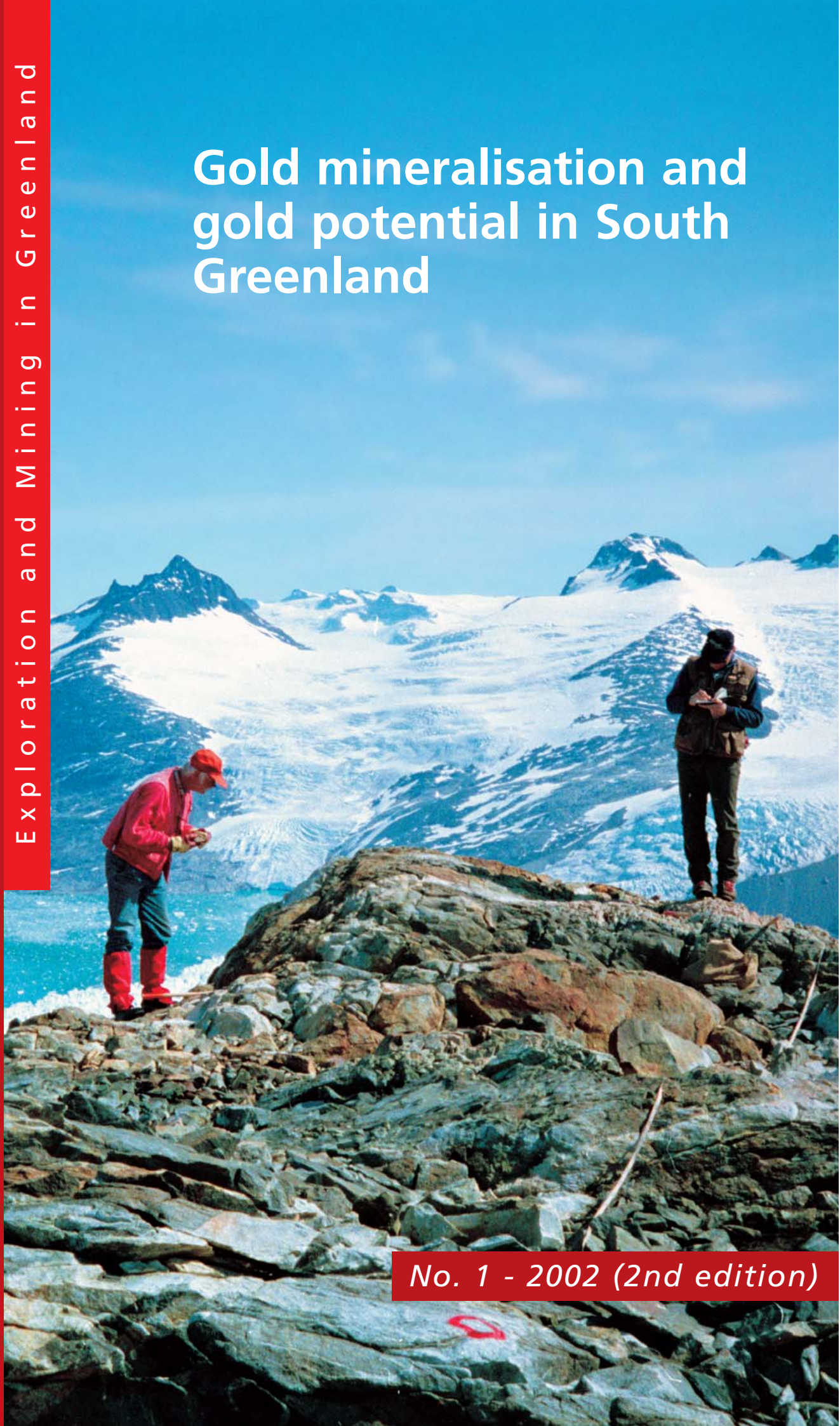
GEOLOGY AND ORE

Exploration and Mining in Greenland

Gold mineralisation and gold potential in South Greenland



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Gold mineralisation and gold potential in South Greenland

Several decades of geological mapping and exploration in South Greenland have demonstrated the existence of geological environments where gold accumulation has developed and potentials for viable gold deposits exist. During this period a number of private companies engaged in exploration activities, including field investigations and diamond drillings. The Geological Survey (GEUS) has provided systematic geological and geochemical mapping, as well as airborne geophysical surveys including radiometry, magnetometry and EM measurements. Stream sediment geochemistry analyses have been used to compile a comprehensive geochemical atlas, and geophysical maps are available in varying scales depending on locality. GEUS has issued a CD-ROM including much of the available data in geo-referenced formats including mineral occurrences. This is also available on the Internet: www.geus.dk/gmom.

Geological setting

South Greenland is dominated by the juvenile Palaeoproterozic Ketilidian orogen (1900–1750 Ma), which covers the southern tip of Greenland. The middle Proterozic Gardar province includes pronounced intrusive complexes (1300–1120 Ma) in the central part of the area. The environments for gold deposition can be grouped into several different geological scenarios:

- Archaean craton composed of high-grade gneisses serving as a basement to Palaeoproterozoic volcano-sedimentary successions
- Ketilidian Border Zone
- A magmatic arc represented by the 30,000 km^2, calc-alkaline Ketilidian Julianehåb batholith and segments of volcano-sedimentary sequences interrelated in
- The Psammite Zone south of the batholith, composed of metasediments and locally volcanic rocks that are deformed and sometimes migmatised and
- The Pelite zone located most southerly and composed of turbiditic sedimentary rocks, which are highly deformed and migmatised. The supracrustal successions are intruded by a rapakivi suite between 1755–1732 Ma.

