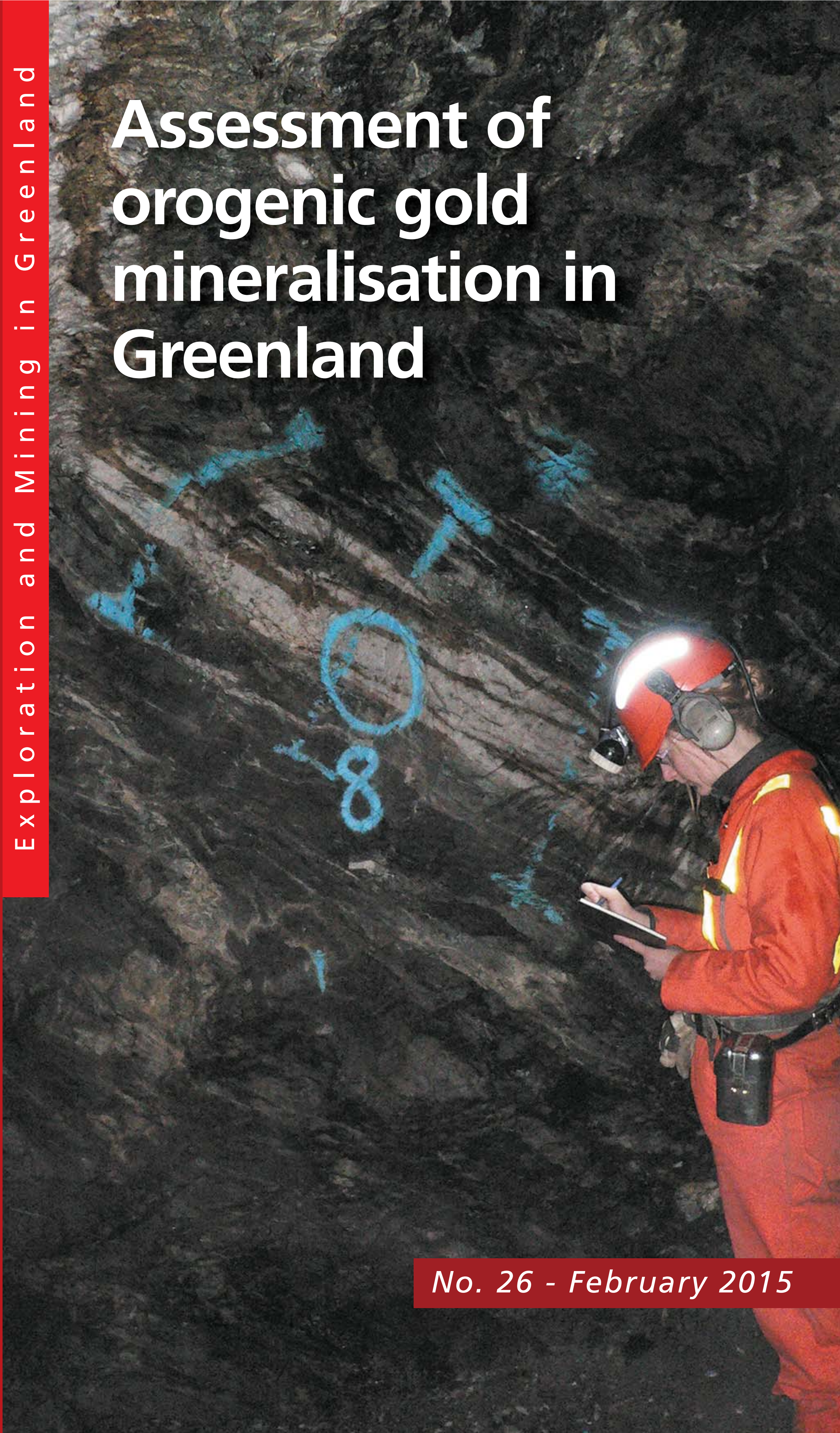
# GEOLOGY AND ORE

Exploration and Mining in Greenland



# Assessment of orogenic gold mineralisation in Greenland

No. 26 - February 2015

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***An orogenic gold deposit has been mined at Nalunaq (South Greenland) from 2004 to 2013 when the operation was closed. A total of 10.65 tons (375,670 oz) of gold was produced during that period. In order to assess the potential for undiscovered orogenic gold deposits in Greenland, a workshop in Copenhagen (November 2014) investigated geological, geochemical and geophysical data. The main conclusion was that areas of South Greenland in relative proximity to the closed Nalunaq gold mine and the Archaean terranes of southern West and South-West Greenland have the highest potential for finding new orogenic gold deposits. The highlights from this workshop are presented here.***

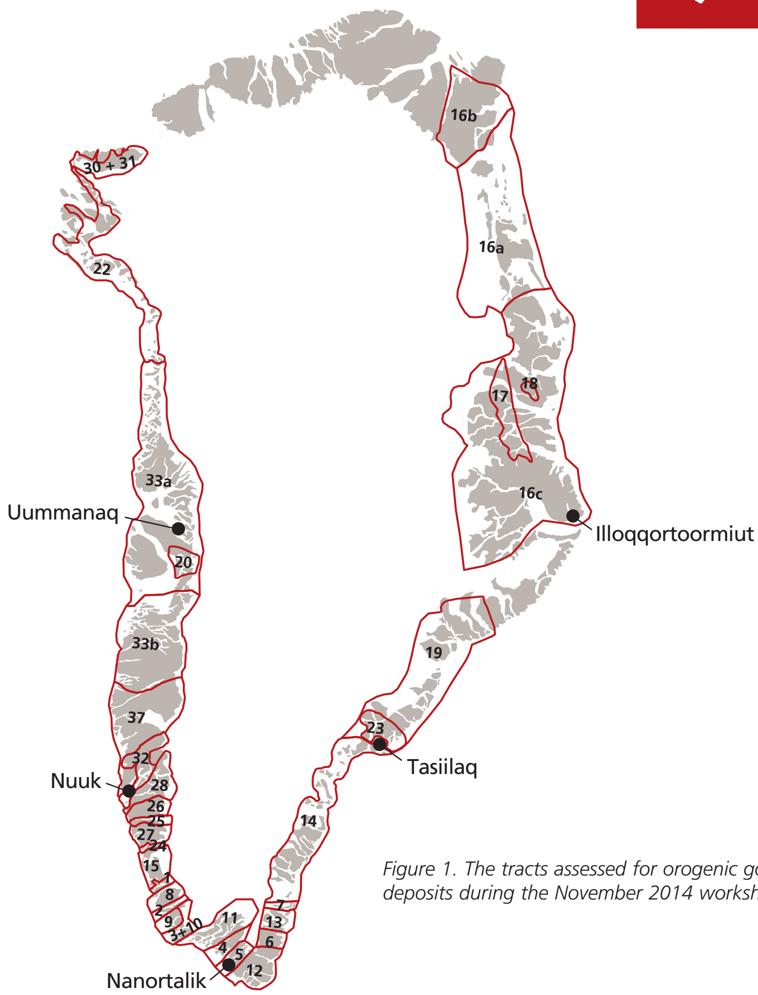


*Figure 1. The tracts assessed for orogenic gold deposits during the November 2014 workshop.*

## Introduction

Gold (Au) was probably the first metal known by mankind and has been extensively used and mined in the last 5,000 years. Gold is still the most important commodity in the mineral exploration industry, and approximately one third of the worldwide exploration investment is used to find gold deposits. Approximately half of the gold is used in jewellery and approximately one third is used as safe investment as many of the National Banks must hold a gold reserve. Only approximately 12% of the produced gold goes into industrial applications such as electronics, medicine and space craft.

