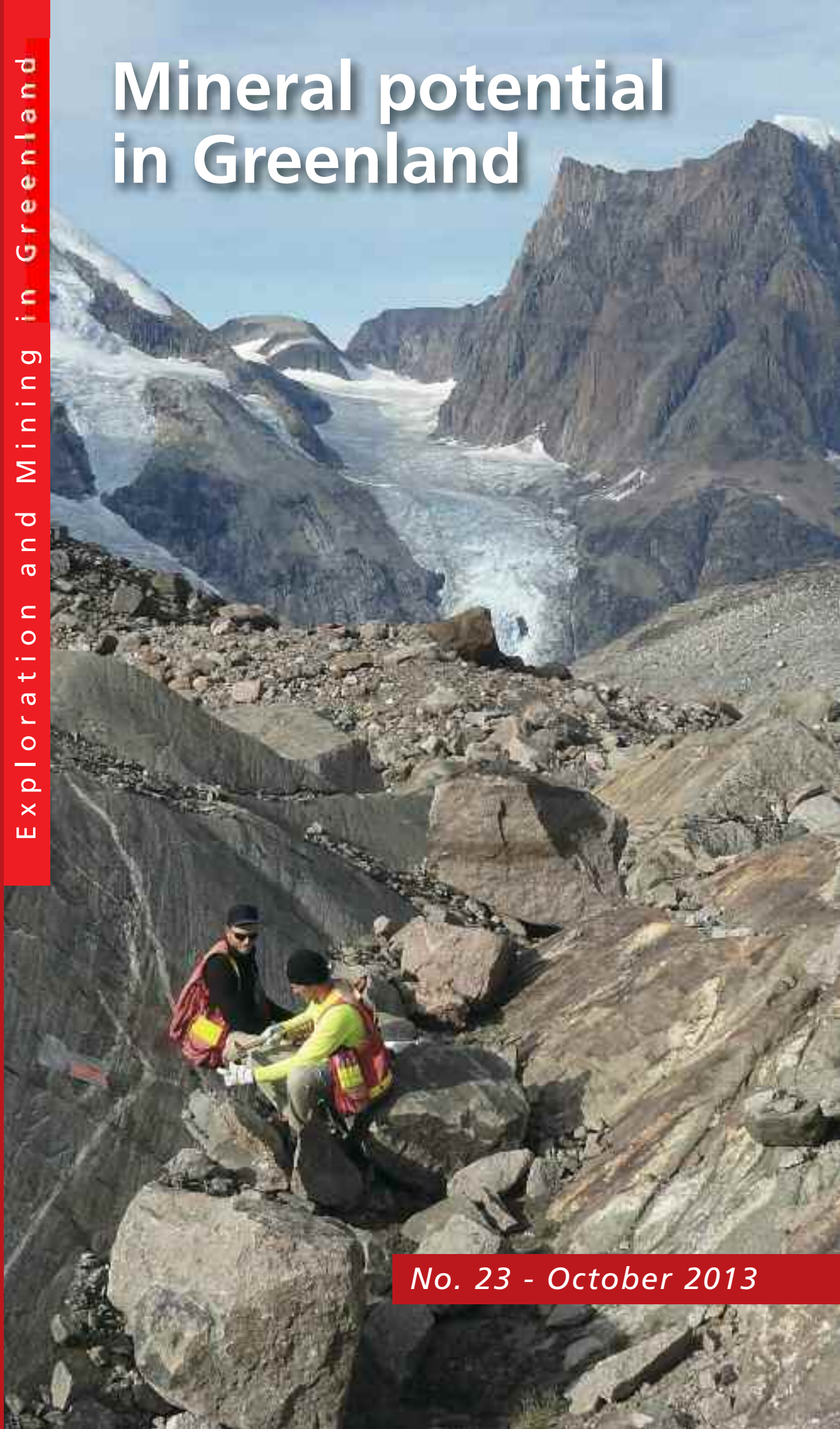




Mineral potential in Greenland



Mineral potential in Greenland



Geologically and geographically Greenland is closely related to northern Canada and Scandinavia. Greenland, the largest island in the world, covers 2,175,600 km². It is 1,250 km from east to west and 2,675 km from north to south. The up to three kilometre thick Inland Ice covers some 80% of Greenland; the ice-free zone around the Inland Ice is up to 300 km wide and covers an area of approx. 410,000 km², which, by comparison, is larger than the area of Germany (357,000 km²).

