DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 2005/8

Greenland geological environments and mineral resources

Henrik Stendal, Karsten Secher, Bo Møller Nielsen,
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GEOLOGICAL SURVEY OF DENMARK AND GREENLAND
MINISTRY OF THE ENVIRONMENT

G E U S

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GEUS

Abstract

The main geological environments in Greenland and their mineral resource have been described and divided into four main geological environments such as infracrustal regions, supracrustal regions, magmatic provinces, and sedimentary basin regions. Within the various geological environment characteristic mineral deposits are outlined.

Within the infracrustal environment, not many mineral occurrences are recorded in Greenland but three types are mentioned: Gold in gneiss, nickel and copper in mafic intrusions, and olivine in ultramafic rocks.

The supracrustal rocks include metasedimentary rocks, metavolcanics and banded magnetite-quartzite formation. Special attention is given to the mafic metavolcanic rocks because of their high rate of mineral potential, not least with gold and base metal deposits. These deposits are often related to greenstone belts with mafic volcanics or mixed mafic volcanic and sedimentary rocks. Other mineral occurrences than gold are iron, copper, chromium, tungsten, as well as industrial minerals.

The mineral occurrences in the magmatic environment are the porphyry system related to Palaeogene alkalic intrusion in East Greenland and associated vein systems with gold and silver; veins related to the Caledonian granite and the Julianehåb batholith, which carries tungsten, arsenic, antimony, and gold; the alkaline intrusions in the Gardar province have niobium, tantalum, zirconium, rare earth elements, and cryolite; carbonatite with niobium, tantalum, apatite and kimberlite-lamproite with diamonds are located within the Kangerlussuaq region of West Greenland.

Many of the globally known mineral occurrence types in sedimentary environments also occur in Greenland. Examples are copper in sandstones in Neoproterozoic and Triassic clastic sediments; lead and zinc in shale/carbonate sequences are widespread in the sedimentary basins; a fossil placer represents a placer deposit and celestite an evaporite deposit; lead-zinc veins in sediments occur in the Mesters Vig area including the now closed Blyklippen Pb-Zn mine, East Greenland.

The aeromagnetic data responses of different geological environments yield valuable information on both the primary geological settings and subsequent geological events. The data can be used on a regional scale, but can also be used at smaller scales when descriptions and interpretations of processes related to specific environments or mineral occurrences/mineralizing events are required.

On a regional scale, aeromagnetic data from infracrustal environments will often reflect the deformation and metamorphic history. In general, prograde granulite facies conditions result in heterogeneous higher magnetic anomaly levels than regions at lower metamorphic grade. Large-scale structures and tectonics crosscutting or separating infracrustal environments will in many cases be represented as abrupt changes and/or lineaments in anomaly patterns.

Supracrustal lithologies are in most cases characterized by low magnetic anomaly levels. Strongly magnetic rocks, especially ultrabasic/ultramafic lithologies, result in high magnetic level, local short-wavelength anomalies.

The aeromagnetic responses of magmatic provinces depend mainly on the composition of the magmatic rock. The shape and outline of an intrusion is in most cases derivable from the aeromagnetic responses. The magnetic anomaly levels of extruded basalts are in many cases dominated by the polarity of the Earth's field at the extrusion time.

Rocks from non-metamorphosed sediment depositional environments contain in most cases only a small amount of magnetite. Consequently, such environments are characterized by relatively low and smooth level of magnetic anomaly responses, indicating the thickness of the sediments.

Introduction

The aim of this report is to give an overview of the main geological environments in Greenland and elucidate the mineral resource possibilities within such environments. The main geological environments of Greenland are defined as:

- Infracrustal regions
- Supracrustal regions
- Magmatic regions
- Sedimentary basin regions

The infracrustal and supracrustal regions consist of the Archaean and Palaeoproterozoic basement in Greenland. The infracrustal rocks within the crust (below the weathering surface) consist mainly of gneiss, tonalitic and granitic rocks of Archaean and Palaeoproterozoic age. A smaller proportion of the basement is mafic to ultramafic rocks, which is no more than 1% of the exposed area.

Supracrustal rocks are an integrated part of the basement rocks. In this context rocks older than 1600 Ma. Later metamorphic and deformation events have folded the supracrustal rocks together with the gneisses. The supracrustal rocks include metasedimentary rocks, metavolcanics and banded magnetite-quartzite formations. Special attention is given to the mafic metavolcanics (greenstone belts) because of their considerable mineral potential, not least with gold and base metal deposits. Archaean and Palaeoproterozoic supracrustal rocks are in many parts of the world (e.g. Canada, Australia) prosperous for Archaean lode gold deposits and for volcanic-hosted massive sulphides (VHMS). These deposits are often related to greenstone belts with mafic volcanics or mixed mafic volcanic and sedimentary rocks. Compared to Canada and Australia the greenstone belts in Greenland are smaller and more fragmentary, though differences in definition plays a role for their conceived extents.

The magmatic environment is represented in all periods of the evolution of the crust. In this context, it is the aim to define magmatic provinces and not small individual intrusions, and only important *magmatic provinces* are charcterised and described. In magmatic deposits associated with mafic rocks both sulphides and oxide ores are common. Magmatic sulphide ores are thought to form because of droplets of an immiscible sulphide-oxide liquid forming within silicate magma and then becoming concentrated in a particular location. Certain elements, notably the transition metals Fe, Co, Ni, Pd, Pt, Rh, Ru, Ir, and Os together with Cu and Au, partition strongly into the sulphide-oxide liquid, and thus become concentrated with it (Naldrett 1989). For ore deposits associated with silicic magmas the origin and evlution can be subdivided in three stages:

1. The origin of the silicic magma;
2. Intrusion and fractionation processes;
3. Volatile evolution and separation (Whitney 1989).

Various types of ore deposits are spatially and temporally related to silicic magmas such as porphyry systems, skarn deposits, volcanic epithermal deposits, and exhalative massive sulphide deposits.

A sedimentary environment can be erosional or depositional. In this report depositional environment is the main issue and is characterized in terms of physical (mechanical), biological and chemical deposits making up sedimentary sequences. The focus will be on sedimentary sequences that are part of a regional sedimentary basins. Sedimentation involves physically and chemically derived mineral matter from sources external to the basins or from chemical or physical processes within basins. The ore-forming processes include mechanical mineral concentrations, synsedimentary mineral precipitates, diagenesis and epigenetic formations with metal sources that are internal and/or external to basins (Eidel 1991; Force 1991). The synsedimentary deposits are placers, iron, evaporites, and metalliferous black shales. The diagenetic type is copper in sandstones, which however by some authors are recognised as synsedimentary. The epigenetic deposits are the shale or carbonate-hosted Zn-Pb+Ba and base metal veins within the sedimentary basin.

The description and modelling of the most typical deposit for respective geological environment are also included in this report. The description is not a record of all mineral occurrences in Greenland but should be thought of as illustrative examples of what are to be expected within a certain geological environment.

The characteristic geophysical signature of the geological environments is outlined. The focus is on the aeromagnetic responses of different geological environments. Although gravity, electromagnetic, radiometric and seismic carry relevant information, their responses will not be addressed here. The data in the examples are taken from geophysical surveys carried out by GEUS unless otherwise stated.

The objectives of the geological environment descriptions, which are the base of this report, will in the near future provide the base for, the outlining of metallogenetic provinces, and based on these assessments and recommendations of potential areas for mineral deposits within the various geological environments in Greenland.

Geological environments

The main geological environments in Greenland and their mineral resource have been described and divided into four main geological environments such as infracrustal regions, supracrustal regions, magmatic provinces, and sedimentary basin regions.

The various geological environments have a variety of mineral occurrences. A number of mineral occurrences are described under the specific environment heading (Table 1; Fig. 3). The descriptions are put into a format slightly modified from the occurrence descriptions found in (Stendal *et al.* 2004). The individual descriptions of the deposits can be found in the Appendix as data sheets.

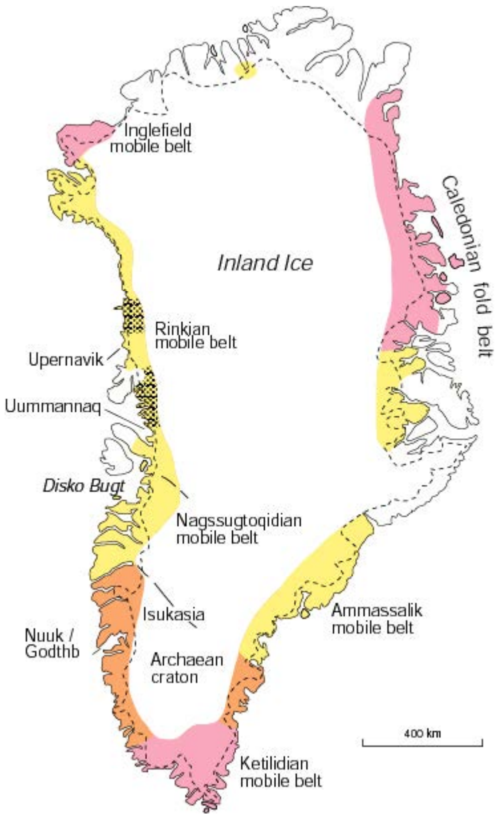


Figure 1. *Simplified map of the distribution of Archaean and Palaeoproterozoic basement provinces in Greenland (modified after Henriksen et al. 2000). Orange: Archaean craton; yellow: Reworked Archaean – dotted = Palaeoproterozoic supracrustal rocks; Pink: Mainly juvenile Palaeoproterozoic rocks. White: Younger formations.*

Infracrustals

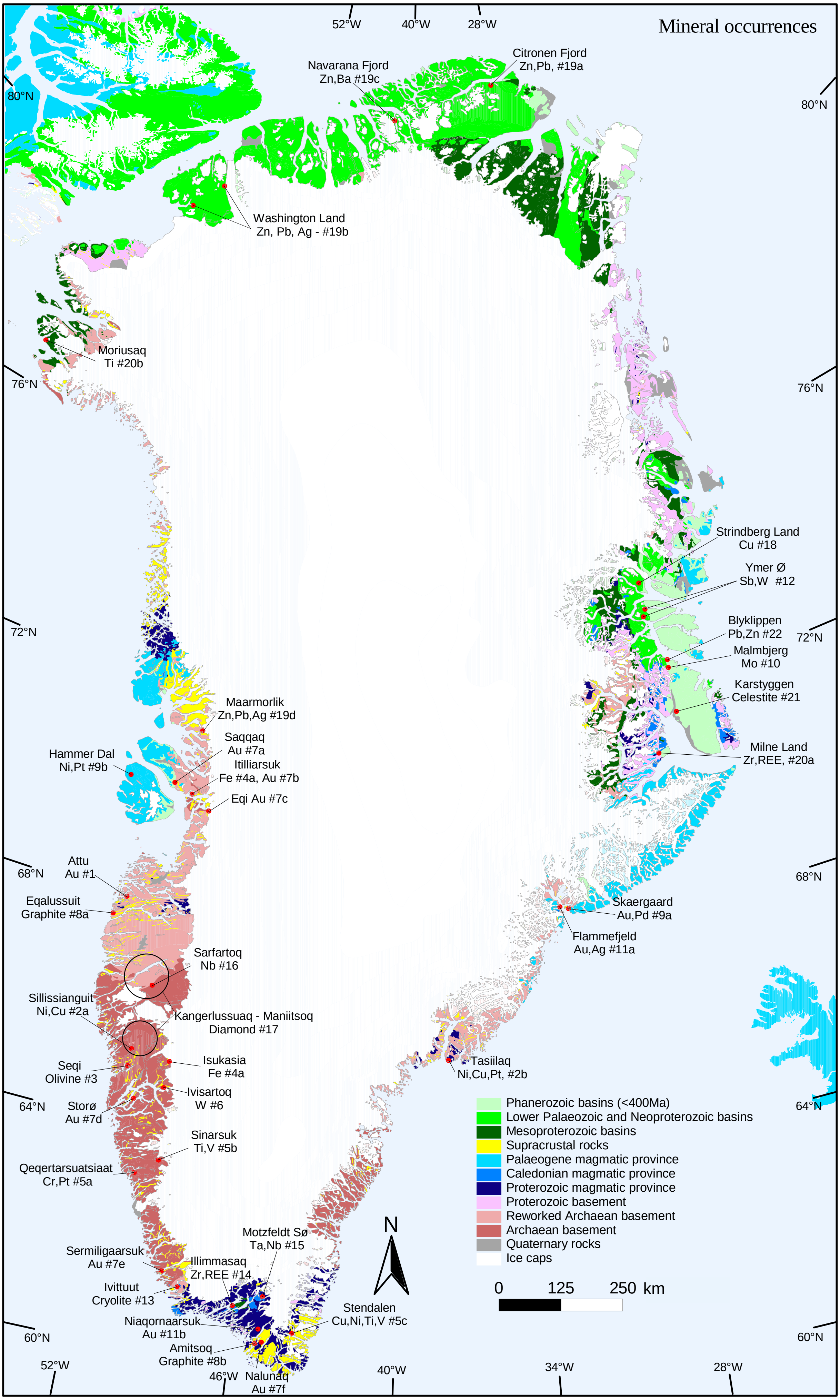
The Precambrian basement comprises of infracrustal and supracrustal rocks, principally including rocks older than 1600 Ma. About half of the ice-free area of Greenland consists of Archaean and Palaeoproterozoic rocks (Henriksen *et al.* 2000a). The basement can conveniently be divided into three types of provinces (Fig. 1):

1) Archaean rocks (3700-2600 Ma), almost unaffected by later orogenic activities – e.g. Nuuk – Isua region.
2) Archaean basement, reworked during Palaeoproterozoic times (2000-1700 Ma) e.g. – the Rinkian, Nagssugtoqidian mobile belts and the extension to the Ammassalik Mobile Belt on the East Coast of Greenland.
3) Areas with juvenile Palaeoproterozic rock (2000-1750 Ma) – e.g. Ketilidian mobile belt.

Some granitoids, which could have been designated, as Palaeoproterozoic basement rocks, are in this context marked as magmatic Proterozoic rocks on the maps (Figs. 2 & 3). This is the case for e.g. the juvenile Julianehaab batholith of the Ketilidian mobile belt, the igneous Arfersiorfik intrusive suite of the Nagssugtoqidian mobile belt, the dioritic intrusive of Ammassalik mobile belt, and the Prøven granite of the Rinkian mobile belt. In the text below some Archaean and Palaeoproterozic basements are not described in detail, e.g. the Melville – Thule region and large areas of the Caledonides in East Greenland.

Figure 2. *Map (insert next page) of the main geological environments of Greenland. AMB: Amassalik Mobile Belt; CO: Caledonian Orogeny; EO: Ellesmerian Orogeny; IMB: Inglefield Land Mobile Belt; KMB: Ketilidian Mobile Belt; NAC: North Atlantic Craton; NMB: Nagssugtoqidian Mobile Belt; RMB: Rinkian Mobile Belt.*

Figure 3. *Map (insert following page) of selected mineral occurrences within the main geological environments of Greenland. AC: Archaean Craton; AMB: Amassalik Mobile Belt; CO: Caledonian Orogeny; EO: Ellesmerian Orogeny; IMB: Inglefield Land Mobile Belt; KMB: Ketilidian Mobile Belt; NMB: Nagssugtoqidian Mobile Belt; RMB: Rinkian Mobile Belt.*


Mineral occurrences
52°W
40°W
28°W
80°N
76°N
72°N
68°N
64°N
60°N
46°W
34°W
Navarana Fjord
Zn,Ba #19c
Citronen Fjord
Zn,Pb, #19a
Washington Land
Zn, Pb, Ag - #19b
Moriusaq
Ti #20b
Strindberg Land
Cu #18
Ymer Ø
Sb,W #12
Blyklippen
Pb,Zn #22
Malmbjerg
Mo #10
Karstyggen
Celestite #21
Milne Land
Zr,REE, #20a
Maarmorlik
Zn,Pb,Ag #19d
Saqqaq
Au #7a
Itilliarsuk
Fe #4a, Au #7b
Eqi Au #7c
Hammer Dal
Ni,Pt #9b
Attu
Au #1
Eqalussuit
Graphite #8a
Skaergaard
Au,Pd #9a
Flammefjeld
Au,Ag #11a
Sarfartoq
Nb #16
Sillissianguit
Ni,Cu #2a
Kangerlussuaq - Maniitsoq
Diamond #17
Seqi
Olivine #3
Isukasia
Fe #4a
Tasiilaq
Ni,Cu,Pt, #2b
Ivisartoq
W #6
Storø
Au #7d
Sinarsuk
Ti,V #5b
Qeqertarsuatsiaat
Cr,Pt #5a
Phanerozoic basins (<400Ma)
Lower Palaeozoic and Neoproterozoic basins
Mesoproterozoic basins
Supracrustal rocks
Palaeogene magmatic province
Caledonian magmatic province
Proterozoic magmatic province
Proterozoic basement
Reworked Archaean basement
Archaean basement
Quaternary rocks
Ice caps
N
0 125 250 km
Motzfeldt Sø
Ta,Nb #15
Sermiligaarsuk
Au #7e
Illimmasaq
Zr,REE #14
Ivittuut
Cryolite #13
Niaqornaarsuk
Au #11b
Stendalen
Cu,Ni,Ti,V #5c
Amitsoq
Graphite #8b
Nalunaq
Au #7f

Archaean

The Nuuk region (description adopted and modified from Appel *et al.* (2003) and Hollis *et al.* (2004) forms the central part of the Archaean craton of southern West Greenland, which is contiguous with the Nain craton in eastern Labrador in the late Archaean and Palaeoproterozoic (Fig. 4). It is largely composed of early and Middle to late Archaean grey orthogneisses of tonalitic-trondhjemitic-granodioritic (TTG) affinity. Granitic gneisses formed by partial melting from the TTG suite are also very common in the eastern part of the Nuuk region, and a late Archaean swarm of inclined, undeformed granite sheets occurs in its central part. Within the Archaean craton of the Maniitsoq area a suite of noritic-gabbroic rocks occur (Secher 1983). The age of this 'norite belt' is unknown but it is most likely that the rocks were intruded during the later part of the Archaean plutonism in the area, probably succeeding the intrusion of the Finnefjeld gneiss complex (3034 Ma) within the Akia terrane (Garde 1997). Many ultramafic bodies occur in the basement e.g. in the Fiskefjord area. Many of those bodies are olivine rich and often dunitic in composition. These bodies are granular, medium-grained dunite, olivine rich peridotites (Garde 1997).

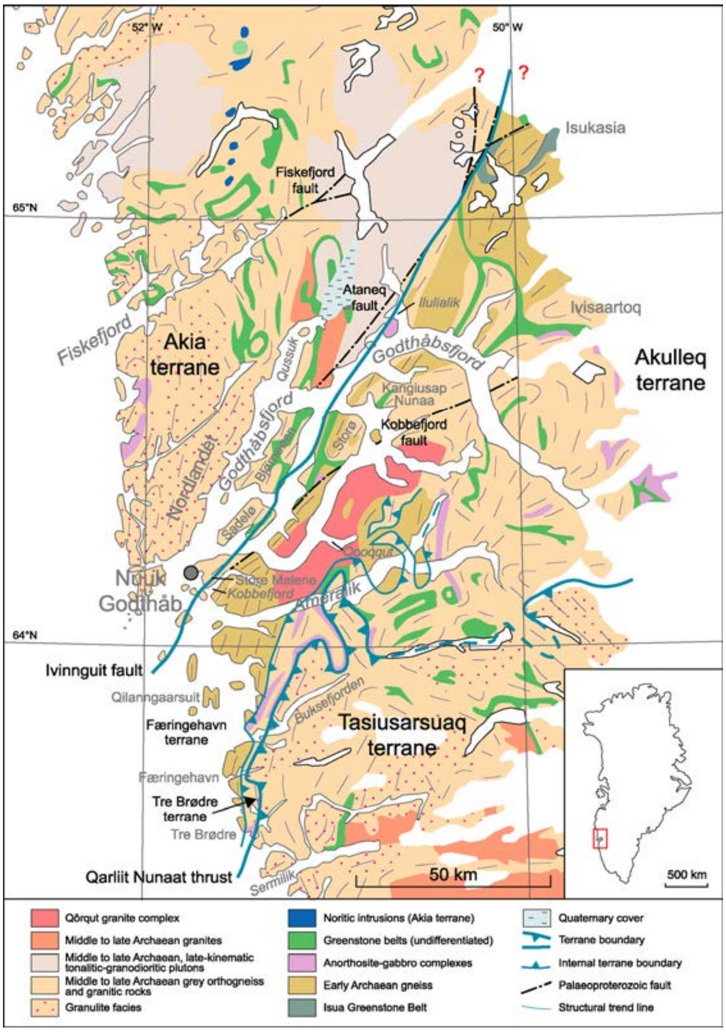


Figure 4. *Geological map of the Nuuk region from Appel et al. (2003).*

Palaeoproterozoic mobile belt (reworked Archaean)

The northern flank of the Archaean North Atlantic Craton (Nain Province in Canada) consists in southern Greenland of the Nagssugtoqidian and Ammassalik Mobile Belts representing a deeply eroded Palaeoproterozoic tectonic belt (Kalsbeek 1989). The northern part of Greenland includes the Rinkian Mobile Belt (van Gool *et al.* 2002) and the Inglefield Mobile Belt (Dawes 1988; Dawes 2004). The Palaeoproterozoic mobile belts were the sites of orogenic activity in the period 1.95 – 1.65 Ga. Most of these Palaeoproterozoic Mobile belts consist of reworked Archaean rocks but also include Palaeoproterozoic supracrustal rocks and intrusive rocks. The supracrustal rocks are dominated by pelitic and semipelitic metasediments ($\pm$graphite) with minor marble and calc-silicate rocks. Major intrusive rocks are the Arfersiofik quartz diorite complex within the Nagsugtoqidian Mobile Belt dated to 1920 Ma (Nutman *et al.* 1999). The Ammassalik Mobile Belt is intruded by three diorites ('Ammassalik Intrusive Complex'), which is dated to 1886$\pm$2 Ma (Hansen & Kalsbeek 1989).

Between the two orogenic belts in West Greenland (Nagssugtoqidian and Rinkian Mobile Belts) an enclave of Archaean supracrustal rocks (Disko Craton) is enveloped in the Palaeoproterozoic mobile belts. This enclave includes supracrustal rocks and intrusives dated at c. 2.8 Ga (Kalsbeek & Taylor 1999) and plays a central role for the gold potential of the region.

Palaeoproterozoic mobile belt (juvenile)

The Ketilidian Mobile Belt (KMB) is a Palaeoproterozoic mobile belt (McCaffrey *et al.* 2004) in the North Atlantic region to the west with counterparts on the Baltic Shield to the East. The Ketilidian orogen of southern Greenland can be divided from northwest to southeast into (Fig. 5):

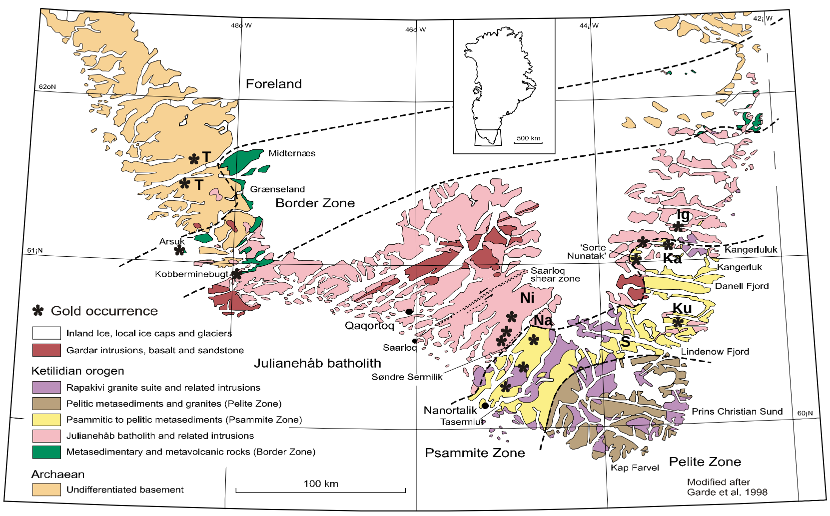


Figure 5. Simplified geological map of South Greenland and location of gold occurrences. Ig = Igusait; Ka = Kangerluluk; Ku = Kutseq; Na = Nanortalik peninsula; Ni = Niaqornaarsuk peninsula; S = Stendalen gabbro; T = gold occurrences with Taartoq greenstone belt.

- A border zone in which the crystalline rocks of the Archaean craton are unconformably overlain by Ketilidian supracrustal rocks; the supracrustal rocks become progressively involved in the Ketilidian metamorphism and deformation towards the south.
- A major polyphase pluton, referred to as the Julianehåb batholith; in addition, numerous contemporaneous appinite dykes, intermediate to ultramafic synplutonic dykes with primary biotite or hornblende, were emplaced into the evolving batholith including the Stendalen gabbro
- Extensive areas of Ketilidian supracrustal rocks, mainly psammitic and pelitic rocks with subordinate interstratified mafic volcanic rocks, which are intruded by a rapakivi granite suite. Intrusions in all the above mentioned rock types comprise the rapakivi suite, which was emplaced between 1755-1740 Ma (Hamilton 1997; Hamilton *et al.* 1996) and rocks belonging to the Mesoproterozoic Gardar Province. The latter lies in a rift zone in the middle of the Julianehåb batholith (see later). Within and outside the main rift zone alkaline plutonic intrusions and numerous generations of dykes were emplaced at different times (Emeleus & Upton 1976; Kalsbeek *et al.* 1990a; Thorning *et al.* 1994; Upton & Emeleus 1987).

Supracrustals

Supracrustals comprise rocks that now appear as integrated parts of the basement rocks (Fig. 6). The supracrustal rocks include metasedimentary rocks, metavolcanics and banded magnetite-quartzite formations. Special attention is given to the mafic metavolcanics (grenstone belts) because of their high rate of mineral potential, not least with gold and base metal deposits.

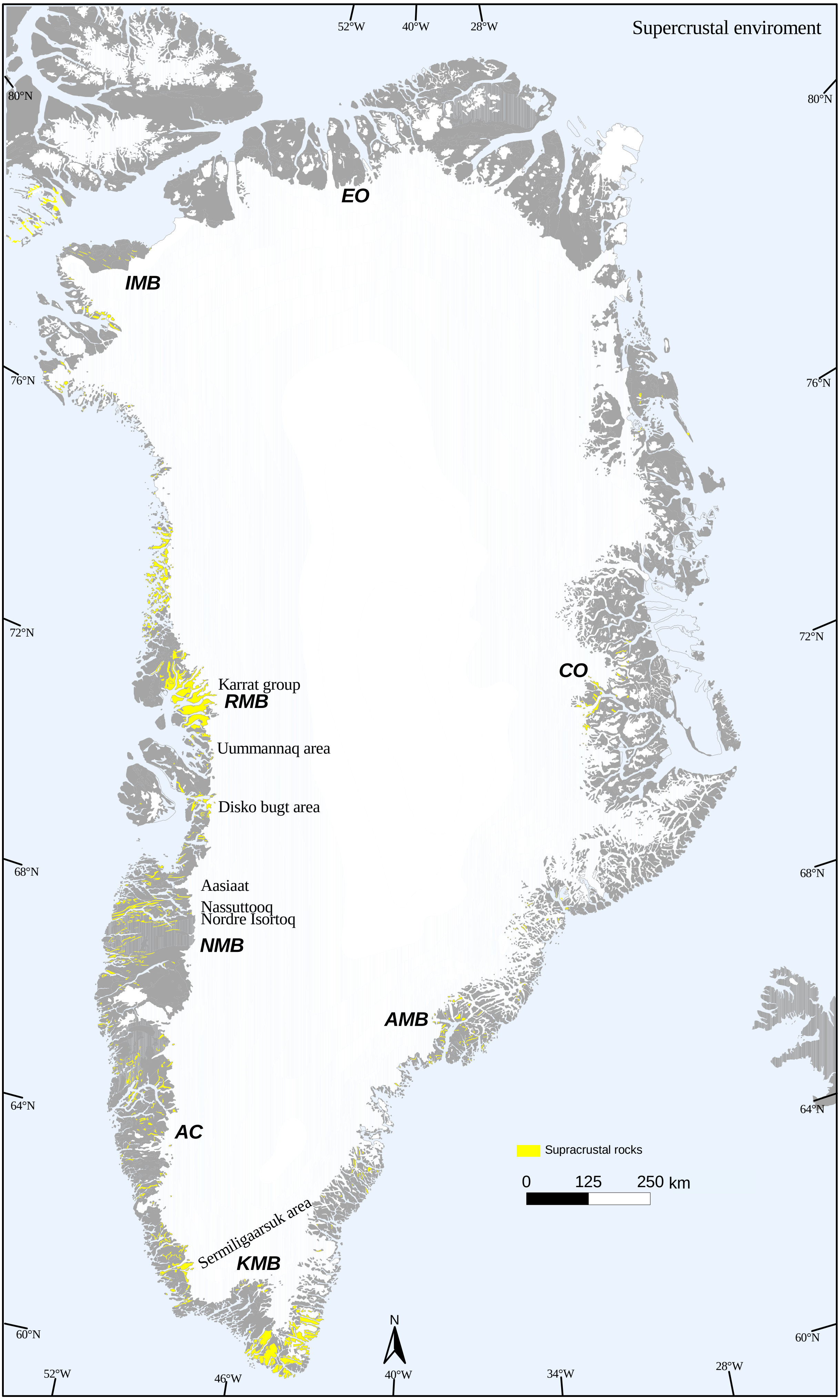
In the American Geological Institute 'Glossary of Geology' (Jackson 1997) greenstone and greenstone belts are defined as follows:
Greenstone is a field term applied to any compact dark-green altered or metamorphosed basic igneous rock (e.g. spilite, basalt, gabbro, dolerite) that owes its colour to the presence of chlorite, actinolite, or epidote.
Greenstone belts is a term applied to elongate belt like areas within Precambrian shields that is characterised by abundant *greenstone.* An individual belt may contain the deformed and metamorphosed rocks of one or more volcano-sedimentary piles, in each of which there is typically a trend from mafic to felsic volcanics. The resultant volcano-sedimentary complexes are of economic interest as host rocks for presumably volcanogenic metal deposits.

If the above definitions is used and transfered to specific Greenland conditions the characterisation of '*Greenland greenstone belts'* would be as follows:

Archaean and Proterozoic sequences of metamorphosed sedimentary rocks interlayered with volcanic flows and breccias. The basalt in greenstone belts often exhibits pillow structures. The sedimentary rocks are predominantly greywacke, with interbedded shale, sandstone, carbonates and conglomerate. Greenstone belts also often include iron formations. Greenstone belts are commonly associated with extensive granitic intrusions.

Supracrustal rocks are found in Greenland in all areas with infracrustal rocks and terranes, they contain Precambrian metasedimentary successions, and comprise 5-10% of the infracrustal areas. Greenstone belts within supracrustal rocks in Greenland are located in the Disko Bugt area in the Nassuttooq area, in the Nuuk region, in the Sermiligaarsuk area, and in South Greenland. In the Uummannaq area, the Palaeoproterozoic Karrat Group comprises a sedimentary basin but in this report is it described under the heading of supracrustal rocks because the age is older than 1600 Ma. It is only large and extensive supracrustal sequences, which are described in detail and in chronological order below.