The biggest current gold producers are China, Australia, USA, Russia and South Africa. Although gold is enriched in the Earth's crust by different mechanisms forming different deposit types, orogenic gold deposits constitute 40% of the world's gold resources.

In November 2014, a workshop on the 'assessment of the orogenic gold potential in Greenland' was arranged by the Geological Survey of Denmark and Greenland (GEUS) and the Ministry of Mineral Resources (MMR) - formerly Ministry of Industry and Mineral Resources to stimulate new gold exploration campaigns in Greenland. The purpose for the workshop was to assess the potential of undiscovered orogenic gold deposits in the upper 1 km of the Earth's crust and to rank the most prospective areas. The methods for the assessment and ranking of the individual tracts were designed to comply with the 'Global Mineral Resource Assessment Project' procedures defined by the US Geological Survey (USGS).

This edition of Geology and Ore highlights the main results from the workshop, including descriptions of the most important orogenic gold provinces in Greenland. A recent geological review of orogenic gold provinces in southern West and South-West Greenland is given in Kolb *et al.* (2013), and a review on gold occurrences in South Greenland can be found in Stendal & Frei (2000). Other Geology and Ore volumes covering the description of orogenic gold mineralisation are nos. 1, 9 and 11. A comprehensive GEUS report documenting all results from the workshop will be available during 2015.

## Methodology

The evaluation of the potential for undiscovered orogenic gold deposits was carried out according to the standardised process utilised in the Global Mineral Resource Assessment Project. In this process, an expert assessment panel uses all available knowledge and data for a specific region (tract) to assess the possibility of finding undiscovered deposits within this tract to a depth of 1 km (Fig. 1). The assessment panel consisted of sixteen geologists from the USGS, the Geological Survey of Finland (GTK), GEUS, MMR and private exploration and consulting companies; each with specific knowledge on relevant aspects of the Greenland geology or expertise in orogenic gold deposits. After geological presentation and discussion, the members of the assessment panel made their individual estimates (bids) of the number of undiscovered deposits they believed could be found under the best circumstances in a tract. A final discussion in the panel resulted in a consensus bid that was used as input to statistical simulation. Based on the grade-tonnage model for Proterozoic and Archaean orogenic gold deposits from Finland, Sweden and Australia recently compiled by GTK for their own assessment, this simulation provides a prediction on how much undiscovered gold ore can be expected in a specific tract.

## Orogenic gold mineralisation

Orogenic gold deposits, also referred to as lode-gold, quartz vein-hosted gold and gold-only deposits, are hydrothermal deposits formed during focussed fluid flow in an orogen during metamorphism and deformation (Fig. 2; Goldfarb *et al*. 2005; Groves *et al*. 1998). Regional reviews of orogenic gold deposits have shown that the majority formed at 1–3 kbar and 250–400°C in greenschist to lower amphibolite facies, but lower and especially higher temperature counterparts have also been recognised. These gold deposits are collectively characterised by their common structural control, and similar hydrothermal alteration (Si, K, Rb, Ba, Li, Cs, Tl, S, $H_2O$, $CO_2$ enrichment) and metal (Au-Ag ± As, Sb, Te, W, Mo, Bi) association (Table 1). The gold is hosted in quartz-vein systems, hydrothermal alteration zones and altered mylonites in shear- and fault-zone systems.

The genetic concept is the crustal continuum model that describes orogenic gold deposits, which formed at different *P–T* conditions equivalent to lower greenschist to lower granulite facies levels over an interval of 20–25 km in the middle to upper crust (Fig. 2; Goldfarb *et al*. 2005; Groves *et al*. 1998). It proposes the syn-metamorphic upward migration of auriferous fluids from deep-seated sources along structural conduits such as shear and fault zones. Differences in *P–T* conditions of orogenic gold formation have been used to subdivide the deposits into epizonal (150–300°C, 0.5–1.5 kbar), mesozonal (300–475°C, 1.5–3 kbar), and hypozonal (475–700°C, 3–6 kbar). Phanerozoic orogenic gold deposits formed in accretionary orogens such as the North American Cordillera in fore-arc to back-arc settings. Although other genetic models are also discussed in academia, this does not affect the key parameters of the gold mineral system (Table 1). The critical and important factors of the orogenic gold mineral system are an active pathway for hydrothermal fluids, the fluid throttle and the site of gold deposition. In geological terms these are: (1) long-lived, polyphase shear and fault zones at continental margins that transect the lithosphere; (2) complex, smaller-scale deformation zones that are spatially associated with permeability barriers and rocks of contrasting competency; and (3) heterogeneous host rocks with a large chemical gradient or chemically reactive rocks that would be in disequilibrium with the ore fluid.

The largest orogenic gold deposits are the Golden Mile deposit in Western Australia with 1,800 tons Au and the Hollinger-McIntyre deposit in Ontario, Canada with 987 tons Au (Table 1). The tonnage of orogenic gold deposits varies largely between a few thousand tonnes to more than several hundred million tonnes of ore (Fig. 3). Historically, the average grade of orogenic gold deposits has been *c*. 5–15 g/t (equiv. to ppm) Au until the start of the new century. Since then cut-off