Mineral potential in Greenland

The mineral occurrences in a region are determined by the geological environment and the geological processes forming the mineral accumulations. The environments are a reflection of the geotectonic evolution and thus linked to global plate tectonic scenarios through time. Greenland spans most of the Earth's geological history and most of the geological environments encountered on the Earth. This is also reflected in a great diversity in the mineral deposits and mineralisation styles identified throughout Greenland. This issue of *Geology and Ore* provides a general overview of the presently known mineral potential in Greenland for various commodities and mineralisation styles. The overview is based on information from various editions of *Geology and Ore* and the reader is therefore recommended to read the individual editions of *Geology and Ore* referenced herein for more comprehensive descriptions.

Geological framework for mineralisations

Principally, Greenland is composed of an Archaean basement core zone: the North Atlantic Craton, the margins of which were reactivated during Proterozoic orogenic events (the Nagssugtoqidian–Rinkian orogen in West and South-East Greenland), and more juvenile magmatic-dominated crust was added to South and



Large piles of well-sorted cryolite ore in the process of being manually loaded onto the ship Thelma at the Ivittuut Cryolite Mine (1920) in South Greenland. The open pit mine was active from 1854 to 1987.

North Greenland (the Ketilidian and the Inglefield Land mobile belts, respectively). The Ketilidian environment in South Greenland was also affected by a later failed rift-system: the Gardar Province. Successively, starting in the Mesoproterozoic and continuing into the Palaeogene era, large sedimentary basins were added along the continent–ocean margins in North, East and West Greenland. Fold belts, either in the form of an inverted sedimentary basin (the Ellesmerian Fold Belt) or as a fold-and-thrust belt (the East Greenland Caledonian orogen), occur in North and East Greenland, respectively. Finally, sea-floor spreading in West and East of Greenland were accompanied by large volumes of plateau basalts. The magmatic activity in East Greenland also resulted in numerous intrusions.

