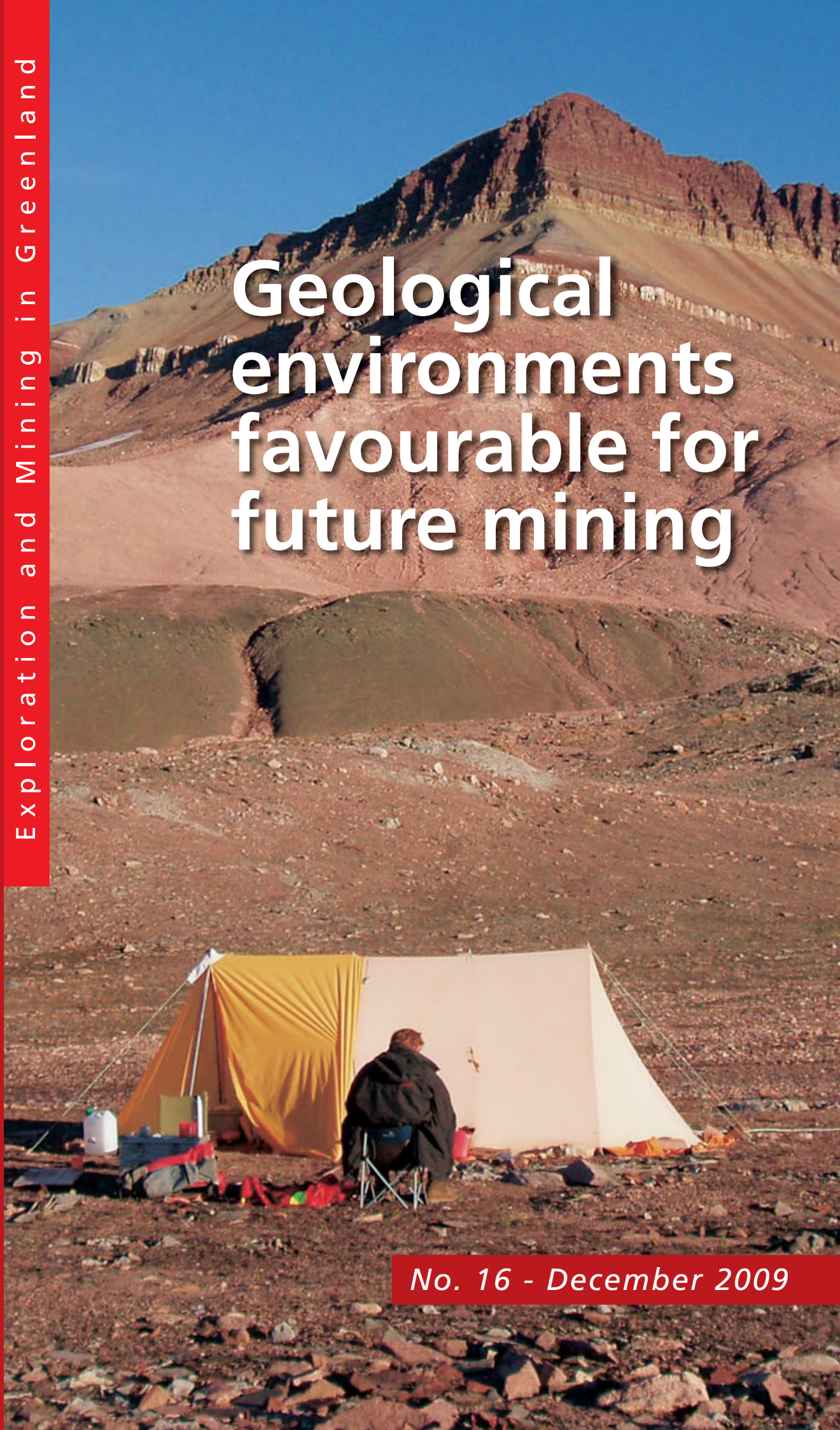




Geological environments favourable for future mining





Greenland and its geological environments favourable for future mining

Shield formation and cratonisation in Greenland, created by the formation of continental and oceanic crust, occurred in Archaean time by the amalgamation of oceanic and new arc-formed crust following emplacement of tonalite-trondhjemite-granodiorite plutons. This was succeeded by orogenic deformation and greenschist to granulite facies metamorphism. At the same time during the Archaean period of huge crustal formation, major mineral deposits of gold and banded iron formations were developed in granite-greenstone terranes in southern West Greenland. Ultramafic to mafic intrusions in greenstone belts occurred in Greenland as major carriers of chrome-nickel-vanadium. From Palaeoproterozoic time, orogenic activity and rifting evolution created profound possibilities for the existence of viable economic occurrences. This is exemplified by magmatic and sedimentary environments in large scale, even gigantic, accumulations of commodities related to intrusions, fold belts and sedimentary basins.