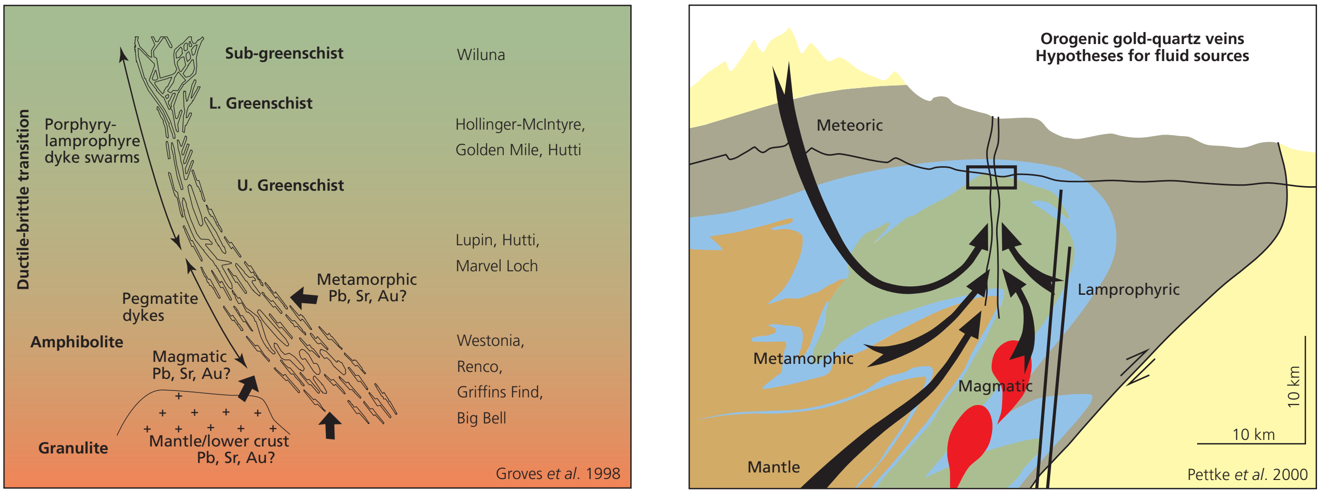


*Figure 2.* ***Left:*** *Schematic sketch of the crustal continuum model for orogenic gold deposits, illustrating a crustal-scale shear zone focussing auriferous fluids from different sources. Major examples of the typical orogenic gold deposits are given.* ***Right:*** *Sketch of possible fluid migration paths in an orogenic setting. Gold mineralisation occurs in shear zones and folded metamorphosed wall rocks, often in higher order structures close to the main terrane boundary.*

## Economic and geological characteristics of orogenic gold deposits

| | | |
|---|---|---|
| ***Economic characteristics*** | | |
| Typical size | A few thousand tonnes to > 100 Mt | |
| Typical grade | 5 to 15 g/t, lower in recent open pit or large-scale operations | |
| Greenland | Nalunaq: 714,000 t at 15 g/t Au | |
| International | Golden Mile: 119 Mt at 10.7 g/t Au<br>Hollinger-McIntyre: 101 Mt at 9.9 g/t Au<br>Barberton: 27 Mt at 10.7 g/t<br>Homestake: 148 Mt at 10.7 g/t<br>Fäboliden: 90 Mt at 1 g/t | |
| ***Geological characteristics*** | | ***Assessment criteria*** |
| Tectonic context | Accretionary orogen, Archaean granite-greenstone belts | Orogenic setting |
| Age | Neoarchaean (2.74–2.54 Ga),<br>Palaeoproterozoic (2.1–2.0 and 1.91–1.77 Ga),<br>Neoproterozoic (700–600 Ma),<br>Silurian to Carboniferous (430–300 Ma),<br>and Cretaceous to early Palaeogene (120–50 Ma) | Terrane age was used where data was available |
| Structure | Terrane boundary, major crustal-scale shear zone | Major shear zone (if data available) |
| Metamorphism | Mainly greenschist facies and lower amphibolite facies | Greenschist facies and amphibolite facies, also retrograde from granulite facies |
| Lithology | Metamorphic, often chemically reactive and heterogeneous metamorphic rocks | Chemically reactive rocks and heterogeneous sequences as additional positive argument |
| Alteration | Mainly localised tens of metres-scale halo around auriferous zones, including carbonates, sulphides, micas and amphiboles | Alteration halo as additional positive argument (if data available) |
| Geochemistry | Si, K, Rb, Ba, Li, Cs, Tl, S, $H_2O$, $CO_2$ enrichment | Not used |
| Metal association | Au-Ag ± As, Sb, Te, W, Mo, Bi | Anomalies in stream sediment and whole-rock data (where available) |

*Table 1. Main characteristics and assessment criteria for orogenic gold deposits.*

grades decreased due to increasing gold prices and currently even deposits with less than 1 g/t Au on average are mined in places. Orogenic gold deposits are gold-only deposits producing generally no other commodity. The lower-grade examples are mined in open pit operations, whereas the often high-grade nature of this type of deposit makes them a primary target for underground operations, and also a target for artisanal mining in many developing countries. The Nalunaq deposit in South Greenland has been mined from 2004–2013 and 10.65 tons Au from c. 714,000 tons of ore at a grade of 15 g/t Au have been produced, which is average in tonnage but slightly higher in gold grade when compared with orogenic gold deposits worldwide (Fig. 3).

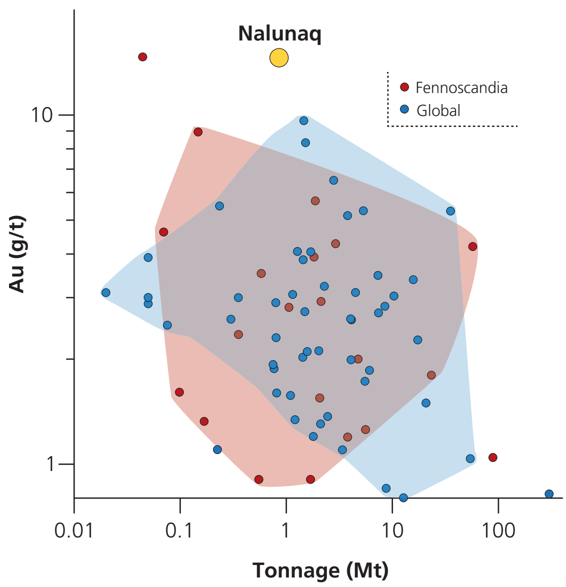


*Figure 3. Diagram plotting ore grade (Au in g/t) against the proven amount of ore (tonnage in million tons (Mt)) of the Nalunaq gold deposit and selected orogenic gold deposits from Scandinavia (Fennoscandia) and elsewhere (global). These data were used in the model for the statistical calculations. Courtesy of GTK. The Nalunaq gold deposit has comparable tonnage to the deposits in the model, suggesting that the model is able to correctly characterise Greenlandic deposits.*