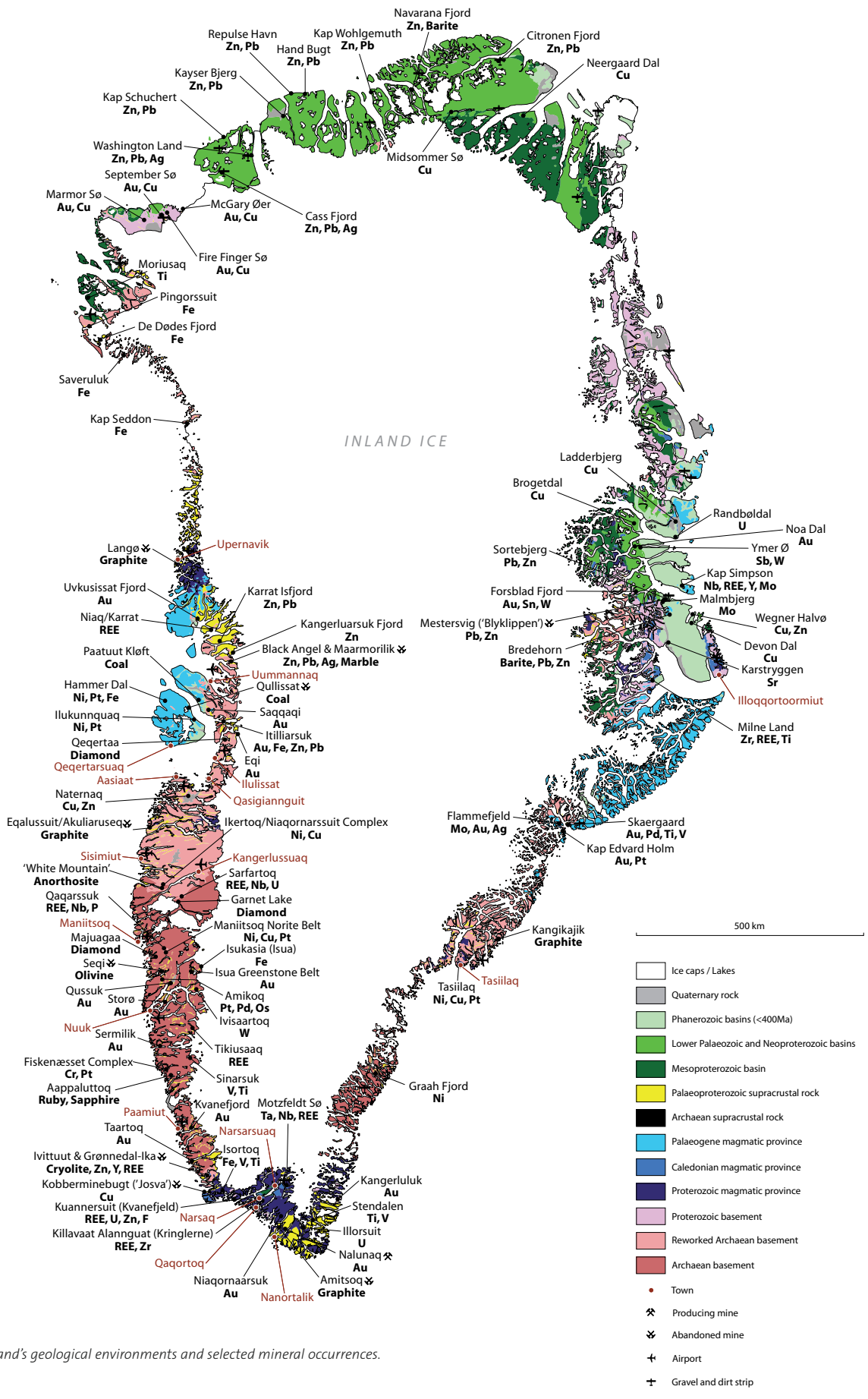
Geological Environments

An obvious place to look for mineral deposits is where accretion of crust formation occurs. This is demonstrated in several places in Greenland such as the Archaean island-arc formation at Qussuk in the Nuuk region and the Palaeoproterozoic Ketilidian orogen.

Prosperous periods for metal formation of the Precambrian are:

- Eoarchaeon (3.8–3.7 Ga) with BIF
- Meso–Neoproterozoic (3.1–2.6 Ga) with arc-related and orogenic gold and BIF
- Palaeoproterozoic (2.0–1.8 Ga), especially with gold and uranium in the Ketilidian orogen
- Mesoproterozoic (1.5–1.3 Ga) rift-related Gardar alkaline province with specialty metals: REE, zirconium, niobium, uranium and tantalum
- Caledonian Neoproterozoic sediments in East Greenland with copper and tungsten.

The Phanerozoic sediments are targets for stratiform and stratabound occurrences of base metals i.e. SEDEX (sedimentary exhalative) and MVT (Mississippi Valley-Type) deposits. The Neoproterozoic carbonatites and kimberlites are successful targets for REE, niobium and diamond. Some of the large deposits are found in these groups. Real giant, large-tonnage deposits are located within the Palaeocene complexes such as the Skaergaard intrusion (gold, platinum and palladium) and Malmbjerg (molybdenum).



Greenland's geological environments and selected mineral occurrences.



Bulkcarrier (2006) alongside the deep-water pier at the now closed (2011) olivine mine at Seqi in southern West Greenland. The deposit is located in a dunitic body with 95–99% olivine with a high magnesium content.

The promising exploration targets fall within these categories with a priority for gold, platinum-group elements, diamonds, coloured gemstones (ruby and sapphire), zinc, molybdenum, nickel, iron and zirconium. Speciality metals such as REE, niobium, tantalum and unique industrial minerals are also potential targets. The most diverse type of commodity is the gold occurrences. Gold is remarkable as it can be deposited at all crustal levels. The deepest level of gold formation is at depths of 15–25 km (orogenic gold in greenstone belts). Shallow gold deposits formed in a granitic gold-copper environment are known from South Greenland. Formation of near surface epithermal deposits are found both in Archaean rocks (Qussuk) and in Palaeogene magmatic systems such as the Skaergaard intrusion. Syngenetic, volcanic, exhalative gold-bearing accumulations are stratiform to stratabound occurrences which are recognised in the Saqqaq, Eqi and Sermiligaarsuk areas. Greenland hosts a wide range of geological environments and related mineralising processes. Geological environments and deposit types are in many situations comparable to those found in Canada, Scandinavia and Australia.