Figure 6. *(Following page): Supracrustal rocks in the basement of Greenland. AC: Archaean Craton; AMB: Amassalik Mobile Belt; CO: Caledonian Orogeny; EO: Ellesmerian Orogeny; IGB: Isua Greenstone Belt; IMB: Inglefield Land Mobile Belt; KMB: Ketilidian Mobile Belt; NMB: Nagssugtoqidian Mobile Belt; RMB: Rinkian Mobile Belt.*


Supercrustal enviroment
52°W
40°W
28°W
80°N
76°N
72°N
68°N
64°N
60°N
EO
IMB
Karrat group
RMB
Uummannaq area
Disko bugt area
Aasiaat
Nassuttooq
Nordre Isortoq
NMB
CO
AMB
AC
Sermiligaarsuk area
KMB
Supracrustal rocks
0
125
250 km
N
52°W
46°W
40°W
34°W
28°W

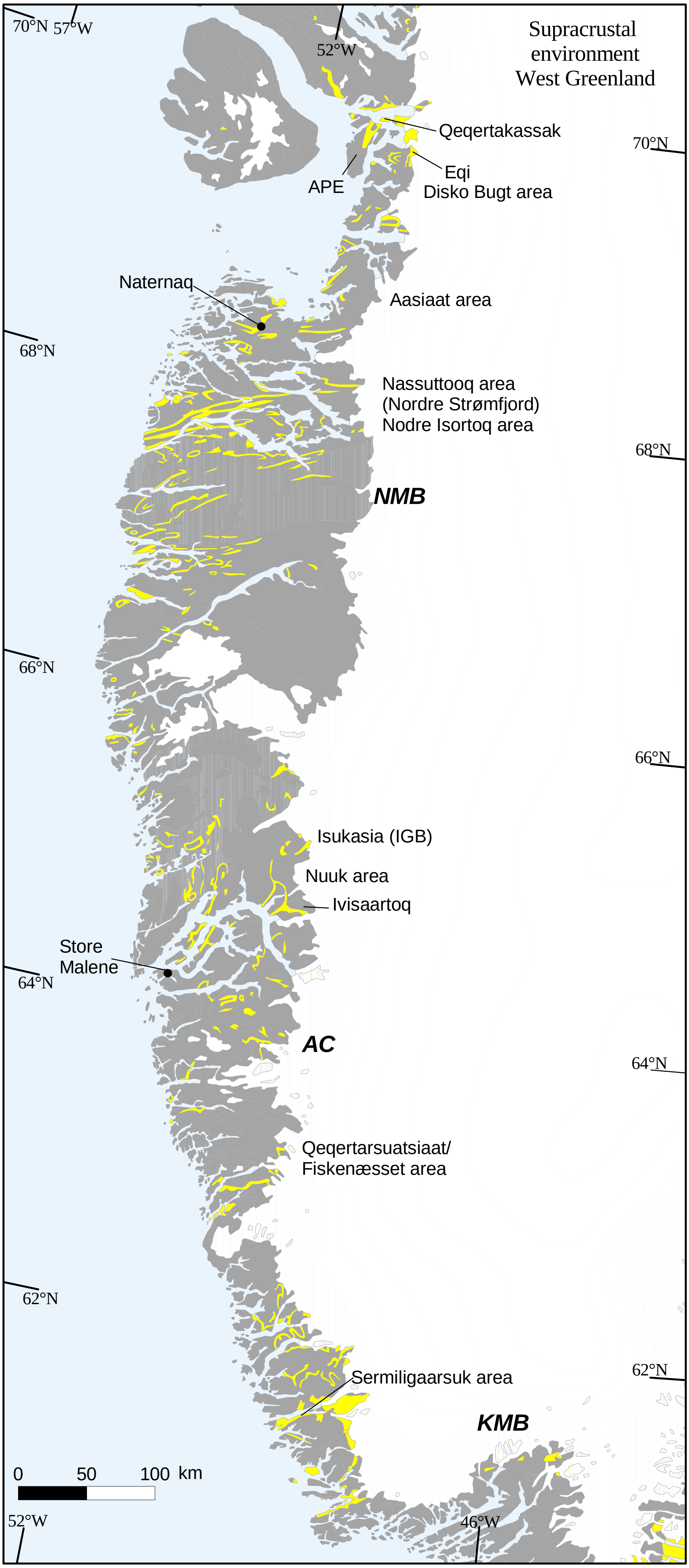
Nuuk area

Early Archaean greenstone belts

The following description of the Nuuk region (Fig. 4) is summarised from a compilation the econnomic potential of the greenstone belts in the Nuuk region (Appel *et al.* 2003). It has been known for 30 years that the Isua Greenstone Belt (IGB; Fig. 6) rocks at Isukasia are at least 3.7 Ga old (Moorbath *et al.* 1973). This has not been changed much, but debate persists whether deposition occurred closer to 3.7 or 3.8 or even whether or not there are two separate periods of deposition within this time range (e.g. (Nutman *et al.* 1997). There is no convincing evidence for in situ rocks older than ca. 3.8 Ga. Modelling age from Isua reveals the least radiogenic Pb-isotopic composition so far found on Earth, namely in small lead occurrences in the IGB (Appel 1978; Frei 2000; Frei & Rosing 2001; Richards & Appel 1987).

The IGB consists of high and low strain domains, some of which appear to be of slightly different age. The dominating rock types are pillow-structured tholeiitic and high Mg-basaltic rocks. Intercalated in the lavas are extensive bands of chert and banded iron formation as well as garnet-mica schists occasionally with staurolite representing metamorphosed fine-grained sediments. Abundant ultramafic bands of various compositions but of unknown origin are seen. The IGB has suffered several metamorphic events. The area has also been repeatedly deformed. Carbonate alteration of the IGB took place during several events (Rosing *et al.* 1996). The first alteration event took place at and immediately below the sea floor at ~3.8 Ga. Later events are coeval with the metamorphic events. Carbonate alteration apparently was most penetrative in the western part of the IGB. Several post-metamorphic events have been recorded at the IGB. The events have not been dated, but among them, a Qooqqut age heating event has been recorded. Late shear zone hosted quartz veins are recorded from different parts of the IGB.

Figure 7. *(Following page): Supracrustal rocks of West Greenland. AC: Archaean Craton; IGB: Isua Greenstone Belt; KMB: Ketilidian Mobile Belt; NMB: Nagssugtoqidian Mobile Belt.*



Supracrustal environment West Greenland
70°N 57°W
52°W
Qeqertakassak
70°N
Eqi
Disko Bugt area
APE
Naternaq
Aasiaat area
68°N
Nassuttooq area
(Nordre Strømfjord)
Nodre Isortoq area
68°N
NMB
66°N
66°N
Isukasia (IGB)
Nuuk area
Ivisaartoq
Store
Malene
64°N
AC
64°N
Qeqertarsuatsiaat/
Fiskenæsset area
62°N
62°N
Sermiligaarsuk area
KMB
0
50
100 km
52°W
46°W

Late Archaean Greenstone belts

These greenstone belts are well exposed from the coastal region south of Nuuk to the Inland Ice at Ivisaartoq. The late Archaean greenstone belts age relationships are uncertain. They are enclaves in mid-Archaean gneisses and are cut by the ~2.5 Ga Qooqqut granite. It is possible that several generations of greenstone belts occur, but so far, it has not been proven. The contact relationships between the mid-Archaean greenstones and the surrounding gneisses are always obscure. Often the contacts are either intrusive or strongly sheared.

The best-preserved greenstone enclave is found at Ivisaartoq (Fig. 7), which is described, well in (Brewer *et al.* 1984; Chadwick 1985; Chadwick 1986; Chadwick & Coe 1988). Further detailed work has been carried out at the coastal region (Beech & Chadwick 1980). (Appel & Garde 1987) have mapped Store Malene Mountain next to Nuuk in detail. The greenstone belts have all been metamorphosed under amphibolite facies conditions and been repeatedly deformed. A new mapping project of the greenstone belts in the Nuuk area has started in the summer 2004 and the preliminary results are given in Hollis *et al.* (2004).

The greenstone belts extend southwards to the Qeqertarsuatsiaat/Fiskenæsset area where anorthositic rocks are bordered by amphibolite units, into which they are believed to have been intruded (Henriksen *et al.* 2000). The anorthositic rocks form a single stratiform intrusion, the Fiskenæsset complex (Myers 1985), which has been dated at c. 2850 Ma (Ashwal *et al.* 1989). The main rock types are metamorphosed anorthosite, leucogabbro and gabbro together with minor ultramafic rocks. The Fiskenæsset Complex has undergone folding.

Disko Bugt area

The Archaean supracrustal rocks (greenstone belt) of the Ataa Sund and Torsukattak areas do not form a continuous belt. The belt has been observed into the following areas (Fig. 8): Arveprinsen Ejland, Oqaatsut, Anap Nunaa, Qingaarsuaq and Eqi-Maniitsoq south of Torsukattak, and north of Torsukattak Saqqaq, Naajat Qaqqaat – Itilliarsuk, Itilli and Nunataq (Garde & Steenfelt 1999a). The supposed Archaean supracrustal fragments north of Torsukattak differs in lithology compared to those south of Torsukattak. The apparent lack of lithological and structural correlation across Torsukattak, between the Nuussuaq domain and the Ataa domain, suggests that the fjord hides an ENE-WSW-trending structural discontinuity - a shear zone (Garde & Steenfelt 1999b). The following supracrustal units occur along the southern coast of Nuussuaq: Saqqaq, Itilliarsuk, Itilli and Nunataq. Detailed descriptions of the region have changed over the years. The first details can be found in (Escher & Burri 1967) but more modern descriptions are found in (Garde & Steenfelt 1999a), (Garde *et al.* 1999a), (Rasmussen & Pedersen 1999); and (Higgins & Soper 1999). The Palaeoproterozoic supracrustal rocks are mainly found south of Torssukattak (Fig. 8).

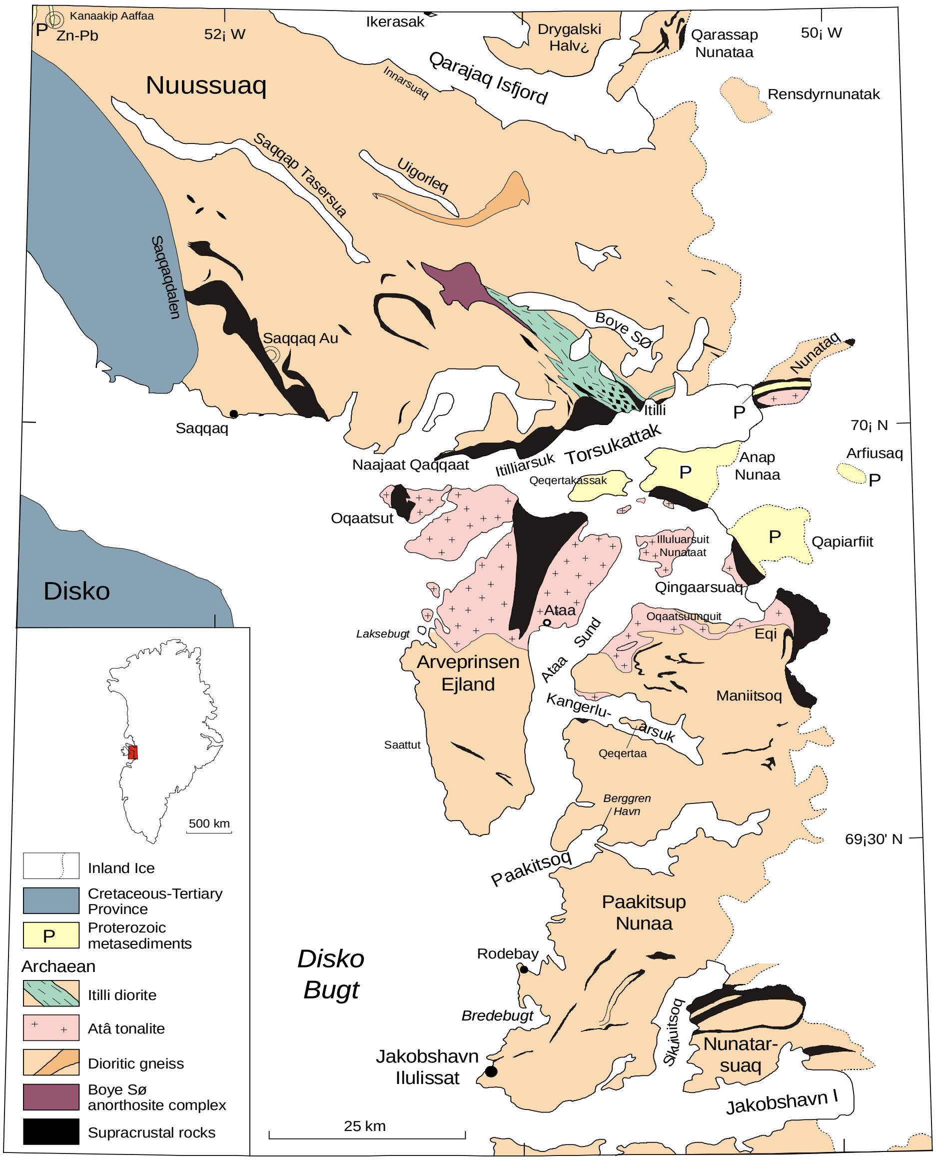


Figure 8. *Simplified geological map of the Disko Bugt area – from Garde & Steenfelt (1999).*

The two largest Archaean supracrustal sequences of the northern Disko Bugt occur south of Torsukattak, at Arveprinsen Ejland and Eqi-Maniitsoq, and they show the same general lithological evolution. In both areas a thick sequence dominated by greenstones is overlain by a thinner sequence characterised by siliciclastic and acid metavolcanic rocks. Based on primary features of pillow lavas it can be seen that the whole greenstone sequence is inverted (Stendal *et al.* 1999a). In the northeastern part of Arveprinsen Ejland the Archaean supracrustal rocks are intruded by a voluminous mafic sill complex (Marshall & Schønwandt 1999).

The greenstone sequence

The greenstone sequence in the Arveprinsen Ejland and Eqi-Maniitsoq areas can be divided into three units:

(a) a lower unit of massive to pillowed greenstones,
(b) a middle unit of greenstones with frequent layers of mafic and felsic volcaniclastic sediments interlayered with felsic igneous rocks,
(c) an upper unit dominated by greenstones of mixed extrusive (pillow lavas) and intrusive origin.

The total thickness of the greenstone sequence is about 3-4 km (Garde & Steenfelt 1999a; Stendal *et al.* 1999a). This is a minimum estimate, since the Inland Ice covers the base of the sequence and the primary volcanic structures of the area are distorted by ENE-WSW stretching. The greenstone succession on Arveprinsens Ejland is intruded by the Atâ pluton and its base is therefore unknown.

The Palaeoproterozoic sedimentary sequence unconformably overlying the Archaean rocks is approximately 3.5 km thick and comprises shallow marine clastic sediments and minor marble (Garde & Steenfelt 1999a). The central part of the area is extensively albitised, e.g. Qeqertakassak (Kalsbeek 1992; Ryan & Escher 1999). Mafic dykes, and dykes and ultramafic lamprophyre and lamproite with ages of c. 1750 Ma are common (Marker & Knudsen 1989; Skjernaa 1992).

Sermiligaarsuk area

The Archaean craton in the Sermiligaarsuk area (Fig. 7) is composed of tonalitic orthogneiss with mafic igneous enclaves and slivers of supracrustal rocks. According to existing age determinations most of the gneiss precursors formed between 2800 and 3000 Ma ago (Kalsbeek *et al.* 1990a). A major supracrustal unit, the Tartoq Group, comprises a greenstone association of mafic metavolcanic rocks and metasediments, which have been intruded by a granite dated at 2940 Ma. The metavolcanics and metasediments are several kilometres thick and comprise of a volcano-sedimentary sequence, which carry gold occurrences (Appel & Secher 1984; Evans & King 1993; Schjøth *et al.* 2000b; Stendal & Schønwandt 2000).

Aasiaat, Nassuttooq and Nordre Isortoq areas

Several thin belts of supracrustal and intrusive rocks occur within the reworked Archaean gneiss terrain of the Nagssugtoqidian Orogen (Fig. 7). The supracrustal enclaves in the Aasiaat area comprise mafic metavolcanic units tentatively regarded as formed in a volcanic arc environment. The supracrustal enclaves, e.g. Naternaq, comprise thick sequences of metasediments including marble, in addition to mafic metavolcanic rocks, and such assemblages suggest platformal or intracontinental basin settings. Iron-formations, especially sulphide facies, are common in the supracrustal rocks of this area.

Supracrustal rocks are common within the Nassuttooq area, where they occur as strongly deformed and metamorphosed ENE trending bands. Metasediments including subordinate marble predominate in the supracrustal bands. Collectively, the supracrustal enclaves in the northern Nassuttooq area are termed Nordre Strømfjord supracrustals. Isotope data for detrital zircons have confirmed that several of these are Palaeoproterozoic and deposited during the subduction stage(s) of the orogenic evolution (1930 to 1870 Ma; van Gool *et al.* 2002). The lithologies and mineral occurrences suggest that both platform and arc/back-arc type deposits are represented.

The Nordre Isortoq supracrustal belt comprises metasediments and metavolcanic strata that are occasionally rich in sulphides. Available isotope data suggest that a proportion of the rocks are Archaean, and that Palaeoproterozoic sediments are present (Connelly & Mengel 2000; Marker *et al.* 2004).

Uummannaq area

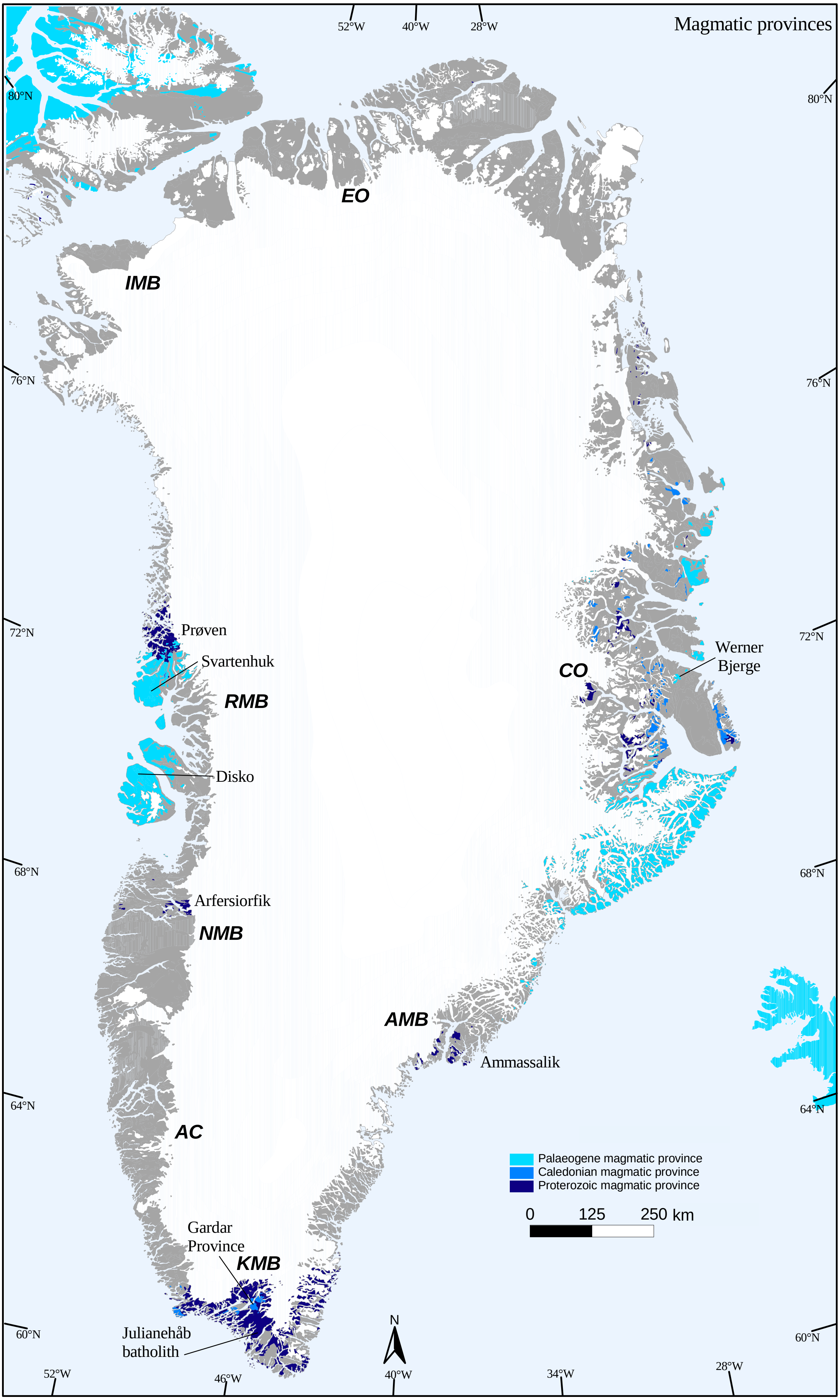
Within the Rinkian mobile belt (~1850 Ma; Foxe mobile Belt in Canada) in the Uummannaq area, West Greenland (Fig. 6), a several kilometres thick succession of Palaeoproterozoic supracrustal rocks lies, the Karrat Group (Henderson & Pulvertaft 1967). The Karrat Group is divided into three formations, the Qeqertarssuaq and Mârmorilik Formations (lowest) and the Nûkavsak Formation. The Qeqertarssuaq and Mârmorilik Formations are regarded as correlatives in different depositional sub-basins. The Qeqertarssuaq Formation consists mainly of siliciclastic rocks: quartzite, pelitic and semi-pelitic schist up to two km in thickness. The Mârmorilik Formation consists almost entirely of dolomite and calcite marble, with a basal unit of orthoquartzite and semi-pelitic schist (Garde 1978). The formation is c. 1.6 km thick. The Black Angel Zn-Pb deposit is hosted in the marbles near the top of the formation.

The upper and also the most extensive formation of the Karrat Group (Fig. 6) is the Nûkavsak Formation, a more than 4 km thick unit built up of metagreaywacke-pelitic schist interpreted as turbidites (Henderson & Pulvertaft 1967). The Karrat Group has been intruded by the Prøven igneous complex consisting of hypersthene granite and leucogranite (Henderson & Pulvertaft 1987). A Rb-Sr whole rock isochron of the hypersthene granite yields an age of 1860±25 Ma (Kalsbeek 1981), thus providing a minimum age for the Karrat Group.

South Greenland

In the Ketilidian mobile belt extensive areas consist of supracrustal rocks, mainly psammitic and pelitic rocks with subordinate interstratified mafic volcanic rocks intruded by a rapakivi granite suite (Fig. 5). The psammite rocks, south-east of the batholith, have a sharp boundary to the Julianehåb batholith, which is partly defined by steep NE-SW trending shear zones as seen along the south eastern coast of the Søndre Sermilik fjord. The psammite rocks include basic metavolcanic rocks, variably migmatised pelitic- and semi pelitic rocks, calcareous metasediments, a bedded massive-pyrrhotite/graphitic-chert horizon, dolerites, S- and I-type granites and syn- and post kinematic appinite dykes and post kinematic rapakivi granites. The psammites are interpreted to represent intra- and forearc sediments, eroded from the Julianehåb batholith and deposited in fluvial and shallow marine environments between the batholith and the oceanic area to the south (Chadwick & Garde 1996). This happened shortly after 1800 Ma as the batholith emerged above sea level and was unroofed. The southern tip of Greenland comprises mainly flat lying, intensely migmatised pelitic rocks. The pelitic rocks consist mainly of turbidite sediments, deposited in deeper offshore settings compared with the fluvial and shallow marine environments of the psammites (Garde *et al.* 1997b). The evolution of the Ketilidian Mobile Belt is reviewed in (Garde *et al.* 1998a; Garde *et al.* 1997b; Garde *et al.* 1998b; Garde *et al.* 2002; McCaffrey *et al.* 2004).

Figure 9. *(Following page): Magmatic provinces of Greenland. AC: Archaean Craton; AMB: Amassalik Mobile Belt; CO: Caledonian Orogeny; EO: Ellesmerian Orogeny; IMB: Inglefield Land Mobile Belt; KMB: Ketilidian Mobile Belt; NMB: Nagssugtoqidian Mobile Belt; RMB: Rinkian Mobile Belt.*



Magmatic provinces
52°W
40°W
28°W
80°N
80°N
76°N
76°N
72°N
72°N
68°N
68°N
64°N
64°N
60°N
60°N
52°W
46°W
40°W
34°W
28°W
EO
IMB
Prøven
Svartenhuk
RMB
Disko
Arfersiorfik
NMB
AC
Gardar
Province
KMB
Julianehåb
batholith
CO
Werner
Bjerge
AMB
Ammassalik
Palaeogene magmatic province
Caledonian magmatic province
Proterozoic magmatic province
0
125
250 km
N

Magmatic environment

The magmatic provinces described here are the Palaeproterozoic Ketilidian batholith (Julianehåb batholith) of South Greenland, the Mesoproterozoic Gardar Province of South Greenland, the province of carbonatites and kimberlites of West Greenland, the Caledonian granites of East Greenland, the Palaeogene basaltic provinces of East and West Greenland, and the alkaline granitoid intrusions of East Greenland. Some of the intrusions, which have not been described, are the Arfersiorfik diorite complex, Prøven granite and the diorite complex in the Ammassalik region.

Julianehåb batholith (Ketilidian)

The Julianehåb batholith covers c. 30,000 km^2 and comprises intrusive complexes within the domain (Figs. 5 & 9). A small part of the Archaean craton, which is intruded by Ketilidian granites, as well as a narrow belt of Ketilidian foreland supracrustals is included in the chemically defined domain. Ages of intrusive units within the batholith domain span the period from 1855 to c.1800 Ma. The older units within the batholith are strongly deformed while younger (around 1800 Ma) granite, monzonites and diorites (appinites), show little or no deformation. The major phases of the deformation formed several NNE or NE trending, sinistral shear zones through the batholith. The intrusions are calc-alkaline or slightly alkaline in character and are interpreted to have formed from juvenile Proterozoic magmas (Kalsbeek & Taylor 1985b). The Ketilidian granites intruding the Archaean basement are enriched in large-ion lithophile elements (LILE). For more details about the batholith see e.g. (Garde *et al.* 1998a; Garde *et al.* 1997b; Garde *et al.* 1998b; Garde *et al.* 2002; McCaffrey *et al.* 2004).

The Gardar Province

The Mesoproterozoic Gardar province is geochemically in great contrast to the surrounding Julianehåb granite and Archaean orthogneisses (Figs. 5 & 9). The Gardar event involved three main phases of rifting and associated intrusion of alkaline magmas (Upton & Emeleus 1987). The first two phases developed along fault zones with directions between E-W and ENE-WSW. Stretches of these faults are discernible in the maps of aeromagnetic data. The third rifting episode formed an ENE graben in which lavas and sediments are still preserved. The evolution of the three main stages is:

1) Early Gardar (1300-1270 Ma) includes sandstone deposits and flood basalts and three central complexes of nepheline syenite. The sandstones and flood basalts rest unconformably on a basement of the Julianehåb batholith. Early Gardar central complexes include the 1280 Ma Motzfeldt nepheline syenite centre which is strongly enriched in Zr, Ta, Nb, REE, U, and Th.
2) Mid-Gardar (1250-1200 Ma) was a period characterised mainly by dyke intrusion. Intrusions were emplaced in the most western part of the Gardar province, in the Archaean craton to the north of the Ketilidian formations and in the granitoids of the Julianehåb batholith. The most important of the intrusions with respect to economical potential is the Ivittuut granite that hosts the famous cryolite deposit (Pauly & Bailey 1999).

3) Late Gardar (1185-1120 Ma) includes the largest volumes of intrusive Gardar lithologies and spreads over the entire province. The central complexes are mainly composed of nepheline syenite, syenite, and alkaline granite. The most investigated and notable intrusion from an economical point of view is the peralkaline and agpaitic Ilimaussaq intrusion. The Ilimaussaq intrusion consists of nepheline syenite with uncommon rock types like sodalite foyaite, naujaite, kakortakite, and lujavrite. All of these rocks are strongly enriched in F, Zr, Zn, REE, Y, U, and Th and the Ilimaussaq intrusion is recognised as a major resource of speciality metals. The most westerly syenite intrusion in the Gardar province is the large and multiple Nunarsuit intrusive complex that formed around 1125 Ma ago (Kalsbeek *et al.* 1990b). Recently the Paatusoq syenite complex in Paatusoq fjord on the South-East coast of Greenland was recognised to be of late Gardar age (Garde *et al.* 1997b; Grocott *et al.* 1999).

Carbonatite and kimberlite suite in southern West Greenland

The following description is adopted and modified from (Jensen *et al.* 2003; Jensen & Secher 2004; Jensen *et al.* 2004). Southern West Greenland hosts the major alkaline province with a variety of ultramafic - alkaline rocks (Fig. 10). The alkaline province includes swarms of dykes described as kimberlites and lamproites (Larsen 1991a; Larsen 1991b). These rock types are widely distributed in the Sisimiut–Sarfartoq–Kangerlussuaq region, as well as the region just south of Sukkertoppen Icecap. Lamproitic dykes in the adjacent Sisimiut region are around 1.2 Ga old, and the kimberlitic dykes in both the Sarfartoq and Sisimiut regions have ages of around 0.6 Ga (Larsen & Rex 1992). A precise spatial relationship between the intrusive events resulting in kimberlitic rocks and carbonatites has not been established but work is undergoing (S.M. Jensen per.com.). The alkaline ultramafic dykes within the Sisimiut–Kangerlussuaq and Sarfartoq regions intrude either side of the border zone between the Archaean craton and the Palaeoproterozoic Nagssugtoqidian orogen (Secher & Larsen 1980).

Kimberlitic rocks within the undisturbed Archaean craton south of Sukkertoppen Icecap appear to be of the same age (~590 Ma) as the alkaline rocks in the Sarfartoq–Kangerlussuaq region (Jensen & Secher 2004). A genetic relation to the Mesozoic Qaqqaarsuk carbonatite is thus unlikely. The rocks are found within an area of c. 50 × 50 km and the kimberlites are emplaced as dykes, up to 2-m wide. The 170 Ma Qaqqaarsuk complex (Knudsen 1989) located in the area south of Sukkertoppen Ice Cap, represents the youngest alkaline magmatic event.

The only other area with a significant number of kimberlitic occurrences in West Greenland is in the Paamiut–Ivittuut region near the southern boundary of the Archaean craton. Dykes and sills, rarely more than one m wide, have been reported. A few age determinations suggest emplacement in the Mesozoic around 170–200 Ma.