*Table 2. Summary of consensus bids from the November 2014 assessment workshop.*

| Tract name | Tract Area (km²) | Consensus bid on the number of undiscovered orogenic gold deposits at different confidence levels | | | | | Summary statistics | | |
|---|---|---|---|---|---|---|---|---|---|
| | | N90 | N50 | N10 | N05 | N01 | Number of unknown deposits | Deposit density | Mean estimate of undiscovered orogenic gold (metric tons) |
| 1 | 702 | 1 | 2 | 4 | 7 | 10 | 3 | 3.6 | 44 |
| 2 | 866 | 2 | 5 | 7 | 11 | 13 | 5 | 5.7 | 87 |
| 3+10 | 1,543 | 0 | 1 | 2 | 4 | 6 | 1 | 0.8 | 22 |
| 4 | 1,961 | 0 | 0 | 2 | 3 | 5 | 1 | 0.4 | 14 |
| 5 | 2,078 | 4 | 6 | 10 | 16 | 23 | 6 | 3.5 | 110 |
| 6 | 787 | 0 | 2 | 3 | 4 | 5 | 2 | 2.3 | 32 |
| 7 | 205 | 0 | 0 | 0 | 1 | 3 | 0 | 0.7 | 3 |
| 8+9+15+26+27 | 12,277 | 0 | 0 | 2 | 5 | 7 | 1 | 0.1 | 15 |
| 11 | 4,367 | 0 | 0 | 1 | 2 | 3 | 0 | 0.1 | 7 |
| 12 | 4,402 | 1 | 2 | 4 | 6 | 8 | 2 | 0.5 | 41 |
| 13 | 635 | 0 | 0 | 0 | 1 | 3 | 0 | 0.2 | 2 |
| 14 | 7,967 | 0 | 0 | 2 | 4 | 6 | 1 | 0.1 | 15 |
| 16a | 19,297 | 0 | 2 | 10 | 20 | 50 | 6 | 0.3 | 96 |
| 16b | 14,985 | 1 | 2 | 3 | 5 | 10 | 2 | 0.2 | 40 |
| 16c | 65,921 | 1 | 3 | 8 | 16 | 36 | 5 | 0.1 | 91 |
| 17+18 | 7,715 | 2 | 4 | 8 | 12 | 20 | 5 | 0.7 | 92 |
| 19 | 8,728 | 0 | 1 | 2 | 4 | 6 | 1 | 0.1 | 23 |
| 20 | 2,344 | 2 | 4 | 5 | 8 | 10 | 4 | 1.6 | 67 |
| 22 | 5,733 | 0 | 1 | 2 | 5 | 7 | 1 | 0.2 | 24 |
| 23 | 3,238 | 0 | 0 | 2 | 4 | 6 | 1 | 0.3 | 13 |
| 24 | 543 | 0 | 0 | 2 | 3 | 5 | 1 | 1.4 | 13 |
| 25 | 751 | 0 | 0 | 2 | 2 | 4 | 1 | 0.9 | 12 |
| 28 | 5,191 | 0 | 0 | 2 | 3 | 6 | 1 | 0.1 | 14 |
| 30+31 | 5,206 | 0 | 1 | 3 | 6 | 9 | 2 | 0.3 | 29 |
| 32 | 5,211 | 4 | 7 | 11 | 20 | 33 | 8 | 1.6 | 150 |
| 33a | 29,440 | 0 | 2 | 6 | 11 | 15 | 3 | 0.1 | 55 |
| 33b | 25,338 | 0 | 0 | 2 | 3 | 5 | 1 | 0.1 | 12 |
| 37 | 16,892 | 0 | 1 | 3 | 5 | 7 | 2 | 0.1 | 28 |

*N90, N50, N10, N05, N01 = Confidence levels; a measure of how reliable a statistical result is, expressed as a percentage that indicates the probability of the result being correct. A confidence level of 10% (N10) means that there is a probability of 10% that the result is reliable. Deposit density = The total number of deposits per 1000 km².*

## Undiscovered orogenic gold deposits

A total of 28 tracts have been assessed for undiscovered orogenic gold deposits. They have been defined on the 1:500 000 scale geological map of Greenland, based on geological knowledge, geochemical anomalies and known gold occurrences (Figs 1 and 4). Only tracts that fulfil at least one of the critical assessment criteria for orogenic gold have been chosen (Table 1) and extracted as geo-referenced polygons. The consensus bids on the number of undiscovered orogenic gold deposits are summarised in Table 2. The 28 tracts cover an area of 254,324 km² in total.

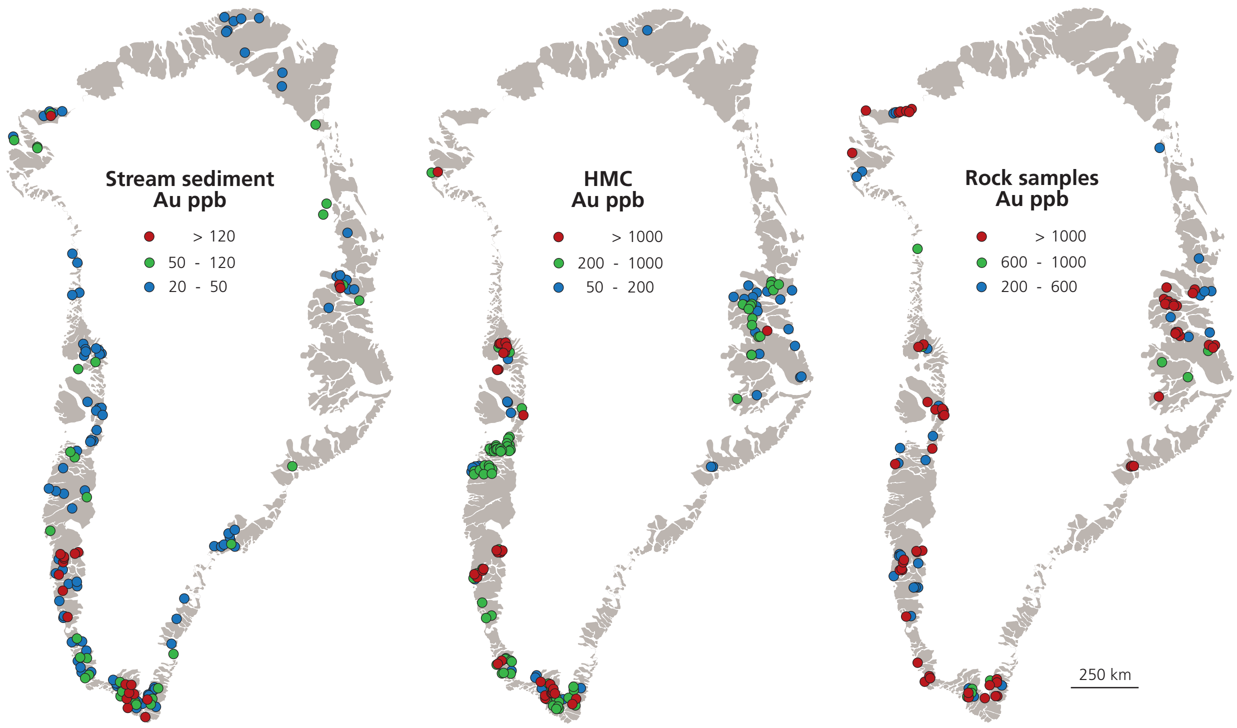


*Figure 4. Geochemical gold anomalies in various sample sets from localities in Greenland. The most prospective areas for orogenic gold deposits are represented in southwestern and southern Greenland. Anomalies in northwestern and eastern Greenland are related to other types of gold deposits.* ***Left:*** *Stream sediment samples with Au > 20 ppb.* ***Centre:*** *Heavy mineral concentrates (HMC) with Au > 50 ppb collected by GEUS, Nordisk Mineselskab A/S and NunaMinerals A/S.* ***Right:*** *Rock samples collected by GEUS and Nordisk Mineselskab A/S with Au > 200 ppb.*

## Tartoq gold province

The Tartoq gold province (Tract 2) in South-West Greenland was ranked as the area with the highest prospectivity for orogenic gold deposits in Greenland in terms of tract size (Table 2). This was based on the number of known orogenic gold occurrences and prospects, and the favourable geology including a major greenschist facies shear-zone system in an Archaean orogenic setting (Kolb 2011, Kolb *et al*. 2013). Reasonably sized Archaean greenstone belts host two orogenic gold prospects with widespread chlorite-ankerite-pyrite alteration (Fig. 5), a typical feature observed in giant orogenic gold provinces elsewhere (e.g. Golden Mile and Hollinger-McIntyre). Mineral exploration in the late 1980s and early 1990s focussed on the Nuuluk and Iterlak occurrences, however using a volcanic-hosted massive sulphide mineralisation model. The drilling campaign was not able to identify larger sulphide orebodies and was therefore stopped. Hence, the full potential for orogenic-style gold mineralsation remains untested.