Gold and pathfinder elements

The gold potential of South Greenland is indicated in the geochemical mapping by the distribution of high values for gold (Au) and pathfinder elements like arsenic (As) and antimony (Sb) in the fine fractions (<0.1 mm) of stream sediments. Using this information together with gold anomalies in bedrock and in heavy mineral concentrates of stream sediments, the potential for gold mineralisations currently recognised is concentrated in specific regions and smaller areas.

The most prospective areas are around the Sermiligaarsuk Fjord, at the southern margin of the Julianehåb batholith domain, and within large parts of the Psammite Zone.

Gold occurs in various settings and localities:

- **Archaean Tartoq Group greenstone**
  Sermiligaarsuk
- **Palaeoproterozoic Border Zone**
  Arsuk and Kobberminebugt
- **Julianehåb batholith**
  Qoorormiut, Niaqornaarsuk, Igutsaat
- **At the border between Julianehåb batholith and Psammite Zone**
  Kangerluluk and Sorte Nunatak
- **Psammite Zone**
  Nalunaq, Lake 410, Ippatit and Kutseq

A visit to these localities will reveal a variety of environments and mineral occurrences. They are briefly described here, with emphasis on the geological setting and including some important analytical results.

Sermiligaarsuk

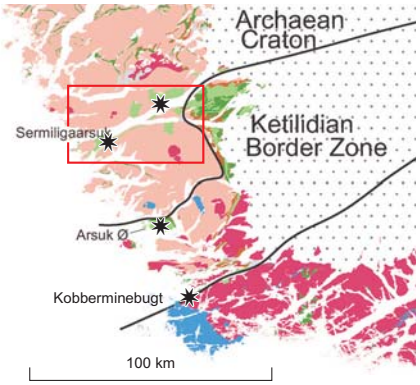
The Tartoq Group gold mineralisation is significant in two areas. Gold occurs in three principal modes within the carbonate schists:

1) In disseminated pyrite in quartz-ankerite lenses (1-2 m by 5-10 m). In the quartz association the gold occurs as inclusions (10-30 m) in pyrite grains. Other sulphides include arsenopyrite, chalcopyrite, tennantite, and chalcocite. The highest grade is 50 g/t, but typical values are 5-8 g/t and a fineness of 700-800.

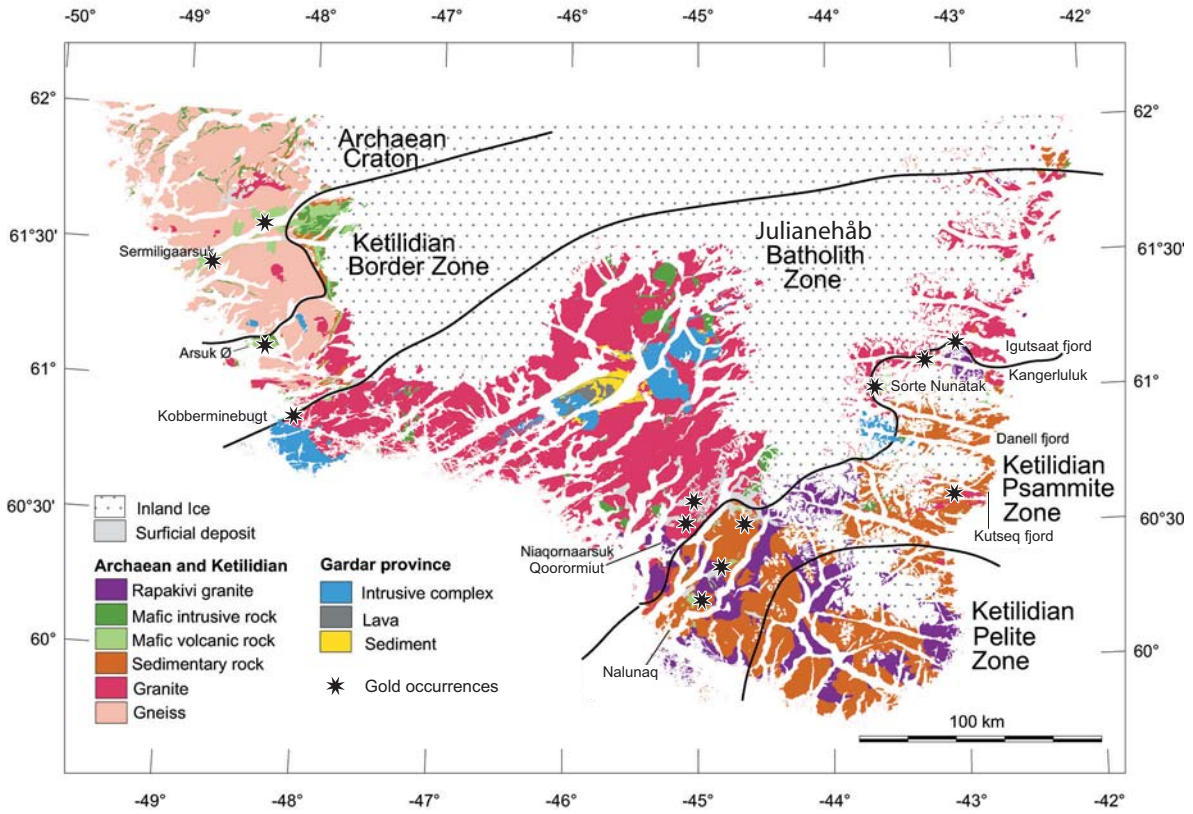
2) In pyrite associated with massive and semi-massive arsenopyrite aggregates.