The search for mineral resources

Greenland has rather high exploration and mining expenses. Before World War II, development of mineral targets in Greenland was largely ignored by the international mining industry, although the mining of cryolite went on continuously from 1856 to 1987. Greenland has since then, as a frontier region, been especially sensi-

tive to market fluctuations in metal prices, and as Greenland, in addition to this, does not have a home-market for the commodities, the interest from the industry to develop mineral targets has been limited.

Large parts of Greenland have never been subjected to detailed exploration campaigns. There is a fair chance of finding giant deposits in Greenland since a number of deposits at present are already categorised as 'giants' such as the deposits: Isukasia (Isua), Motzfeldt Sø, Kvanefjeld (Kuanersuit), Kringlerne (Killavaat Alannuat), Skaergaard, Malmbjerg and Citronen Fjord. The present review demonstrates that the geological environments and the related mineral deposits are in many ways similar to those found around the world. This means that the potential for new mineral discoveries that can sustain mining are excellent.

Precious metals: gold and platinum-group elements

The Palaeoproterozoic Ketilidian mobile belt in South Greenland is a well-established gold province that hosts both orogenic gold and granitic gold-copper mineralising styles. Capping the granites are mafic volcanic rocks that also carry gold. The Nalunaq Gold Mine is the only occur-



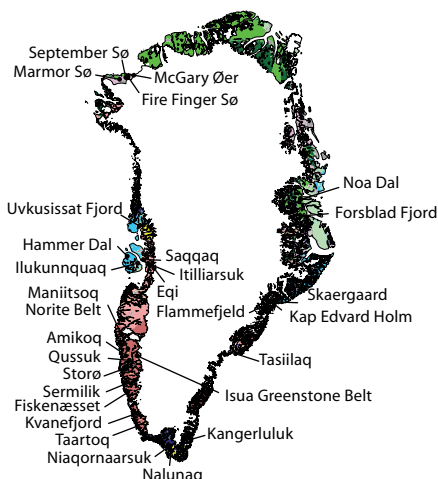
The Storø Gold Prospect in the central part of Nuup Kangerlua (Godthåbsfjord), southern West Greenland. Courtesy: NunaMinerals AIS.



Three-dimensional geological model of the Skaergaard layered intrusion in southern East Greenland – a potential world-class, multi-element deposit with the main commodities being PGEs and Au. The digital elevation model is draped with Aster scenes. The outline of the intrusion is indicated. Locations of drill holes released to the public are shown in blue. One of the modelled bowl-shaped, PGE-bearing layers (Pd5) within the layered intrusion is shown in green. The green line indicates the outline of the intrusion at the surface. 200 m contour lines are in red. Modelling by GEUS.



The face of Gabbrofeldt (1200 m) in the Palaeogene Skaergaard intrusion, southern East Greenland. The three leucocratic layers of the Triple Group can be seen below the top of Gabbrofeldt. The gold and PGE mineralisation is located in the lower part of the Triple Group.



Greenland's main geological environments and known precious metal occurrences.

rence found viable for mining, but several other gold occurrences are known throughout South Greenland. The North Atlantic Craton in southern West Greenland constitutes another region, in which several areas may pose a potential for gold. Here the gold is related to typical Archaean orogenic gold mineralising systems that correlate temporally with, and is related to, ductile deformation along first-order structure. The most investigated occurrence within these settings is the Storø gold prospect, north-east of Nuuk. On the east coast of Greenland, gold and PGE-bearing reefs within the mafic layered Palaeogene Skaergaard Intrusion pose



Mining operation in South Greenland. The Nalunaq gold mine is located in a gold-bearing quartz vein system.