- **Nuuluk:** Gold is hosted in quartz-ankerite veins in four 0.5 m wide, parallel tabular zones. These zones form a 350 to 400 m wide and 4 to 5 km long NNE-trending, moderately WNW-dipping hydrothermally altered zone. The quartz-ankerite veins contain as much as 50 ppm Au in grab and drill-core samples. The host rocks are mainly magnetite- and graphite schist with a typical mesozonal alteration zone of ankerite, chlorite, quartz, pyrite, arsenopyrite, pyrrhotite, chalcopyrite, tennantite and gold. Locally, ultramafic rocks contain talc, serpentine, fuchsite, dolomite as hydrothermal alteration assemblage.

- **Iterlak:** Banded quartz-pyrite rocks host the gold mineralisation up to >5 ppm at Iterlak, which was initially interpreted as syngenetic exhalative sulphide mineralisation. The sulphides and gold, however, replaced magnetite-grunerite-quartz banded iron formation in two NNE-trending, approx. 100 m wide and 200 to 400 m long zones. Hydrothermal alteration in the wall rocks is muscovite, quartz, ankerite, pyrite and chlorite. Talc-carbonate schist has a talc-ankerite-chlorite-pyrite alteration assemblage.

- **Amitsuarsua:** Amitsuarsua is a relatively large (*c.* 12 km long and up to 4 km wide) greenstone belt, which is only poorly investigated. Gold mineralisation of as much as 1 ppm is hosted in zones of carbonate alteration, silification and sulphidation.

- **Other areas:** In the Tartoq gold province, there are also smaller areas of greenstone that show hydrothermal alteration for several hundred metres along strike, surrounding foliation-parallel laminated quartz veins. They are only poorly investigated, but have the potential to host gold mineralisation.

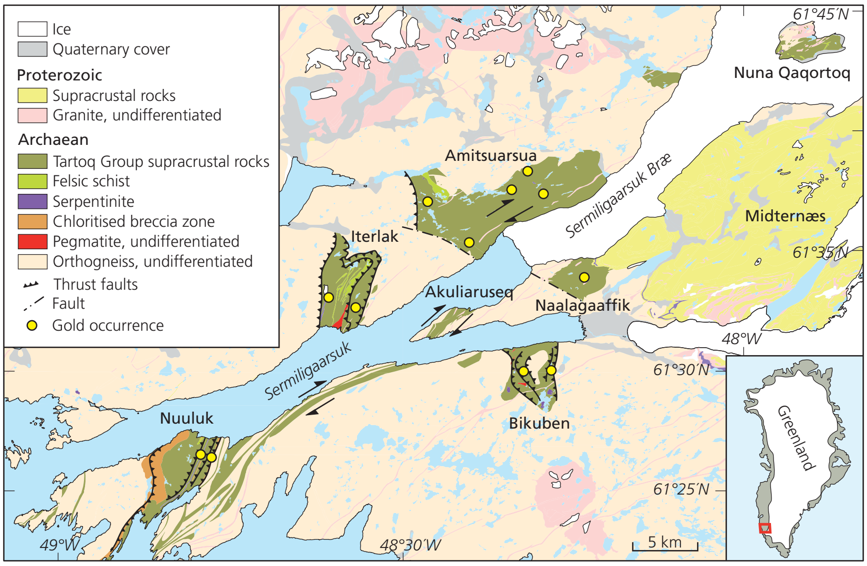


*Figure 5.* ***Top:*** *Geological map of the Tartoq gold province showing the Nuuluk and Iterlak prospects and other gold occurrences in the greenstone belts.* ***Left:*** *Finely laminated banded iron formation at Iterlak with grey iron-oxide and white quartz-rich layers. This is the host rock of orogenic gold mineralisation at Iterlak.*

*Figure 5.* ***Right:*** *Iron-stained mineralisation at Nuuluk. The rusty red colouration stems from weathering of pyrite in the auriferous hydrothermal alteration zones. The strong lamination of the host rock is a result of deformation in a shear zone associated with gold mineralisation.*

## Paamiut gold province

The Paamiut gold province (Tract 1) in South-West Greenland was ranked as the area with the second highest prospectivity for orogenic gold deposits in terms of tract size (Table 2). The Paamiut gold province is characterised by amphibolite facies greenstones, major retrograde shear zones in the lower amphibolite facies and abundant late-tectonic granites in an Archaean orogenic setting (Kolb 2011, Kolb *et al*. 2013). The area has attracted only limited exploration, although stream sediment samples record a pronounced gold anomaly. Four gold prospects have been identified during field work and exploration (Fig. 6).

- **Akuliaq:** Limited exploration has been carried out on the Akuliaq peninsula, identifying up to 12 ppm Au in hydrothermal alteration zones and up to 4 ppm in quartz veins. Auriferous quartz veins form lenses in foliation-parallel, NE-trending, 2–4 km long shear zones. They are generally 2–20 cm wide, although a few reach 20 m in width. Amphibolite is the primary host rock and developed a quartz, hornblende or orthoamphibole, biotite, tourmaline, pyrrhotite, arsenopyrite and, locally, garnet, and muscovite alteration assemblage that is characteristic for the transition between mesozonal and hypozonal conditions.

- **Mellembygden:** Laminated quartz vein sets with 10–20 m spacing and 30 to 50 cm thickness can be followed over 3–5 km along strike. The shear zones are developed at the contact between amphibolite and orthogneiss. One grab sample returned as much as 2.6 ppm Au. No systematic exploration has been carried out to map the extent of the mineralisation. Hydrothermal alteration assemblages contain epidote, tourmaline, carbonate, titanite, pyrite and chalcopyrite in addition to hornblende, biotite, muscovite, quartz, and the sulphides in orthogneiss.

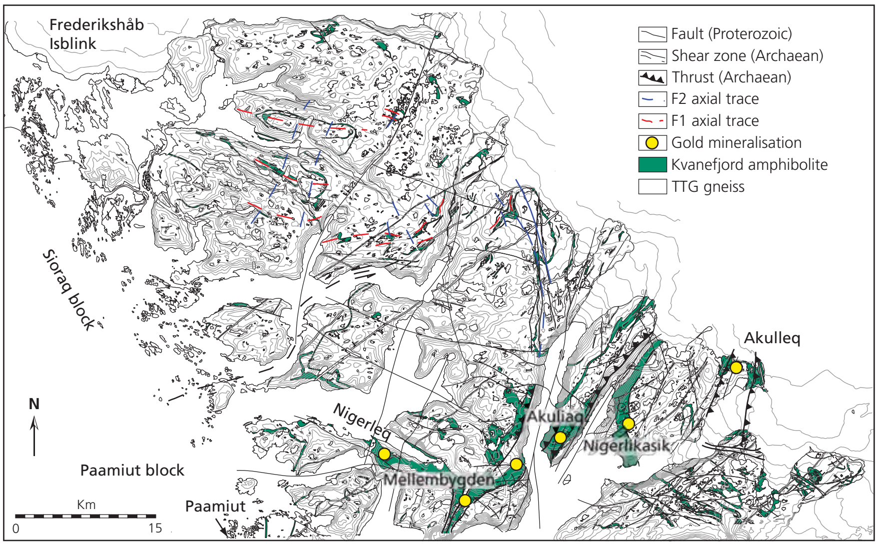


*Figure 6.* ***Top:*** *Geological map of the Paamiut gold province showing the basic geology and gold occurrences.* ***Bottom:*** *Geologist working on a section across an auriferous structure in Mellembygden.*

- **Nigerlikasik:** At Nigerlikasik, quartz veins range in thickness from a few millimetres to as much as 3 m for 30 m along strike. Although analyses of grab samples only returned gold values in the higher ppb-range, quartz veins and hydrothermal alteration assemblages are similar to the auriferous structures on Akuliaq. No exploration programme has been designed to identify a possible gold mineralisation.