3) In sulphide facies iron-formations.

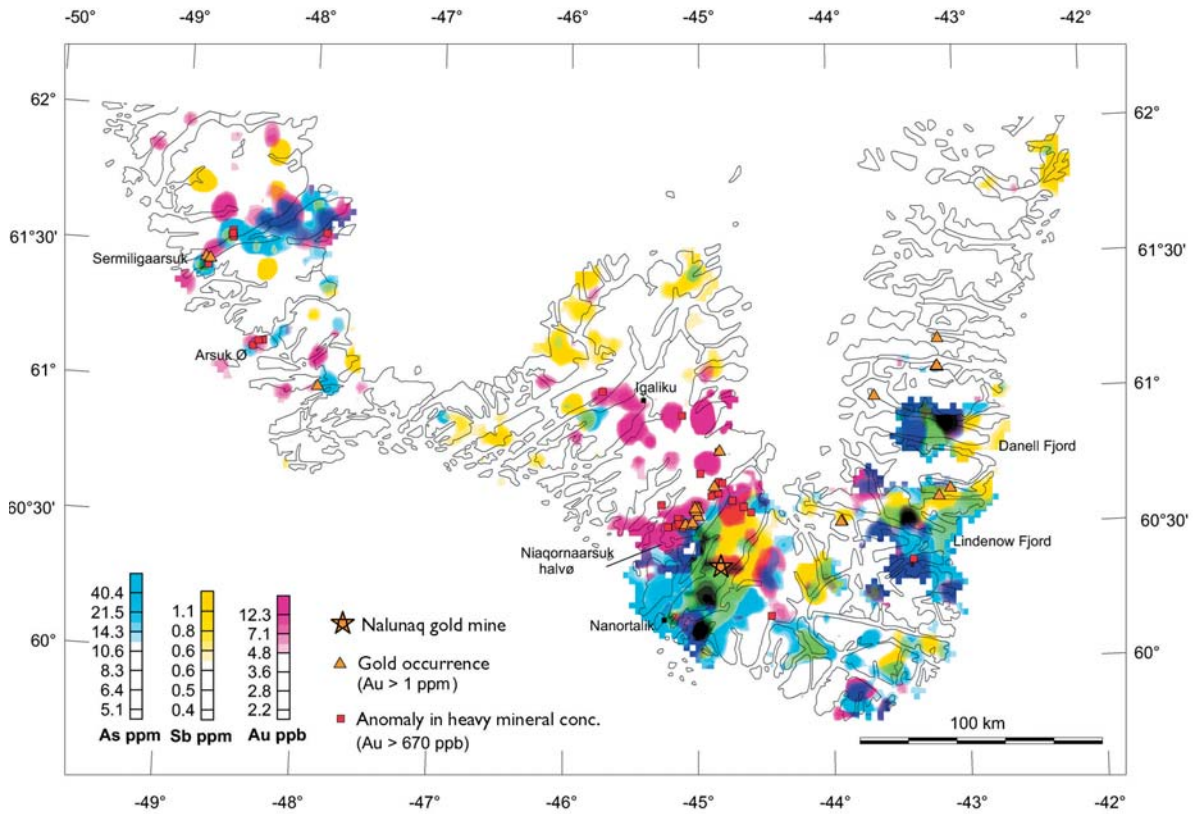
It has been suggested that gold was introduced into the Taartoq greenstones during the formation of stratiform exhalites with massive-sulphide and chert. Regional metamorphism resulted in recrystallisation and segregation of the chert into compact quartz bodies and residual massive-sulphide. Subsequent episodes of shearing and intensive carbonate alteration along the shear zones, together with pyritisation of a possible pyrrhotite-arsenopyrite assemblage from the protolith, led to the liberation and accumulation of gold and chalcopyrite along the re-crystallised grain boundaries.



Geological map around Sermiligaarsuk in South Greenland.



Geological map of South Greenland.



Gold potential of South Greenland indicated by distribution of gold, arsenic and antimony in stream sediments.

Arsuk Ø

Arsuk Ø is located within the Border Zone of the Ketilidian mobile belt. On this island there are exposed supracrustal successions of volcanics and metasediments. Bands of mafic metavolcanics, up to 300 m thick, are intercalated within the metasediments. This mixed sequence of volcanics and sediments is overlain by more than 3000 m of pillow lavas, volcanic breccias, agglomerates, tuffs and massive mafic lava flows.

A number of small mineralisations are located on Arsuk Ø. Contents of gold, zinc and copper are generally low; two settings are usually recognized:

1) rusty chert horizons in the pillow lava sequence and
2) quartz veins in the pillow lava sequence.