Introduction

Exploration and development of mineral resources in Greenland, as a 'greenfield' region with rather high exploration and mining expenses, have been depending on market fluctuations in metal prices. A realistic interpretation of the situation with regard to a high number of immature occurrences is that continuous and persistent exploration, compared to e.g. Canada, has not been done in Greenland. Mineral exploration in Greenland is based on the knowledge of a large number of key occurrences only exploited to a limited degree. Large parts of Greenland never faced detailed exploration campaigns although the potential for some of the more important mineralisation types and commodities is present. The known deposits in Greenland are analogue to those found in famous, exploitable geological environments around



Banded iron formation in a sequence of amphibolite and pelitic gneiss in the Pituufik area, Melville Bugt, North-West Greenland. The width of the banded iron formation varies from 0.7 to 1.6 m.



Rusty iron sulphide mineralisation (gold-bearing) within a hydrothermal altered sequence of supracrustals at Qussuk, southern West Greenland.

the world and therefore the opportunity to find new giant deposits is likely.

Environment scenarios

Archaean environments: Geological evolution and mineral potential

The Meso- to Neoarchaeal eras are the most prolific periods of crustal production

in the Earth's history and consequently characteristic of major global mineral deposits as also experienced in the geological evolution of Greenland. These environments were associated with deformation and metamorphism from greenschist to granulite facies conditions.

The well-studied Nuuk region in southern West Greenland reflects the prevailing



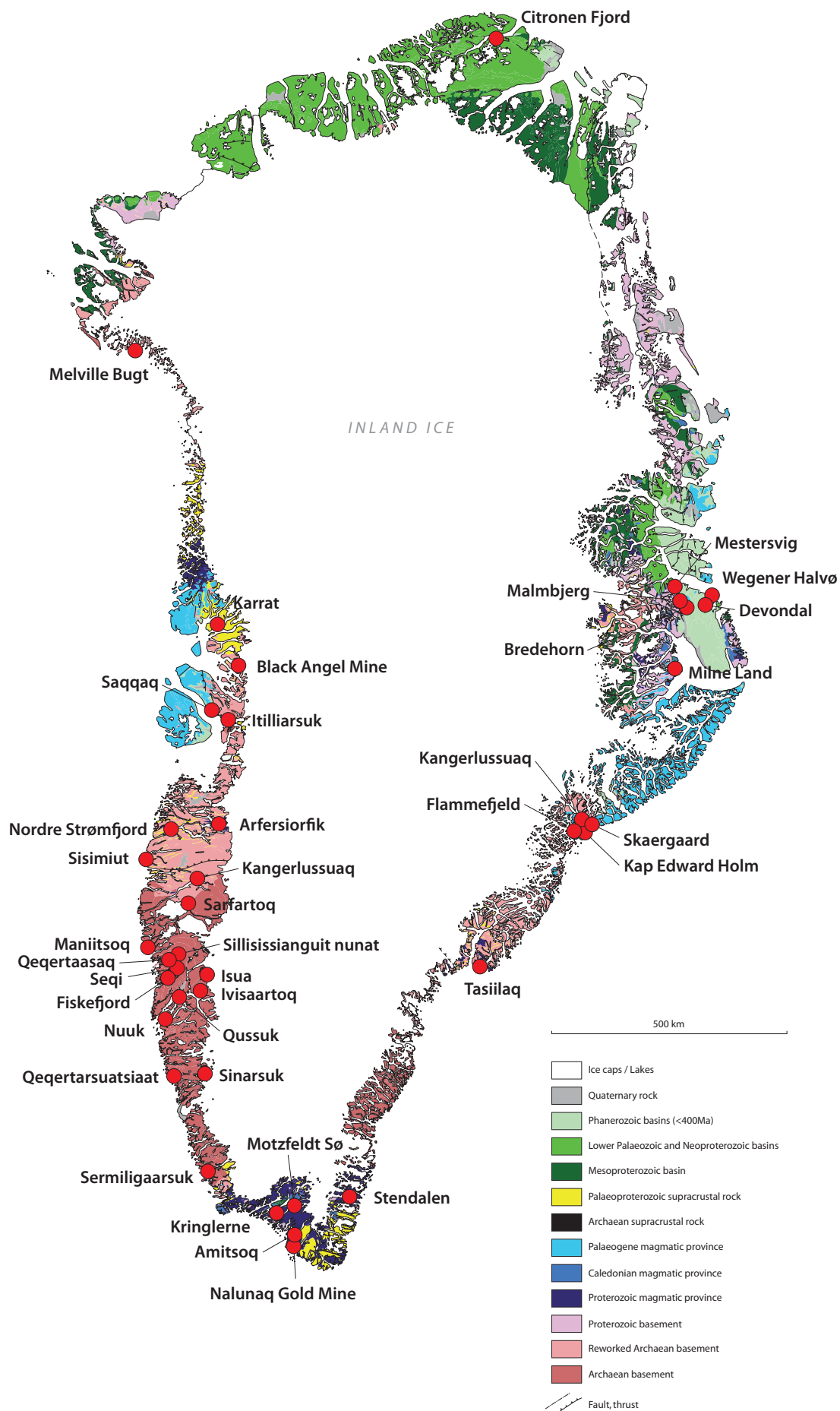
A general view from the Qingaaq Mountain on Storø, southern West Greenland, towards north-east with the central part of Godthåbsfjord to the left. The camp is placed on the ridge (Little Qingaaq) in a supracrustal sequence of amphibolite, iron formation, ultramafic rock, garnet-schist and fuchsitzite-quartzite, intruded by pegmatites and later dolerite dykes. The supracrustal rock sequence of the Aappalaartoq mountain (1440 m a.s.l.) located 4–5 km farther north is partly hidden in the clouds.