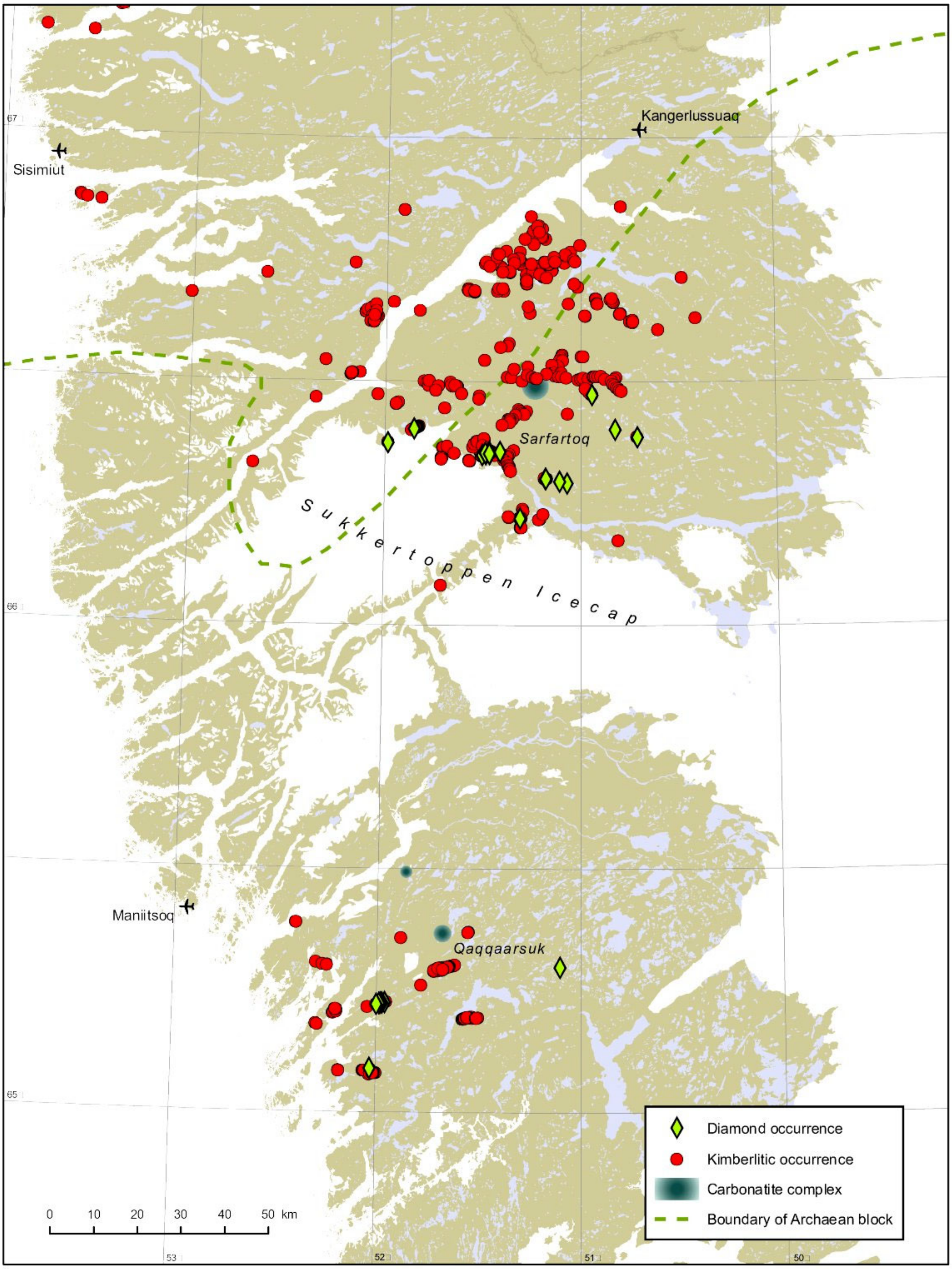


Figure 10. *Kimberlitic rocks and carbonatites (Sarfartoq and Qaqarssuk) of southern West Greenland.*

Caledonian granite

Caledonian intrusions in East Greenland (Fig. 9) were emplaced between 435 and 425 Ma (Higgins *et al.* 2004; Kalsbeek *et al.* 2001; Rex & Higgins 1985; Steiger *et al.* 1979). Granodiorites and granites are the most abundant types and occur widespread within the latitudes 70° - 76°N. Most of the granites are S-type granites. In the middle to northern part of this region the granite were mainly intruded along the boundary zone between the Eleonore Bay Supergroup and the metamorphic complexes. In the southern part the intrusions are more widespread and also within the crystalline complexes (Henriksen *et al.* 2000a).

Palaeogene magma provinces

The Palaeogene magmatic provinces in both West and East Greenland are major eruption sites in a continental margin setting (Fig. 9). The volcanic products were formed during the initial phase of continental break-up and initiation of sea-floor spreading in the early Palaeogene. Volcasnism was initiated c. 61 Ma ago in both East and West Greenland. The main flood basalt volcanism occurred between 61 and 59 Ma ago in West Greenland and between 57 and 53 Ma ago in East Greenland. The flood basalts covered Mesozoic – early Paleocene sedimentary basins and lapped on to the Precambrian basement (Henriksen *et al.* 2000a). In East Greenland tholeiitic intrusions like the Skaergaard intrusion (Irvine *et al.* 1998; Wager & Brown 1968) belong to a main group of tholeiitic gabbro intrusions, some of which have subordinate proportions of ultramafic components. They formed mainly between 55 and 50 Ma ago, whereas felsic intrusions dominated by quartz syenite, monzonite and granite (Nielsen 1987a) formed over an at least 25 Ma long period. This happened after the onset of seafloor spreading in the North Atlantic (Gleadow & Brooks 1979; Nielsen 1987b; Nielsen 2002; Tegner *et al.* 1998). The syenitic and granitic intrusive centres in the Mesters Vig area generally form composite complexes, which are younging from NE to SW. The oldest complex in NW gives ages from 40 to 34 Ma, whereas the SE area (Malmbjerget) yields ages from 31 to 21 Ma (Schønwandt 1988). The youngest basaltic volcanics in East Greenland are 13 Ma old (Storey *et al.* 1998). Nielsen (2002) gives an overview of all the Palaeogene intrusions and magmatic complexes in East Greenland, 66° to 75°N.

Sedimentary depositional environment

The sedimentary basins are: the Mesoproterozic Thule Group, Krummedal succession, Independence Fjord Group, and the Eriksfjord Formation, the Neoproterozic Hagen Fjord Group, Eleonore Bay Supergroup and Phanerozoic sedimentary basins of East, West and North Greenland (Fig. 11).

Mesoproterozoic basins

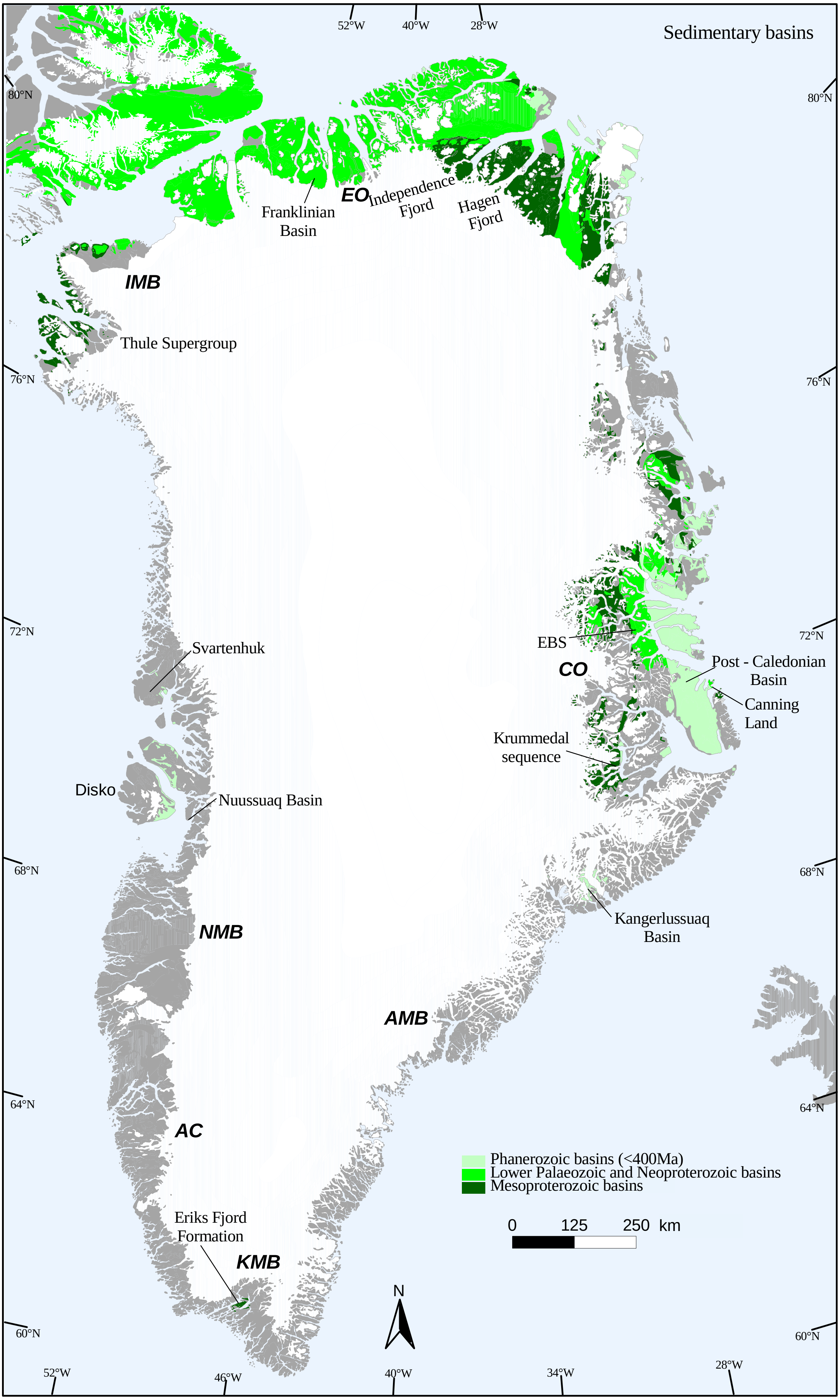
Thule Supergroup

The intracratonic Thule Basin of northern Baffin Bay is preserved between 76^{o} and 79^{o}N in Greenland and Ellesmere Island, Canada. The Mesoproterozoic Thule Supergroup contains little deformed and unmetamorphosed strata at least six km thick. The succession is composed of continental to shallow marine sediments with prominent red bed units, and one main interval of basaltic volcanic rocks (Dawes 1997; Dawes 1999).

Krummedal sequence

The Mesoproterozoic ‘Grenvillian’ event are imprinted in the crystalline rocks of the Caledonian fold belt in central East Greenland. A thick sequence of Mesoproterozic metasediments, the Krummedal sequence rests on Palaeoproterozoic and Archaean basement (Higgins 1988). The Krummedal sequence consists of pelitic, semipelitic, and quartzitic rocks generally metamorphised within the amphibolite facies. Metamorphism, deformation and granite intrusions happened from 1000-930 Ma ago (Henriksen *et al.* 2000a; Henriksen *et al.* 2000b). The main part of the Mesoproterozoic rocks occurs in the western part of the area with a few exceptions from the eastern part e.g. Clavering Ø and Liverpool Land.

Figure 11. *Sedimentary basins of Greenland. AC: Archaean Craton; AMB: Amassalik Mobile Belt; CO: Caledonian Orogeny; EBS: Eleonore Bay Supergroup; EO: Ellesmerian Orogeny; IMB: Inglefield Land Mobile Belt; KMB: Ketilidian Mobile Belt; NMB: Nagssugtoqidian Mobile Belt; RMB: Rinkian Mobile Belt.*


Sedimentary basins
52°W
40°W
28°W
80°N
80°N
Franklinian
Basin
EO
Independence
Fjord
Hagen
Fjord
IMB
Thule Supergroup
76°N
76°N
72°N
72°N
Svartenhuk
EBS
CO
Post - Caledonian
Basin
Canning
Land
Krummedal
sequence
Disko
Nuussuaq Basin
68°N
68°N
Kangerlussuaq
Basin
NMB
AMB
64°N
64°N
AC
Phanerozoic basins (<400Ma)
Lower Palaeozoic and Neoproterozoic basins
Mesoproterozoic basins
0
125
250
km
Eriks Fjord
Formation
KMB
N
60°N
60°N
52°W
46°W
40°W
34°W
28°W

Independance Fjord Group

The sedimentation in North Greenland started in Mesoproterozoicum *c*. 1380 Ma (Sønderholm & Jepsen 1991; Surlyk 1991b). The Independance Fjord Group consists of a more than 2-km thick sandstone-dominated succession consisting of intracratonic fluvial and aeolian sediments and minor lacustrine sediments. These deposits were intruded around 1230 Ma by the Midsommersø doleritic sills and dykes (Kalsbeek & Jepsen 1983). Extrusive equivalents (Zig-zag Dal Basalt Formation) covering an area of more than 10,000 km^2 comprise at least 1350 m of quartz tholeiitic lava flows (Kalsbeek & Jepsen 1984).

Eriksfjord Formation

In the Gardar province approximatly 3400-m thick succession of sandstones (1800-m) and lavas (1600-m) referred to as Eriksfjord Formation (Poulsen 1964) were accumulated within an ENE-WSW-trending continental rift. The sediments and volcanics rest unconformably on Ketilidian granite. The age of the Eriksfjord Formation is 1200–1170 Ma (Paslick *et al.* 1993).

Neoproterozoic basins

Hagen Fjord Group

The Hagen Fjord Group, North Greenland (Fig. 11) is deposited in a basin formed between 800 and 590 Ma and is interpreted as the early phases of rifting of the Iaptetus Ocean. The succession includes up to 1000 m of shelf deposits and more than 2500 m of turbidites and conglomerates. The Hagen Fjord Group unconfomably overlies the peneplained Independance Fjord sandstones and Zig-Zag Dal basalts (Sønderholm 1995; Sønderholm & Jepsen 1991).

Eleonore Bay Supergroup

The Neoproterozoic Eleonore Bay Supergroup, central East Greenland (Fig. 11) comprises an up to 16-km sedimentary succession. The sediments are shallow water deposits in a major sedimentary basin extending between 72^o and 76^oN latitudes in the central part of the region (Fig. 1) except for an outlier at Canning Land (C) (Higgins & Soper 1994; Sønderholm & Tirsgaard 1993). Siliciclastic-carbonate rocks evolved from siliciclastic deposits over mixed siliciclastic-carbonate sediments to carbonate deposits dominate the lithologies. The Eleonore Bay Supergroup is unconformably overlain by the Tillite Group of a 700-800 m thick succession of Vendian age (610-570) Ma and includes two glacigene diamictite formations (Hambrey & Spencer 1987). The evolution of the Greenland Caledonides has recently been described in detail and the Eleonore Bay Supergroup is defined to part of the Franz Joseph Allochton also hosting Caledonian granites (Higgins *et al.* 2004).

Phanerozoic basins

East Greenland

The Lower Palaeozoic of East Greenland (Fig. 11) comprises 4000 m of Cambrian-Ordovician sediments (Haller 1971; Henriksen 1985; Peel 1982). The Devonian sediments unconformably overlie Ordovician and older rocks. More than eight km of continental siliclastic sediments were deposited with some volcanic intervals (Hartz & Andresen 1995; Larsen & Bengaard 1991; Olsen 1993; Olsen & Larsen 1993).

The north-south extending sedimentary basin along the east coast of Greenland forms an approximately 600 km long depositional basin that comprises the coastal region of central East and North-East Greenland (Pedersen 2000). Basin formation was initiated as a result of post-Caledonian crustal collapse during the Middle Devonian. This resulted in up to 17 km of sediment deposition ranging from Devonian to Cretaceous in age is present within the basin. The sedimentary pile is dominated by thick sequences of immature continental molasse sediments of Devonian to Lower Permian age, which are unconformably overlain by a succession of marine, lacustrine and continental deposits up to 5000 m thick (Larsen & Bengaard 1991; Larsen & Olsen 1991; Olsen 1993; Olsen & Larsen 1993). The Jameson Land Basin contains a stratigraphically complete succession of Upper Permian to earliest Cretaceous sediments. The deposits both include shallow marine clastic sediments, alluvial and aeolian sediments, and marginal marine sediments such as carbonates and evaporites (Surlyk 1990; Surlyk 1991a). A basement consisting of Precambrian to Lower Palaeozoic rocks and felsic intrusives of Caledonian age frames the sedimentary basin.

North Greenland – Franklinian Basin

The Franklinian Basin extends from Canada to eastern North Greenland (Figs. 11 & 12), a distance of approximately 2000-km and its formation lasted from *c*. 640 Ma to 380 Ma (Higgins *et al.* 1991; Peel & Sønderholm 1991; Surlyk 1991b). The first stage of the basin evolution occurred close to the Precambrian-Cambrian boundary. The basin comprises a southern shelf and slope, and a northern deep-water trough. The shelf sediments are a carbonate platform and the trough sediments are mainly turbidites. In Late Devonian – Early Carboniferous occurred the closure of the Franklinain Basin (Ellesmerian Orogeny). The evolution and sedimentation patterns in the Franklinian Basin are also influenced by the closure of the Iapetus ocean and Caledonian orogenic uplift especially in eastern North Greenland (Surlyk 1991b).

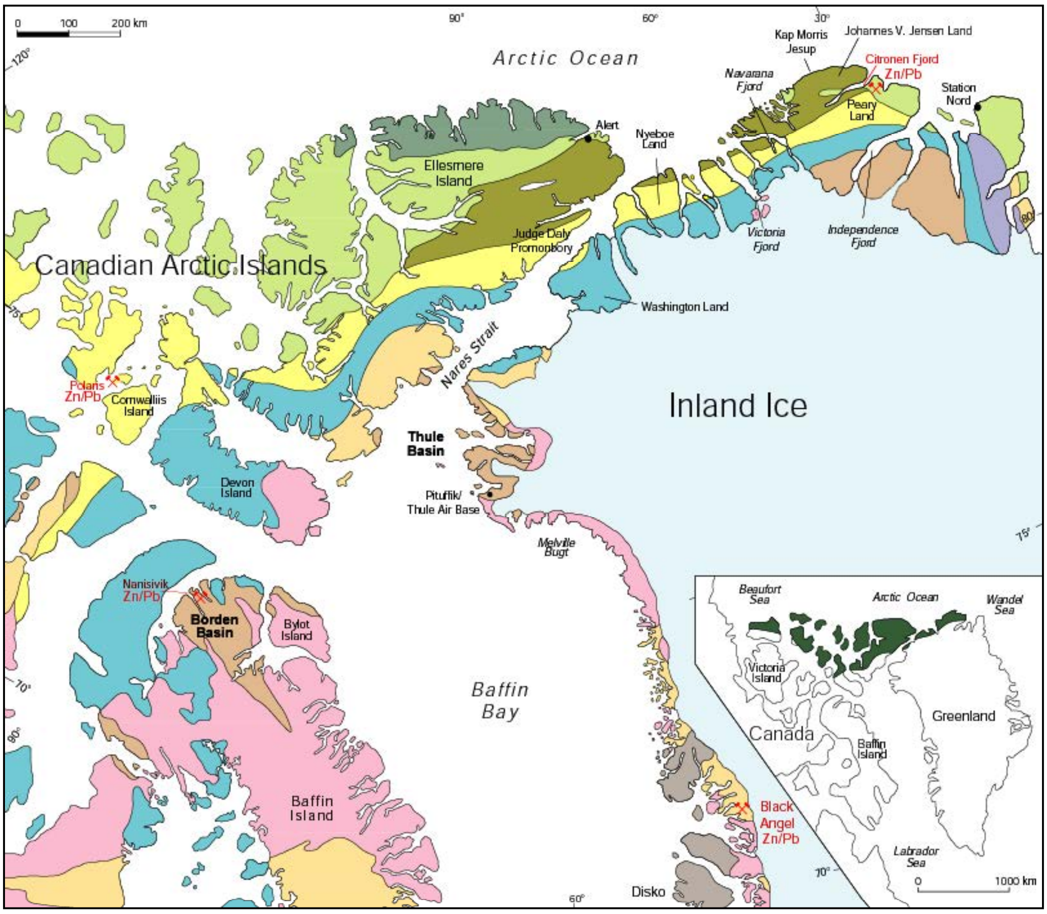


Figure 12. *Geological map of northern Greenland and adjacent parts of the Canadian Arctic Islands from van der Stijl & Mosher (1998).*

Central West Greenland

Cretaceous-Tertiary sediments of central West Greenland occur in the Disko-Svartenhuk Halvø region (69^{o}-72^{o}N), where Lower Tertiary basalts overlie them (Fig. 11). The sediments are deposited in the Nuussuaq Basin and the maximum thickness of the sediment package exceeds eight km, but the age and character of the deepest sediments are not known (Chalmers *et al.* 1999; Christiansen *et al.* 1995). The sediment comprises fluvial delta deposits, turbidites, mudstones, and coal (Dam 2000; Dam *et al.* 2000; Pedersen & Pulvertaft 1992).

Southern East Greenland

The Kangerlussuaq Basin, East Greenland (Fig. 11) has one km of clastic sediments and up to eight-km thick pile of volcanic rocks (mainly basalts) is deposited in Cretaceous to Lower Tertiary.

Mineral resources within the geological environments

The various geological environments have a variety of mineral occurrences. Several of these are described under the specific environment heading (Table 1; Fig. 3). The aim is to describe some of the mineral occurrences representing the specific environment but also to illustrate the range and differences between types of occurrences within the same environment. The descriptions are put into a format slightly modified from the occurrence descriptions found in (Stendal *et al.* 2004). The individual descriptions of the deposits can be found in the Appendix 1 as data sheets. The suffixes (e.g. 4a, 4b) mean that the specific type under the head number 4 has several different types of deposits within the same geological environment.

Infracrustals

Within the infracrustal environment, not many mineral occurrences are recorded in Greenland from Table 1 three types are included: Gold in gneiss, nickel and copper in mafic intrusions, and olivine in ultramafic rocks (Fig. 3).

Gold in gneiss (#1)

The Attu area lies within the southern part of the Northern Nagssugtoqidian Orogen (NNO). The metamorphic grade is amphibolite facies. Steep- and shallow-dipping shear and fault zones are common in contact zones between different types of lithologies. Major fault zones generally strike NNE–NE. The major Nordre Strømfjord shear zone (van Gool 2002) is located c. 20 km to the south. The Attu gold prospect is a replacement gold occurrence related to a shear/mylonite zone striking along the contact between brown gneisses and amphibolites within the Nagssugtoqidian orogenic belt. The amphibolites is Archaean layered mafic rocks (Stendal *et al.* in press a). The mineral occurrence is small, less than 0.5 m wide, and can be followed along strike for a couple of hundred metres. The mineral assemblage is pyrite, chalcopyrite, gold and magnetite. The timing of gold mineralisation is interpreted to be mid-Archaean (Stendal *et al.* in press a).

Nickel and copper in mafic intrusions (#2)

A number of bodies of mafic igneous rocks situated in a 15 x 75-km tract belong to the Maniitsoq norite belt around Sillisissanguit Nunaat. The dominating rocks are leucogabbronorite, locally with massive sulphide segregations. The size of the individual norite bodies varies from 2x4 km to only a few metres across (Secher 2001). Sulphide occurrences are scattered throughout the norite belt. The sulphides are pyrrhotite, chalcopyrite, pyrite and pentlandite, which are creating gossans and rustzones (Secher & Stendal 1989). The Ni-content of the mineralised rocks is up to 2 %. The norite belt has relatively high Pd and Pt contents, up to 0.6 and 2.2 ppm respectively. Gold yields up to 2.1 ppm. Platinum and gold show mobility as part of later mineralisation processes (Secher 2001).

Olivine in ulramafic rocks (#3)

In many places of the basement in Greenland ultramafic bodies occur. In the Fiskefjord area, several lens-shaped ultramafic bodies are 2–3 km long. Many of those are olivine rich peridotites and often dunitic bodies. These bodies are granular, medium-grained olivinite, and olivine rich peridotite (Garde 1997). Several of the bodies also have chromite and magnetite. The Seqi olivine occurrence is fully exposed and has been subject to limited drilling and surface sampling by Crew Development Ltd. in 2004. Mineable (open pit) resources, derived from drilling to about 50-m depth, are estimated at 46 million tonnes. Gravimetric studies have indicated a resource potential in excess of 100 million tonnes.

Supracrustal rocks (greenstones)

The supracrustal rocks of the Archaean craton comprises a variety of mineral occurrences containing iron, gold, copper, chromium, tungsten, as well as industrial minerals. In Greenland several prospective gold occurrences occur, all are in greenstone belts. The occurrences are located in the Disko Bugt (Saqqaq, Itilliarsuk, Eqi), Nuuk (Storø), and Taartoq (Sermiligaarsuk) greenstone belts. Many occurrences have been recorded with disseminated to semi-massive to massive sulphides hosted in greenstone sequences comprising rocks of both volcanic and sedimentary origin, called volcanic massive sulphides (VHMS). Most of such occurrences are of limited extent and are normally not enriched in base metals. No further attention will be directed to the VHMS deposit type. The examples chosen to illustrate the different deposit types are listed in Table 1 and located on Figure 3.

Banded Iron Formation (#4a,b)

Banded iron formations are found in many places within the Archaean and reworked Archaean craton in Greenland e.g. in the Isua area, in the Disko Bugt area, in the Melville bugt area. The Isukasia (Isua) iron deposit, northeast of Nuuk is a banded iron formation (Appendix 1 - #4a) with 32% iron and a resource of 2000 Mt. This is probably the oldest banded iron formation (~3.7 Ga) in the world.

The Itilliarsuk banded iron formation is located on the south side of the Nuussuaq peninsular. The iron formation occurs within a 2.5 km thick supracrustal sequence consisting of felsic and mafic volcanics intercalated within more than two km thick sequence of siliciclastic rocks dominated by mica-garnet schists (Appendix 1 - #4b). The resource is 150-200 million t of ore grading 20% Fe (Gothenborg & Morthorst 1981).

Mafic layered intrusions (#5a,b,c)

Within supracrustal sequences mafic layered intrusions are important host rocks for metals like chromium, vanadium, copper and nickel. Metamorphosed anorthosites and associated gabbroic rocks make-up a distinctive formation of the Archaean craton in the Qeqertarsuatsaat/Fiskenæsset area. The Fiskenæsset anorthosite complex hosts a large chromitite deposit (Appendix 1 - #5a). The anorthosite complex is intruded into amphibolite units. The chromitite depsoits are distributed over an area of ~3,200 km^2. The estimation of the resources include 2.5 Mt of 32.7% Cr_2O_3 in one location, and more widespread 100 Mt of low-grade ore (Ghisler 1970; Ghisler 1976). Significant platinum, vanadium and titanium values are also reported from the complex. Within the same supracrustal belt, gabbro intrusions from Sinarsuk comprise vanadium and titanium (Appendix 1 - #5b).

In the Ketilidian Mobile Belt, the Stendalen gabbro is a folded, sheet-like body at least 8 km in length and several hundred metres thick (Garde *et al.* 1997a). It is composed of gabbro, leucogabbro, and diorite, locally with primary banding and divided into two main units: a lower layered gabbro unit and an upper homogeneous gabbro to diorite unit. The complex encloses sulphides, including pyrrhotite, minor pyrite, chalcopyrite, cobaltite, and graphite (Stendal *et al.* 1997). A magnetite-rich zone separates the lower layered gabbro from the upper homogeneous gabbro. The zone varies in thickness and reaches a maximum width of 20 m. The magnetite-rich zone contains sulphide-rich bands with 5 vol. % pyhrrotite, 20 vol. % ilmenite, 10 vol. % magnetite and pyrrhotite, and less than 1% chalcopyrite (Birkedal 1998). The magnetite bearing samples reach 0.2% V Appendix 1 - #5c).

Ivisartoq tungsten (#6)

The Nuuk region hosts a major tungsten province, with scheelite occurring in virtually every greenstone enclave. The Mid- to Late-Archaean greenstone is clearly the most prospective for tungsten deposits especially in altered komatiites (Appel 1994). Channel sampling at Ivisaartoq revealed 0.44% WO_3 over 2.5 m.

Saqqaq gold (#7a)

The Saqqaq greenstone comprises felsic metasedimentary rocks with subordinate mafic and ultramafic metavolcanic units. The sequence may represent deposition in a continental rift or at an active continental margin. The age is not known, but believed to be Archaean. Gold occurs in a 1 to 2 m thick garnet-quartz-rich layer situated at the boundary between ultramafic lavas and mica schist (Garde *et al.* 1999b). Gold values are in the range of 1–16 ppm over 1–2 m and the auriferous bed can be followed for at least 4 km (Stendal *et al.* 2004; Stendal & Schønwandt 2003).

Itilliarsuk gold (#7b)

The metasediment-dominated supracrustal sequence along the south coast of Nuussuaq hosts large, rusty-weathering iron-formations in the form of both magnetite-rich bands and semi-massive sulphide. Mica schist with disseminated pyrrhotite and pyrite attains a thickness of about 150 m. Epigenetic gold mineralisation is found at several sites within sulphide-rich schists, quartz veins, and shear zones (Stendal *et al.* 2004; Stendal & Schønwandt 2003).

Eqi gold (#7c)

The metamorphosed mafic and felsic volcanic rocks is part of a 2.8 Ga old volcanic island arc. Three types of gold mineralisation are found (Stendal *et al.* 1999b). Syngenetic gold occurs in up to 20-cm thick lenses of semi-massive pyrite situated in a 50–200 m wide zone between rhyolitic lava and sericite-rich sediment. Hydrothermal activity associated with the volcanism at Eqi resulted in pervasive carbonate alteration along N–S trending zones. The carbonatised rocks consist of ankerite, chlorite, fuchsitic mica and disseminated pyrite. The third kind of gold mineralisation is hosted by a 10 m wide and 100-m long breccia zone and is clearly epigenetic and situated immediately west of a major N–S trending thrust zone (Stendal *et al.* 2004; Stendal & Schønwandt 2003).

Storø gold (#7d)

Presently, gold is the most prospective of the metals with a potential for future exploitation within the Nuuk region. The high crustal level of the Faeringehavn terrane, the occurrence of greenstone belts and the long geological history with shearing and faulting renders the NNE-trending zone from Nuuk to Isukasia favourable for gold mineralisation (Appel *et al.* 2000; Appel *et al.* 2003). The zone follows a terrane boundary and hosts the known gold showings on Storø and at Isukasia. The gold is hosted in the greenstones especially in garnet-bearing rocks.

Taartoq gold (#7e)

In the Sermiligaarsuk area Archaean gneiss is overlain by the Tartoq Group greenstone belt. The basement gneiss has ages ranging from 2980-3500 Ma and Taartoq supracrustals are assumed to be late Archaean, deposited between 2500 and 3000 Ma. The Tartoq Group (Bridgwater *et al.* 1973; Higgins 1968; Higgins & Bondesen 1966) comprises several greenstone occurrences along the north and south side of the fjord, Sermiligaarsuk. The Tartoq Group gold mineralisation is significant in two areas. Gold occurs in three principal manners within the carbonate schists: 1) in disseminated pyrite in quartz-ankerite lenses (1-2 m by 5-10 m); 2) in pyrite associated with massive and semi-massive arsenopyrite aggregates; and 3) in sulphide rich iron-formations. Gold is suggested to have been 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 (Schaefer *et al.* 2000; Schjøth *et al.* 2000a; Steenfelt *et al.* 2000).