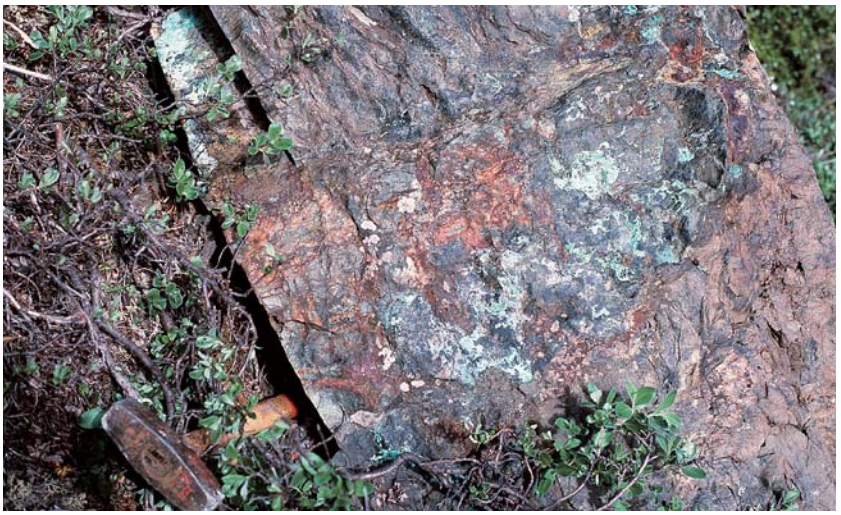
Samples show up to 300 ppb gold. The copper content reaches close to 2000 ppm in rusty metabasic rocks and Zn contents up to nearly 900 ppm are recorded in tuff within disseminated sulphides.

Kobberminebugt

The copper deposits in the Kobberminbugt were previously thought to be Ketilidian in age but some preliminary Pb isotopes of bornite suggest an early Gardar age. The region is characterised by Gardar intrusives and the northwestern border zone between the Palaeoproterozoic Ketilidian orogen and the Archaean basement complex. A vein system in a main fault and shear zone is mineralised with bornite and chalcocite. The fault plane is co-planar with the lithological interfaces in the host rocks and separates mylonitic felsitic schist in the footwall from amphibolite schist in the hanging wall. The fault zone is about 130 cm wide, but the sulphide-mineralised layer is only up to 32 cm in thickness. The bornite-chalcocite lenses have accessory ilmenite, magnetite, hematite, chalcopyrite, electrum and native copper.

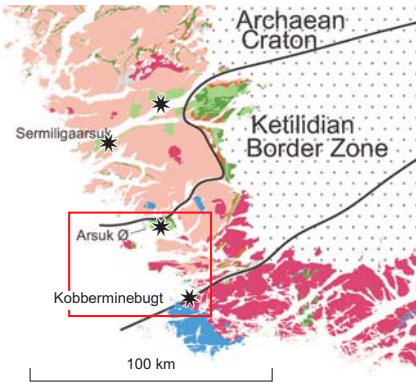
Chalcopyrite and locally bornite is disseminated (up to 5 vol % of sulphides in the greenstones hosting the ore in the area between Josva mine and Rinks Havn.

A view at the Tartoq Group greenstones (dark) with intercalations of meta-chert layers (light), hosting gold occurrences, eastern part of Sermiligaarsuk. Persons for scale.

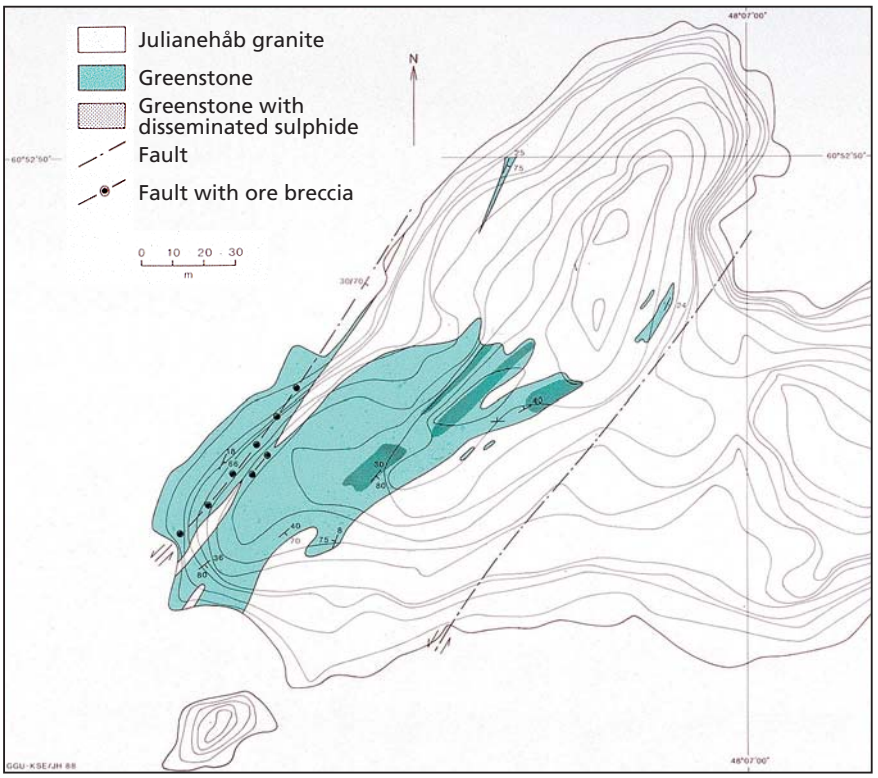


Close-up of solid pyrite-arsenopyrite layer partly malachite stained, eastern Sermiligaarsuk. Hammer head is 10 cm.

View of basic metavolcanics at Blaalershavn, eastern Arsuk Ø.



Geological map around Arsuk Ø and Kobberminebugt in South Greenland.



Detailed geological map around Josva Mine, showing location of the mineralisation.

Close-up of the Josva Mine copper vein with solid bornite. Knife for scale.