shield formation and cratonisation of the Archaean era. The oldest recorded plate tectonic events recorded in Greenland are recognised in the 3.8–3.7 Ga Isua greenstone belt, Isukasia terrane. In the central Nuuk region, the Mesoarchaeoan Qussuk-Bjørneøen supracrustal belt is interpreted as an island-arc complex of the age 3.1 Ga. At the same time, the Mesoarchaeoan Ivisaartoq greenstone belt (~3.1 Ga) in the Kapisilit terrane is formed in a supra-subduction zone oceanic crust. The various Archaean terranes in the Nuuk region were juxtaposed by accretionary plate tectonic processes through the Meso- to Neoarchaeoan eras with associated orogenic deformation and metamorphism.

The infracrustal rocks within this part of Greenland are dominated by 3.8–2.7 Ga gneisses and granites that embed the supracrustal rocks with minor mafic and ultramafic rock sequences, granite bodies and pegmatites attached. Apart from the Nuuk region, supracrustal rock environments are found in the Disko Bay, central



Rhythmic igneous layering within a norite body at Sillisissanguit nunat, the Maniitsoq norite belt, southern West Greenland.



Map of the main geological environments in Greenland.



Outcropping hornblendite at the Amitsog Island in the Nanortalik area, South Greenland.

West Greenland, in the Melville Bugt, North-West Greenland and in the Sermiligaarsuk region, South-West Greenland.

The Archaean environments and their possible plate tectonic settings recognised in Greenland suggest that Archaean plate tectonics may be similar to the tectonics operating in the Phanerozoic era. Some of the Archaean high-grade metamorphic gneiss-amphibolite associations are considered to resemble granite-greenstone belts, but in general they are exposed in deeper sections of the crust than in similar sections in Canada and Australia.