- **Akulleq:** At Akulleq, hydrothermal quartz veins are common, but they are cut by later structures and have been metamorphosed. The mineral assemblage in quartz vein halos is quartz, plagioclase, clinopyroxene, garnet, chalcopyrite, arsenopyrite and pyrrhotite, indicating the higher metamorphic conditions reaching granulite facies in the wall rocks. Quartz in the veins is recrystallised and gold may have been remobilised. This area is scientifically interesting, but may not be the best exploration target, due to metamorphic and tectonic overprint.

## South Greenland gold province

The Nalunaq gold deposit that was mined from 2004–2013 is located in this gold province north of the Nanortalik settlement. Tract 5 covers an area around the closed mine, which is known for several gold occurrences and has attracted mineral exploration in the last years (Figs 1 and 7). Gold and arsenic (As) anomalies in stream sediment samples are widespread (Fig. 4). Tract 6 encompasses the eastern extension of tract 5 and is also known for Au and As anomalies, and several gold occurrences and prospects (Figs. 1, 4 and 7; Stendal & Frei 2000). Both tracts are located in the Palaeoproterozoic Ketilidian orogen at the contact of an arc batholith-like granite-gneiss terrane (Julianehåb batholith) to the north, and a possible fore-arc terrane of accreted meta-sedimentary and meta-volcanic rocks to the south. Although no major structure was mapped along this contact and geophysical methods do not show a significant anomaly, the gold occurrences cluster around this contact. In the same geological setting, the Phanerozoic orogenic gold deposits of the circum-Pacific rim are located (Goldfarb *et al.* 1998). Based on the favourable geological setting and timing, the gold anomalies and known occurrences, both tracts were rated very prospective for orogenic gold mineralisation.

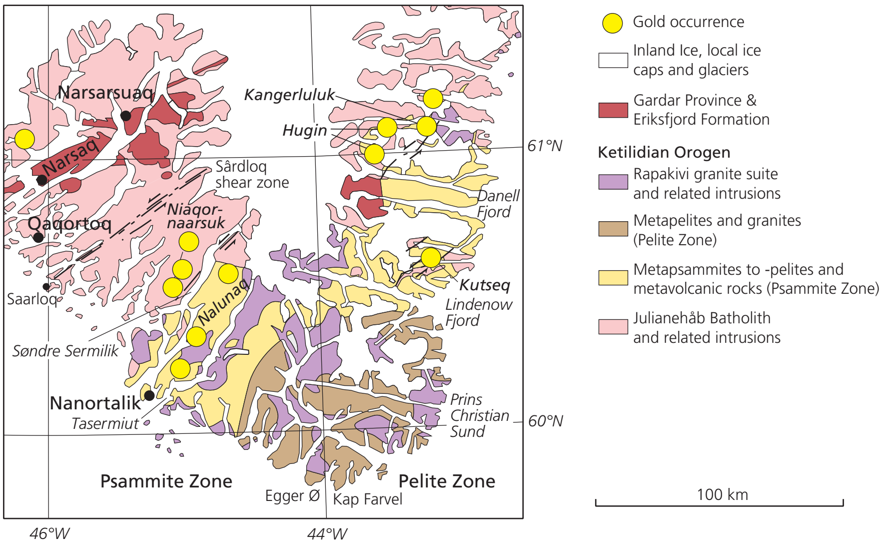


*Figure 7. **Top:** Geological map of the South Greenland gold province showing the Nalunaq gold deposit and the other prospects. **Centre:** Underground photograph from the Nalunaq gold mine showing the auriferous quartz vein crosscutting the greenish calc-silicate or skarn alteration. The quartz vein is approx. 40 cm wide. **Bottom:** Large (1–2 mm) visible gold grains in quartz of the auriferous quartz vein. Gold is closely associated with the dark minerals due to reaction between the hydrothermal fluid and the minerals (clinopyroxene).*

- **Nalunaq gold deposit:** Gold mineralisation is hosted in laminated quartz veins in a reactivated reverse shear zone. Several different descriptions of the hydrothermal alteration assemblage exist in the literature about a calc-silicate (clinopyroxene-garnet-plagioclase) alteration in the host rock amphibolite (Bell & Kolb 2013; Kaltoft *et al.* 2000; Stendal & Frei 2000). Recent investigations proved that this calc-silicate or skarn alteration formed pre-mineralisation and was overprinted by the auriferous quartz veins (Fig. 7). The hydrothermal alteration assemblage consists of biotite, quartz, rutile, arsenopyrite, tourmaline, gold, löllingite, Bi-sulphosalts, scheelite and maldonite. The current idea is that the orogenic gold mineralisation overprinted earlier skarn alteration in the middle amphibolite facies and formed at *c.* 1790 Ma during Palaeoproterozoic orogeny.

- **Vagar gold prospect (Niaqornaarsuk):** The Vagar prospect on the Niaqornaarsuk peninsula consists of approx. 20 gold occurrences, each with gold-contents in the ppm range. The occurrences cluster around a NE-trending dextral shear zone (Stendal & Frei 2000). The best target to date (Amphibolite Ridge, Fig. 8) is characterised by 1-4 m wide auriferous quartz vein sets with a minimum strike and down-dip continuity

*Figure 8. Panorama view of the Amphibolite Ridge, part of the Vagar gold prospect. (looking due south). Quartz-veins are outcropping on the left (east) side of the ridge in the saddle (centre of image). Potassic-feldspar altered granitoids are seen in the foreground (Copyright SRK 2012).*

of 600 m and 300 m, respectively. Grab, channel and diamond core samples return very high gold grades (nunaminerals.com). Auriferous quartz veins and alteration zones are hosted in amphibolite and granodiorite to granite gneiss. The hydrothermal alteration assemblage is K-feldspar, quartz, muscovite, chlorite, titanite, calcite, pyrite, chalcopyrite, Bi-tellurides, Bi-sulphosalts, gold and bismuth.