Cu-mineralised conglomerate of the Revett Cu type at the Ladderbjerg Cu deposit in the Permian Huledal Formation, Jameson Land Basin, central East Greenland.

another mineralisation style. Other Palaeogene intrusions may also pose a potential for precious metals. In the same region as the Skaergaard intrusion, orogenic gold occurrences have been described from the Archaean basement.

Similarly, but not as well-investigated, gold occurrences or indications are known from the north-eastern part of Disko Bugt, central West Greenland and from central East and North-East Greenland. More information about precious metals in Greenland can be found in Geology and Ore nos. 1, 8, 9, 11, 14 and at www.greenmin.gl.



Greenland's main geological environments and known base metal occurrences.

**Base metals:
zinc, copper and lead**

Several sedimentary basins in Greenland are well-known for their zinc deposits and potential. The best known is the Palaeoproterozoic Karrat Group in northern West Greenland, which hosts MVT mineralisation including the former Black Angel zinc-lead mine, and the Phanerozoic Franklinian Basin in North Greenland, which hosts both MVT and SEDEX zinc-lead deposits of which the most well-investigated is the Citronen Fjord deposit. Also sedimentary successions in East Greenland are well-known to contain zinc-deposits, in this case also sedimentary copper mineralisation, e.g. in the form of sedimentary-hosted reduced-facies (Kupferschiefer) type, is known from Triassic and Permian rocks of the Upper Palaeozoic–Mesozoic Jameson Land basin. Another type of zinc-lead mineralisation, also found within this basin and which includes the former Blyklippen lead-zinc mine, occurs within quartz veins hosted by Permian sandstone in the Mestersvig area. More information about base metals

The black shale of the Upper Permian Ravnefjeld Formation on Wegener Halvø is a known host of reduced-facies Cu-type mineralisation in central East Greenland. Maximum values from grab samples show 11.5% Zn, 7.7% Pb and 0.35% Cu.

The Navarana Fjord Zn occurrence is located in the area north of 81 degrees north. The deposit is associated with the Navarana Fjord escarpment which marks a shelf and trough facies shift in the Franklinian Basin. This facies border is believed to be one of the guiding controls on the formation of zinc mineralisations in North Greenland. Several zinc occurrences and zinc anomalies in stream sediment samples are associated with the structure.

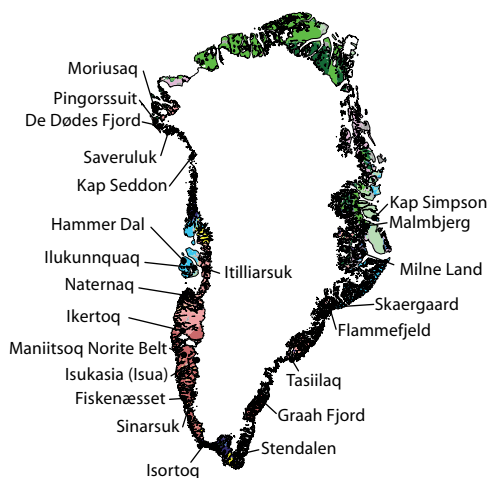
in Greenland can be found in Geology and Ore nos. 2, 5, 18, 21 and at www.greenmin.gl.

Iron and ferro-alloys: iron, nickel, titanium, chromium, molybdenum and vanadium

Banded iron formation (BIF), which is the main source for iron worldwide, is known from Archaean basement settings in most parts of West Greenland. The most well-known and investigated deposit is the Isukasia (Isua) iron deposit, which is located 150 km north-east of the capital Nuuk. However, numerous BIF occurrences are also known from the Baffin Bay region in North-West Greenland, which also has been delineated as an iron province. These occurrences are likely to be temporally related to occurrences also found in Canada on Baffin Island, of which the proposed Mary River iron-ore project is the most prominent. The Isortoq iron-titanium-vanadium occurrence in South



The Malmbjerg molybdenum deposit in the Palaeogene Werner Bjerger complex, central East Greenland.



Greenland's main geological environments and known iron and ferro-alloys occurrences.

Greenland constitutes another type of mineralisation as it is hosted in a mineralised troctolite dyke. Nickel occurrences

are known from numerous places in Greenland; the most pronounced are the nickel occurrences within the Maniitsoq



Chromitite banded anorthosites from the Fiskenæsset anorthosite complex, southern West Greenland.