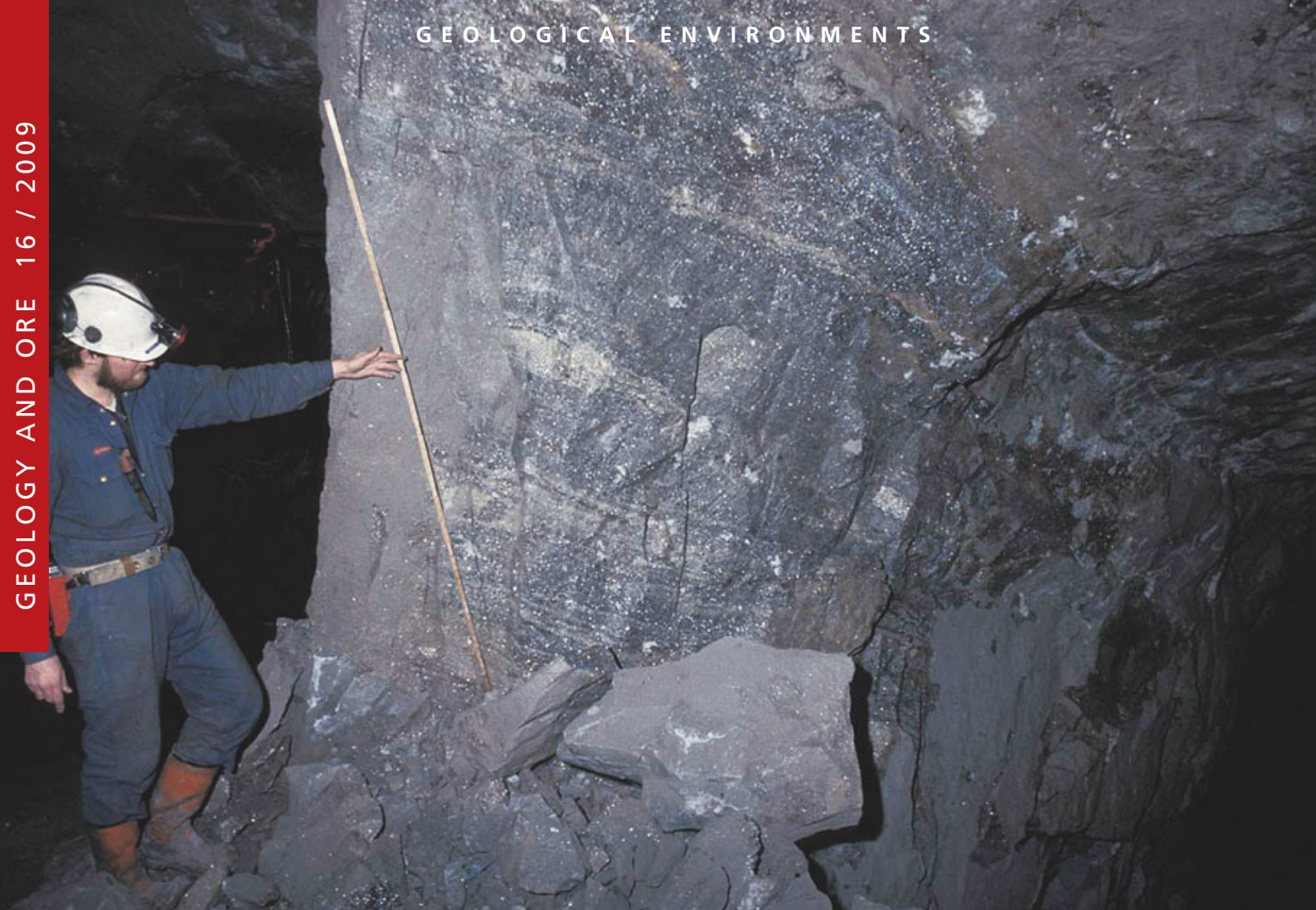
The 3.07 Ga island arc complex at Qussuk hosts metamorphosed high-sulphide gold occurrences. The gold occurrences at Sermiligaarsuk, South-West Greenland and at Saqqaq, central West Greenland represent stratiform gold-arsenic occurrences within volcanic-associated sulphidation facies rocks, which may have formed in an arc-related setting. During the periods of accretion tectonics and metamorphism, hydrothermal fluids migrate into major structures resulting in the formation of orogenic gold deposits, which, world-wide, are typical of most Neoproterozoic granite-greenstone belts, as

found in the Disko Bay and Nuuk regions with a typical gold-arsenic association. In the Archaean era the number of gold occurrences peaked world wide and this is associated with the most productive periods of continental crust formation ~2.7 Ga. In Greenland, the gold-bearing greenstone belt at Storø has an age of ~2.64 Ga,

while all other known gold occurrences in Greenland are older than 2.7 Ga, with a peak of formation at around 3.1 Ga and 2.8 Ga. Chemical sedimentation gave rise to Algoma type banded iron-formations (BIF), which, in Greenland, include three main BIF localities, the most famous being the Isua BIF in the Isua supracrustal belt



The open pit quarry at the Seqi Olivine Mine, southern West Greenland, in an early stage of the operation in 2006.