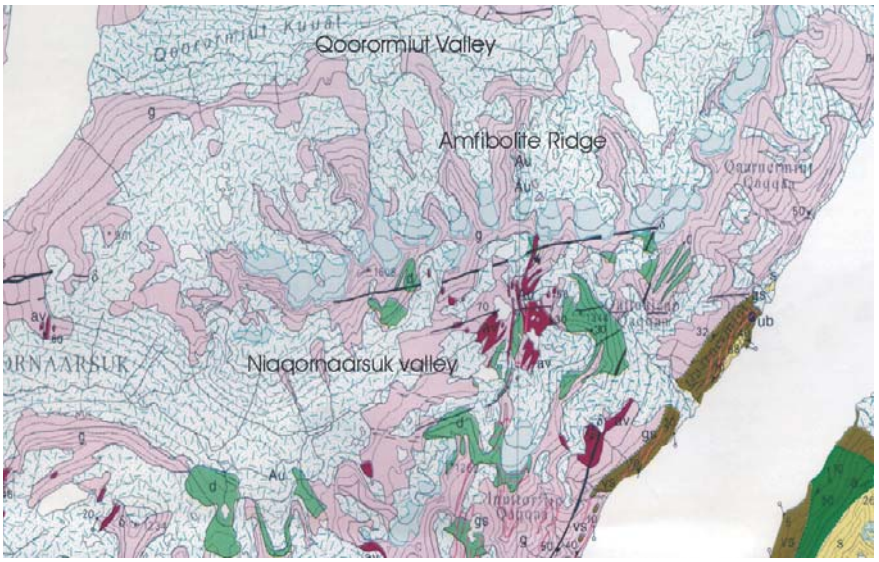
The average copper concentration in the ore vein is 3.5%, which was mined between 1904 – 1915. The ore contains up to 1.5 ppm gold and a consistently high content of up to 250 ppm silver. Total production from the Josva mine did not exceed 90 tonnes of copper extracted from 2,200 tonnes of ore with small additional amounts of gold (0.5 kg) and silver (50 kg). The size of the remaining ore body at Josva mine is estimated to be 2000–3000 tonnes of ore containing 30–40 tonnes of copper.

Qoorormiut

The gold occurrence in the Qoorormiut valley is associated with quartz veins in amphibolite dykes hosted in batholith granite. Gold occurs in quartz veins, striking NE-E and dipping steeply to the west. The veins are 0.5 – 5 m wide and discontinuous, but can be followed up to 200 m along the strike. Individual quartz veins rarely exceed 10 m in length. The youngest undeformed quartz vein is associated a hydrothermal mineral assemblage and gold-sulphide mineralisation.

Several stages of mineralisation are identified e.g. pyrite (I) + arsenopyrite (I), gold, electrum, galena, chalcopyrite, pyrite (II), and arsenopyrite (II+III). They were later followed by sphalerite mineralisation. Fluid inclusion studies show aquaceous CO_2 and CO_2-CH_4 inclusions with up to 15 mol% CH_4 in the late mineralised fluids. The gold is precipitated from the CO_2-CH_4 fluids. The temperature of formation for the mineralisation is 200–400°C and at a pressure between 0.5 and 1.5 kbar.

The gold concentration varies significantly in this type of mesothermal gold



Geological map of the Qoorormiut–Niaqornaarsuk area.

mineralisation and reaches 380 ppm in thin silicified shear zones (<1 m wide). One six-metre chip sample in a vein of milky quartz gave 114 ppm Au and a second six-metre chip sample in rusty, locally carbonated amphibolite with small quartz veinlets, gave 147 ppm Au.

Niaqornaarsuk

The gold mineralisation in the 'Niaqornaarsuk valley' and 'Amphibolite Ridge' is related to quartz veins, metabasic rocks and hydrothermally altered batholith granite of Ketilidian age, i.e. 1850-1780 Ma. The Niaqornaarsuk valley hosts two prominent types of mineralisation:

1. molybdenite quartz veins in a NE–SW striking zone
2. gold mineralisation.

The molybdenite-quartz veins do not carry significant gold (<100 ppb). This type of mineralisation occurs where shear zones and quartz veins cut amphibolites and granitoids. In the hydrothermal alteration halo, the granitoids have been subjected to bleaching, silicification, and albitisation, and contain traces of Fe-sulphides (sulphidation) and locally arsenopyrite containing 50-200 ppb Au. Rusty and altered diorite-gabbro contains 1-2 vol.% magnetite and shows up to 3400 ppb Au. The gold mineralisation in second order structures is located near the roof of the Julianehåb batholith and is characteristised by the element association Au-Bi-(As-Mo-W).

Ippatit and Lake 410

The Ippatit and Lake 410 occurrences are hosted in Ketilidian amphibolites, which

The smelting plant at the Josva Mine, 1911.