Close-up of folded, banded quartz-magnetite ore in a 1 m outcrop at Isua, southern West Greenland.

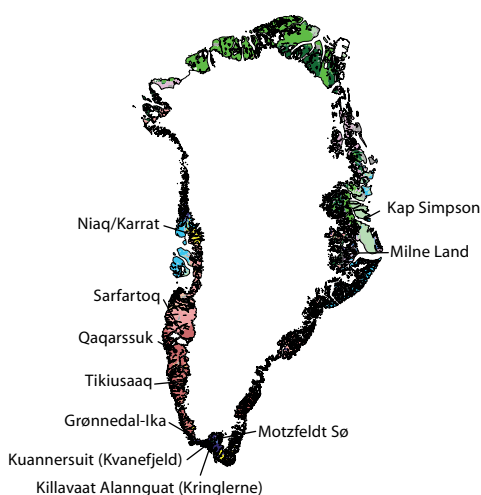


The Isua deposit in southern West Greenland. View to the north-east along the margin of the Inland Ice. The iron deposit is situated along the ice margin near the arrow. Photo: Claus Østergaard.

Nickel Province (Norite Belt) in southern West Greenland, the Ikertoq occurrence south of Sisimiut in central West Greenland and the Tasiilaq occurrence in South-East Greenland. All may represent conduit-type nickel mineralisations. Other areas with indications of occurrences of

similar types are present in South Greenland and central East Greenland. Nickel mineralisation associated with flood-basalt activity is known from the Palaeogene West Greenland Basalt province on the island of Disko and may be analogue to Norilsk type mineralisation. Other areas

with voluminous flood-basalts are present in the Palaeogene East Greenland Basalt Province and in the Mesoproterozoic Zig-Zag Dal Basalt formation, eastern North Greenland. These may also pose a potential for accumulations of nickel although no occurrences have yet been discovered. Molybdenum is known from the Palaeogene Climax-type porphyry deposit at Malmbjerg, central East Greenland. Similar style mineralisation may be present at the Flammefjeld occurrence further to the south. Chromium, vanadium and titanium occurrences are known from the Fiskenæsset gabbro-anorthosite complex (Sinarsuk) in southern West Greenland. Other gabbro-anorthosite complexes in southern West Greenland, as well as in the Thule area in North-West Greenland, may also hold a potential for ferro-alloys. More information about iron and ferro-alloys in Greenland can be found in *Geology and Ore* nos. 6, 8, 14, 17, 19, 24 and at www.greenmin.gl.



Greenland's main geological environments and known specialty metals occurrences.

Specialty metals: REE, niobium, tantalum and zirconium

The Gardar Province in South Greenland has long been recognised for its well-endowment of specialty metals. REE occurrences are especially well-investigated from the Kvanefjeld (Kuannersuit) and Kringlerne (Killavaat Alannguat) deposit within the Ilímaussaq intrusive complex; with the former also containing uranium and zinc and the latter also containing zirconium, tantalum and niobium. Also the Motzfeldt Sø intrusion contains a large deposit of niobium and tantalum together with REE. Other intrusive rocks of the Gardar Province may hold potential for occurrences of specialty metals. Further north, within the North Atlantic Craton, carbonatite intrusions at Qaqarssuk and Sarfartoq contain other REE occurrences as well as occurrences of tantalum, niobium and uranium. Other carbonatites in southern West Greenland like the Tikiusaaq and the Grønnedal-Ika carbonatites may pose a potential for other specialty metal accumulations. Other known REE occurrences are e.g. at Niaq in northern West Greenland within the Palaeoproterozoic metasediments and metavolcanics of the Karrat Group and at Milne Land within a Mesozoic palaeoplacer in central East Greenland. Other settings that may hold a potential for specialty metals are



Gossan zone developed in a nickeliferous sulphide lump within a norite pod, the north-eastern part of the norite belt in southern West Greenland.

e.g. Palaeogene alkaline intrusions at Kap Simpson in central East Greenland. More information about specialty metals deposits can be found in Geology and Ore nos. 10 and 20 and at www.greenmin.gl.