Rib pillar inside the 'Black Angel Mine' with high grade banded Zn-Pb ore. A reopening of the mine is presently considered (Nov. 2009) with mining of the pillars as part of the plan for renewed exploitation.



View of the mining area at Nalunaq Gold Mine, South Greenland. Exposed quartz veins are outcropping on the mountain slope above the mining camp in the valley.

(~3.8 Ga), in the north-western Nuuk region. The two other iron accumulations are also large in size; the Itilliarsuk BIF (~2.85 Ga) and the Melville Bugt BIF (~2.7 Ga).

Within the West Greenland granite-greenstone terranes, the main mafic to ultramafic magmatic complexes carry major deposits such as chromitite (\pm PGE) in layered anorthosite complexes (Qeqertarsuaat) and in gabbroic complexes with magnetite and ilmenite (Sinarsuk) and olivine in the peridotite-dunite complexes (Seqi).

Nickel-copper mineralised komatiitic and tholeiitic lava-flows and sills are not known in Greenland as in the Canadian and Australian greenstone belts. However, the potential for similar deposits within the reworked Archaean rocks of the Nagssugtoqidian orogen in West to East Greenland and within the supracrustal rocks of the North Atlantic craton in the Nuuk and Fiskefjord region are favourable.



Sampling in nickel-copper sulphide mineralisation hosted within a metasedimentary sequence, associated with dioritic and ultramafic rocks at Tasiilaq, South-East Greenland. Photo: NunaMinerals A/S

Palaeoproterozoic environments

The Palaeoproterozoic era is world wide characterised by crustal amalgamation and formation of large orogenic belts from collision and subduction around 1900 Ma. The established Archaean to early Palaeoproterozoic stable lithospheric plates permitted the formation of sedimentary basins, deposition of platform sediments and the development of continental margin troughs.

Several Palaeoproterozoic orogenic belts occur in Greenland as the Ketilidian orogen, South Greenland and in the Inglefield Land mobile belt in North-West Greenland. Supracrustal belts, including greenstone rocks, are sparse within these orogens but occur as thin sequences dominated by amphibolitic rocks and subordinate metasedimentary rocks, mainly schist. It is usually difficult to distinguish between reworked Archaean and Palaeoproterozoic rocks unless age determinations are carried out.

In the Nagssugtoqidian, several 1950 Ma supracrustal sequences as at Naternaq and Ataneq contain syngenetic massive sulphide

occurrences; however none of these with a significant base metal content. Intrusive suites around 1900 Ma at Arfersiorfik and Sisimiut and equivalent rocks in the Ammassalik area are associated with Nagssug-

toqidian convergence and the subduction of the oceanic lithosphere prior to the main collision. Only copper-nickel occurrences within the Ammassalik Intrusive complex are recorded in this context.



The Malmbjerg molybdenum granite hosted deposit, viewed from south-west, positioned between two glaciers. The top of the mountain (to the left) reaches a height around 1700 m and the glacier is at c. 700 m. The granite cupola (light yellow-brown) is intruded into the overlying bedded sandstone (dark brown).



The Sarfartoq carbonatite complex viewed westwards along the valley. The reddish slope (raising 400 m from the valley bottom) in the centre is representing the outcropping carbonatitic core of the complex.



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.

The degree of exploration within the southern part of the Rinkian orogen is limited but some major discoveries have been done. The SEDEX-type Black Angel deposit at Maarmorilik and the sulphide-gold occurrences in the Karrat Isfjord are prominent. The Karrat Group and the northern Rinkian orogen may in addition hold potentials for orogenic gold and VMS occurrences.

The juvenile Ketilidian orogen is a gold province with several gold prospects in

different settings including the Nalunaq Gold Mine. The gold is related to the later stages of the batholith formation (1800–1770 Ma) with precipitations both in supracrustal rocks and granitoids.