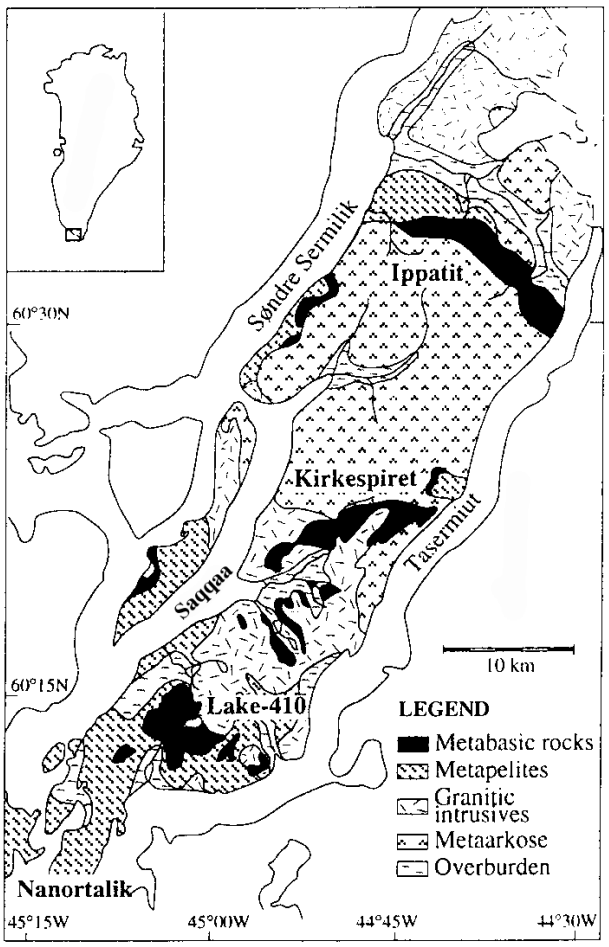
A look along the 'Amphibolite Ridge', hosting mineralised quartz veins. Mountaineers on the slope for scale.

have been interpreted to represent a suite of pyroclastic rocks, lavas, pillow lavas, and dolerites. Associated meta-sediments in the area include stratiform, rusty sulphide and graphite-rich horizons. The amphibolites host quartz veins with minor sulphides. The quartz veins are often associated with calc-silicate alterations.

The gold content is low; a rusty section of bedded chert and graphitic schist shows 20–120 ppb Au and 500–2000 ppm As, and quartz veins in meta-pelites return up to 830 ppb Au.

The host rock is considered to be part of the same sheet of meta-volcanic rocks, which also hosts the Nalunaq gold prospect at Kirkespiret (see map).Within the central Nanortalik peninsula, the amphibolite sheet has been disrupted and partly engulfed by late granite diapirs, dated to app.1805 Ma. The gold mineralised horizons at both Nalunaq and Lake 410 are located close to the roof of the granite batholith. The gold is concentrated in quartz-veined

Granodiorite, hydrothermally altered, Niaqornaarsuk.



Geological map of the Nanortalik peninsula.

amphibolite. The quartz veins are sub-concordant and contain minor sulphides, mainly arsenopyrite and chalcopyrite. At both localities the gold content has been found to be low, ranging from 20–830 ppb, and associated with As in the range 500–3000 ppm.

Nalunaq

The Nalunaq gold prospect is hosted in meta-pelites and meta-basic rocks of Ketilidian age (1850–1800 Ma) at the Nanortalik peninsula. Two major gold-bearing veins occur. They strike along a NE ductile thrust zone that dips 40° to 55° SE. The gold mineralised vein system is 1700 m long and 0.1 to 2 m wide, hosted in fine-grained mafic volcanic rocks. The mineralogical characterisation of the mineralisation classifies the deposit as a low-sulphur system consisting mainly of pyrrhotite, löllingite, pyrite, arsenopyrite, chalcopyrite, gold and electrum. Fluid inclusions in quartz veins at Nalunaq vary in composition from the predominantly aqueous saline fluids to CO_2-CH_4 aqueous mixtures. Salinities are high with 17–38 wt% NaCl. Preliminary interpretation of the fluid inclusion data suggests precipitation of gold at 525–575°C and about 2.5 kb.

The vein system is part of the development of the Ketilidian orogen with quartz veins formed in the late stages of the Julianehåb batholith formation. Pb isotopes of different mineralised occurrences in South Greenland indicate two stages of gold emplacement. A first stage is related to the Palaeoproterozoic regional deformation and metamorphism (1792–1785 Ma), during which sediment-hosted gold was epigenetically concentrated into shear zones and vein systems. The source indications for Pb in these occurrences are compatible with a juvenile c. 2000 Ma old source compatible with that of the direct supracrustal host rocks to these occurrences. The gold mineralisation is epigenetic and high-grade (average 18 g/t Au) and total resources are 1,234,000 ounces.

Visible gold in Nalunaq quartz veins.

The Nalunaq mine valley. The mining camp is located at the valley floor.

Kutseq

In the area around Kutseq fjord on the southeast coast of Greenland, mineralised amphibolite rocks are intercalated within a sequence of psammite and semi-pelitite gneiss. An arsenic-gold association is hosted in shear zones and in dykes in the amphibolites. The mineralised shear zones vary from abundant small layers, 10–20 cm thick and 10–12 m long, to large shear structures up to 12 m across and 500–600 m long.

Gold is found within occurrences of sulpho-arsenides and arsenides. Up to a few vol.% of disseminated pyrrhotite and arsenopyrite occur within the shear zones. The element contents vary significantly with Au concentrations of up to 38.5 ppm and As concentrations of up to 6%. Slightly discordant felsic dykes (10–40 cm) carry pyrrhotite and arsenopyrite. As content reaches 1.7% and Au is up to 200 ppb.

In the As-Au association, arsenopyrite geothermometry suggests precipitation temperatures for arsenopyrite-löllingite-pyrrhotite and gold at 440–560 °C. Gold is introduced during an early stage of the formation and was partly re-mobilised during cataclastic shear movements. It has been suggested that the As-Au association represents an epigentic mesothermal, lode type of gold accumulation, with genetic relations to the gold mineralisation in the Nanortalik region (see above).