Nalunaq gold (#7f)

The gold mineralisation in Nalunaq, Ipatit, Lake 410 (Nanortalik district, Southwest coast), and Kutseq (Southeast coast) are all related to shearing and quartz veins in mafic rocks of Ketilidian age (1850-1800 Ma). The mafic rocks are island-arc tholeiites, which are thrusted over psammitic rocks (Kaltoft *et al.* 2000; Lind *et al.* 2001); (Kaltoft *et al.* 2000; Petersen *et al.* 1997; Stendal *et al.* 1997). The supracrustal rocks are intruded by post-kinematic biotite granites and subsequently by anorogenic rapakivi granites around 1750 Ma (Garde *et al.* 1997c; Garde *et al.* 2002; Kalsbeek & Taylor 1985b). The gold-mineralised vein system at Nalunaq is 1700 m long and 0.1 to 2 m wide (Gowen *et al.* 1993; Kaltoft *et al.* 1998; Lind *et al.* 2001; Petersen *et al.* 1997; Petersen & Pedersen 1995).

Graphite within supracrustal rocks (#8a,b)

Graphite is abundant in Palaeoproterozoic sulphide-rich supracrustal rocks in both West and South Greenland. The Nordre Strømfjord supracrustal belt is particularly enriched, where graphite is hosted by pelitic metasediments (Akuliaruseq/Eqalussuit – Appendix - #8a). The largest resource has been calculated to contain 5.3 million t of flake graphite ore having an average content of 9.5% carbon (Pedersen 1992). Other resource figures are published as mineable tonnage 1,370,000 at a grade of 14.1% C (Bondam 1992). The graphite is considered to represent metamorphosed bituminous and sulphide rich strata deposited in a volcanic arc or back-arc environment associated with the Nagssugtoqidian subduction.

In the Ketilidian Mobile Belt of South Greenland the graphite deposit (Amitsoq – Appendix 1 - #8b) is hosted in graphitic schists embedded in strongly sheared cordierite-sillimanite-biotite gneisses (Bondam 1992; Mosher 1995). The ore consists of finely disseminated crystalline graphite flakes in a quartz-rich groundmass, accompanied by pyrite and biotite. The graphite is flaky with flakes up to 15 mm in size. The graphite content is 20-24 vol. %. The original ore body is estimated to *c*. 250 000 tons. The Amitsoq graphite mine produced a total of 6.000 t graphite averaging 21% graphite.

Magmatic provinces

A porphyry system is related to Palaeogene alkalic intrusion in East Greenland e.g. the porphyry molybdenite deposit, Malmbjerget (Fig. 3). The associated vein systems are gold and silver bearing such as Flammefjeld. Veins related to the Caledonian granite and the Julianehåb batholith carries tungsten, arsenic, antimony, and gold. The alkaline intrusions in the Gardar province have niobium, tantalum, zirconium, rare earth elements, and cryolite. Carbonatite with niobium, tantalum, apatite and kimberlite-lamproite with diamonds are located within the Kangerlussuaq region of West Greenland (Fig. 3).

Mafic intrusions with PGE and gold (#9a)

In East Greenland, the tholeiitic Skaergaard intrusion (Irvine *et al.* 1998; Wager & Brown 1968) belongs to a main group of tholeiitic gabbro intrusions. The Skaergaard deposit is one of the giant palladium deposits of the world. The deposit is hosted in a layered gabbro intrusion, which has a surface exposure of 55 km^2 and contains stratiform gold-PGE mineralisation. Maximum grades are 5.8 g/t gold, 3.7 g/t palladium, and 1.7 g/t platinum. The resource for gold is 43 Mt grading 2.4 g/t, which is more than 3 million ounces of gold.

Mafic extrusions with nickel (#9b)

In the Nuussuaq – Disko region Palaeogene flood basalts overly Upper Cretaceous and Tertiary sediments. Palaeogene dykes in the region contain nickel-bearing pyrrhotite and native iron, such as the Hammers Dal complex in the northwest Disko. The presence of Norilsk-type nickel deposits associated with PGE has recently lead to nickel exploration in the region.

Porphyry intrusions with molybdenum (#10)

The Palaeogene igneous province of the Mesters Vig area forms a prominent NE-SW trending line of plutonic-subvolcanic centres traceable for approximately 125 km from the Werner Bjerge Complex in the SW to Kap Parry in the NE (Schønwandt 1988). Syenites and granites are the dominant rock types of the intrusive centres. (Fig. Xx). The Werner Bjerge Complex comprises the porphyry Mo deposit, Malmbjerget, which is a Climax type deposit. The Malmbjerget molybdenum deposit is dated to have been emplaced at 25.8$\pm$0.1 Ma based on Re-Os and $^{40}Ar/^{39}Ar$ methods (Brooks *et al.* 2004). The porphyry system has an orebody of 150 million tons with 0.23% MoS_2 at a cut-off of 0.16% MoS_2 (Schønwandt 1988).

Veins related to granite with gold (silver, molybdenum; #11a)

The Palaeogene Flammefjeld Complex is situated near the contact of the Kangerlussuaq syenite intrusion. The presumed youngest intrusive rocks comprise the 500 x 800 m sub-volcanic Flammefjeld complex. The vein-type mineralisation centred on Flammefjeld is confined to brittle structures and shows similarities with epithermal gold-silver veins of low-sulphidation type generated at shallow depths, i.e. within *c.* 1.5 km of the Earth's surface (see e.g. Sillitoe 1993). Quartz-veinlets as a stockwork type mineralisation have pyrite and molybdenite (Schønwandt 1988).

Veins related to granite with gold (bismuth, tungsten; #11b)

The gold occurrence related to the Julianehåb Batholith (Niaqornaarsuk and Igusait) occurs in quartz veins, in aplites, in sheared metabasic rocks, and in the hydrothermally altered granitic batholith rocks (Stendal & Frei 2000; Stendal & Grahl-Madsen 2000; Stendal *et al.* 1995). The gold bearing vein system is part of the Julianehåb batholith formation. The emplacement of the juvenile I-type Julianehåb Batholith lasted from 1850-1800 Ma with late stage intrusions until 1770 Ma as the youngest (Garde 1998; Hamilton *et al.* 1996). Emplacement of the various gold occurrences is considered to have taken place in the late stage of the batholith formation (1800-1770 Ma) before the intrusion of rapakivi granites.

Gold occurrences related to the Julianehåb batholith are seen as lode/shear zone hosted types within the batholith itself (Au-Bi-(Ag-As-Cu-W-Mo)) or within the volcanic-sedimentary sequence (Au-Cu). The gold prospects form a row of gold mineralisation in a NE –SW striking zone along the southern rim of the Julianehåb batholith. The dominant gold bearing fluids are H_2O-CO_2-CH_4 and the precipitation temperatures are in the range of 200-400^oC at around 1 Kb (Stendal & Frei 2000).

Veins related to granite with tungsten and antimony (#12)

Mineral occurrences related to Caledonian intrusions and faults comprise tungsten and stibnite mineral occurrences on Ymer Ø, East Greenland. Tungsten and antimony mineral occurrences (Hallenstein & Pedersen 1983; Hallenstein *et al.* 1981; Pedersen & Stendal 1987) contain scheelite and stibnite. The occurrences are part of the Ymer Ø Group within the Upper Eleonore Bay Supergroup. The scheliite and stibnite occurrences are hosted in brecciated carbonates in minor fault zones and the grade of tungsten is high. The mineral occurrences on Ymer Ø reflect a crude zonation with scheelite and stibnite at a higher stratigraphic level than pyrite, galena, sphalerite, chalcopyrite and locally arsenopyrite with gold at lower levels of the Upper Eleonore Bay Supergroup (Pedersen & Stendal 1987).

The occurrences in the fault zones are without direct magmatic association. The Caledonian granite has probably played a part in the formation of W and Sb. Diamond drilling of one of the scheelite and stibnite veins indicate 42000 Mt with 0.7% W and 108000 Mt with 3.5% Sb (Harpøth *et al.* 1986). Locally this vein-type mineralisation, especially the arsenic-bearing vein, has gold contents up to a few parts per million (Pedersen 1993).

Alkaline intrusion with cryolite (#13)

The Ivittuut cryolite mine was hosted in one of the Gardar intrusive complexes (Pauly and Bailey 1999). The cryolite body is located within the roof zone of a 300-m wide pipelike alkali-granite intrusion. The cryolite deposit is divided into a siderite-cryolite, a pure cryolite, a fluorite-cryolite, and a fluorite-topaz unit, above a large siderite and quartz mineralised unit (Pauly and Bailey 1999). The deposit formed when F-rich post-magmatic fluids from deeper parts of the Ivittuut granite intensively leached, metasomatised and re-mobilised the central top part of the granite pipe to form a homogeneous supercritical fluoride-rich melt. The cryolite deposit originally contained 3.8 million tons or ore with 58% cryolite, including the fluorite-topaz unit underlying the western part of the deposit. To this was added an underlying mass of quartz with siderite of 8.5 million tons to a total resource of 12.3 million tons of ore (Pauly and Bailey 1999).

Alkaline intrusion with zirconium and special metals (#14)

A repeated, layered sequence of three subtypes of the kakortokite referred to, as red, black, and white kakortokite dominates the southern part of the Ilimaussaq intrusion. Individual layers of kakortokite are up to 3 m thick. Zirconium is hosted in the rock forming mineral eudialyte that contains 8-14% ZrO_2, 2-6% RE_2O_3 and 1% Nb_2O_5. Large masses of naujaite have more than 1% ZrO_2, eudialyte-rich lujavrites 1-2% ZrO_2 and the eudialyte-rich layers of kakortokite more than 2.5% ZrO_2. The Zr/Hf ratio varies from 30 to 70. It is estimated that the kakortokite exposed above sea level contains about 60 million tons of ZrO_2 and about 6.5 million tons of Nb_2O_5 in 4 billion tons of rock. Red kakortokite is calculated to contain a resource of at least 0.8 million tons ZrO_2, 39,000 tons Y_2O_3, and 0.2 million tons RE_2O_3. The average grade in red kakortokite is 6% ZrO_2, 0.2% Nb_2O_5, 3% RE_2O_3, 0.2% Y_2O_3, 400 ppm Ta, and 1000 ppm Hf (Kalvig & Appel 1994; Sørensen (ed.) 2001).

Nepheline syenite with niobium and tantalum (#15)

The Motzfeldt Centre of the Igaliko Nepheline Syenite Complex is dated to 1310+10 Ma (Tukiainen 1988) and is one of the major central complexes in the Gardar province. The Motzfeldt Centre is composed of multiple intrusions of syenite with a wide range in textural and compositional characteristics. The syenites were emplaced into the Palaeoproterozoic Julianehåb Batholith and unconformably overlying Gardar supracrustal rocks. Peralkaline residua gave rise to a complex of late peralkaline sheets of microsyenite and pegmatite and hydrothermal alteration with associated Th-U-Nb-Ta-Zr-REE bearing minerals. The metals are mainly concentrated in pyrochlore (Nb, Ta, U, REE), thorite (Th), zircon (Zr), and bastnaesite (REE, Th). The tantalum content in the pyrochlore varies from 1.3% to 8.3%. In general, the Nb/Ta ratio is 11. The Nb-Ta resource estimate indicates a mineralised rock volume of more than 500 million tons with average contents of 0.14% Nb, 120 ppm Ta, 60 ppm U and 90 ppm Th. With the cut-off grade at 250 ppm Ta, the estimated reserve is at least 30 million tons.

Carbonatite with niobium and tantalum (#16)

The Sarfartoq carbonatite, together with kimberlitic rocks from the Kangerlussuaq region, belongs to the well-known and widespread ’North Atlantic alkaline province’, which has representatives in both eastern Canada and Scandinavia (Secher & Larsen 1980). The pyrochlore deposit was formed during one of several magmatic phases of the Sarfartoq carbonatite intrusion (Secher & Larsen 1980). The pyrochlore is accumulated late in the igneous history as vein shaped bodies in a marginal zone surrounding a central carbonatite mass. The age of the Sarfartoq carbonatite complex is around 600 Ma, based on K/Ar age determinations (Larsen & Rex 1992; Larsen *et al.* 1983; Larsen & Rønsbo 1993). The 'Sarfartoq 1' is a high grade, low tonnage type of deposit. There is an expected minimum of 0.1×10^6 ton of mineralised rock, calculated to a depth of 50 m, carrying 15 %, Nb_2O_5 and 0.18 %, Ta_2O_5. Maximum values are as high as 58 % Nb_2O_5 and 0.58 % Ta_2O_5. This calculation is based only on surface observations.

Kimberlite-lamproite with diamond (#17)

Alkaline ultramafic dykes in the Sisimiut–Kangerlussuaq and Sarfartoq areas intrude the border zone between the Archaean craton and the Palaeoproterozoic Nagssugtoqidian orogen (Secher & Larsen 1980). The alkaline rocks were intruded along the Archaean border zone during continental rifting following the opening of the Iapetus sea at the dawn of the Cambrian (Secher & Larsen 1980). The region comprises several clusters of kimberlitic dykes and sills (more than 200 outcrops), that appear to be controlled by pre-existing joint systems or concordant with the enclosing gneiss. A large number of dykes are located in the vicinity of the Sarfartoq carbonatite complex (Jensen *et al.* 2003; Jensen & Secher

2004; Larsen 1991b). Diamonds have been found within some of the many kimberlitic dykes in the area. The dykes commonly contain numerous mantle xenoliths ranging in size from a few millimetres to several decimetres. The kimberlitic dykes in both the Sarfartoq and Sisimiut regions have ages of around 0.6 Ga (Larsen & Rex 1992).

In total around 900 diamonds (microdiamonds and a few macrodiamonds) have been found in dykes. Only dykes located within the unreworked Archean craton are known to be diamondiferous. The dykes are often subvertical, 1–2 m wide, and traceable for many hundreds of metres (Jensen *et al.* 2003; Jensen & Secher 2004; Jensen *et al.* 2004).

Sedimentary basins

In Greenland sedimentary basins, copper in sandstones is typical within Neoproterozoic and Triassic clastic sediments of East Greenland (Fig. 3). Lead and zinc in shale/carbonate sequences are widespread in the sedimentary basins of both East and North Greenland. A fossil placer in Milne Land represents a placer deposit and an evaporite deposit can be seen as the Permian celestite deposit at Karstryggen, East Greenland. The lead-zinc veins in mainly lower Permian sediments are the vein system in the Mesters Vig area including the closed Blyklippen Pb-Zn mine, East Greenland (Fig. 3).

Sandstone with copper (#18)

In the Neoproterozoic basin in central East Greenland strata-bound copper occurrences (Fig. 24) are located in the Eleonore Bay Supergroup (Ghisler *et al.* 1980a; Ghisler *et al.* 1980b; Ghisler *et al.* 1980c; Stendal 1979; Stendal 1980; Stendal & Ghisler 1984; Stendal & Hock 1981). The Tillite Group of a 700-800 m thick succession of Vendian age (610-570) Ma unconformably overlies the Eleonore Bay Supergroup. The Tillite Group includes two glaciogene diamictite formations (Hambrey & Spencer 1987).

The strata-bound copper mineralization 0.2 to 2 m thick is found at different stratigraphic levels in Neoproterozoic shale and quartzite and extends over a distance of 275 km. Eight levels of strata-bound occurrences are recorded). The Lyell Land Group is dominated by sandstone/quartzite and green quartzitic shale and comprises three levels with copper. In the top of the group copper is emplaced in a white quartzite. Epigenetic overprinting resulted in adding antimony to the copper bearing layers on Strindberg Land. The grade of copper in the mineralized zones is in general low (<1%). Mainly diagenetic processes, but were later modified by metamorphic mobilisation and locally enriched by hydrothermal solutions, probably concentrated the strata-bound copper sulfides.

Shale-hosted zinc-lead (#19a)

A major Lower Palaeozoic zinc-lead deposit occurs in the Franklinian basin. The deposit is hosted in argillaceous lithologies, which are deposited just north of the carbonate platform margin in Peary Land. The Cironen Fjord deposit is a SEDEX-type, shale-hosted massive sulphide consisting of pyrite, sphalerite and galena. The total tonnage of sulphides is estimated to exceed 350 million tons. The overall base metal resource is estimated at 20 million tons of 7% Zn, with a higher grade core of 7 million tons containing 9% Zn and 1% Pb (van der Stijl & Mosher 1998).

Carbonate-hosted zinc-lead (#19b,c)

The carbonate-hosted lead-zinc-silver deposit in Washington Land (#19b – Appendix 1) was discovered by the Geological Survey of Denmark and Greenland (GEUS) in July, 1997 (Jensen 1998; Jensen & Schønwandt 1998). Washington Land is made up of a Cambrian – Lower Silurian carbonate platform and a Lower Silurian reef belt succession of the Franklinian Basin. The mineralization is associated with strongly dolomitised carbonates with variable parageneses. Both pyrite-dominated, sphalerite-galena-dominated and pyrite-sphalerite galena-rich mineralised rocks occur (Jensen 1998; Jensen & Schønwandt 1998). Visually estimated Zn and Pb grades vary from close to nil to over 20% Zn and 10% Pb. Silver figures are normally anomalous up to *c.* 170 ppm (Jensen 1998).

The Navarana Fjord area in North Greenland is hosted in deep-water sequence (Jakobsen 1989; Jakobsen & Stendal 1987). Epigenetic sphalerite occurs in the Navarana Fjord Anticline. The sphalerite and associated subordinate barite constitute 60-70% of the matrix of a one-metre wide breccia zone situated centrally in a 5-7 m wide vertical calcite vein. The vein is emplaced in a fault fracture intersecting dolomites (Steenfelt 1991). The age of the mineral occurrence is not known, but is believed to be contemporaneous with the faulting of the Franklinian orogen. No tonnage estimation of the deposit is known.

Carbonate-hosted Palaeoproterozoic zinc-lead (#19d)

The Black Angel lead-zinc mine is hosted in the Marmorilik Formation of the Palaeoproterozoic Karrat Group (Garde 1978; Henderson & Pulvertaft 1987). The main ore bodies are hosted in calcitic marble and dolomite marble. The massive ore consists of pyrite, sphalerite and galena. The main accessory ore minerals are pyrrhotite, chalcopyrite, tennantite and arsenopyrite. Opinions on the genesis of the ores has varied from a sabkha model to the Mississippi Valley type (Carmichael 1988; Pedersen 1981) but at present the most likely model is considered to be a SEDEX-type model. The black Angel deposit comprised 13.6 million tons grading 12.3% Zn, 4.0% Pb and 29 ppm Ag. In the mining period from 1973 to 1990 11.2 million tons was excavated (Thomassen 1991).

Placer deposit with special metals (#20a)

A fossil zircon-monazite placer in Jurassic sandstone was detected as thorium anomalies during an airborne radiometric survey carried out by Nordisk Mineselskab A/S and the Research Establishment RISØ in 1970. Exploration comprised trenching and shallow diamond drilling. The heavy mineral sands occur as irregularly distributed 10-40 cm thick lenses within a c. 20-m thick unit of arkosic sandstone (Harpøth *et al.* 1986). The heavy mineral sands are rich in garnet, ilmenite, rutile, zircon, and monazite. The 20-m thick basal unit is estimated to contain 5 million tons with 1-3.8% Zr and 0.5%-1.9% REO (Harpøth *et al.* 1986). A *c.* 10 tons selective bulk sample from five pits has been investigated metallurgically. The average content of heavy minerals was 33 wt.% and consists of 40-50 % TiO_2 minerals (anatase), 20-30 % zircon, 10-15 % monazite, and 10-30 % iron oxides and garnets.

Placer deposit with titanium (#20b)

Ilmenite-rich placers occur at Moriusaq in the Thule (Pittuffik) region. Active beaches have an average grade of 43% TiO_2, while raised beaches near Moriusaq have grades of 12% TiO_2 (Dawes 1989; Ghisler & Thomsen 1971). Black sands occur along the entire coast in the region. The most conspicuous exposures occur on the active beaches. The darkest sands are concentratrated in diffuse layers (up to 50-cm thick); lighter coloured sandy beaches can be streaked with concentrations of dense black sands. The black sands on the uplifted beaches are associated with much coarser material and in general these deposits contain a smaller concentration of heavy minerals (Dawes 1989).

Evaporite with celestite (#21)

Strabound celstite ($SrSO_4$) mineralization in Upper Permian carbonates occurs at Karstryggen in Jameson Land. The Karstryggen formation comprises a marine marginal carbonate and evaporite sequence (Harpøth *et al.* 1986). The Karstryggen formation hosting the celestite deposit is dominated by limestone deposited in hypersaline shallow marine environment. The celestite deposit occurs in a 80 km^2 area with $SrSO_4$ content of 15-30% over sveral metres thickness. In general the intensity of the occurrence varies considerable both laterally and vertically but with a total tonnage of 25-50 million tons at a grade of *c.* 50% $SrSO_4$ (Harpøth *et al.* 1986).

Veins in sandstone with lead-zinc (#22)

Mesters Vig is the only area in central East Greenland where mining has taken place at the Blyklippen Mine, which was in production in the period between 1955 and 1962. The Mesters Vig area consists of Carboniferous, Permian and Triassic sediments intruded by Palaeogene doleritic dykes and sills. The Blyklippen lead-zinc deposit comprised a sulphide lens within a major quartz vein zone. The mined-out sulphide lens was 2-10 m thick, 300 m long and 160 m high. It consisted of 65% quartz, 15% sphalerite, 10% galena, 5-10% baryte and trace amounts of chalcopyrite and fahlore (Harpøth *et al.* 1986). Production totalled nearly 550,000 tons of ore grading 9.3% Pb and 9.9% Zn.

Geophysical signature

This section will focus on the aeromagnetic responses of different geological environments. Many of the surveys were partly financed by the Government of Greenland. For more information on the aeromagnetic data and also their relationship to different geological environments in Greenland see e.g. Nielsen & Rasmussen (2000), Rasmussen & van Gool (2000), Rasmussen *et al.* (2001), Rasmussen (2002), Nielsen (2004) and Nielsen & Rasmussen (2004).

Total magnetic field intensity data, obtained during aeromagnetic surveys, reflect certain properties of the rock sources, mirroring both primary geological settings and the result of the subsequent geological history. Because of this close relationship, such data can be integrated with other types of geoscientific data and successfully be used to characterise and unravel the elements of geological environments.

As both the original settings and their histories of development greatly vary from one place to another, the observations given here must be thought of as a generalisation. When dealing with total magnetic field intensity data the extractable information from the data is dependent on both quantity and quality of the original data, and the processing the data have been subjected to. The non-uniqueness is a property of many geophysical potential fields and presents a challenge in dealing with this sort of data. Thus, in addressing, the geophysical responses of the different geological environments other areas outside Greenland are referenced.

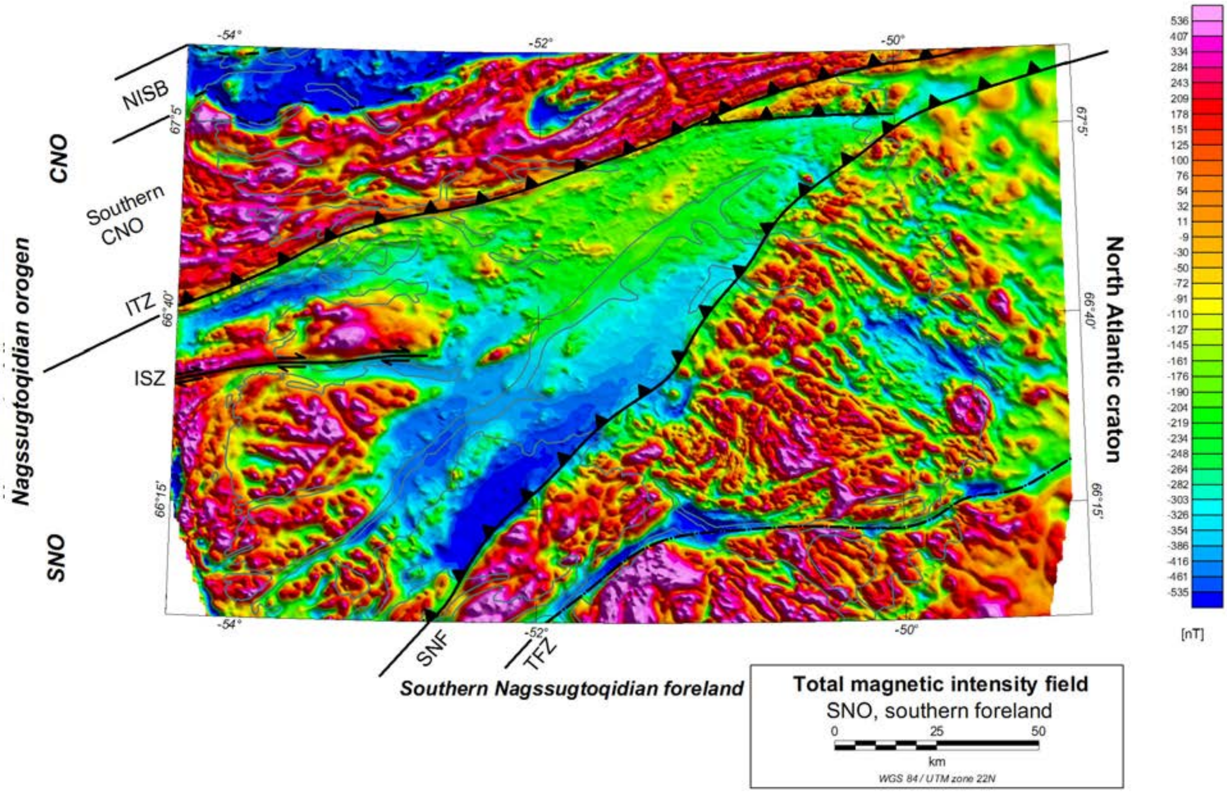
The magnetic properties of a rock and subsequently the level of magnetisation as reflected in the aeromagnetic field, are largely controlled by the content of mainly magnetite and to a lesser extent other ferromagnetic minerals (ulvöspinel, titanomagnetite, maghemite, pyrrhotite).

Infracrustal environments

As defined earlier, infracrustal rocks within the crust consists mainly of gneiss, tonalitic and granitic rocks of the Archaean and Palaeoproterozoic basement of Greenland. Regions dominated by infracrustal rocks are often characterised by complex aeromagnetic anomaly patterns reflecting the results of deformation, metamorphism and structural trends and features intersecting the area. On a large scale, these regions exhibit, in general, a higher level of magnetisation, where infracrustal regions in granulite facies are characterised by higher magnetic anomaly levels than regions in lower metamorphic facies.

During retrograde reaction magnetite is generally destroyed due to the oxidizing role of water and mineral reaction where magnetite break down to iron-bearing hydrous silicate minerals. Thus, infracrustal regions under retrograde amphibolite facies will in general be characterised by a smooth, homogenous low intensity, magnetic anomaly field. Examples of these anomaly patterns are seen at Søndre Strømfjord in West Greenland (Fig. 13). Middle to deeper crustal levels exposed in Precambrian regions represent originally constant oxidation state and high vapour pressure. Thus, continuous regions of high magnetisation can indicate highly oxidative condition in middle to deeper crustal levels (Airo 1999; Nielsen & Rasmussen 2004).

Figure 13. *Total magnetic intensity field for the area around Søndre Strømfjord – covering*



the Southern Nagssugtoqidian Orogen (SNO) and the northernmost part of the North Atlantic Craton (Southern Nagssugtoqidian foreland) in West Greenland. The large triangular low magnetic homogenous response in the middle of the area corresponds to a large infracrustal gneiss area, reworked and deformed under Palaeoproterozoic retrograde amphibolite facies conditions. The area south of the Southern Nagssugtoqidian Front (SNF) showing up with more heterogeneous high magnetic responses is in Archaean granulite facies. The north of the Ikertôq thrust zone (ITZ) in the southernmost part of the Central Nagssugtoqidian Orogen (CNO), which also is characterised by the high heterogeneous anomaly pattern is in Palaeoproterozoic granulite facies brought up by overthrusting. Abbreviations not given above: NISB, Nordre Isortoq steep belt; TFZ, Tasersiaq fault zone. The total magnetic field intensity is illuminated with from 315° at a 45° inclination. Figure from Nielsen & Rasmussen (2004).

Of special interest for work with mineral occurrences is of course the result of the rock's interaction with hydrothermal fluid systems. In many cases, such processes clearly influence the aeromagnetic response in an infracrustal region, as they do in many other geological environments. Depending on the fluid composition and other factors, the hydrothermal activities can either create or destruct ferromagnetic minerals.

Extensional fracture/fault zones at nearest-surface levels are characterised by low pressure and oxidizing conditions. This leads to an oxidation of magnetite to hematite (Henkel & Guzmán 1977). However, the infracrustal region in Greenland represents middle to deeper sections of the crust with brittle-ductile and ductile conditions associated with high pressure and constant oxidation. Crustal scale fault and shear structures under such conditions are commonly accompanied by a decrease in magnetisation caused by reaction between mafic hydro silicates, iron oxides and interacting fluids under ductile middle crustal (e.g. the Nordre Strømfjord shear zone, Fig. 14). Under brittle conditions, in the upper part of the crust, the magnetite is not as easily destroyed. Consequently, in general, the presence of brittle conditions in faults in former middle crustal levels yielding a distinct low magnetisation level indicates that the brittle nature of the faults was developed later than the process that created the magnetic expression (Airo 1999).