- **Hugin gold prospect (Kangerluluk, Sorte Nunatak):** A larger, *c.* 20 m wide shear-zone system is mineralised with gold and copper in quartz veins, and the occurrences at Kangerluluk and Sorte Nunatak are probably connected via this shear zone (nunaminerals.com; Stendal & Frei 2000). The auriferous quartz veins have a quartz, biotite, chlorite, chalcopyrite, pyrrhotite, gold, bornite, chalcocite alteration halo. Grab samples contain as much as 120 ppm Au and 4 wt% Cu. Channel samples returned 3.1 metres at 9.3 ppm Au. The high copper grades originate from copper sulphides that occur as lenses in the shear zone. This is explained by an orogenic gold overprint of a previous volcanic-hosted massive sulphide mineralisation in the metamorphosed basaltic host rock.

## Ataa gold province

The Ataa gold province (Tract 20) is situated north and east of Ataa in the north-eastern Disko Bay area (Fig. 1). Two Archaean greenstone belts, the amphibolite facies Saqqaq–Itilliarsuk and the greenschist facies Ataa–Eqi belts, are separated by the Torsukattak shear zone and host three orogenic gold occurrences (Fig. 9; Garde *et al*. 1999; Stendal *et al*. 1999).

Based on criteria such as Archaean age, metamorphic grade, gold occurrences and geochemical anomalies, this area was ranked as one of the most prospective for orogenic gold deposits in Greenland. However, the area was overprinted by Palaeoproterozoic orogeny that possibly deformed and remobilised the Archaean mineralisation.

- **Saqqaq:** Gold mineralisation is hosted in the strongly silicified Saqqaq shear zone, separating serpentinite and laminated amphibolite from overlying garnet-mica schist. The mineralisation is tabular, 2–5 m wide and *c.* 1200 m long. Gold grades are 1.8–4.2 ppm Au and on average 1 ppm over 2.5 m. Higher-grade zones occur in the shear zone along strike with as much as 11.4 ppm Au over 2.2 m.

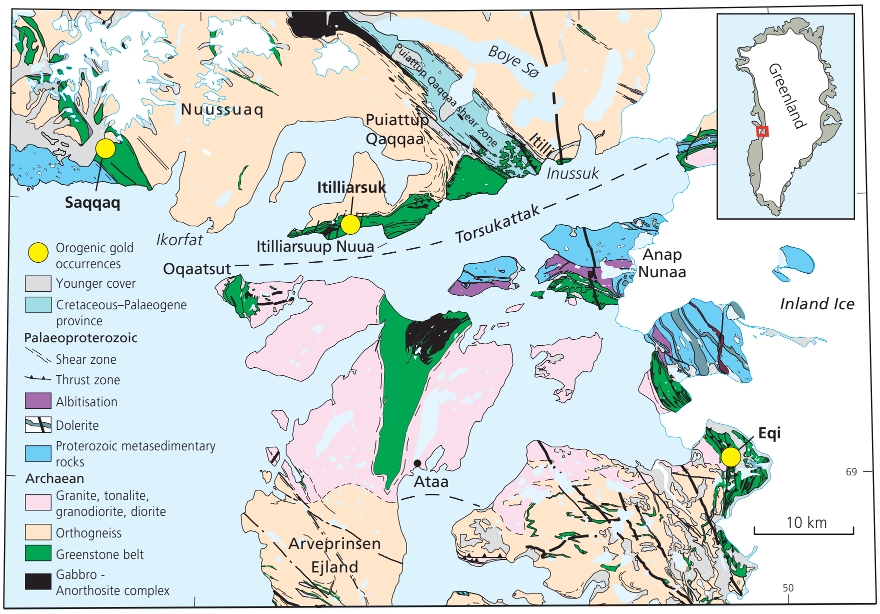


*Figure 9. Geological map of the Ataa gold province.*

Hydrothermal alteration is quartz, garnet, fuchsite, biotite, chlorite, actinolite, titanite, tourmaline, pyrrhotite, arsenopyrite, gold, niccolite, wolframite and scheelite.

- **Itilliarsuk:** Near-vertical shear zones host discontinuous auriferous quartz veins in various host rocks ranging from banded iron formation and amphibolite to biotite schist. Six auriferous zones with maximum strike length of 500 m contain as much as 15.1 ppm Au over 2.8 m in channel samples.

- **Eqi:** Gold mineralisation occurs at the contact between metamorphosed basalt, komatiite and felsic volcanic rocks. The contact is characterised by a 100–200 m wide hydrothermal alteration zone consisting of ankerite, chlorite, fuchsite, tourmaline and pyrite as a typical mesozonal alteration assemblage. Centimetre-wide quartz veins are ubiquitous, locally forming brecciae. The proximal sulphide assemblage is pyrrhotite, pyrite, chalcopyrite, sphalerite, bismuth, bismuthinite, arsenopyrite and gold. As much as 12 ppm Au over 3.2 m in a channel sample is recorded.

## Godthåbsfjord gold province

The Godthåbsfjord gold province (Tract 32) in southern West Greenland was estimated to host most possible orogenic gold deposits in Greenland, but at a lower density (Table 2, Fig. 1). The positive evaluation was based on the number of known orogenic gold occurrences and prospects and the favourable geology including a major shear zone in an Archaean orogenic setting. The panel compared the geology and orogenic setting to the similar Southern Cross domain in Western Australia that hosts 45 mines (closed and in operation).

The Godthåbsfjord gold province is an area, where several Archaean terranes assembled during Neoarchaean orogenies (Fig. 10). A major shear-zone system, the