Kangerluluk

The gold-bearing sulphide mineralisation is hosted in a 200–300 m thick mafic volcano-sedimentary supracrustal sequence exposed in an area of app. 4 km^2. The supracrustals rest unconformably on granites and granodiorites of the Julianehåb batholith. The supracrustal sequence is composed of four rock suites that can be grouped into the following lithofacies:

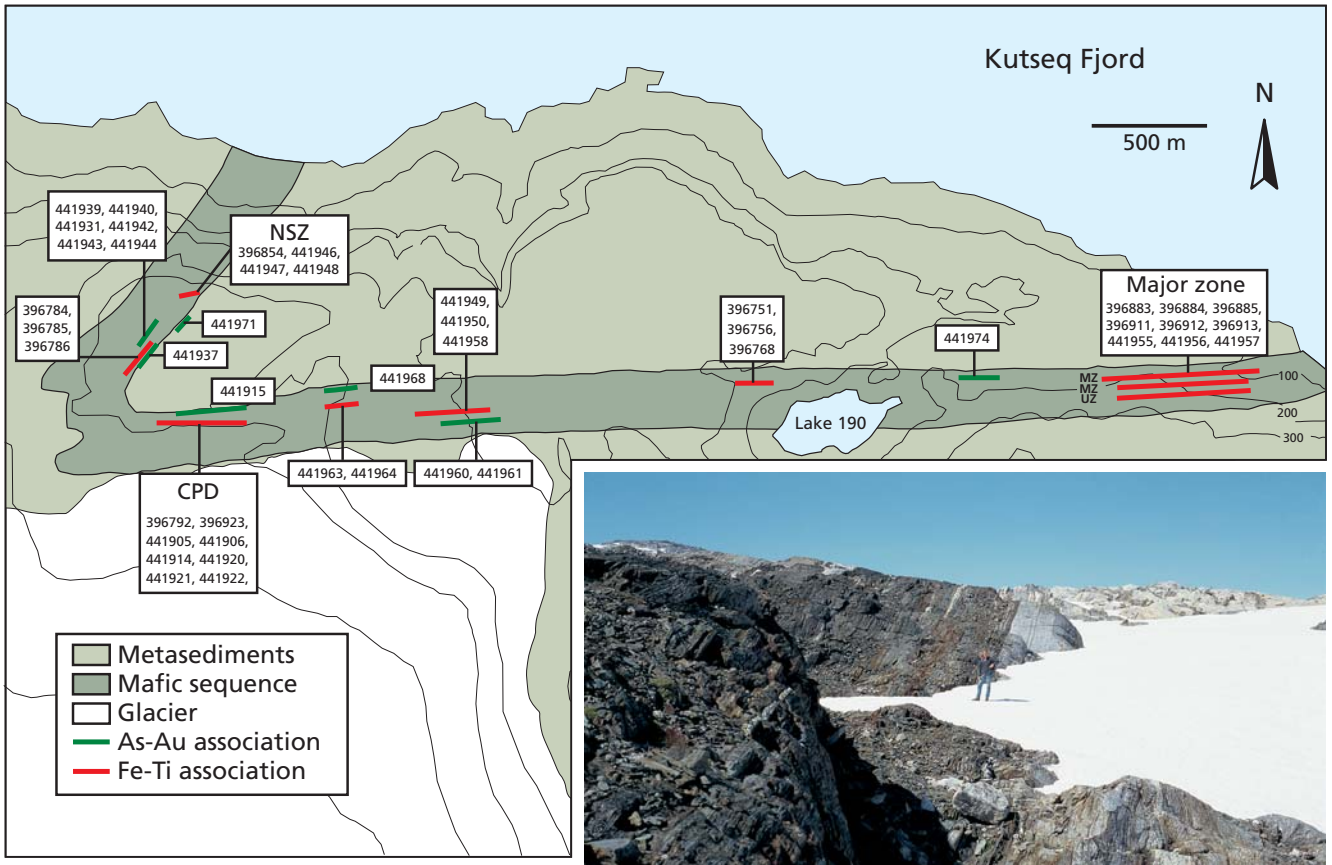
(1) conglomerate-sandstone;
(2) pyroclastics;
(3) volcanic suites dominated by pillow lavas; and
(4) a volumetrically subordinate 'pepperitic' lithofacies.

The entire sequence dips 30° to the north, is locally tightly folded, and is metamorphosed in lower amphibolite facies.

Alteration and mineralisation

Syn-volcanic alteration: The volcanic rocks were subjected to extensive, pervasive, syn-depositional hydrothermal alteration and seawater interaction. The matrix between pillows is dominated by epidote, is very CaO rich (24-30 wt.%), and shows no significant gold (20-31 ppb) or copper concentration. Pyrite - pyrrhotite are disseminated throughout the rock sequence. These are typical sulphide minerals of syn-depositional processes.

Early, post-volcanic alteration: Early Early, post-volcanic alteration assemblage and associated mineralisation is related to large faults and/or shear zones that cut the supracrustal package. The alteration is controlled by the lithology of the host



Geological map of the Kutseq area, South-East Greenland.

A view along the contact between mafic rocks and grey metasediment, Kutseq.

rock. Quartz veins occur within the sedimentary lithologies 'quartz association', and epidote-bearing minerals occur within the mafic volcanic lithologies 'epidote association'. The ore minerals related to the 'quartz association' are dominated by pyrrhotite and pyrite (up to a few vol.%). Locally massive pyrrhotite (up to 5-cm thick layers) occurs at the contacts between sediments and more massive quartz veins. Up to 40 cm wide silicified alteration halos with very high gold concentrations are associated with the quartz veins. A grab sample from such a halo contains 118 ppm Au. Chip samples from two localities gave averages of 1.1 ppm Au and 1.6 wt. % Cu over half a metre and 3.3 ppm Au and 1.6% Cu over half a metre, respectively.