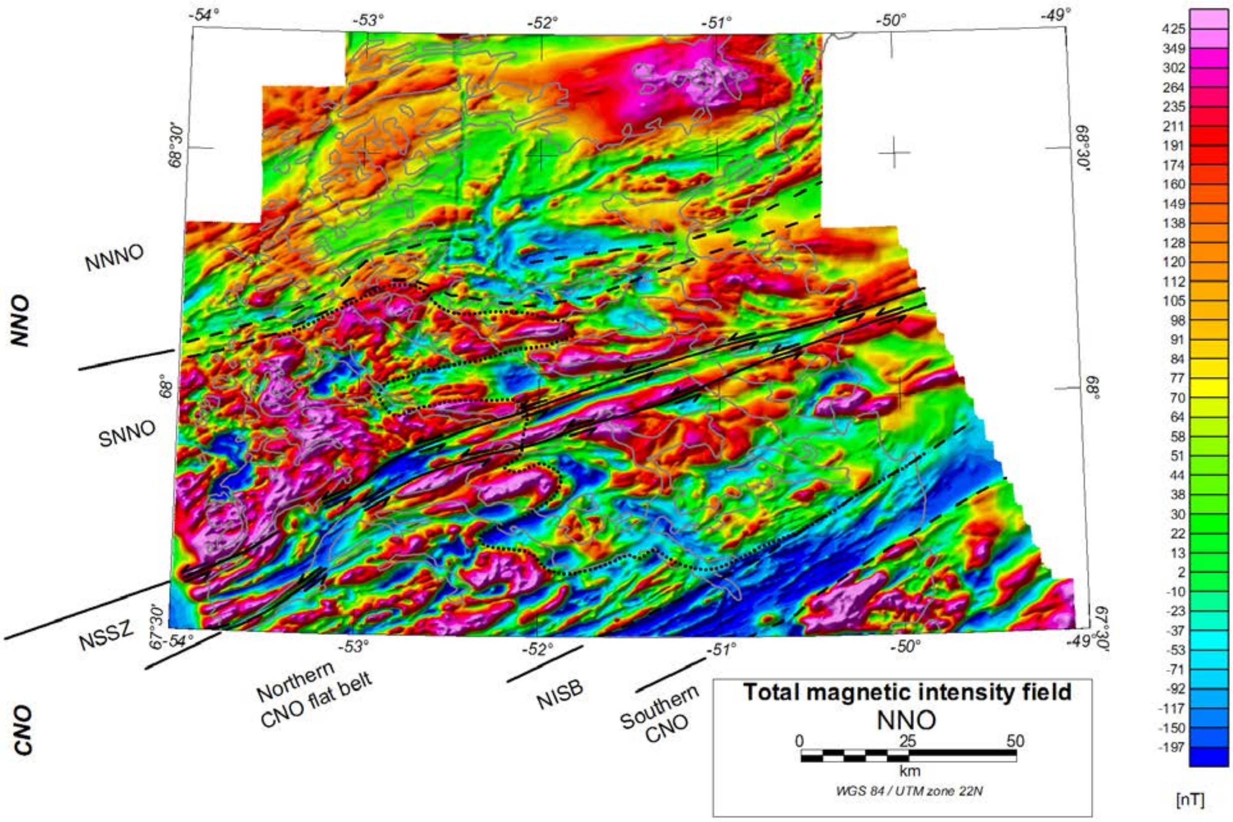


Figure 14. *Total magnetic field intensity for the Nordre Strømfjord shear zone (NSSZ) and surrounding areas. The shear zone is characterized by several well defined elongated short wavelength anomalies; these are thought to reflect both sheared supracrustal sequences within the zone and a general destruction of magnetite due to circulating fluid and hydrothermal activity within specific horizons or structures (faults) during shearing. The total magnetic field intensity is illuminated with from 315° at a 45° inclination. Abbreviation previously not given: NNO, Northern Nagssugtoqidian Orogen; NNNO and SNNO, Northern and Southern part of the NNO. Figure from Nielsen & Rasmussen (2004).*

Supracrustal environments

In general, supracrustal belts and greenstone belts in Greenland are in most cases outlined by magnetic lows. This is in agreement with the observations by Grant (1985), who observed a distinct correlation between greenstone belts and regional magnetic lows. Grant (1985) explain the lows as a result of the magmas, which gave birth to the volcanism in these belts differentiated mainly along the calc-alkaline trend. This leads to end-members that are generally low in iron, hence resulting in rocks with low magnetite-producing capacities. Also former metamorphosed greenstone belts, expressed as schists and gneisses that most likely have been derived from volcanogenic and sedimentary lithologies are outlined as magnetic lows in the Canadian Shield (Grant 1985).

In general, the belts are often expressed as narrow elongated low magnetic belts – mirroring the size and shape of the supracrustal belts. Though of low intensity, an undulation in the aeromagnetic field across a belt is seen, reflecting different magnetic properties of continuous strata. This often results in a magnetic banding of the belts. However, also strong magnetic rocks are present in supracrustal and greenstone belts. Cherty iron-formation and ultramafic intrusions will often be expressed as intense, local short-wavelength magnetic anomalies (Figs. 15 and 16). In areas of retrograde metamorphism and reworking, the responses of the infracrustal and supracrustal rocks are homogeneous and without much contrast. Grant (1985) submits aeromagnetic surveying as a very effective remote-sensing tool for the identification of greenstone belts and former greenstone belts and the experiences in Greenland very clearly supports this.

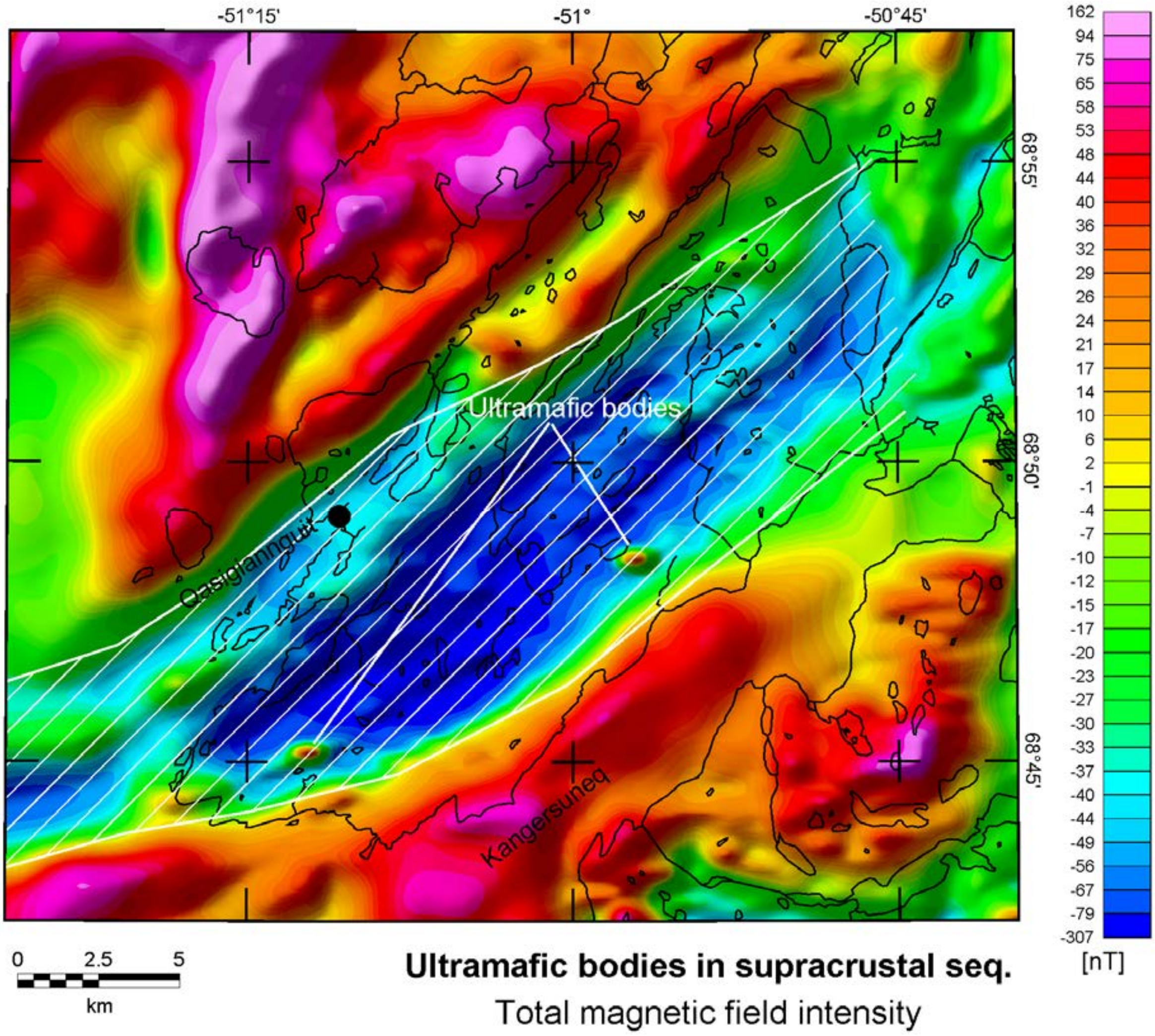


Figure 15. *Supracrustal rocks with ultramafic bodies at the town of Qasigiannguit in the south-eastern part of Disko Bugt. The supracrustal rocks are surrounded by gneiss lithologies on all sides. The total magnetic field intensity is illuminated with from 315° at a 45° inclination.*

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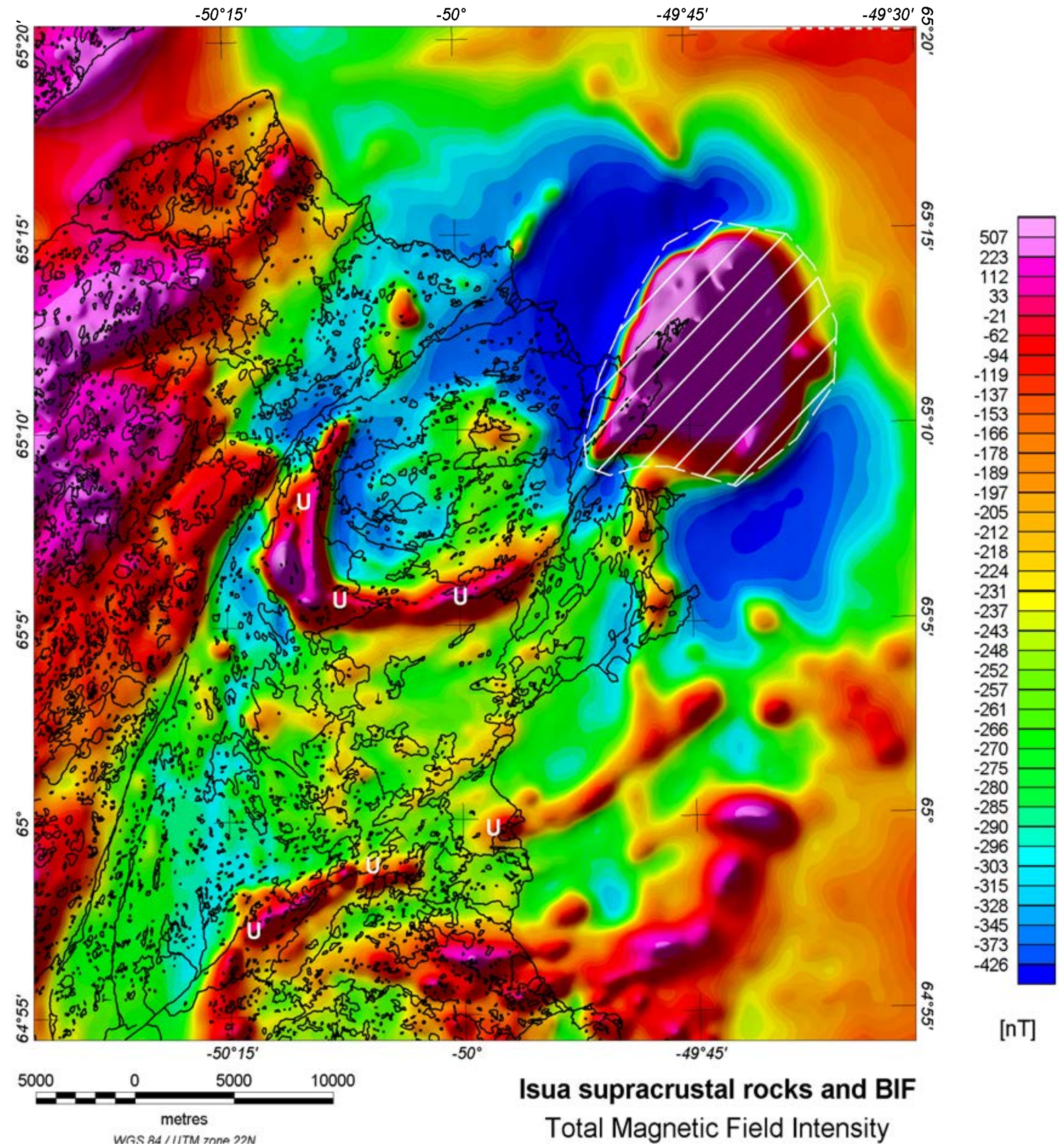

Figure 16. *The total magnetic field intensity at the large Isua banded iron formation (hatched polygon) is characterised by a very spectacular, distinct and highly magnetic response (20 000 nT). The horse-shoe-shaped anomaly and the train of high magnetic anomalies further to the south (labelled U) are generated by ultrabasic lithologies. The total magnetic field intensity is illuminated with from 315° at a 45° inclination*

Magmatic environments

The potential field responses of magmatic environments depend to a large degree on which types of magmatic rock are present. Therefore, the different environments described earlier in this report will be addressed separately.

Ketilidian Julianehåb batholith

The Julianehåb batholith domain in South Greenland (Figs. 5 and 17) consists of several intrusives. The intrusions are calc-alkaline or slightly alkaline in character and interpreted to have formed from juvenile Proterozoic magmas (Kalsbeek & Taylor 1985a). The batholith comprises granite, monzonite and diorites (appinites). Granites are in a relatively oxidized state and will therefore be expected to contain strongly magnetic iron oxides. This is also the case in South Greenland, where the batholith domain is expressed as a high magnetic zone (Fig. 18). Different separated magnetic anomalies may represent separated intrusives.

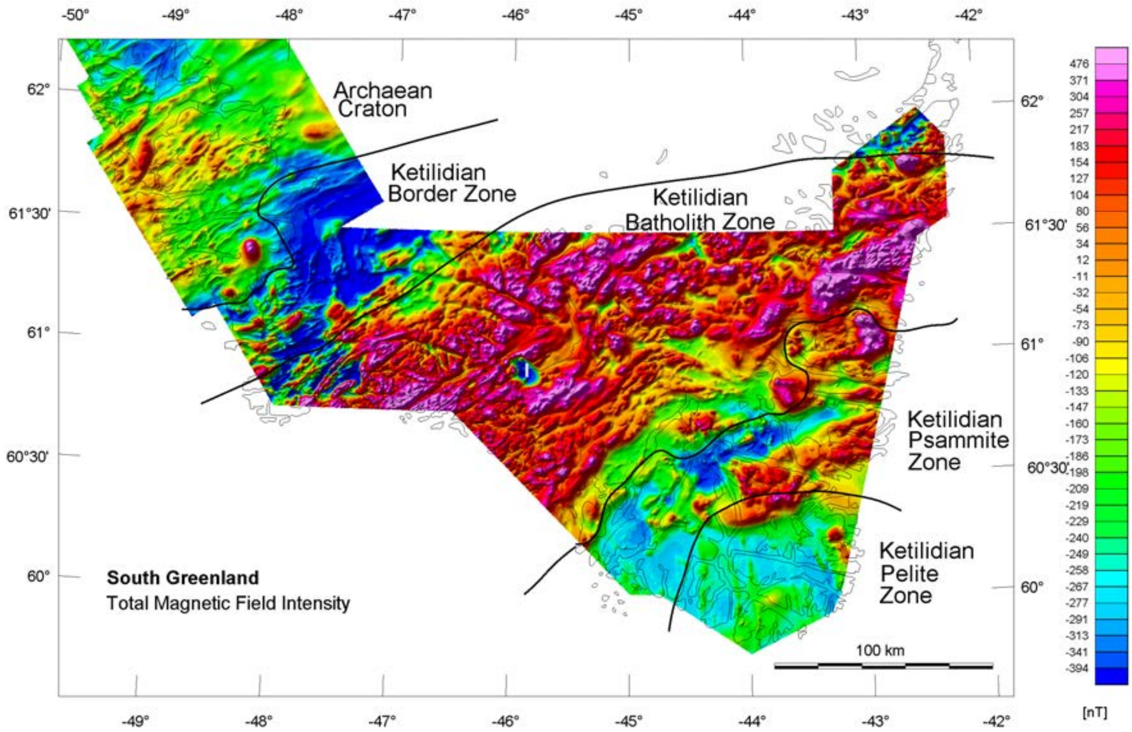

Figure 17. *Total magnetic field intensity for South Greenland.*

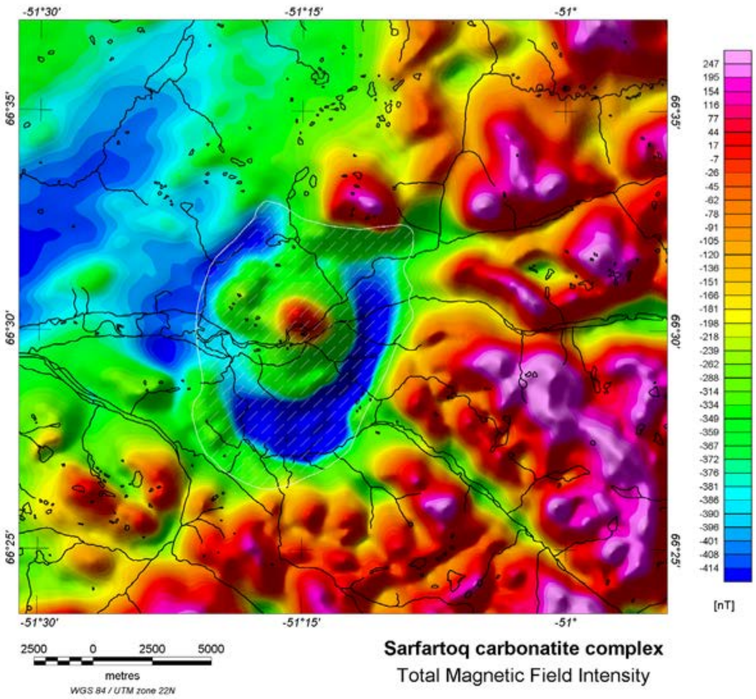

Figure 18. *Total magnetic field intensity from the Sarfartoq carbonatite complex and surroundings. The mapped surface exposure of the complex is indicated by a hatched polygon. The total magnetic field intensity is illuminated with from 315° at a 45° inclination.*

The Gardar province

The most silica-undersaturated intrusive complexes, Ilímaussaq alkaline complex in particular, create magnetic minima (label I in Fig. 19) while the saturated seem not to differ much in magnetic response from the Ketilidian Batholith intrusives.

Carbonatite and kimberlite suite

In general, carbonatite complexes in Greenland are associated with distinct short-wavelength circular to oval shaped anomalies when measured at altitude. These anomalies can often be seen to be associated with narrow bands of magnetite or magmatite sheets, when measured at the surface. The 600 Ma Sarfartoq carbonatite complex (Secher 1976; Secher & Larsen 1980; Secher & Thorning 1982) is characterized by a high magnetic field in the centre of the complex caused by the presence of magnetite (Fig. 18). The surrounding magnetic low is caused by hydrothermal alteration of the host rocks. The 170 Ma Qaqqaarsuk carbonatite complex (Knudsen 1989) located in the area south of Maniitsoq/Sukkertoppen Ice Cap represents the youngest alkaline magmatic event. However, not so clear, this complex shows similar anomaly patterns as the Sarfartoq complex (Fig. 19).

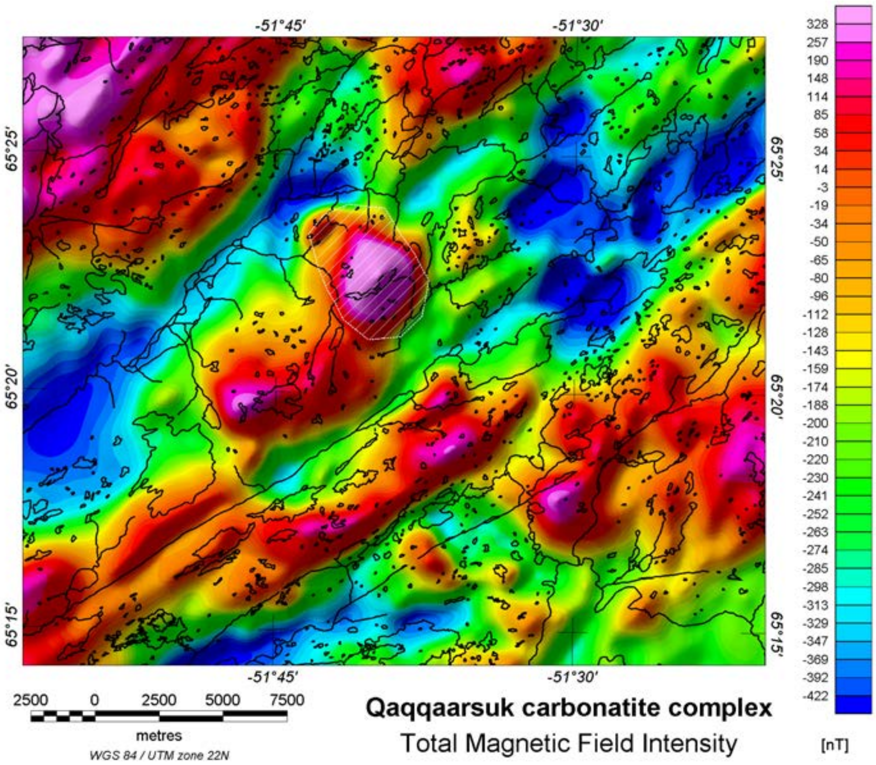

Figure 19. *The surface outline of the Qaqqaarsuk carbonatite complex is outlined by a hatched polygon. The total magnetic field intensity is illuminated with from 315° at a 45° inclination.*

Only detailed aeromagnetic surveys are able to detect the effects of the kimberlitic dykes in the area. The magnetic properties of the dykes are variable, but in general, the dykes are expressed as magnetic highs, when compared to the country rocks. An exceptional example of the magnetic signature of kimberlitic dykes comes from the thickest known dyke in Greenland located in an area south of Søndre Strømfjord. The dyke is at least 5 km long and 20 m wide and is evident as a distinct short-wavelength linear high intensity magnetic anomaly (Fig. 20).

Caledonian granite

Similar to the granites in South Greenland, the Caledonian granodiorites and granites are expected to yield high intensity magnetic anomalies with shapes outlining the intrusives.

Palaeogene magmas

In most cases, when Palaeogene extruded basalts are present, these dominate the magnetic response, both onshore and offshore. Differences in polarities of different basalt extrusions are governed by the polarity of the Earth's field during formation and are clearly defined by alternating highs and lows in the magnetic field values (Fig. 22), as are Palaeogene doleritic dykes and sills. An example of the responses from a large sill complex intruded in a sedimentary basin is seen in the Jameson Land Basin (Fig. 21) located on the

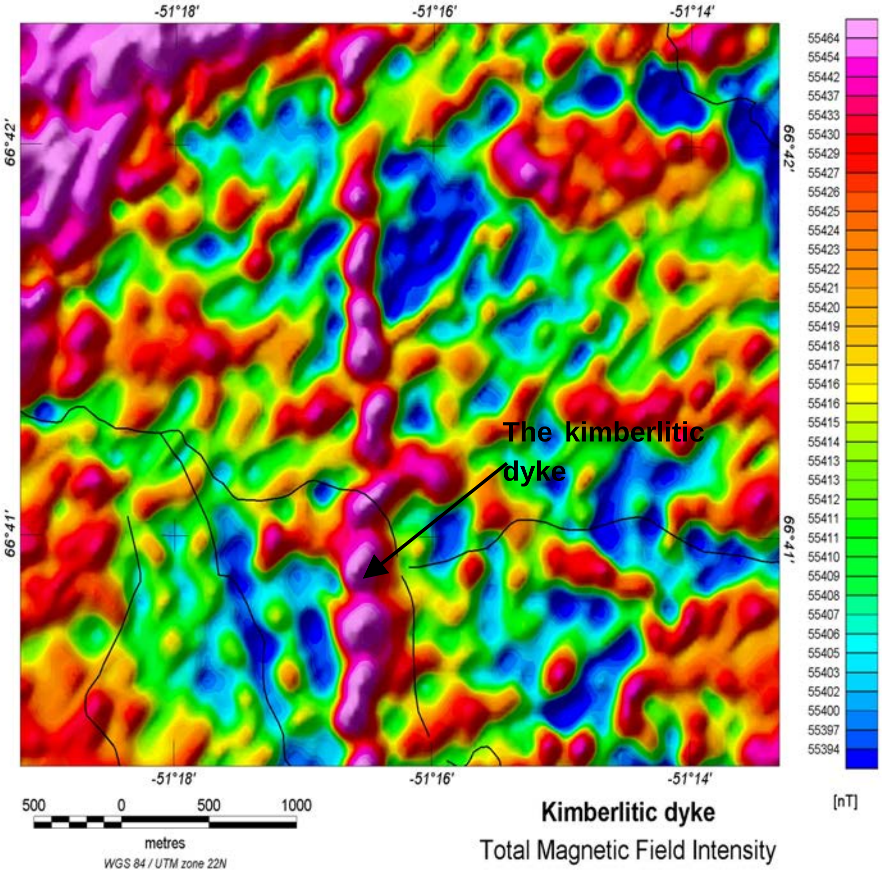

Figure 20. *Magnetic total field anomaly of a 5 km long and 20 m wide N-S orientated kimberlitic dyke is seen in the middle of the map. Data from helicopter-borne detailed DIGHEM survey carried out for the JV Citation Resources, BHP-Billiton and Cantex. The total magnetic field intensity is illuminated with from 315° at a 45° inclination. The original line spacing was 125 m and the senor altitude was 25 m over terrain (Stephens 1998).*

East Coast of Greenland. Another example is located offshore in the northern part of the Disko Bugt (Fig. 22).

Palaeogene intrusives are also clearly visible in the aeromagnetic anomaly patterns. The responses of the intrusives depend on their composition, specifically their content of magnetic minerals. An example of aeromagnetic patterns associated with Palaeogene intrusives in East Greenland is given in Figure 23.

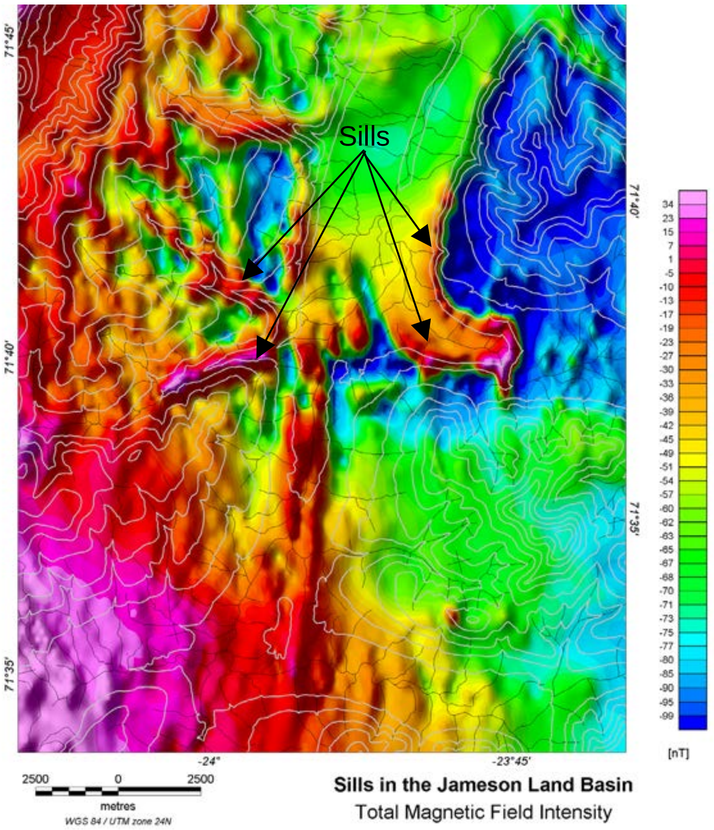

Figure 21. *Examples of aeromagnetic patterns caused by exposed sills at Ørsted Dal in the northern part of the Jameson Land sedimentary basin in central East Greenland. Though, iron skarn occurrences parallels to and probably also caused by the sill also influence the patterns (Nielsen 2000). The contour lines for the topography (grey lines) are shown together with the major rivers (black lines). The total magnetic field intensity is illuminated with from 315° at a 45° inclination. Note that anomalies are mostly created at the edges of magnetic bodies.*

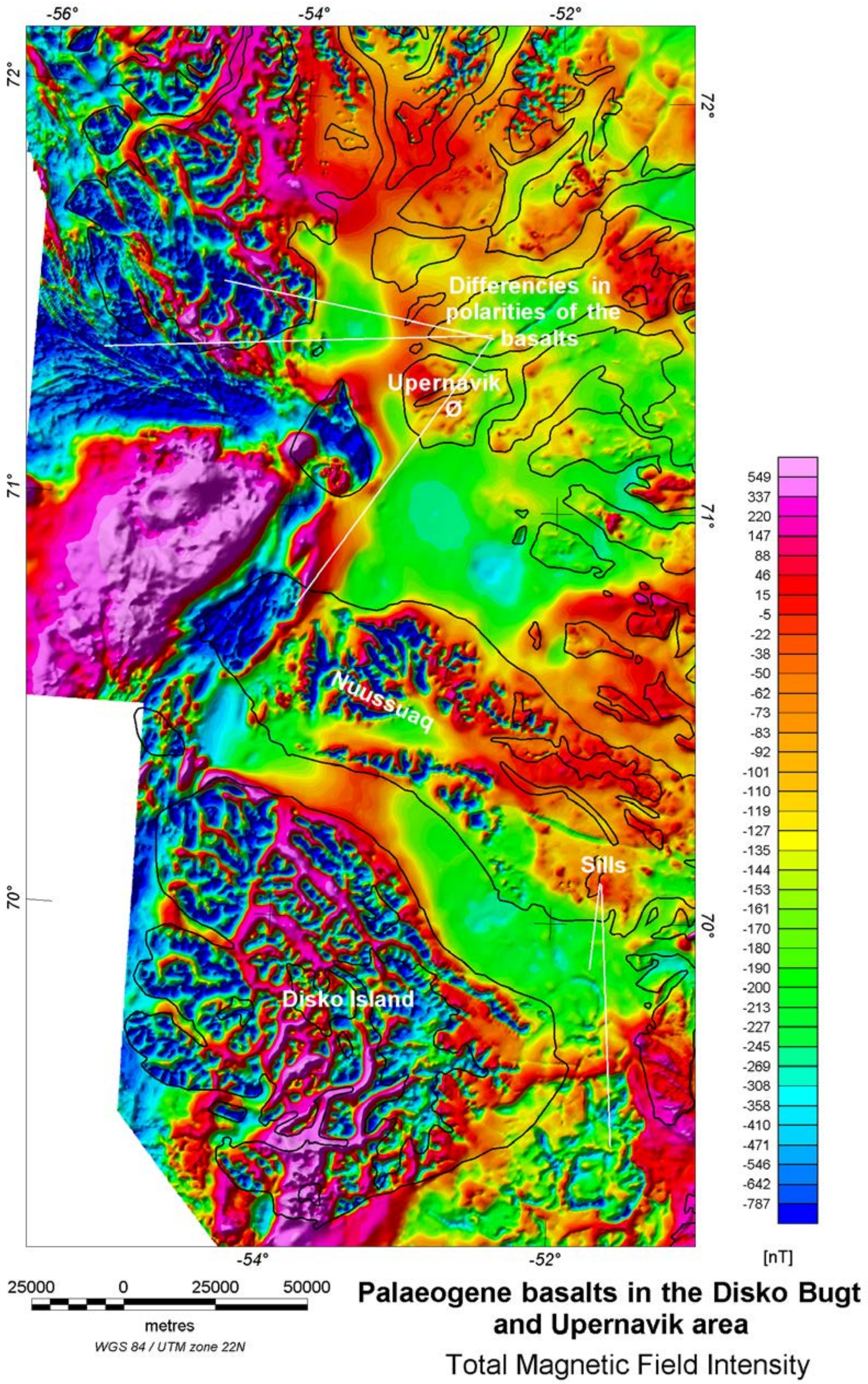

Figure 22. *Aeromagnetic expression of Palaeogene basalts in the Disko Bugt and Upernavik area. For further details see Rasmussen (2002). The total magnetic field intensity is illuminated with from 315° at a 45° inclination.*

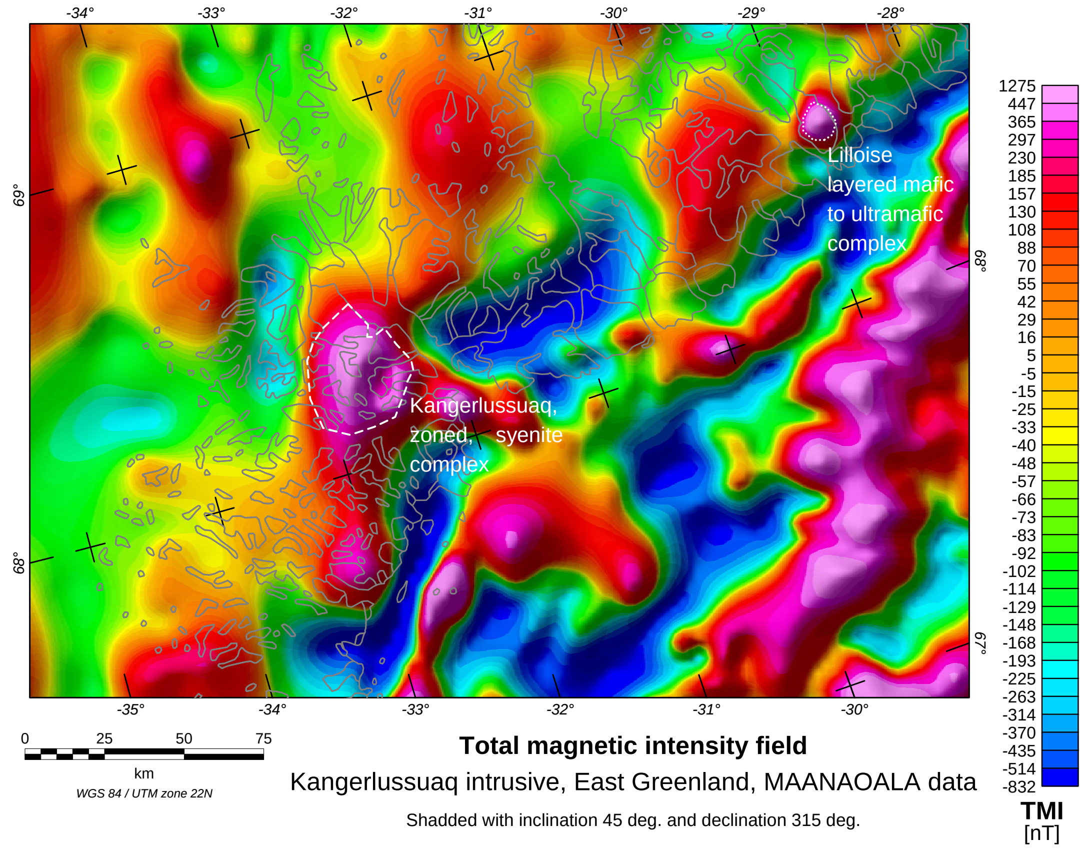

Figure 23. *Example on aeromagnetic patterns of intrusive complexes. The aeromagnetic data covering East Greenland comes from very regional data compilation 'Magnetic anomalies of the Artic and North Atlantic oceans and adjacent land areas' (Verhoef et al. 1996). The data in this compilation mainly originates from very regional and older surveys. However, as seen, even very regional aeromagnetic data sets are able to reflect the Palaeogene intrusives in East Greenland. The high magnetic response of the Kangerlussuaq complex is not believed to represent the alkaline surface-near parts of the complex, but may represent an underlying large mafic part of the complex (pers. com. T.F.D. Nielsen, GEUS). The total magnetic field intensity is illuminated with from 315° at a 45° inclination.*

Sedimentary depositional environments

Non-metamorphosed sedimentary rocks contain in most cases only a very small amount of magnetite because magnetite is unstable in the low-temperature, highly oxidizing environment of chemical weathering and sedimentation (Grant 1985). Consequently, sedimentary depositional environments are characterised by relative low and smooth level of magnetic anomaly responses, which often originates as attenuated anomalies associated with the underlying basement. Magnetic properties in sedimentary rocks will be continuous along the sedimentary layering and discontinuous across this layering. In many cases, crosscutting structures and differences in magnetic properties between different sedimentary lithologies in sedimentary strata are still visible as distinct anomaly patterns. Compared to plutonic and migmatised rocks, the magnetisation is lower but magnetic properties of sedimentary rocks are more variable. During compaction, the ferric hydroxides forms hematite and no significant quantities of magnetite are produced during diagenesis (Grant 1985).