Gemstones: diamond, ruby and sapphire

After a long period of intense studies and exploration campaigns, the northernmost part of the North Atlantic Craton in southern West Greenland, comprising the area from north of Nuuk to the area north

Søndre Strømfjord, is established as a diamond-bearing province with an overwhelming number of known kimberlite and lamproite dyke and sill occurrences. Diamonds have been discovered in several places and at the Garnet Lake kimberlite occurrence, east of Sukkertoppen Iskappe, detailed investigations and testing have been carried out. Southern West and South West Greenland still pose potential for the discovery of other diamondiferous kimberlites and lamproites. Discoveries of kimberlite and lamprophyre dykes further north, in the eastern part of the Disko



Drilling at the Kvanefjeld multi-element deposit in 2011. Photo: Greenland Minerals and Energy.



The layered kakortokites of the Kringlerne deposit within the Ilimaussaq intrusive complex in South Greenland. The kakortokites are zirconium and REE-rich cumulates.

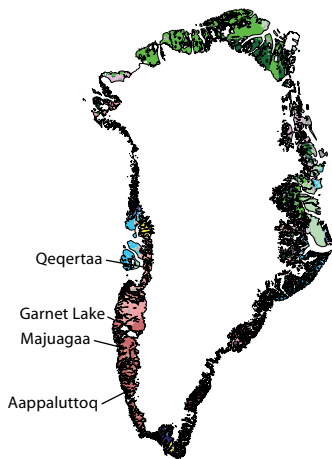


2.51 carat diamond extracted from the Garnet Lake dyke near Kangerlussuaq in southern West Greenland. Copyright: Hudson Resources Inc.

other gemstone targets. Similarly, Palaeoproterozoic deformed Archaean basement rocks in central West and South-East Greenland may also hold a potential. More information about gemstones in Greenland can be found in Geology and Ore nos. 4 and 7 and at www.greenmin.gl.

Land of present and future opportunities

Almost all geological time periods and geological environments pose potential for a wide range of different commodities. Many of the favourable commodity regions have only been scratched by exploration campaigns and most of these discoveries were made by conventional exploration methods. Still, many large deposits of metals have to be discovered and developed. In spite of Greenland's, in



Greenland's main geological environments and known localities for gemstones.

Bugt area, central West Greenland, within Palaeoproterozoic deformed Archaean basement rocks, have also been investigated for their diamond potential. On the island of Qeqertaa (near Arveprinsen Eiland), this has led to the discovery of

diamonds. Again, numerous untested dykes may still pose a potential for new discoveries. Ruby and pink sapphires were discovered in the mid 1960es in the Fiske-næsset area in southern West Greenland. Since then, each new exploration campaign has led to new discoveries. The most investigated and tested is the Aappaluttoq deposit. Other areas within the Nuuk and the Maniitsoq regions have also yielded discoveries of rubies. It is believed that the above areas pose potential for