The greenstone belts in the Palaeoproterozoic belts outside South Greenland are considered to have a low potential for gold deposits. One exception is in Inglefield Land to the North where gold is related to shear zones and hosted by Palaeoproterozoic deformed gneiss and supracrustal rocks.

Iron-Oxide-Copper-Gold (IOGC) deposits have not hitherto been realized in Greenland. In general IOCGs are hosted by cratonic or continental margin environments with extensional tectonics in which mantle underplating may be critical. IOGC settings are favourable in North-West and South-West Greenland, in environments related to craton edges.

Magmatic development and mineral potential (<1600 Ma)

Known major intrusive events are the Mesoproterozoic Gardar Province in South Greenland, the Neoproterozoic North Atlantic alkaline province and the Jurassic province of carbonatites in West Greenland. Other major intrusions described are granites in East Greenland associated with Caledonian events, intrusions associated with the rifted Palaeogene basaltic provinces of East and West Greenland as well as the alkaline granitoid intrusions of East Greenland. Regions dominated by extrusive volcanism are the Palaeogene flood basalt provinces in East and West Greenland.

Mineral occurrences in the Proterozoic and Mesozoic scenarios are mainly associated with a stable craton or incipient rifting and initial basin formation. The Mesoproterozoic Gardar Province comprises three intrusive phases related to initial rifting of which alkaline phases carry large deposits of niobium, tantalum, zirconium, rare earth elements and cryolite.

The North Atlantic alkaline province is believed to be a result of the opening of the Iapetus Ocean around 615 Ma. The carbonatites in West Greenland have a definitive potential for niobium, tantalum, rare earth elements and apatite. The Neoproterozoic kimberlite dykes in the West Greenland Kangerlussuaq–Maniitsoq region hold a promising diamond potential. The mineral occurrences in the Palaeogene magmatic environment comprise deposits like the porphyry molybdenum deposits related to alkaline intrusions in East Greenland and associated vein systems with gold and silver. The Skaergaard gabbro intrusion hides a world-class deposit with gold, palladium and platinum. The Palaeogene alkaline and mafic igneous



Magmatic layering (dm-scale) in the Palaeogene Kap Edward Holm gabbro intrusion, southern East Greenland.

rocks together with the flood basalt provinces in East and West Greenland are typical frontier areas except around the known deposits.

The Labrador located Voisey's Bay nickel-copper-cobalt deposit type has not yet been found in Greenland. It is well-established that the geology of north-eastern Labrador correlates with southern West Greenland and the Nain craton in Canada and the North Atlantic craton in Greenland once formed a coherent Archaean crustal block. Some of the better potential areas in Greenland for deposits similar to Voisey's Bay are in the area around the 1800 Ma Stendalen gabbro in eastern South Greenland, plutonic members and dykes related to the 1400–1200-Ma Gardar province in western South Greenland, and the ultramafic to gabbroic rocks intruded into the Palaeoproterozoic sulphide-bearing metasediments in the Nordre Strømfjord region in West Greenland.

Looking at the Palaeogene basalts in West Greenland they have, from a mineral resource point of view, been compared with the Noril'sk Region. These rocks are

characterised by depletion of copper-nickel and platinum group elements in the basalts. The West Greenland system is comparable with the Noril'sk system, but the sulphide saturation took place at high level in the crust, whereas at the type locality the saturation event took place at

depth with subsequent injection of sulphide-bearing magmas into higher levels. The Ilkunnuaq sediment-contaminated sulphide-rich mafic dyke has been suggested to be a possible candidate for a Noril'sk type deposit.



The Stendalen layered gabbro complex. In the foreground light coloured psammites, followed by a rust zone (to the right) within the layered gabbro complex. The cliff face is 600–700 m, South-East Greenland.

Sedimentary environments and mineral deposits (<1600 Ma)

Major intercontinental-rift-related sedimentary successions are recognised as the Mesoproterozoic Thule Group, the Independence Fjord Basin and the Krummedal succession in North and East Greenland, the Neoproterozoic Eleonore Bay Supergroup in East Greenland and the Phanerozoic sedimentary Franklinian basin in East and North Greenland. The East Greenland sedimentary basins are rift-related with huge thicknesses of sediments including clastic sediments and carbonates. The North Greenland environment is the platform type with dominating carbonates and flysch sediments. SEDEX lead-zinc type deposits in the shale sequences are found in the sedimentary basin in North Greenland. Carbonate-hosted lead-zinc (MVT) has been found in platform carbonates both in North and East Greenland.