Summary

Geological environments

The main geological environments in Greenland and their mineral resource have been described and divided into four main geological environments such as infracrustal regions, supracrustal regions, magmatic regions, and sedimentary basin regions. Within the various geological environments characteristic mineral deposits are outlined (Table 1).

About half of the ice-free area of Greenland consists of Archaean and Palaeoproterozoic rocks and comprise mostly infracrustal rocks. These infracrustal rocks are divided into three types of domains:

1. Archaean rocks (3700-2600 Ma) almost unaffected by later orogenic activities – e.g. Nuuk – Isua region.
2. Archaean basement reworked during Palaeoproterozoic times (2000-1700 Ma) e.g. – the Rinkian, Nagssugtoqidian mobile belts and the extension to the Ammassalik Mobile Belt on the East Coast of Greenland.
3. Areas with juvenile Palaeoproterozic rock (2000-1750 Ma) – e.g. Ketilidian mobile belt.

Within the infracrustal environment, not many mineral occurrences are recorded in Greenland from Table 1 includes three types: Gold in gneiss, nickel and copper in mafic intrusions, and olivine in ultramafic rocks.

Supracrustals comprise rocks, which are integrated parts of the basement rocks. In this report it is rocks older than 1600 Ma. Later metamorphic and deformation events have folded the supracrustal rocks together with the gneisses. The supracrustal rocks include metasedimentary rocks, metavolcanics and banded magnetite-quartzite formation. Special attention should be given to the mafic metavolcanics because of their high rate of mineral potential, not least with respect to gold and base metal deposits. These deposits are often related to greenstone belts with mafic volcanics or mixed mafic volcanic and sedimentary rocks. Other mineral occurrences than gold are iron, copper, chromium, tungsten, as well as industrial minerals.

The magmatic provinces described are the Palaeproterozoic Ketilidian batholith of South Greenland, the MesoproterozoicGardar Province of South Greenland, the province of carbonatites and kimberlites of West Greenland, the Caledonian granites of East Greenland, the Palaeogene basaltic provinces of East and West Greenland and the alkaline granitoid intrusions of East Greenland. The mineral occurrences in the magmatic environment include the porphyry system related to Palaeogene alkalic intrusion in East Greenland and associated vein systems with gold and silver; veins related to the Caledonian granite and the Julianehåb batholith, which carries tungsten, arsenic, antimony, and gold; the alkaline intrusions in the Gardar province have niobium, tantalum, zirconium, rare earth elements, and cryolite; carbonatite with niobium, tantalum, apatite and kimberlite-lamproite with diamonds are located within the Kangerlussuaq region of West Greenland.

The sedimentary basins described in details are the Mesoproterozic Thule Group, Krummedal succession and Independence Fjord Basin, the Neoproterozic Eleonore Bay Supergroup and Phanerozoic sedimentary basins of East and North Greenland. Many of the globally known types of mineral occurrences in the sedimentary environment also occur in Greenland. Examples are copper in sandstones in Neoproterozoic and Triassic clastic sediments; lead and zinc in shale/carbonate sequences are widespread in the sedimentary basins; a fossil placer represents a placer deposit and celestite an evaporite deposit; lead-zinc veins in sediments occur in the Mesters Vig area including the closed Blyklippen Pb-Zn mine, East Greenland.

Geophysical environments

The aeromagnetic data responses of different geological environments yield valuable information on both the primary geological settings and subsequent geological events. The data can be used on a regional scale, but can also be used on smaller scales when descriptions and interpretations of processes related to specific environments or mineral occurrences/mineralizing events are required. The considerations given on the aeromagnetic responses represent a generalization; the ambiguity of the total magnetic field intensity represented by the aeromagnetic data hinder an unambiguous interpretation of the data and many different processes may influence the magnetic properties.

On a regional scale, aeromagnetic data from infracrustal environments will often reflect the deformation and metamorphic history. In general, prograde granulite facies conditions results in heterogeneous higher magnetic anomaly levels than regions at lower metamorphic grade. Large-scale structures and tectonics crosscutting or separating infracrustal environments will in many cases be represented as abrupt changes and/or lineaments in anomaly patterns, smaller-scale structures, such as folds, faults, thrust and shear zones, will also be represented as lineaments. The responses of such geological features in the aeromagnetic data will often be more pronounced when these are influenced by hydrothermal fluid systems.

Supracrustal lithologies are in most cases characterized by low magnetic anomaly levels. When the supracrustal sequences consist of alternating continuous bands of different lithologies these results in elongated belts of alternating anomalies at different levels. Strongly magnetic rocks, especially ultrabasic/ultramafic lithologies, result in high magnetic level local short-wavelength anomalies.

The aeromagnetic responses of magmatic environments depend mainly on the composition of the magmatic rock. The shape and outline of an intrusion is in most cases derivable from the aeromagnetic responses. Granites at relatively high oxidation state are expected to contain a high content of strongly magnetic iron oxides and will consequently results in a high magnetic anomaly level. The magnetic anomaly levels of extruded basalts are in many cases determined by the polarity of the Earth’s field at the time of extrusion.

Rocks from non-metamorphosed sedimentary depositional environments contain in most cases only a small amount of magnetite. Consequently, such environments are characterized by relatively low and smooth level of magnetic anomaly responses, which often originates as attenuated anomalies associated with the underlying basement.

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Appendix

Mineral occurrence descriptions

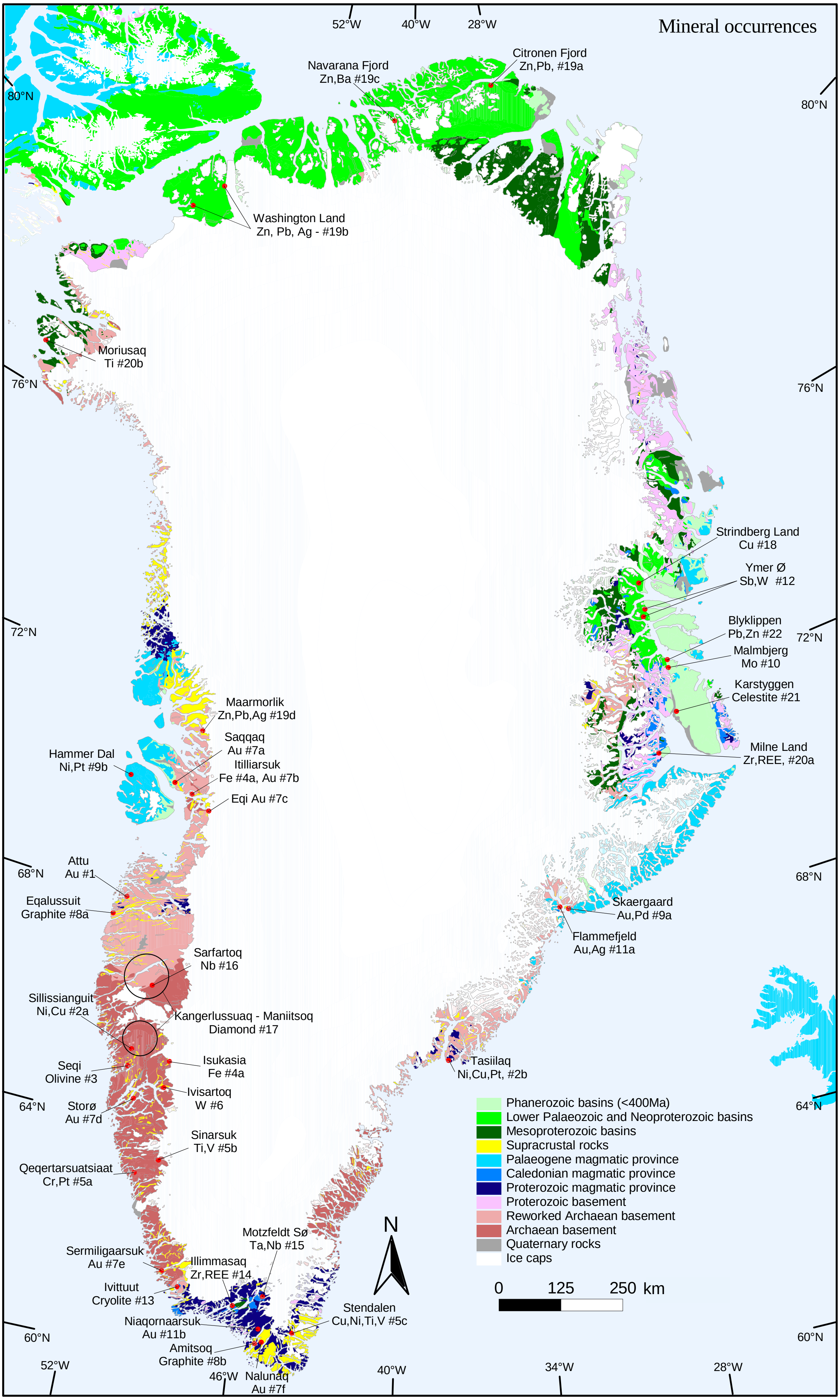
Figure 24. *Strindberg Land copper occurrence (malachite-staining) in quartzite.*

The various geological environments have a variety of mineral occurrences (e.g. Fig. 24). The aim is to describe some of the mineral occurrences representing the specific environment but also to illustrate the range of differences between the type of occurrence within the same environment. The descriptions are put into a format slightly modified from the occurrence descriptions found in (Stendal *et al.* 2004). The individual descriptions of the deposits can be found as data sheets on the following pages. For convenience and an overview, the mineral occurrences described under the specific environment-heading Figure 3 (Fig. 25) and Table 1 from the main text is repeated below.

Primary geological environment	Id #	Host rocks	Commodity	Examples
Infracrustals	**1**	Gness/granite	Gold	Attu, WG
	2a	Mafic intrusion	Nickel, copper	Sillissianguit, WG
	2b	Mafic intrusion	Nickel, copper	Tasiilaq; EG
	3	Ultramafic intrusion	Olivine	Seqi, WG
Supracrustals	**4a**	Greenstone	Iron - BIF	Isuakasia, WG
	4b	Greenstone	Iron - BIF	Itilliarsuk, WG
	5a	Mafic intusions (layered) in greenstone	Chromium, vanadium, copper, nickel	Qeqertarsuatsiaat, WG
	5b	Mafic intusions (layered) in greenstone	Vanadium	Sinarsuk, WG
	5c	Mafic intusions (layered) in greenstone	Copper, nickel, titanium, vanadium	Stendalen, SG
	6	Greenstone	Tungsten	Ivisartoq, WG
	7a	Greenstone	Gold	Saqqaq, WG
	7b	Greenstone	Gold	Itilliarsuk, WG
	7c	Greenstone	Gold	Eqi, WG
	7d	Greenstone	Gold	Storø, WG
	7e	Greenstone	Gold	Sermiligaarsuk, SG
	7f	Greenstone	Gold	Nalunaq, SG
	8a	Schist in supracrustal rock	Graphite	Eqalussuit, WG
	8b	Schist in supracrustal rock	Graphite	Amitsoq, SG
Igneous Deposits	**9a**	Mafic intrusion and extrusion	PGE, gold	Skaergaarden, EG;
	9b	Mafic intrusion and extrusion	PGE	Hammer Dal, WG
	10	Granitic intrusions (porphyry)	Molybdenum	Malmbjerg, EG
	11a	Veins related to granite	Gold, (silver)	Flammefjeld, EG
	11b	Veins related to granite	Gold	Niaqornaarsuk, SG
	12	Veins related to granite	Tungsten, antimony	Ymer Ø, EG
	13	Alkaline intrusion	Cryolite	Ivittuut, SG
	14	Alkaline intrusion	Zirconium	Ilimaussaq, SG
	15	Nefeline-syenite intrusion	Niobium, tantalum	Motzfeldt Sø, SG
	16	Carbonatite	Niobium	Sarfartoq,WG
	17	Kimberlite-lamproite	Diamond	Kangerlussuaq and Maniitsoq, WG
Sedimentary Deposits	**18**	Sandstone	Copper	Strindberg Land, EG
	19a	Carbonate/shale	Zinc, lead	Citronen Fjord, NG
	19b	Carbonate/shale	Zinc, lead	Washington Land, NG
	19c	Carbonate/shale	Zinc, lead	Navarana Fjord, NG
	19d	Carbonate/shale	Zinc, lead	Maarmorilik, WG
	20a	Palaeoplacer	Special metals	Milne Land, EG
	20b	Placer	Titanium	Moriusaq, NG
	21	Evaporite	Strontium (celestite)	Karstryggen, EG
	22	Veins in sandstone	Lead, zinc	Blyklippen (Mesters Vig), EG

Table 1 *Mineral deposits within the defined geological environments of Greenland.*

Figure 25*. Map of mineral occurrences within the main geological environments of Greenland. AC: Archaean Craton; AMB: Amassalik Mobile Belt; CO: Caledonian Orogeny; EO: Ellesmerian Orogeny; IMB: Inglefield Land Mobile Belt; KMB: Ketilidian Mobile Belt; NMB: Nagssugtoqidian Mobile Belt; RMB: Rinkian Mobile Belt.*



Mineral occurrences
52°W
40°W
28°W
80°N
76°N
72°N
68°N
64°N
60°N
46°W
34°W
N
Citronen Fjord
Zn,Pb, #19a
Navarana Fjord
Zn,Ba #19c
Washington Land
Zn, Pb, Ag - #19b
Moriusaq
Ti #20b
Strindberg Land
Cu #18
Ymer Ø
Sb,W #12
Blyklippen
Pb,Zn #22
Malmbjerg
Mo #10
Karstyggen
Celestite #21
Milne Land
Zr,REE, #20a
Maarmorlik
Zn,Pb,Ag #19d
Saqqaq
Au #7a
Itilliarsuk
Fe #4a, Au #7b
Hammer Dal
Ni,Pt #9b
Eqi Au #7c
Attu
Au #1
Eqalussuit
Graphite #8a
Skaergaard
Au,Pd #9a
Flammefjeld
Au,Ag #11a
Sarfartoq
Nb #16
Sillissianguit
Ni,Cu #2a
Kangerlussuaq - Maniitsoq
Diamond #17
Seqi
Olivine #3
Isukasia
Fe #4a
Tasiilaq
Ni,Cu,Pt, #2b
Ivisartoq
W #6
Storø
Au #7d
Sinarsuk
Ti,V #5b
Qeqertarsuatsiaat
Cr,Pt #5a
Motzfeldt Sø
Ta,Nb #15
Sermiligaarsuk
Au #7e
Illimmasaq
Zr,REE #14
Ivittuut
Cryolite #13
Stendalen
Cu,Ni,Ti,V #5c
Niaqornaarsuk
Au #11b
Amitsoq
Graphite #8b
Nalunaq
Au #7f
Phanerozoic basins (<400Ma)
Lower Palaeozoic and Neoproterozoic basins
Mesoproterozoic basins
Supracrustal rocks
Palaeogene magmatic province
Caledonian magmatic province
Proterozoic magmatic province
Proterozoic basement
Reworked Archaean basement
Archaean basement
Quaternary rocks
Ice caps
0 125 250 km

1

Locality name: **Attu**

Area: **Kangaatsiaq region**

GSC deposit type: **17 – Vein copper**

Commodities: **Gold (copper)**

Geological characteristics:

Description of occurrence: A prominent shear zone in the southern Attu area is 100–330 m wide. This zone has a complicated structure and consists of three parallel fault systems, that strikes NNE and dips 60–70^{o} W. A gold-bearing mylonite and shear zone cut through granulite and/or high amphibolite facies gneisses. The shear zone is pegmatised with 30–40 cm wide veins consisting of red K-feldspar and quartz with occasional magnetite. The estimated relative volume of pegmatite in the shear zone varies from 1–10 % in the shear zone (Stendal *et al.* 2002).

Geotectonic setting: Archaean gneisses and amphibolites.

Depositional environment/Geological setting: The best gold-bearing zone is found in a coastal profile along the mylonite and shear zone. The mylonite zone is silicified at the contact to the mineralised zone.

Age of mineralisation: Pb isotopic data of magnetite from the host rocks define a ^{207}Pb-^{206}Pb errorchron age of 3162 $\pm$43 Ma (MSWD = 0.5) and results of other minerals from the mineralisation lie close to this reference errorchron, indicating a more or less contemporaneous setting. Consequently, the timing of gold mineralisation is interpreted to be Late Archaean.

Host/Associated rock types: The host rocks to the gold prospect are brown gneiss and amphibolite.

Deposit form: The core locality is a cliff exposure consisting of 5–20 cm wide bands of mylonite and a rusty band (10–20 cm) with pyrite, magnetite and some chalcopyrite. The fault/shear zone can be followed along strike in northeasterly direction for several kilometres.

Texture/Structure: Pyrite and chalcopyrite replace magnetite. The magnetite is cataclastic but recrystallised magnetite does also occur.

Ore mineralogy: Magnetite, pyrite, chalcopyrite and gold.

Gangue mineralogy: Quartz, K-feldspar, muscovite, biotite and carbonates (calcite, dolomite or ankerite).

Weathering: Sulphide-rich parts are weathered to goehtite.

Ore controls: Mineralisation is within, or near, favourable mylonite/shear/fault zone. The gold is positively correlated with the sulphide and copper content.

Genetic models: The occurrences are hydrothermal and controlled by faults/shears. In the fault/shear systems vein and breccia zones occur.

Analytical data: The main gold locality has gold values from 2.3 to 5.8 ppm. Other localities in the same type of fault structure have 90 ppb Au (id. no. 67) 2.24 ppm and 124 ppb Au.

Exploration:

The site was found among an Ujarassiorit sample delivered in 2000. GEUS has visited the locality during fieldwork in 2001 and in 2002.

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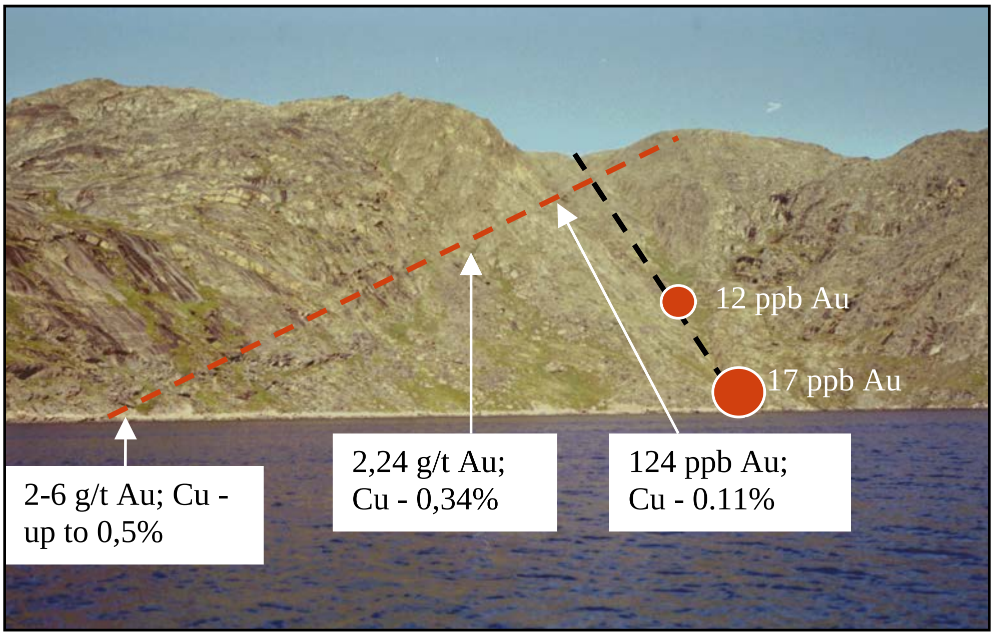

Figure 26. *The shear zone hosting the gold mineralisation south of Attu is indicated by the dashed red line. Gold and copper values in the white boxes are from rock samples. The red circles indicates locations for sampled stream sediments – and their gold content.*

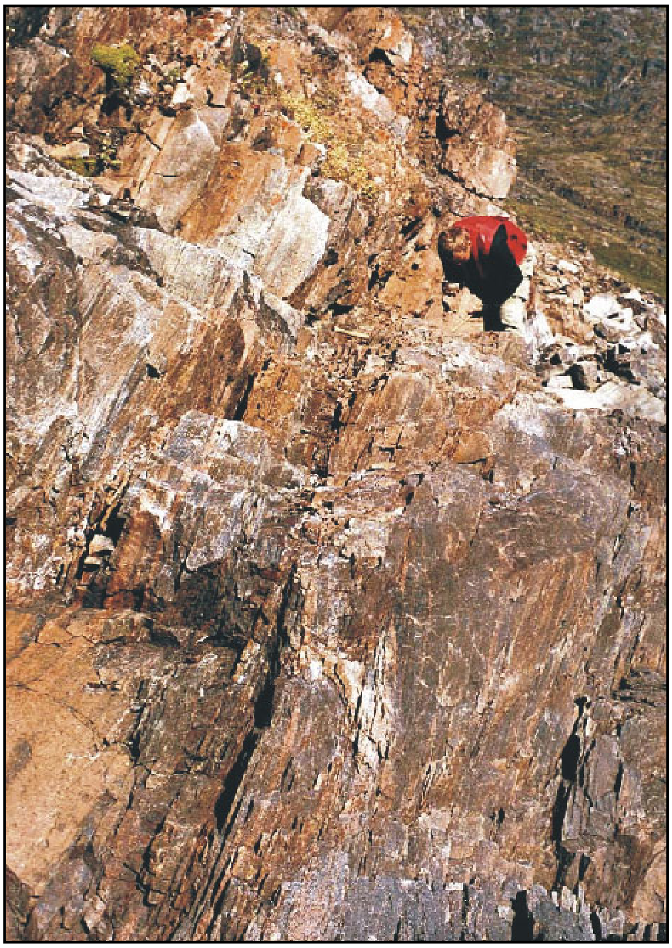

Figure 27. *The shear zone with mylonite and associated magnetite, pyrite and gold mineralisation, south of Attu.*

Figure 28. *Close-up of the gold bearing horizon in the shear zone with malachite staining (just above the white scale card, 5 cm wide).*

2a

Locality name: **Sillisissanguit Nunaat**

Area: **Maniitsoq**

GSC deposit type: **27.0 – Magmatic nickel -copper – PGE deposit**

Commodities: **Nickel and copper**

Geological characteristics:

Description of occurrence: A corridor rich in norite intrusions (‘The norite belt’) is located east of Maniitsoq and forms a 15 x 75 km belt of isolated bodies of basic rocks which intruded into the regional gneiss complex of the Akia terrane. The size of individual bodies varies from 2 x 4 km to only a few metres across. The rocks consist predominantly of melagabbronorite to leucogabbro, generally referred to as noritic rocks. Igneous textures and primary igneous layering are locally preserved. Elevated Ni and Cu concentrations were found in sulphide showings of magmatic origin, with some degree of metamorphic remobilisation.

Additionally the area is characterised by several horizons and layers of amphibolite, locally with pillow structures .The number of amphibolite layers is increasing towards the southern and eastern part of the area.

The noritic rocks are locally seen with gradual transistion into coarser grained leuconoritic and leucogabbroic rock types. The norite is typically very homogeneous but at a few localities igneous banding is noted with alternating layers composed of plagioclase and hypersthene with accessory chromite (Secher 1982).

Geotectonic setting: The ‘Norite belt’ located along the eastern flank of the domed Finnefjeld gneiss complex may be part of a tectonic setting structurally controlled by the Finnefjeld intrusion and later exposed to slight deformation.

Depositional environment/Geological setting: The norite is more or less unaffected by the high grade retrograde metamorphism observed in the surrounding basement (Garde 1991). A division in a northern and southern part of the ‘Norite belt’ was based on field observations (Secher 1982), with the northern part characterised by few large norite bodies and a southern part consisting of several small pods of norite.

Age of mineralisation: The age of the norite belt is uncertain, but likely around 3.0 Ga. Post-kinematic diorite intrusions in the Niaqunngunaq/Fiskefjord region, 2975 ± 13 Ma, south of the norite belt, have many aspects in common with the norite belt rocks and may be consanguineous with them (Garde 1991, 1997; Secher 2001).

Host/Associated rock types: The sulphides are located within noritic rocks.

Deposit form: Different modes of sulphide accumulation are recognised such as disseminations, veinlets, interstitial fillings and massive lumps. The Ni-Cu sulphide occurrences show a rather uniform Pd /Pt dispersion picture compared to other known occurrences related to large layered intrusions.

Texture/Structure: The occurrences are typically scattered as single spots and lenses, less than 5 m and rarely exceeding 25 m in length. Consequently, an ore reserve is difficult to calculate and has for the Ni+Co+Cu content so far been estimated as probably too small for economic exploitation (Keto 1998).

Ore mineralogy: The mineral assemblage is rather uniform, with pyrrhotite as the predominant mineral accompanied by chalcopyrite, pyrite and pentlandite in a primary texture together with pyrite, linneaite, bravoite and magnetite in a replacement texture. The average sulphide content in the mineralised rocks is around 2 vol% and locally up to 25% of the total rock volume.

Weathering: The sulphides are as a rule creating rustzones and gossans in outcrops (Secher & Stendal 1989).

Ore controls: The sulphide occurrences are scattered throughout the norite belt.

Genetic models: Ni-Cu sulphide occurrences are related to large layered intrusions. Later processes have influenced the accumulation of sulphides.

Exploration:

The noritic rocks have been the targets of nickel exploration since 1965 (Nielsen 1976; Secher 2001). Ni- values are varying around 1% with peak values up to 2% in sulphide rich lenses.

PGE analyses have only been carried out on few samples during exploration campaigns up to now. KØ mentioned (as reported in Nielsen (1973)) the typical Ni:Pd+Pt ratio in the sulphide mineralisation as in the order of 50 000:1. Similar and higher values were found by Secher (1988), varying up to 5000:1 in PGE enriched samples. The value of the PGE content is slightly increased as a function of the amount of sulphide, i. e. where later processes have influenced the accumulation of Pd + Pt and Au. Especially Pt and Au show mobility as part of later mineralisation processes, resulting in anomalous values of up to 2.1 ppm for each element (Secher 2001).

A detailed analysis programme focussing on PGEs reveals (Secher 2001):

- Peak values of Pd in three samples are 0.6 ppm and in five sample 0.2–0.4 ppm from mineralised norite as well as in amphibolite.
- A peak value for Pt in one sample is 2.2 ppm and in four samples 0.7 ppm, all from heavily mineralised and altered gabbro/amphibolite. Five samples show values of 0.2–0.6 ppm in mineralised norite.
- In total four samples show values for PGE (Pd+Pt) at 1.0–2.7 ppm in mineralised rocks.
- One sample shows an anomalous Au value of 2.1 ppm in slightly mineralised norite.

The showings are generally a few tens of metres long, and although observed in large numbers, were estimated to be of sub-economic size. The limited amount of sulphides within the 'Norite belt' apparently reduces the potential for PGE mineralisations.