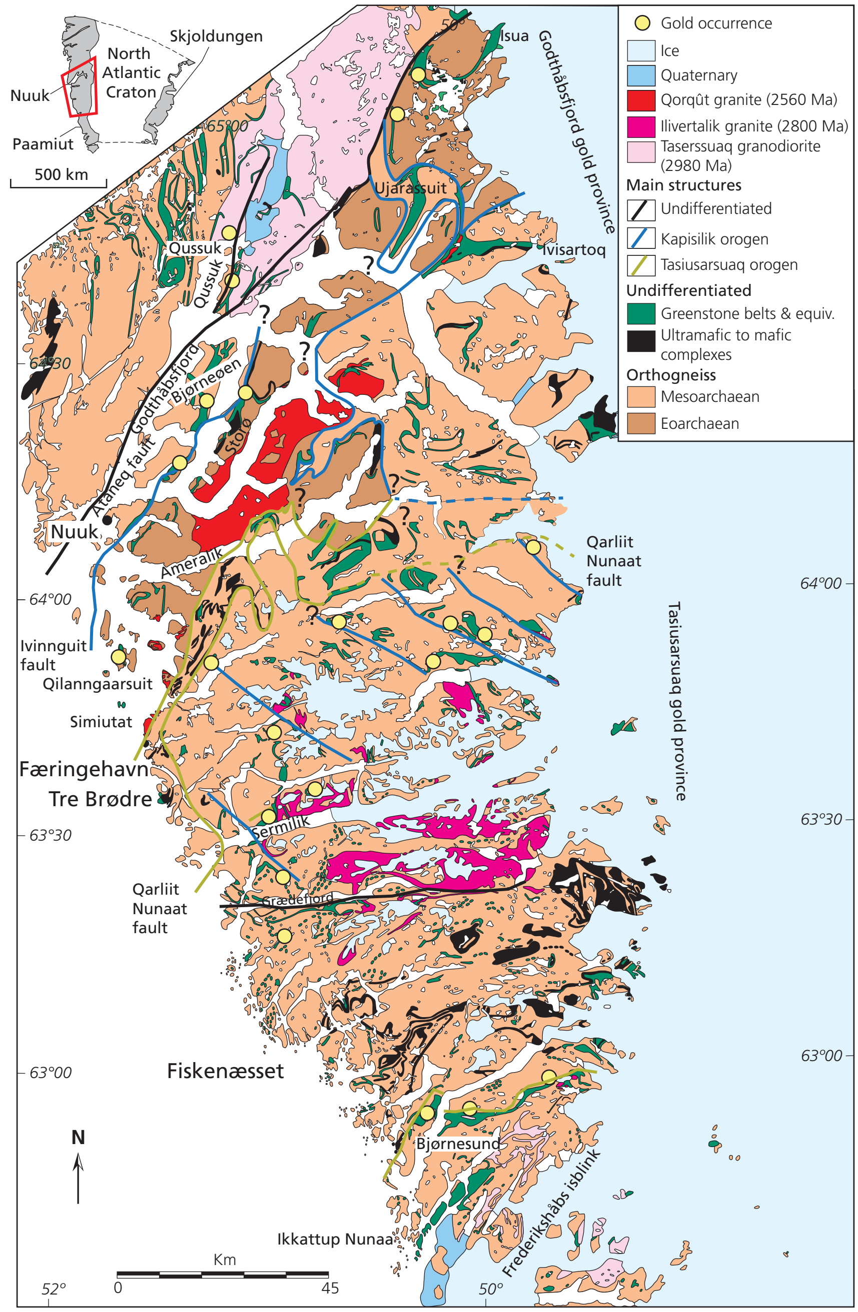


*Figure 10. **Top:** Geological map of the Godthåbsfjord gold province showing the various prospects and gold occurrences. **Facing page:** Visible gold and pyrrhotite in a quartz vein; drill core from the Storø prospect.*

Ivinnguit–Ataneq fault, formed by retrograde amphibolite facies shearing, cutting orthogneiss and greenstone belts. Four orogenic gold occurrences, Qilanngaarsuit, Bjørneøen, Storø and Qussuk, have been explored to varying extent and investigated scientifically. Reviews of research and exploration activity are given in Kolb *et al.* (2009, 2010, 2013). Numerous gold occurrences and anomalies are known from the area defined by Tract 32.

- **Qilanngaarsuit:** Gold is hosted in laminated quartz veins and hydrothermal alteration zones in as much as 8 m wide zones in a regional-scale synclinal

fold structure. The mineralisation can be followed for several hundred metres along strike with elevated gold contents of up to 0.8 ppm Au in grab samples. The hydrothermal alteration assemblage is hypozonal and consists of garnet, quartz, plagioclase, biotite, sillimanite, pyrrhotite, chalcopyrite and gold.

- **Bjørneøen:** Gold mineralisation occurs in magnetite-quartz veins in *c.* 160 m long and 1.8 m wide zones close to a fold hinge, probably forming a saddle reef geometry. As much as 4 ppm Au is found in grab samples. Hydrothermal alteration halos are hypozonal and characterised by garnet, quartz, biotite, actinolite, chlorite and pyrite. A metamorphosed volcanic-hosted massive sulphide occurrence is found in the near proximity.

- **Storø:** The Storø gold deposit has been drilled extensively in two prospects, Qingaaq Mountain and Aappalaartoq. At Qingaaq Mountain, gold is hosted in laminated quartz veins in a saddle reef geometry in the Main Zone and the BD Zone. Hydrothermal alteration zones with lenses of quartz veins and laminated quartz veins are 10 to 50 m wide. The hypozonal assemblage consists of garnet, quartz, plagioclase, biotite, sillimanite, pyrrhotite, chalcopyrite, orthoamphibole, gold, löllingite, sphalerite, molybdenite, tellurides, ilmenite, local K-feldspar and diopside. The BD Zone is 9 m wide with up to 20 g/t Au over 2.5 m, and the Main Zone contains up to 50 g/t Au over 2 m with wider sections of 60 m at 2.9 g/t Au in surface channel samples. Approx. 65% of the gold is recoverable by gravity means and more than 90% with additional cyanide treatment.

- **Qussuk:** The Qussuk gold prospect forms a 20 km-long and 1 to 3 km wide zone with ≤ 0.6 m wide quartz veins surrounded by 1 to 2 m wide biotite-dominated alteration zones. The hypozonal alteration assemblage consists of quartz, hornblende, garnet, tourmaline, epidote, muscovite, pyrrhotite, gold and chalcopyrite. Gold grades in diamond core, channel and grab samples range between 1 and 22 g/t in veins and alteration zones. Channel samples yield up to 21.7 g/t Au over 1.5 m and drill core intersections 12.6 g/t Au over 1.1 m.

## Other interesting target areas

The Archaean Bjørnesund and Sermilik orogenic gold occurrences are located in Tracts 24 and 25, respectively (Figs 1 and 10). Although they record gold in quartz veins in the ppm-range, the overall geology of these tracts in the Tasiusarsuaq gold province has been rated less prospective than the Archaean tracts described above.

Greenland has orogens that formed during the most prospective eras for orogenic gold globally (Table 1), including Neoarchaean orogens, Palaeoproterozoic orogens and the Caledonian orogen in eastern Greenland. The level of geological knowledge and data varies greatly for these generally prospective areas. Individual orogenic gold occurrences are described from Tracts 19 and 22, but our understanding of these Archaean terranes is poor. No orogenic gold occurrences are known from the Palaeoproterozoic Nagssugtoqidian, Rinkian and Inglefield Land orogens (Tracts 14, 19, 22, 23, 30, 31, 33, 34, 37; Fig. 1), which may be related to their generally high-metamorphic grade. However, in particular the Rinkian and Inglefield Land areas are poorly investigated. The Caledonian orogen has not been examined for orogenic gold occurrences, although it has all the ingredients that would make it a prospective area, including greenschist facies metamorphism, large shear-zone systems, syntectonic granite intrusions and few orogenic gold occurrences in a Caledonian thrust system (Harpøth *et al*. 1986).

*Panoramic view of Aappalaartoq on Storø seen from Qingaaq Mountain to the northeast. A number of gold prospects are located in a 12 km² area between the two mountain ranges. Copyright MMR.*

## Concluding remarks

Greenland is regarded as very prospective for orogenic gold deposits in its Neoarchaean, Palaeoproterozoic and Palaeozoic orogens. The potential ranges from prospects where drill targets can be defined with relatively little effort to greenfield targets in poorly known areas. The assessment resulted in the definition of very prospective tracts in South Greenland in proximity to the closed Nalunaq gold mine and at several other localities in western Greenland. All areas of high prospectivity are close to settlements with access to good infrastructure and ice-free waters.

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**Front cover photograph**

*Geologist mapping a stope wall in the Nalunaq gold mine underground operation. The auriferous quartz vein is composed of several parallel laminae, dipping moderately to the southwest. The rusty red colour is iron-staining and stems from sulphide weathering. The dark host rock (amphibolite) also shows internal banding parallel to the auriferous vein, representing compositional variation.*


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