Many of the well-known types of mineral occurrences of the sedimentary environment type also occur in Greenland.

Examples are copper in sandstones in the Neoproterozoic and the Mesozoic clastic sediments; lead and zinc in the shale/carbonate sequences in the sedimentary basins; placer deposits and evaporite deposits. Celestite and barium deposits are examples from East Greenland. Lead-zinc veins in sediments occur in the Mestersvig area including the now abandoned Blyklippen mine. Many of the sedimentary basins lie in remote areas and are still frontier regions with respect to exploration.

Concluding remarks

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 are:

- Eoarchaeon (3.8–3.7 Ga) with BIF
- Meso–Neoarchaeon (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, 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 as SEDEX and MVT deposits. The Neoproterozoic carbonatites and kimberlites are successful with their potential 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).

The promising exploration targets fall within these categories with a priority for



The Wegener Halvø Formation carbonate buildups and the overlying black shales of the Ravnefjeld Formation, central East Greenland. Viewed towards the northwest, with the Fleming Fjord (background) and the western part of the peninsula Wegener Halvø in the foreground. The cliff face is approximately 400 m high.



Supracrustal sequence at the Saqqaq gold occurrence. SE–NW orientated cliff face, c. 800 m high. The gold bearing chert horizon just above the snow slope is rusty coloured. Disko Bay region, central West Greenland.

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 this resource accumulation 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 is formed in a copper porphyry environment such as in South Greenland, however, with the present erosion surface only the deep roots of the porphyry system are recognised. Formation of near surface epithermal deposits are found both in Archaean rocks (Qussuk) and in Palaeogene magmatic systems as Flammefjeld. Syngenetic, volcanic, exhalative gold-bearing accumulations are stratiform to stratabound occurrences which are recognised in the Saqqaq 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.

Greenland as a frontier region has rather high exploration and mining expenses and development of mineral targets have to a large extent, (1): before WW II times been ignored by the international mining industry although the mining of cryolite went on continuously from 1856 to 1987, (2): been especially sensitive to market fluctuations in metal prices, and have (3): been ignored because Greenland does not have a home-market for the commodities. Large parts of Greenland have never been subjected to detailed exploration campaigns. There is a fair chance of finding giant deposits in Greenland as a number of deposits at present is categorised as 'giants' such as the deposits: Isua, Motzfeldt Lake, Kringlerne, Skaergaard, Malmbjerg and Citronen Fjord. The present review has demonstrated that the geological environments and the related mineral deposits are in many ways similar to those found world-wide, meaning that the potential for new mineral discoveries which can sustain mining are excellent.



Aerial view of 'Hill 800 m' at the Jurassic Milne Land fossil Zr-REE placer. The deposit is located in the basal part of the 100–200 m thick laminated and cross-bedded sandstone of the Charcot Bugt Formation. The lower part consists of unconsolidated, purple heavy mineral sands, rich in garnet, ilmenite, rutile, zircon and monazite. Palaeogene flood basalts are seen at the uppermost left corner of the picture where individual beds of basalts are outlined by the snow. Milne Land, central East Greenland.



Outcrop of the rhythmically bedded, millimetre- to centimetre-thick bands of white and grey barite and dolomite forming the so-called 'zebra' baryte from Bredehorn, central East Greenland.

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Bureau of Minerals and Petroleum
(BMP)
Government of Greenland
P.O. Box 930
DK-3900 Nuuk
Greenland

Tel: (+299) 34 68 00
Fax: (+299) 32 43 02
E-mail: bmp@gh.gl
Internet: www.bmp.gl



GEUS

Geological Survey of Denmark
and Greenland (GEUS)
Øster Voldgade 10
DK-1350 Copenhagen K
Denmark

Tel: (+45) 38 14 20 00
Fax: (+45) 38 14 20 50
E-mail: geus@geus.dk
Internet: www.geus.dk

Front cover photograph

The Triassic sediments at the south side of Devondal, central East Greenland. The top of the cliff-face is at elevation 700 m a.s.l.

Authors

H. Stendal, B. M. Stensgaard & K. Secher

Editor

Karsten Secher, GEUS

Graphic Production

Carsten E. Thuesen, GEUS

Photographs

GEUS unless otherwise stated

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