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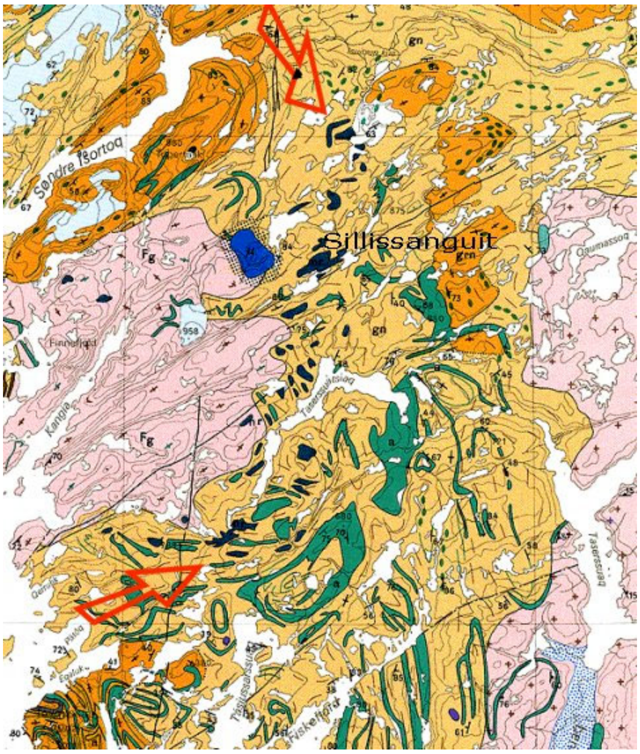

Figure 29. *Geological map of the Sillisissanguit area, West Greenland. The 'Norite Belt' is represented by dark figures between the red arrows. Size of map: 75 x 83 km.*

Figure 30. *Gossan in sulphide rich norite, Sillisissanguit area, West Greenland. Oil drums for scale.*

2b

Locality name: **Ammassalik Island**

Area: **Tasiilaq**

GSC deposit type: **27.0 – Magmatic nickel-copper-PGE deposit**

Commodities: **Nickel, copper**

Geological characteristics

Description of occurrence: The nickel discovery is situated on the south coast of Ammassalik Island 6 km southwest of Tasiilaq, East Greenland. The initial discovery resulted from 52 m of systematic chip sampling of the deeply weathered surface at the discovery outcrop yielding anomalous nickel, copper, platinum, palladium, gold, cobalt and silver.

Geotectonic setting: The terrain of gneiss and supracrustal rocks including banded iron formation and pods of serpentinized ultramafic rocks that are interpreted to represent similar geological terrain to that of Inco Ltd.'s famous Thompson Nickel belt in Manitoba, Canada.

Depositional environment/Geological setting: The prospect is centred on a nickel-copper-PGE-gold showing hosted by serpentinized ultramafics of potentially komatiitic affinity. The ultramafics appear to have originated as sills of basaltic composition that differentiated to layered mafic and ultramafic suites of rocks.

Age of mineralisation: Palaeoproterozoic ages judged from comparison with southern West Greenland.

Host/Associated rock types: Supracrustal rocks including banded iron formation and pods of serpentinised ultramafic rocks.

Deposit form: Mineralisation at the discovery outcrop extends for 90 m along strike and varies in width from 1 to 8 m covering a total area of approximately 440 m^2. Initial fieldwork has traced nickel bearing massive sulphide boulders in scree over 9 km along strike. In addition, similarly mineralised boulders have been found 4 km across strike indicating a second horizon.

Texture/Structure: Metamorphosed and folded supracrustal sequences including sills of basaltic composition.

Ore mineralogy: Pyrrhotite, chalcopyrite.

Gangue mineralogy: Mafic silicates, plagioclase.

Weathering: Heavy gossan.

Ore controls: Igneous accumulation

Genetic models: Ni-Cu sulphide occurrences are related to mafic intrusions. Later processes have probably influenced the accumulation of sulphides.

Analytical data

Analysis of average sample from a 52-m chip shows: 1% nickel, 0.3% copper, 0.012 g/t platinum, 0.239 g/t palladium, 0.155 g/t gold, 553 g/t cobalt and 2.4 g/t silver.

Exploration

The area has been prospected since 1999 By NunaMinerals A/S. GEM Fields Resources LTD has, together with Diamond Fields International, since 2003 operated under an exploration licence covering 55,000 ha on Ammassalik Island. Diamond Fields International has an agreement to acquire an 80% interest in the project on Ammassalik Island. The Company also entered into a JV agreement with NunaMinerals A/S, to earn an initial 65% interest in an additional 8,737 ha adjacent to the original claim concession ('Kitak'). Diamond Fields International is represented by its operator PF&U Mineral Development ApS.

In the field season of 2004 a large scale Electromagnetic/ Magnetic geophysical survey over the Ammassalik Island was carried out. Over 2000 line kilometres of data were collected. Follow up sampling and mapping are planned for 2005, together with an initial drill programme.

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Locality name: **Seqi (Seqinnersuusaaq)**

Area: **Maniitsoq**

GSC deposit type: **28.0 – Mafic/ultramafic rocks and related minerals**

Commodities: **Olivine**

Geological characteristics

Description of occurrence: Within the Fiskefjord area, several lens-shaped olivine rich peridotite (dunite) bodies occur, sized up to 0.5 x 1.5 km as the Seqi body. The Seqi rocks are homogeneous, granular, medium-grained olivinite and olivine rich peridotite. Layering with chromite and magnetite is common in selected parts of the dunite body. (Garde 1997a; Keto & Turkka 1967).

Geotectonic setting: In relation to deep-rooted shear zones within the Archaean basement.

Depositional environment/Geological setting: Ultrabasic igenous complex suggested to be crystallised as a part of an ophiolitic suite.

Age of mineralisation: As a part of a continued crustal accretion in the area the age around 3.0 Ga is determined (Garde 1977).

Host/Associated rock types: Dunitic rocks are situated in a basement of leucocratic orthogneisses and amphibolites with gradational transition from olivine poor peridotite to olivininite (dunite). Metamorphism has reached granulite facies, which invariably is overprinted by phases of amphibolite facies retrogression in the Fiskefjord area (Garde 1977).

Deposit form: The peridotite body is oval shaped, demonstrating a core of 0.3 x 1.1 km of massive dunite, with the long axis trending NE-SW.

Texture/Structure: In brief the body is composed of three varieties of olivine rich rock. Dominating is a homogeneous monomineralic rock, which is underlain by varieties of dunite with chromite layering, and porphyritic dunite, as a part of a suggested layered complex. The body is divided in two halves by a NW-SE trending steep fault.

Ore mineralogy: Olivine (forsterite) make up 98 % of the ore. Accessoric minerals are chromite and locally magnetite (Keto 1967).

Weathering: Olivine is weathering into a yellowish brown sand and partly decomposed (residual) dunite. Because of the colour the ore body is easily distinguished from the country basement rocks.

Ore controls: Layered igneous complex.

Genetic models: Cumulate from an ultrabasic magmatic intrusion, folded and metamorphosed after or during the emplacement.

Analytical data

Data reported from Keto & Turkka (1967):

Sample	SiO2	Al2O3	Fe2O3	FeO	MgO	NiO	LOI	Σ
Dunite (homogeneous)	40.98	0.28	0.96	6.28	49.89	0.38	0.44	99.31

Exploration

The Seqi olivine occurrence is fully exposed and has been subject to exploration with limited drilling and surface sampling by KØ (Keto1967), who also mined a test bulk sample of 12,5 t in 1971 (under the name Itipilua). NunaOil A/S prospected the area a couple of years and from 2003 and onwards Crew Development Ltd. (Seqi Olivine A/S) conducted a renewed exploration and a drilling programme with 22 holes and a large number of assays. Combined geological and geophysical studies have outlined a resource potential in excess of 100 million tonnes (Christiansen 1997; Lappalainen1971; Nielsen 1973).
In June 2004 the LKAB board authorised Minelco to proceed with the commercial arrangements with Crew and to place the olivine deposit into production. Following this decision, Seqi Olivine A/S has been formed as an operating company that will be jointly owned by Minelco and Crew and arrangements made to finance the company in accordance with the agreements between the companies. The company now has an exploitation licence.

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Figure 31. *The Seqi dunite body (yellow-brown) viewed from the air. The size of the body is c. 0.5 x 1 km.*

Locality name: **Isukasia**

Area: **Isua, Nuuk region**

GSC deposit type: **3.2 – Algoma type iron formation**

Commodities: **Iron**

Geological characteristics:

Description of occurrence: The early Archaean greenstone belts throughout the Nuuk region (Fig. 4) are characterised by an abundance of banded iron formation (BIF). BIF occurs mostly as quartz magnetite banded iron formation (oxide facies), but silicate facies consisting of alternating bands of grunerite and magnetite is also common. Carbonate facies iron formation consisting of alternating bands of siderite and magnetite is only found in one band in the Isua Greenstone Belt (IGB). This band is up to 10 m wide and can be traced for several kilometres. Minor minerals in carbonate facies are graphite, colourless amphibole, pyrrhotite and chalcopyrite. In oxide facies iron formation small amounts of actinolite and pyrite occur. Silicate facies with grunerite contain pyrrhotite, chalcopyrite and locally small amounts of gold (Appel 1982). In the easternmost part of the IGB a major body of oxide facies iron formation occurs. Two thirds are concealed under the Inland Ice (Appel *et al.* 2003).

Geotectonic setting: Soon after it was discovered that the Amîtsoq gneisses were early Archaean, it was realised that the Isua Greenstone Belt north-east of Godthåbsfjord is also early Archaean, since it is cut by orthogneisses containing Tarssartôq dykes equivalent to Ameralik dykes (Gill & Bridgwater 1979; Nutman 1986).

Depositional environment/Geological setting: The largest enclave of early Archaean greenstones occurs in the Isukasia area ~150 km northeast of Nuuk. This belt is crescent shaped about 40 km long and up to 4 km wide. Enclaves of greenstones up to several kilometres long and a few hundred metres wide occur in the area between Isukasia and Ivisaartoq. Large ultrabasic bodies with lesser amount of mafic volcanic rocks and banded iron formation dominate these greenstone belts. The early Archaean greenstone enclave at Isukasia has been studied in detail (Appel *et al.* 2003).

Age of mineralisation: The Isua Greenstone Belt (IGB) at Isukasia is at least 3.7 Ga old (Moorbath *et al.* 1973). The debate persists whether deposition was closer to 3.7 or 3.8 or even whether there are two separate periods of deposition within this time range (e.g. Nutman *et al.* 1997). There is no convincing evidence for in situ rocks that they are older than ca. 3.8 Ga, but recent Pb-isotope data on IGB metasediments and Pb-ores (Kamber *et al.* 2001; Kamber *et al.* 2003) suggest that important geochemical features pertaining to pre-4.0 Ga mantle and crust can be recognised.

Host/Associated rock types: Greenstone sequence.

Deposit form: The iron ore is a huge body (hundreds of metres in two directions) consisting of up to 30-cm wide magnetite bands alternating with quartz bands. The ore body is strongly deformed and occurs in a fold hinge. Many pre-deformational dykes cut the iron ore body, which significantly reduces the overall grade.

Texture/Structure: Banded – cm-dm size.

Ore mineralogy: Magnetite and hematite.

Gangue mineralogy: Quartz.

Weathering: Rusty appearance.

Ore controls: Syn-sedimentary precipitation.

Genetic models: Banded iron formation of the Algoma type.

Analytical data:
Kryolitselskabet Øresund A/S carried out drilling for several years and estimated the grade to 32% Fe with a tonnage of about 1.5 billion iron ore (Marcona 1971). On top of the quartz magnetite ore is an estimated 500 million tonnes of quartz hematite banded iron ore. High-grade hematite ore is not exposed, but abundant high-grade hematite float is seen in the area. Rio Tinto Ltd. has drilled this hematite orebody in the late 1990s (Coppard 1998).

Exploration:
In the late 1960's, KØ discovered a major geophysical anomaly in the Isukasia area. Ground check revealed a world class magnetite ore body, partly concealed under the Inland Ice. KØ immediately initiated a large drilling programme and constructed a drill camp at the edge of the ice sheet. Part of the drilling went through the ice. KØ collected bulk samples of magnetite ore for beneficiation tests. The samples were packed in plastic bags and piles of now rather worn plastic bags are still littering the area. Some of the bulk samples were flown down to the head of Godthåbsfjord where mineral collectors now use them (Marcona 1975). KØ furthermore carried out measurements of water flow in the rivers for future hydropower. The company also carried out topographic investigations for construction of a road to the iron mine from the head of Godthåbsfjord.
For a short period, the American iron Ore Company Marcona was involved, but Marcona never contributed significantly to the investigations in the area (Marcona 1975). In 1996 and 1997 Rio Tinto Ltd. carried out a drilling programme in the Isukasia area through the Inland Ice into the underlying ore body. The company proved that there is indeed a very large hematite orebody under the Inland Ice, overlaying the magnetite ore (Coppard 1998). However, Rio Tinto did not find any high grade hematite ore, so they pulled out.

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Figure 32. *The exploration camp at Isukasia in 1981. Exposures of the BIF iron ore in the foreground.*

Figure 33. *The Isukasia iron ore ridge close to the Inland Ice margin, viewed from South. Detail: Float of hematite ore, found along the ice margin.*

4b

Locality name:	**Itilliarsuk**
Area:	**Nuussuaq**
GSC deposit type:	**3.2 – Algoma-type iron-formation**
Commodities:	**Iron**

Geological characteristics:

Description of occurrence: Banded iron-formation occurs 200 m above a ‘rust zone' within the supracrustals. The thickest succession of supracrustal rocks north of Torsukattak occurs in the Itilliarsuk area (Fig. 8). The supracrustal sequence is at least 2.5 km thick. The contact between the supracrustal rocks and the underlying gneisses is strongly tectonised and a basal unconformity has not been located (Garde & Steenfelt 1999c). The sedimentary pile is of presumed Archaean age, and is intruded by gabbroic sills and thin felsic dykes (Fig. 40 in # 7b). The lower 400-m of the succession consist of amphibolite with sheared lenses of ultramafic rocks.

Within and on the top of this succession a polymict conglomerate with felsic and mafic clasts occurs. The felsic clasts resemble the underlying gneisses indicating that the supracrustal succession rest unconformably on the Nuussuaq gneiss (Garde & Steenfelt 1999c). The amphibolite succession is overlain by a more than 2-km thick sequence of siliciclastic rocks dominated by mica-garnet schists. Locally the siliciclastic succession is interlayered with up to 100-m thick amphibolite and metagabbro, and in the middle part very thin BIF horizons also occur. Several hundred metres of felsic volcanic rocks conclude the supracrustal succession. Lower amphibolite facies metamorphism and at least two phases of deformation have affected all rocks (Garde & Steenfelt 1999b; Garde & Steenfelt 1999c).

Geotectonic setting: The geotectonic setting of the Archaean supracrustal rocks of the area north of Torsukattak represent a rift or continental margin environment with more metasediments intercalated in the volcanic sequences than in the island arc setting towards south (Eqi and Arveprinsen Ejland) (Garde & Steenfelt 1999b).

Depositional environment/Geological setting: The banded iron-formation is an approximately 200-m wide sequence of 2–10 cm magnetite-rich cherty bands alternating with quartz-mica schists. The gradual transition zone between the iron-formation and the adjacent rocks in the sequence is characterised by a garnet-hornblende-magnetite bed. Laterally the iron rich strata grade into clastic sediments with accessory amounts of magnetite. The iron-rich beds gradually become poorer in magnetite and richer in garnet and hornblende. Cyclic repetition occurs between the magnetite-bearing bed and the occurrence of garnet and hornblende in distinct beds can be traced over 500 m along strike. This indicates that the transition from iron oxide to iron silicates reflects a primary chemical gradation in the sediment.

Age of mineralisation: The age of the mineralisation is uncertain but likely to be syngenetic with the Archaean host rocks.

Host/Associated rock types: The host rocks are acid and mafic volcanic rocks.

Deposit form: Stratiform beds (Fig. 34).

Texture/Structure: Cm-banding between magnetite, garnet and hornblende and quartz.

Ore mineralogy: Magnetite.

Gangue mineralogy: Quartz, garnet and hornblende.

Weathering: None.

Ore controls: Syngenetic banded iron-formation.

Genetic models: Algoma-type banded iron-formation. The cyclic repetition indicates that the transition from iron oxide to iron silicates reflects a primary gradation in the chemical sediment.

Analytical data:
Averaging 20% Fe.

Exploration:

Kryolitselskabet Øresund A/S initiated exploration in the Itilliarsuk area (Gothenborg & Keto 1986; Gothenborg & Morthorst 1981; Gothenborg & Morthorst 1982). NunaMinerals A/S later carried out some exploration in the area (Nunaminerals 2000). The Kryolitselskabet Øresund A/S has estimated that the best mineralised part covering an area of 130 x1000 m contains a resource of 150–200 million t of ore grading 20% Fe (Gothenborg & Morthorst 1981).

Figure 34. *Banded iron formation from Itilliarsuk. Photo Nunaminerals A/S.*

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5a

Locality name: **Qeqertarsuatsiaat**

Area: **Nuuk**

GSC deposit type: **28.0 – Mafic/ultramafic rocks and related minerals**

Commodities: **Chromium**

Geological characteristics:

Description of occurrence: The chromite deposits cover 4000 km^2 (the Fiskenæsset complex) in the Qeqertarsuatsiaat area in the Archaean gneiss basement of West Greenland. Chromitite layers are associated with an anorthositic rock suite in continuous stratigraphic horizons or smaller lenses within the gneiss. The anorthosite suite is associated with supracrustal amphibolites and comprises 8.5 % of the area under consideration. The layered anorthosite complex has an average thickness of 380 m and an exposed strike length of more than 200 km, which is commonly chromite bearing (Ghisler 1970,1976).

Geotectonic setting: The chromite deposits are confined to chromitite layers, which occur as stratigraphic horizons in the anorthosite unit of the complex. Minor chromite is also found in relic ultramafic layers and lenses at lower stratigraphic levels (Ghisler 1976).

Depositional environment/Geological setting: Stratiform layered igneous complex intruded into a supracrustal greenstone sequence within the Archaean basement. The complexhas later suffered folding in at least three fold phases (Myers 1985).

Age of mineralisation: The Fiskenæsset complex has been dated at c. 2850 Ma (Ashwal *et al*. 1989).

Host/Associated rock types: The layered complex consists of 87 % anorthositic and leuco-gabbroic rocks with minor gabbroic and ultramafic components such as dunite, peridotite, pyroxenite and hornblende, and shows similar stratigraphic sequences from place to place throughout the region. Calcic plagioclase (bytownite-anorthite) and Mg-rich hornblende are the dominant minerals of the complex**.**

Deposit form: The chromite horizons are usually between 0.5 m and 3 m thick, locally reaching maximum thicknesses of 20 m. Augen chromitite - a spotted rock of white plagioclase associated with chromite and hornblende - is the most common rock type. The plagioclase augen are variably deformed, resulting in different structural types of rocks from disoriented to schistose or banded chromitites. Massive hornblende chromitite is also encountered, often occurring as numerous thin layers intercalated with plagioclase.

Texture/Structure: Two types of chromite may be distinguished under the microscope, a poikilitic chromite with numerous silicate inclusions, and a pure chromite. As a result of hydrothermal alteration a number of secondary minerals were formed such as fuchsite and chrome-epidote.The complex with its chromite deposits has undergone high-grade metamorphism and three major phases of folding, which result in outcrops of layers with a complicated interference pattern on both major and minor scales.

Ore mineralogy: Chromite is associated with rutile, ilmenite and sulphides, and may contain exsolutions of magnetite. The silicate component of the chromitites consists of hornblende, biotite and plagioclase. Pyroxenes are only present in the chromitites associated with the ultramafics (Ghisler 1976).

Weathering: Chromite is generally unaffected by weathering. The anorthosite disintegrates into pure plagioclase gravel.

Ore controls: Sequences in layered igneous rocks. The problem of distinguishing between the primary magmatic and secondary metamorphic features of the chromite and associated minerals is thoroughly discussed by Ghisler (1976). Structural, textural and chemical considerations suggest that chromite was recrystallized to varying extent depending on different intensities of deformation under high-metamorphic conditions.

Genetic models: Cumulate from a layered igneous intrusion, which has suffered folding and metamorphism during or after the emplacement. A comparison of the Qeqertarsuatsiaat chromite deposits with other stratiform type occurrences suggests that they represent a distinct new type – the Fiskenæsset chromite metamorphic type.

Analytical data:

An extensive geochemical study of the chromites is presented by Ghisler (1976). Nearly 200 chromite concentrates were analysed by X-ray fluorescence and about 40 samples were investigated with the microprobe. More than 1000 spot analyses of the main elements Cr, Fe, Al and Mg have been carried out. Trace element analyses for V, Ti, Mn, Ni, Co as well as precious metals are carried out as well. The ultramafics contain up to 5% sulphides with 0.1-0.3% Cu and 0.1-0.2 Ni. Peak values of up to 4 ppm of combined PGEs are associated with sulphides. (Bishop *et al.* 1980; Ghisler 1976). Molybdenite occurs locally in all units of the complex (Myers 1974).

Exploration:

Since the discovery of the chromite layers in 1964 (Windley 1967, Ghisler & Windley 1967) the Cr-potential as well as the Ni, PGE and precious stone (ruby) -potential of the deposit has been explored by the company Platinomino A/S from 1970 to 1982. Platinomino A/S was focused on geological mapping of mineralised areas and the company terminated the activity without exploitation attempts. Only the ruby investigation has been continued since 2004 by a new licensee. Work done by the Survey on the applicability of ground magnetics in the chromite prospecting was carried out in the late 1960s (Ghisler & Sharma 1969).

From the economic point of view the primary composition of the chromites rich in Al and Fe, and the association with anorthositic rocks represent characteristic differences compared to other major stratiform deposits such as those connected with the Stillwater, Bushveld, Great Dyke, Sittam-pundi and Bird River complexes.

The estimation of the resources include 2.5 Mt of 32.7% Cr_2O_3 in one location, and more widespread 100 Mt of low-grade ore (Ghisler 1970,1976). The Cr/Fe ratio of the ore is in average around 0.85:1. Significant platinum, vanadium and titanium values are also reported from the complex.

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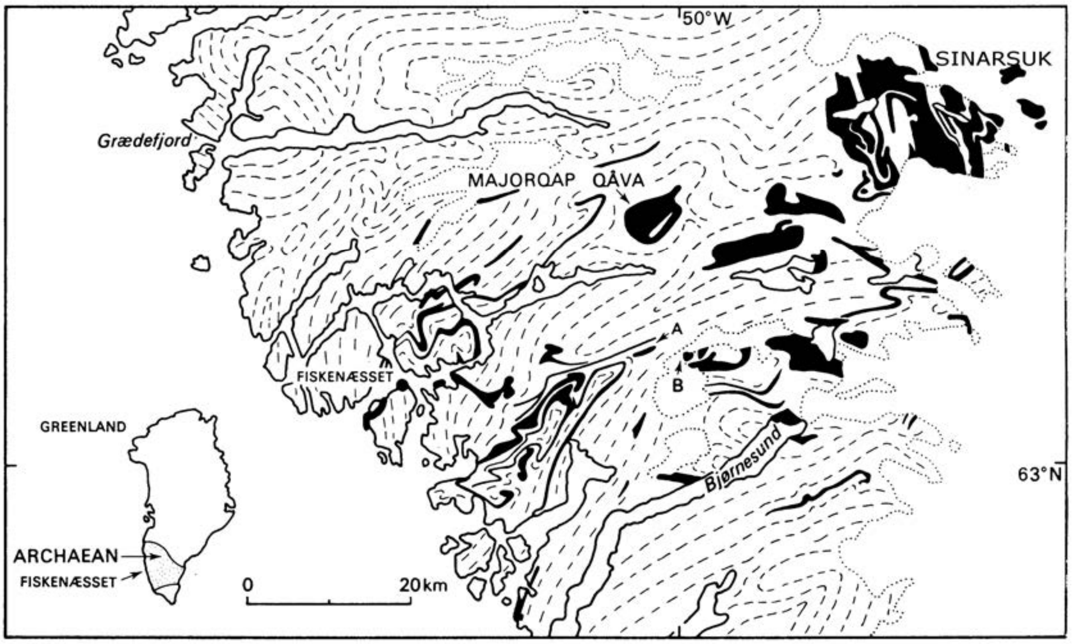

Figure 35. *Geological map of the Qeqertarsuatsiaat (Fiskenæsset) area, West Greenland.*

Figure 36. *Chromitite banded anorthosite from the Fiskenæsset Complex, West Greenland.*

5b

Locality name: **Sinarsuk**

Area: **Qeqertarsuatsiaat**

GSC deposit type: **28.0 – Mafic/ultramafic rocks and related minerals**

Commodities: **Titanium, vanadium**

Geological characteristics:

Description of occurrence: Titanium-vanadium accumulation occurs in magnetite/ilmenite-rich horizons within layered anorthosite-gabbro zones of the Sinarsuk deposit, West Greenland. The deposit is part of the metamorphosed layered Fiskenæsset complex (see **5a**), situated in the upper gabbro unit of the eastern part of the complex. (Grammatikopoulos *et al.* 2002, Myers 1985).

Geotectonic setting: The deposit is confined to gabbroic layers, which occur as stratigraphic horizons in the layered complex.

Depositional environment/Geological setting: Stratiform layered igneous complex intruded into a supracrustal greenstone sequence within the Archaean basement. The complex has later suffered folding in at least three fold phases (Myers 1985).

Age of mineralisation: The Fiskenæsset complex has been dated at c. 2850 Ma (Ashwal *et al*. 1989)

Host/Associated rock types: The layered complex consists of 87 % anorthositic and leuco-gabbroic rocks with minor gabbroic and ultramafic components such as dunite, peridotite, pyroxenite and hornblende, and shows similar stratigraphic sequences from place to place throughout the region. Calcic plagioclase (bytownite-anorthite) and Mg-rich hornblende are the dominant minerals of the complex.

Deposit form: The oxide-rich areas form semimassive layers (35-65 % oxides) up to 1 m, often showing a gradual transition laterally into layers of disseminated oxides (<35% oxides) in up to 15 m wide sections. A section of at least 8 km in length locally shows vanadium enrichment with values of V_2O_5 up to 2.68 wt% in magnetite rich layers.

Texture/Structure: The magnetite/ilmenite is found as mineral graded layers at the base of the upper gabbro unit. The complex has undergone high-grade metamorphism and three major phases of folding, which result in outcrops of layers with a complicated interference pattern on both major and minor scales.

Ore mineralogy: The main oxide minerals are vanadiferous magnetite and ilmenite, comprising 30% to 90% of the rock volume and the ratio of magnetite to ilmenite ranges from 3:2 to 4:1. Ore microscopy shows that magnetite and ilmenite vary between 0.2 mm and 4.5 mm in grain size, but locally they are coarser grained. Electron microprobe analyses indicate that magnetite grains are homogeneous and have a vanadium content, in different mineralised samples, ranging from 1.93 wt% to 2.68 wt% equivalent V_2O_5. Ilmenite hosts abundant and variably sized hematite lamellae, and it has vanadium contents ranging from 0.32 wt% to 0.59 wt% equivalent V_2O_5.

Weathering: Magnetite and ilmenite are generally unaffected by weathering. The anorthosite disintegrates into pure plagioclase gravel.

Ore controls: Layered igneous complex.

Genetic models: Cumulate from an ultrabasic magmatic intrusion, folded and metamorphosed after or during the emplacement.

Analytical data:
Not available.

Exploration:
The Sinarsuk deposit (original name: Dyke Mt.) was discovered and mapped by Platinomino A/S during field work in 1970 (Geisler 1971). The concession was released in 1982 apparently without further follow-up work in the Dyke Mt. Area. The exploration was resumed by Nunaoil A/S 1996-98 including additional mapping and ground geophysics. Preliminary beneficiation tests were conducted, however, the concession was released in 1999.

Preliminary beneficiation of two composite bulk samples showed that the ore can be beneficiated fairly easily using low-intensity magnetic separation at a coarse grind to yield a vanadiferous magnetite concentrate. The presence of hematite lamellae in ilmenite prevents recovery of a satisfactory ilmenite concentrate. However, further laboratory testing is required to establish the final beneficiation program (Grammatikopoulos *et al.* 2002).

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5c

Locality name:	**Stendalen**
Area:	**Lindenow Fjord, SE Greenland**
GSC deposit type:	**27 - Magmatic nickel-copper-PGE**
Commodities:	**Copper, nickel, titanium, vanadium**

Geological characteristics:

Description of occurrence: The Stendalen gabbro (Figs. 5 & 37) is a folded, sheet-like body at least 8 km in length and several hundred metres thick (Garde et al. 1997). It is composed of gabbro, leucogabbro, and diorite, locally with primary banding and divided into two main units: a lower layered gabbro unit and an upper homogeneous gabbro to diorite unit. For details about the Ketilidian orogen see Garde *et al.* (2002) & McCaffrey *et al.* (2004).

Copper-nickel-cobalt (sulphides): The lower part of the complex encloses five rusty-coloured rafts of assumed sedimentary origin. They are 1-15 metres thick and can be traced eastwards for 2 km along Lindenow Fjord (Stendal et al. 1997). Rusty layers are also reported to occur on the north side of the gabbro complex (Birkedal 1998). The rusty rafts are composed of quartz-feldspar-biotite schist with variable amounts of disseminated graphite and sulphides.

Iron-titanium-vanadium (oxides): A magnetite-rich zone separates the lower layered gabbro from the upper homogeneous gabbro. The zone varies in thickness and reaches a maximum width of 20 m. The magnetite-rich zone contains sulphide-rich bands variably enriched in pyhrrotite. About five metres of the zone is semi-massive and contains 20 vol. % ilmenite, 10 vol. % magnetite and 5 vol. % pyrrhotite, and less than 1% chalcopyrite (Birkedal 1998).

Copper-zinc (sulphides) - The meta-sedimentary sequence underlying the Stendalen gabbro complex contains a semi-massive iron-sulphide-bearing pelite layer. It is 5- 10 m thick, several hundred meters along strike and contains up to 10 vol.% graphite and 10 vol.% sulphides.

Geotectonic setting: The gabbro intrusion is part of the Julianehåb Batholith (1850-1800Ma) of the Ketilidian orogen.

Depositional environment/Geological setting:
The raft layers in the gabbro comprises semi-massive sulphides in shear zones.
Magnetic anomalies indicate that the ilmenite-magnetite layer is present throughout the gabbro complex and over an area of at least 2 km^2 (Birkedal 1998).

Age of mineralisation: Comtemporaneously with the formation of the Julianehåb batholith (1850–1800 Ma).

Host/Associated rock types: Gabbro

Deposit form: Sheets/layers of sulphides and oxides.

Texture/Structure: Strata-bound.

Ore mineralogy: Pyrrhotite, minor pyrite, chalcopyrite, and cobaltite, in the sulphide ores. The oxide ores have magnetite, ilmenite, pyrrhotite, chalcopyrite.

Gangue mineralogy: Graphite is abundant in the sulphide layers.

Weathering: Rusty appearrance of all sulphide bearing layers.

Ore controls: Synsedimentary sulphides in the metasediments, which are remobilized into shear zones, The oxide bearing layers are probably due to magmatic layering within the gabbro intrusion.

Genetic models: The oxide occurrences are genetic related to gabbro intrusion. The sulphides are probably part of the metasediments.