Late, post-volcanic alteration: Mineralisation overprints the previously mentioned alteration and mineralisation. Most of the copper-bearing samples show between 0.1 to 1 ppm gold, except for one sample with 6.2 ppm Au and 1.8 wt % Cu.

Igutsaat

A major 5–8 m thick rusty aplite sill striking E–W, is exposed in mafic rocks surrounded by gneiss on the south side of Igutsaat Fjord. The aplite contains 1–2 vol.% of pyrite in disseminated form as well as veinlets. The aplite yields up to 1.4 ppm Au. The mineralisation is comparable to a similar appearance on the SW coast of Greenland within the Batholith Zone (Niaqornaarsuk).

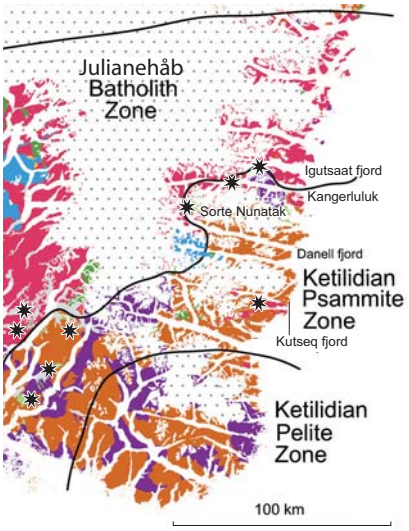
Pb-isotopes and gold emplacement

Pb-isotope studies of different mineral occurrences in South Greenland indicate two stages of gold emplacement. The first stage is related to the regional deformation and metamorphism (1792–1785 Ma), during which sediment-hosted gold was epigenetically concentrated into shear zones and veins. The second stage seems related to late hydrothermal activity. The source of Pb is possibly a mixture of juvenile Pb from the Julianehåb batholith with some contributions from the host rocks around 1780 Ma. The source indications for Pb in these gold occurrences are a reservoir, about 2000 Ma old, which is probably a mafic source because of the gold-copper association and the lack of galena. It is concluded that the initial gold mineralisation was genetically related to metalliferous fluids associated with the emplacement of late stages of the Julianehåb batholith (1800–1770 Ma) followed by local remobilisation.

Gold potential in the Palaeoproterozic

The gold occurrences in the Ketilidian Orogen are classified as 'Intrusion-related

Basic volcanic rocks with pillow structures, Kangerluluk.



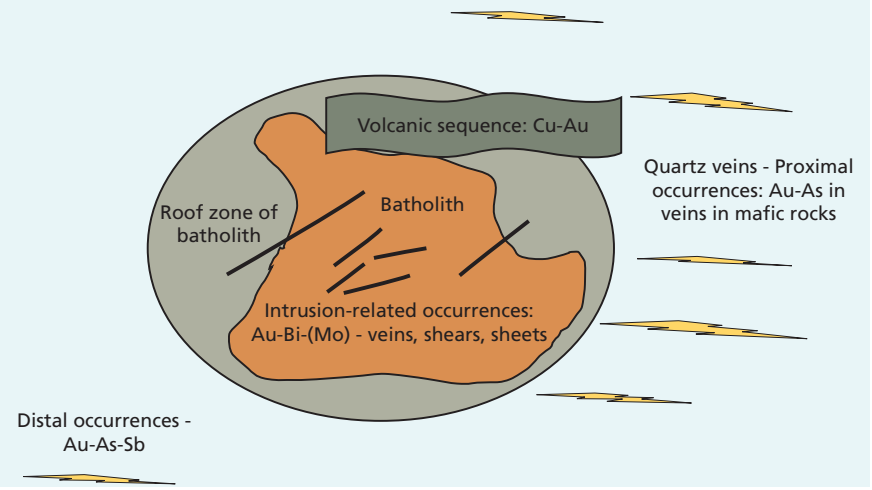
Geological map of SE Greenland.

Gold Systems'. The gold occurrences are found both within the Julianehåb batholith and outside as proximal deposits. Within the batholith, gold is associated to veins, shears, and sheets in Au-Bi-W (Mo) type of mineralisation with disseminated gold. Capping the batholith a Cu-Au association is found in mafic volcanic rocks. Proximal to the batholith are quartz veins carrying Au-As mineralisation in mafic rocks. At present these are the most promising (e.g. Nalunaq).

Concluding remarks

Gold occurrences in South Greenland have been identified within two major geological environments, the Archaean and the Palaeoproterozoic. During exploration activity in the 1980s and the 1990s, knowledge about gold formation improved and consequently the potential for locating viable gold deposits in the future has also improved. As a result of more recent exploration and research, the gold mine at the Nalunaq deposit in the southernmost part of Greenland commenced production in 2004. The Nalunaq gold deposit and the high amount of gold occurrences point to good opportunities for more gold finds in the region.

Rusty aplite sill, 5 m wide, near Igutsaat.



Schematic presentation of the ore setting in South Greenland.

The mine adit at the main level in the Nalunaq gold mine.

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Front cover photograph
Gold exploration in Ketilidian rocks, Danell fjord, SE Greenland.

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