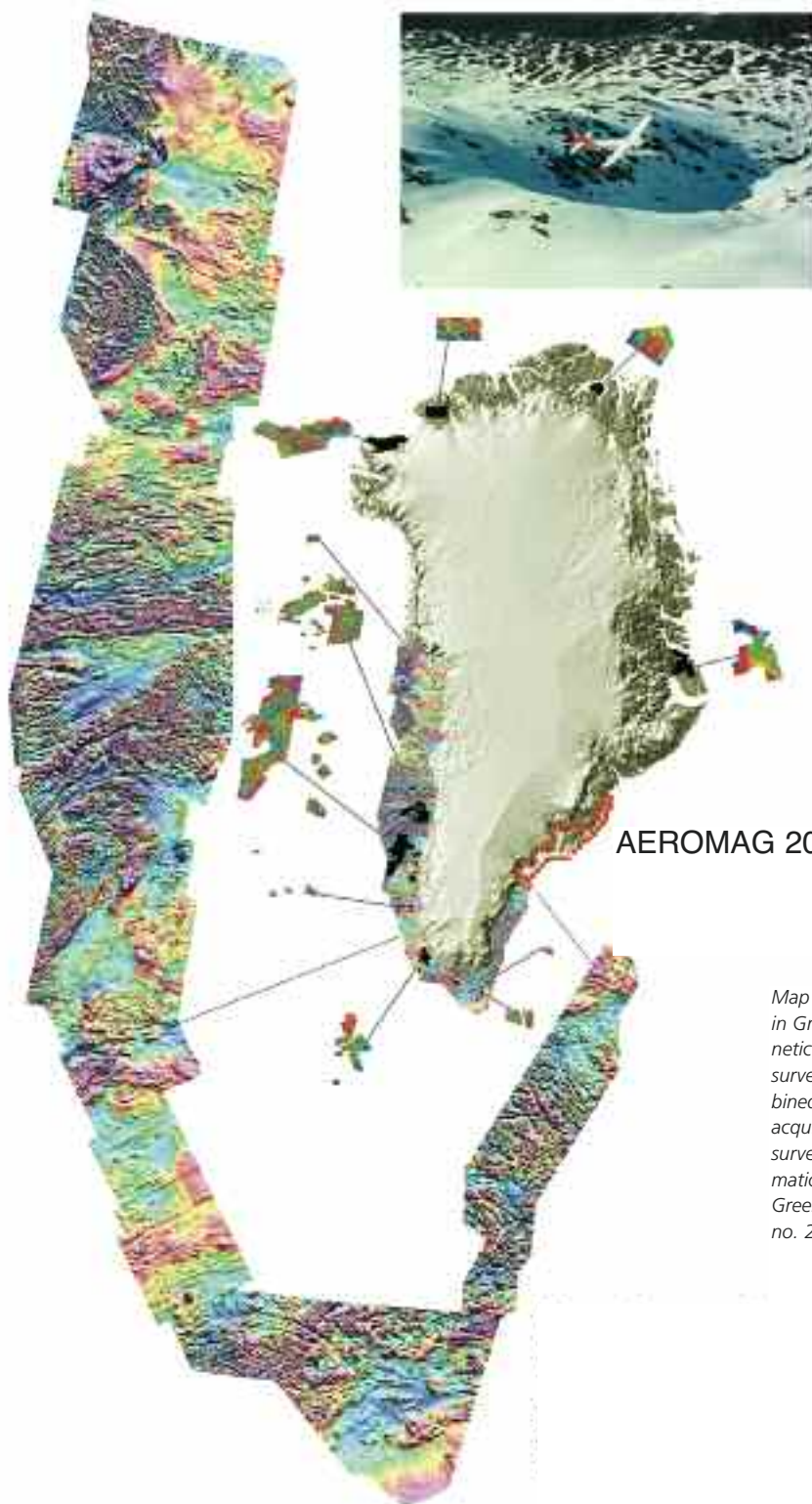


Rubies from Aappaluttoq. From left to right, the stones weigh 0.43, 0.42, 0.77, 0.43, and 0.22 carats. Courtesy: True North Gems.

places, harsh climate and inaccessibility provide challenging conditions, the potential for large deposits – in several cases world-class deposits – is considered favourable and economic viable. With

modern-day exploration techniques (e.g. airborne geophysical surveys and satellite-based remote sensing) and the increasing need for resources, the conditions for both present and future mineral opportu-

nities are good in Greenland, considering the development of presently known mineral resources as well as the discovery of new resources.



AEROMAG 2013

Map of regional and detailed airborne surveys in Greenland. The figure shows merged magnetic field data from regional aeromagnetic surveys and detailed surveys mostly with combined electromagnetic and magnetic data acquisition. The area for the Aeromag2013 survey is indicated on the map. More information about airborne geophysical data from Greenland can be found in Geology and Ore no. 22 and at www.greenmin.gl.



Diamondiferous rock outcrop of a kimberlitic dyke in the Kangerlussuaq region, southern West Greenland. Xenoliths are seen in the dyke as brown nodules within the matrix. Hammer for scale is c. 60 cm

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Front cover photograph

Geologists exploring for mineral deposits in the Skjoldungen region in 2012 as part of the regional Mineral Resource Assessment Programme (MRAPSEG) of the South-East Greenland Archaean craton.

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Printed

October 2013 © GEUS

Printers

Rosendahls · Schultz Grafisk a/s

ISSN

1602-818x