Analytical data:

The metal contents of the sulphide layers within the gabbro reach to 0.8% Cu, 0.5% Ni and 0.1% Co (Birkedal 1998). In general, the gold and PGE contents are low and the maximum value for gold is 169 ppb, for platinum 40 ppb and for palladium 19 ppb. The magnetite bearing samples reaches 0.2% V. The ilmenite-magnetite horizon has about 0.26 % V2O5 (Birkedal 1998). Samples from metasediment just aoutside the gabbro intrusion yielded maximum concentrations of 161 ppb Au, 1.4 % Cu, 0.24% Zn, 0.08 % Ni, 97 ppm Mo, 43 ppm Se, 53 ppm U, and 1160 ppm V (Swager *et al.* 1995).

Exploration:

Stendalen is located 65 km NW of the Prins Christian Sund weather station, about 4 km west of Illukulik on the north side of Lindenows Fjord, just west of the mouth of Nørrearm at N60^{o} 33-35' and W43^{o}42-45'. The Stendalen area was investigated by GEUS in 1992, 1994 and 1996 (Birkedal 1998; Stendal et al. 1997; Swager et al. 1995). Softrock Minerals Ltd. carried out exploration in 1997.

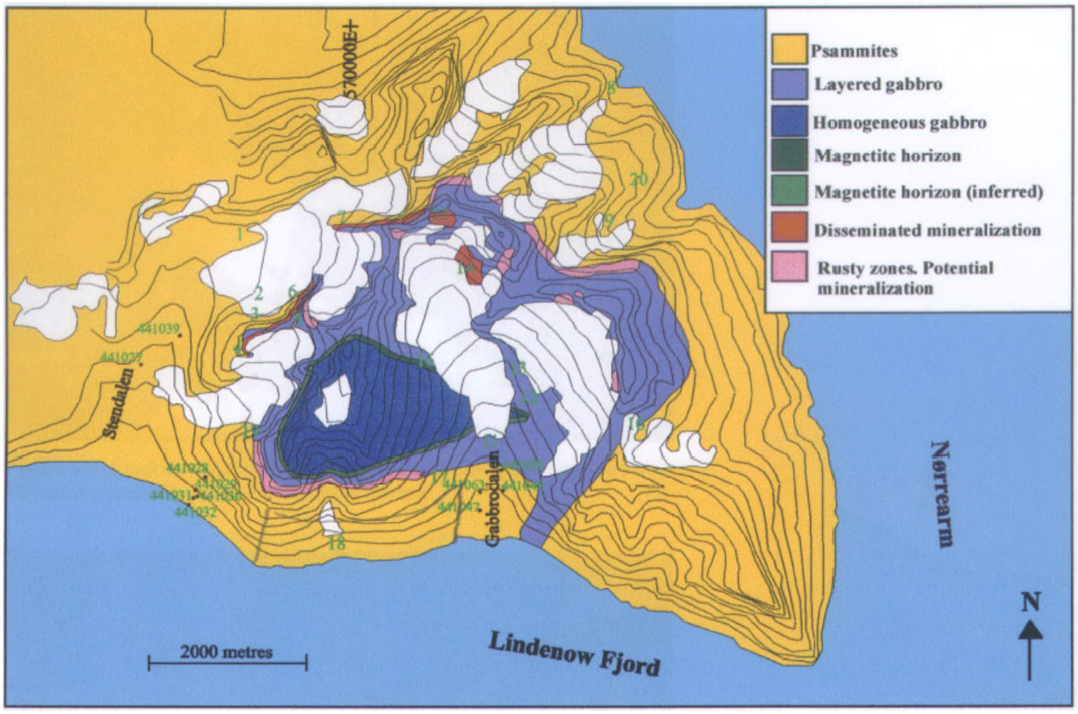

Figure 37. *The Stendalen gabbro complex, Lindenow Fjord, Southeast Greenland. From Birkedal (1998).*

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Locality name: **Ivisartoq**

Area: **Nuuk region**

GSC deposit type: **Not applicable**

Commodities: **Tungsten**

Geological characteristics:

Description of occurrence: Scheelite occurrences are mostly stratabound and occurs in banded amphibolites, tourmalinites and in carbonate altered komatiitic rocks (Appel 1986, 1994). The latter are found in the Ivisaartoq whereas the two former types are most abundant in the coastal area and on Store Malene
(Appel & Garde 1987; Appel 1990; Fig. 4). Scheelite occurs as disseminated grains, as porphyroblasts,
as stringers and veinlets and as up to 25 cm wide veins with massive scheelite. Scheelite mostly has very low molybdenum contents revealed by its bluish fluorescence colours. However, locally white to yellowish fluorescent scheelite is seen in cross cutting stringers. Scheelite is rarely associated with other metals of economic significance.

Geotectonic setting: The scheelite occurrences are interpreted as submarine exhalative and later modified and partly mobilised during subsequent deformation and metamorphism (Appel 1986, 1988, 1994; Appel *et al.* 2003).

Depositional environment/Geological setting: The greenstone belt is more than 40 km long and up to 3 km wide (Chadwick 1986). The belt is dominated by deformed pillow structured, low-K tholeiitic amphibolites, with unambiguous indications of 'way up', which are associated with deformed pyroclastic and pillow structured komatiites, dunitic-harzburgitic sills, stratiform gabbro and pale paragneisses, sometimes sulphide-rich. On grounds of the way up in the pillow lavas, Chadwick (1986) proposed that the oldest rocks in the greenstone belt are pale quartzo-feldspathic paragneisses, ca 500 m thick with thin pyrite-rich often fuchsite-stained quartz schists. The paragneisses were interpreted as metamorphosed acid to intermediate volcaniclastic sediments (Chadwick 1986).

Carbonate alteration is widespread, especially in the Ivisaartoq area. The first alteration event took place after formation of the pillows and is seen as patches of calc-silicate minerals in the pillow lavas. Somewhat later alteration resulted in calc-silicate formation of bands in the pillow lavas (Fig. 38).

Age of mineralisation: Middle Archaean.

Host/Associated rock types: Amphibolites.

Deposit form: Metre-wide veins of diopside, feldspar, garnet and vesuvianite sometimes with abundant scheelite were formed after at least one phase of deformation. The rocks are exceptionally rich in bromine, but with comparatively low chlorine contents yielding highly unusual Cl/Br ratios (Appel 1997).

Texture/Structure: Strata-bound.

Ore mineralogy: Scheelite.

Gangue mineralogy: Diopside, feldspar, garnet, tourmaline and vesuvianite.

Weathering: None.

Ore controls: Syngenetic with the mafic rocks.

Genetic models: Exhalative tungsten formations in mafic rocks together with tourmaline.

Analytical data:

Channel samples revealed grades of 0.44% WO3 over 2.5 m and 0.48% WO3 over 1.5 m. The scheelite-rich zones can be traced with intervals for more than 10 km along strike (Appel 1990).

Exploration:

The first indications of scheelite in the Nuuk region were found in 1982 in heavy mineral concentrates from stream sediments (Appel 1989). Subsequent work showed that the Nuuk region constitutes a tungsten province and that scheelite is widespread especially in the mid- to late-Archaean greenstone belts.

Figure 38: *Boudinaged band of calc-silicates (diopside, garnet and ± vesuvianite ± scheelite) in banded amphibolites in Ivisaartoq. Hammer for scale. From Appel et al. 2003).*

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Locality name: **Saqqaq**

Area: **Nuussuaq**

GSC deposit type: **15.3 – Iron-formation-hosted stratabound gold**

Commodities: **Gold, (nickel, copper)**

Geological characteristics:

Description of occurrence: An auriferous metachert horizon occurs between a mafic/ultramafic metavolcanic sequence and overlying metasedimentary rocks (Garde *et al.* 1999; Thomassen & Tukiainen 1992).The Saqqaq supracrustal rocks occur in a NW-SE striking belt (5 x 29 km), which is enclosed in the Archaean Nuussuaq gneisses (Fig. 8). The exposed thickness of the supracrustal rocks is approximately 0.5 km.

Geotectonic setting: The geotectonic setting of the Archaean supracrustal rocks of the area represents a possibly continental margin or back environment.

Depositional environment/Geological setting: The structural lower part of the sequence comprises 150 m of a mafic to ultramafic unit, which in the uppermost part includes a 3–4 m thick auriferous sulphide-bearing cherty quartzite. This unit is followed by c. 100-m thick mica-garnet schist, which is overlain by several hundred metres succession of interlayered amphibolite and metasediments. A granitoid sill (100 m) has intruded the upper part of the supracrustal rocks. The boundary relationships to the surrounding orthogneisses are not known nor is the direction of younging. Alteration is seen as chloritisation.

Age of mineralisation: The syngenetic mineralisation is Archaean.

Host/Associated rock types: Mafic- to ultramafic rocks.

Deposit form: Stratiform.

Texture/Structure: Disseminated fine-grained sulphides. Grains of native gold up to 20 µm occur both as inclusions in arsenopyrite and as single isolated grains (Garde *et al.* 1999).

Ore mineralogy: The auriferous metachert layer contains a few percent of disseminated iron sulphides with accessory amounts of arsenopyrite and chalcopyrite.

Gangue mineralogy: Quartz.

Weathering: Rusty ultramafic rocks.

Ore controls: Syngenetic mineralisation associated with mafic/ultramafic rocks.

Genetic models: The gold mineralisation is the stratiform type of exhalative origin as interpreted by Thomassen and Tukianinen (1992) and Garde *et al.* (1999). However, NunaMinerals A/S is of the opinion that the gold is related to shear zones. NunaMinerals A/S described the auriferous metachert horizon as the low angle 'Saqqaq shear zone'.

Analytical data:

Gold values in the range of 1 ppm over 2m can be followed for 4 km, but may be traced for a substantially longer distance. Within the continuously mineralised zone, at least three potential gold zones were identified yielding 8.2 ppm over 2 m, 15.9 ppm over 1 m, and 12.2 ppm over 2 m respectively (Nunaminerals 2000). The auriferous metachert layer is also anomalous in As (average 404 ppm), Ni (average 652 ppm) and Cr (average 1403 ppm). Other sulphide-bearing horizons within the mafic/ultramafic unit have proven to be slightly enriched in copper (Thomassen & Tukiainen 1992).

Exploration:

The Saqqaq supracrustal rocks were investigated by GGU during the Disko Bugt Project 1988–1992 (Thomassen & Tukiainen 1992). In 1992 Platinova A/S investigated the supracrustal belt (Atkinson & Rutherford 1992). During the late 1990s Nunaoil A/S and Nuna Minerals A/S did exploration and drilling on the deposit (Bliss 1997; Heilmann 1998; Heilmann 1999; Heilmann 2001; Petersen 1997).

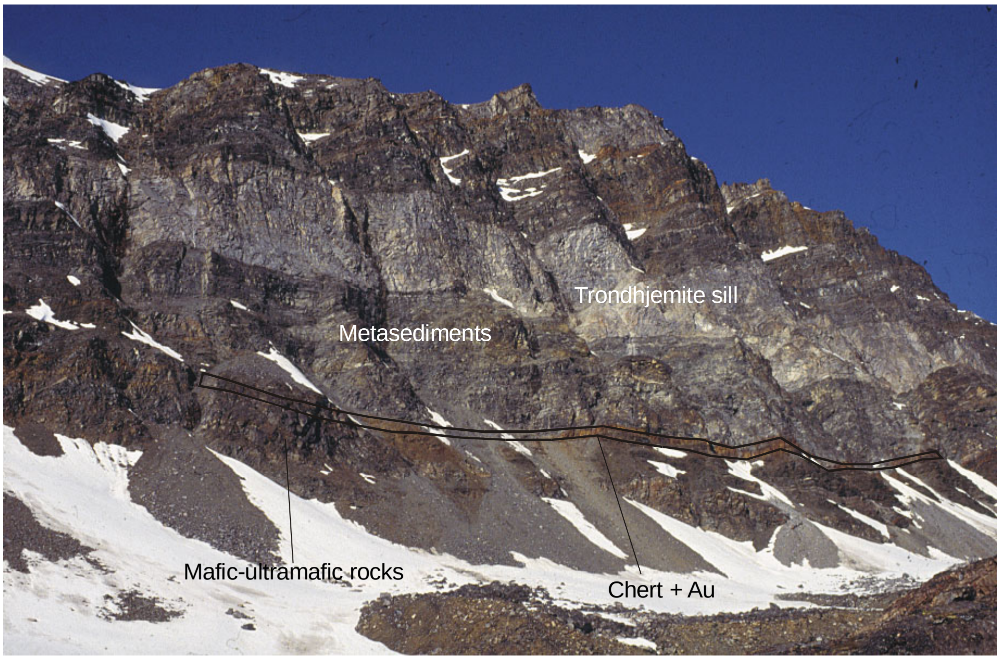

Figure 39. *A section of the Saqqaq supracrustal rocks with rusty metachert.*

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7b

Locality name: **Itilliarsuk**

Area: **Nuussuaq**

GSC deposit type: **15.3 – Iron-formation-hosted stratabound gold**

Commodities: **Gold**

<u>Geological characteristics:</u>

Description of occurrence: Gold mineralisation is observed in shear zones within supracrustal rocks. The supracrustal sequence is at least 2.5 km thick. The contact between the supracrustal rocks and the underlying gneisses is strongly tectonised and a basal unconformity has not been identified. The sedimentary pile is intruded by gabbroic sills and thin felsic dykes. The lower 400-m of the succession consist of amphibolite with sheared lenses of ultramafic rocks. New investigations by NunaMinerals have revealed good gold targets in sulphide-rich schists, quartz veins, and shear zones (Figs. 8 & 40).

Geotectonic setting: The geotectonic setting of the Archaean supracrustal rocks represents an active continental margin.

Depositional environment/Geological setting: The metalliferous mica schist with disseminated pyrrhotite and pyrite make up an about 150-m of the sedimentary sequence. In the middle part of sediments several minor lenses of massive to semi-massive pyrrhotite occur spatially related to thin amphibolite layers. The gold targets are in the sulphide-rich schists, quartz veins, and shear zones. The best target is a shear zone that hosts quartz-sericite rock.

Age of mineralisation: The age is of the mineralisation is uncertain but epigenetic in relation to the Archaean host rocks. The age could be from Archaean to Palaeoproterozoic.

Host/Associated rock types: The amphibolite succession is overlain by a more than 2 km thick sequence of siliciclastic rocks dominated by mica-garnet schists. Locally the siliciclastic succession is interlayered with up to 100-m thick amphibolite and metagabbro, and in the middle part very thin BIF horizons occur. Several hundred metres of felsic volcanic rocks conclude the supracrustal succession. Lower amphibolite facies metamorphism and at least two phases of deformation have affected all rocks. Alteration occurs in and along the vein systems such as sericitisation and silicification.

Deposit form: Veins in shear zones in sericite schist and mafic rocks.

Texture/Structure: Disseminated.

Ore mineralogy: The sulphide-rich schist is associated with gold bearing quartz veins with As-Sb sulphosalts.

Gangue mineralogy: Quartz.

Weathering: The sulphide-rich rocks are yellow-orange (rusty) weathering sulphide-rich mica schist and dark-grey massive sulphide rock, the latter weathering to a brownish gossan ('Rust zone').

Ore controls: Semi-massive ores stratiform layered in sericite schist.

Genetic models: The deposit is part of a volcanic-associated massive sulphide system with gold associated to the sulphide minerals.

Analytical data:

The shear zone hosted gold yields 9 ppm over 1,7 m and a strike length of 125 m. The mineralised structure can be traced 500 m along strike. Core drilling by NunaMinerals reaches the mineralisation 80 m down dip and returned 0.82 ppm gold over 3.1 m.

Exploration:

Kryolitselskabet Øresund A/S initiated exploration in the Itilliarsuk area (Gothenborg & Keto 1986; Gothenborg & Morthorst 1981; Gothenborg & Morthorst 1982). Later exploration was done by Platinova Resources Ltd. and Yellowknife Resources (Blackwell 1989). During the late 90s Nunaoil A/S and Nuna Minerals A/S did exploration and drilling on the deposit (Heilmann 1998; Petersen 1997).

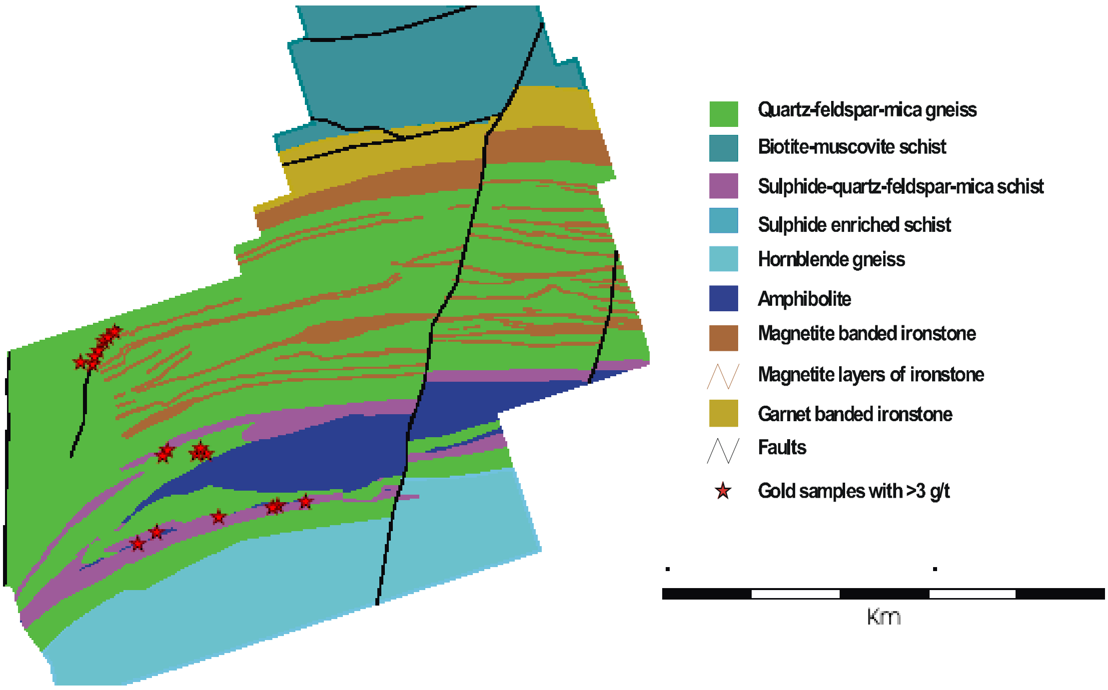

Figure 40. *Geological map of Itilliarsuk - modified from a map provided by Nunaminerals A/S.*

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Locality name:	**Eqi**
Area:	**Disko Bugt**
GSC deposit type:	**15.2 – Quartz carbonate vein gold**
Commodities:	**Gold**

Geological characteristics:

Description of occurrence: Mesothermal gold occurrences at Eqi is located in breccia zones within the Eqi-Maniitsoq greenstone sequence.

Geotectonic setting: The volcanic sequence represents low-K tholeiites to calc-alkaline, bimodal volcanic extrusions. The pillowed lavas represent ocean floor basalts related to an oceanic-island arc or back arc setting. The felsic metavolcanic rocks related to the dome complex at Eqi have geochemical characteristics of volcanic arc rocks. The volcanic arc in the Eqi and Arveprinsen area is formed at c. 2800 Ma (Fig. 8).

Depositional environment/Geological setting: Mesothermal gold at Eqi is discussed by Stendal *et al.* (1999). The pervasive gold mineralisation was caused by hydrothermal leaching and carbonate alteration of the rock pile related to acid igneous activity. The pervasive carbonate alteration has completely destroyed the primary textures of the original rocks. The carbonate alteration is mainly localised to an about 200 m thick zone at the boundary of the rhyolite dome and the hosting greenstone succession. Minor carbonate alteration occurs in up to 5-m thick zones cutting through the rhyolite complex sub-parallel to the fabric of the rocks. Locally centimetre-wide quartz veins occur within the carbonate alteration.

Age of mineralisation: The age is determined indirectly by Pb-Pb isotope investigation of pyrite (Stendal 1998), where the semi-massive sulphides represent a syngenetic stage yielding c. 2800 Ma. This means that the carbonate alteration is a little bit younger.

Host/Associated rock types: The original host rocks are mafic volcanics. The host rocks can be divided into three units: (a) a lower unit of massive to pillowed greenstones, (b) a middle unit of greenstones with frequent layers of mafic and felsic volcaniclastic sediments interlayered with felsic igneous rocks, (c) an upper unit dominated by greenstones of mixed extrusive (pillow lavas) and intrusive origin. The total thickness of the greenstone sequence is about 3–4 km.

Deposit form: The carbonatised mafic rocks cover at the best locality 200x400 m (Stendal *et al.* 1999).

Texture/Structure: Disseminated pyrite and porphyroblasts of pyrite in quartz veins.

Ore mineralogy: Pyrite, pyrrhotite and chalcopyrite.

Gangue mineralogy: The carbonatised rocks consist of ankerite, chlorite, green fuchsite and disseminated pyrite.

Weathering: Limited, except for goethite and malachite staining.

Ore controls: The gold distribution is defined by the quartz-carbonate vein systems.

Genetic models: The gold occurs in pyrite, which is disseminated in the carbonate altered host.

Analytical data:

Part of the carbonate alteration has been chip sampled and analysed with up to 2.3 ppm Au over 2.5 m. Grab samples of the quartz veined rocks vary between 5 ppb and 60 ppm gold (Stendal *et al.* 1999).

Figure 41. *Carbonate alteration and quartz veining of the greenstones (basic rocks) at Eqi.*

Exploration:

Discovery of gold anomalies by the Geological Survey of Greenland (GGU) in north-east Disko Bugt in 1988. It was followed by further exploration by Platinova resources Ltd – Faxe Kalk A/S in 1989–1991 (Knudsen *et al.* 1988; Knudsen *et al.* 1990; Knudsen & Nielsen 1992) and GGU in 1991. NunaMinerals A/S has also done some exploration in the area (Nunaminerals 2000).

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7d

Locality name: **Storø**

Area: **Nuuk region**

GSC deposit type: **15.4 – Disseminated and replacement gold**

Commodities: **Gold**

Geological characteristics:

Description of occurrence: The gold occurrences on Storø are hosted mainly in altered amphibolites, but anomalous gold concentrations are found in most rock types in the greenstone belt. The main gold showing is found in a series of semi-concordant to discontinuous sulphide zones within the amphibolites on the contact to metasediments. The sulphides are mainly pyrrhotite, but arsenopyrite is locally predominant. Visible gold is seen as isolated 0.5 to 2-mm big grains within sulphide-bearing amphibolites. Irregular quartz veinlets and silicification are often associated with gold-bearing zones (Appel *et al.* 2000; Appel *et al.* 2003).

Geotectonic setting: Unknown.

Depositional environment/Geological setting: The greenstone belt on Storø (Fig. 42) is situated at the northern boundary of the Faeringehavn terrane boundary, which can be traced from Nuuk in Southwest to Isuakasia in Northeast (Fig. 4). The greenstone belt at this site comprises a sequence of metasediments and metavolcanics. The sediments consist of garnet-sillimanite schists, rusty quartz mica schists, and quartzites. Quartz muscovite schists are locally fuchsite-bearing and contain appreciable amounts of sulphides mainly pyrrhotite and pyrite. Furthermore, bands of iron formation up to a few metres thick are observed consisting of magnetite, garnet, cummingtonite and feldspar. Locally thin bands of quartz-magnetite banded bands of iron formation are seen (Appel *et al.* 2000; Appel *et al.* 2003; Hollis *et al.* 2004)).

Age of mineralisation: Middle Archaean ~2800 Ma based on Pb isotopes of arsenopyrite (pers.com. R. Frei).

Host/Associated rock types: Calc-silicate altered amphibolites.

Deposit form: At Qingaaq gold showings on Storø has been found in two major zones each with up to six subzones 2 to 10 m wide. One main zone is 60 m and the other is 20 m wide (Fig. 43).

Texture/Structure: Disseminated mineralisation.

Ore mineralogy: Gold, arsenopyrite, loellingite, pyrrhotite and pyrite.

Gangue mineralogy: Garnet, sillimanite, and quartz.

Weathering: Light rusty weathered.

Ore controls: Probably controlled by metamorphism and structures in Middle Archaean.

Genetic models: Disseminated and replacement ore similar for types found in Hemlo and Red Lake in the Abitibi Belt, Ontario, Canada.

Analytical data:

The best drilling intersections at Qingaaq were 10.1 ppm Au over 10 m, another with 37 ppm Au over 1.5 m and 1.9 ppm over 8.5 m (Trepka-Block 1995). Rusty sillimanite schists are found with up to 3.2 ppm Au (Skyseth 1998). A press release from Nunaminerals A/S (25/8-04) announces a new gold zone on Storø with gold values around 20 g/t over a width of 2.5 m.

Exploration:

In the early 1990s scree and stream sediment sampling together with grab sampling of promising outcrops on the two mountains Qingaaq and Aappalaartoq on central Storø drilling was carried out by Nunaoil A/S. In 1995 diamond drilling, detailed geological and structural mapping was done on Qingaaq. Eleven holes were drilled on Qingaaq with a total length of 2000 m and one hole was drilled on Aappalaartoq with a length of 500 m. Nunaminerals A/S has continued the investigations on Storø, recently, they carried out a drilling programme in 2004.

NunaMinerals announced in a press release (25-08-2004) that they have discovered a new gold zone with visible gold. The gold-bearing zone is 2.5 m wide and carries ~20 g/t gold.

Fig. 42. *Greenstone belt (rusty rock sequence), Aappalaartoq Mountain on Storø*

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Figure 43. *Rusty mid- to late-Archaean greenstones with gold mineralisation in both the amphibolite (black), in the rusty metasediment (brown), and in the folded quartz veins in the amphibolite. The site is on the Qingat Mountain in the central part of Storø and several gold-bearing zones occur on the mountain.*

Locality name: **Taartoq**

Area: **Sermiligaarsuk**

GSC deposit type: **15.3 – Iron-formation-hosted stratabound**

Commodities: **Gold, copper**

Geological characteristics

Description of occurrence: Within the Sermiligaarsuk area the Archaean gneiss is overlain by the Tartoq Group greenstone belt. The Tartoq Group gold mineralisation is significant in two areas and gold occurs in different modes within the carbonate schists.

Geotectonic setting: The Taartoq area is considered as an Archaean foreland composed of high-grade gneisses and greenstones (the 'Tartoq Group'). The environments for gold deposition are sequences of volcano-sedimentary supracrustal rocks, which rest unconformably upon the Archaean gneisses of low to medium metamorphic grade. Regional metamorphism resulted in recrystallisation and segregation of the chert into compact quartz bodies and residual massive-sulphide (Schaefer *et al.* 2000; Schjøth *et al.* 2000).

Depositional environment/Geological setting: The Tartoq Group comprises several greenstone occurrences along the north and south side of the fjord, Sermiligaarsuk. Gold is thought to have been introduced into the Taartoq greenstones during the formation of stratiform exhalites with massive-sulphide and chert as sulphide facies BIF. Regional metamorphism resulted in recrystallisation and segregation of the chert into compact bodies of quartz and residual massive-sulphide. Subsequent episodes of shearing and intensive carbonate alteration along the shear zones lead to the liberation and precipitation of gold. (Bridgwater *et al.* 1973; Higgins 1968; Higgins and Bondesen 1966).

Age of mineralisation: The basement gneiss has ages ranging from 2980-3500 Ma and Taartoq supracrustals are assumed to be late Archaean, deposited between 2500 and 3000 (Nutman & Kalsbeek 1994).

Host/Associated rock types: Sequences of metavolcanics and metasediments, several kilometres thick, are observed as dark green and rusty greenstone layers. The northern area (Iterlak) forms a tectonic enclave of greenstones within the basement. The main part of the eastern and south-eastern Iterlak is composed of monotonous greenstones. A characteristic feature of the Iterlak sequence is the abundance of acid meta-tuffs, mostly sericite schists.

The southern area (Nuuluk) includes a prominent zone of high-strain rocks - the Nuuluk Linear Belt, 400 x 4000 m, and characterised by nearly parallel structures and numerous thrusts. This sequence is composed of mixed layers of brown weathered carbonate schist, nodular greenschists and highly sheared volcano-chemical sediments including iron oxide schists, graphitic shales and sericite schists (Evans & King 1993).

Deposit form: Gold occurs in three different modes within the carbonate schists: 1) in disseminated pyrite in quartz-ankerite lenses (1-2 m by 5-10 m); 2) in pyrite associated with massive and semi-massive arsenopyrite aggregates; and 3) in sulphide rich iron-formations (Evans & King 1993).

Texture/Structure: Gold mineralisation is above all confined to linear belts and carbonate-rich zones. The gold is some times visible as discrete droplets within the sulphides on the micro scale as well as in non-sulphide associations.

Ore mineralogy: Gold occurs in pyritiferous quartz lenses and veins in carbonatised shear zones locally reaching up to 50 g/t gold (over 0.6 m), in pyrite-arsenopyrite-quartz layers with gold grades around 8–15 g/t, and low grade gold associated with banded iron formations. Other types, only located in the southern area, involve copper bearing parageneses with chalcopyrite, tennantite, and chalcocite in concordant veins and lenses (grades up to 8 g/t gold). Locally, pyritic schists with varying graphite content carry spahlerite and increased gold values of 2.5 g/t (and up to 6.7 % zinc) (Appel & Secher 1984; Gowen 1991, 1993).

Gangue mineralogy: Quartz and graphite.

Weathering: Pyrite/arsenopyrite is weathering to yellow-brown limonite. Copper rich parts are often unveiled by malachite/azurite staining.

Ore controls: The ratio between the content of gold and silver (true fineness) has been calculated for some of sulphide parageneses in the Nuuluk area. It is noticeable that the gold fineness decreases from layers with arsenopyrite-pyrite (990) towards the tennantite (720) and the chalcopyrite (500) lenses, thus pointing to a trend in mobilisation of the silver during later diagenesis and hydrothermal processes (Appel & Secher 1984).

Genetic models: The gold is thought to have been introduced into the Taartoq greenstones during the formation of stratiform exhalites with massive-sulphide and chert as sulphide facies BIF. Gold occurrences in South Greenland are demonstrated to be located within the Archaean ‘Tartoq Group’ rocks, similar to major gold camps in ‘old’ greenstone belts throughout the World (Stendal (ed.) 2000).

Analytical data

Not applicable

Exploration

Since the discovery of the main gold occurrence in the area in 1971, a number of companies have devoted substantial resources to assessing the ore potential. GEUS has included the area in regional survey projects since the 1950s (Stendal (ed.) 2000).

An extensive exploration activity has been carried out in the 1000 km^2 area, including several drill programmes and geophysical surveying. Renzy Mines Ltd, Cominco Ltd, GREENEX A/S and NUNAOIL A/S carried out most of the exploration projects from the 1970s to the 1990s, whereas GEUS has conducted general and specialised survey work since the 1950s (Secher & Kalvig1987). Short hole drillings (Winkie) were initially carried out in 1982, with 23 holes totalling 460 m. Later, the two most impressive occurrences in the Nuuluk and the Iterlak areas have been core drilled. Work to drill 13 holes totalling 1364 m down to a maximum of 120 m was carried out in 1993.

Among the geophysical exploration results is a remarkable feature of the Nuuluk area with a significant VLF anomaly in the Western Carbonate Zone. Pyritic schists with graphite and banded sphalerite are observed in both the northern and southern portion of the zone. The geophysical anomaly suggests a large conductive zone, which could be equivalent to a sulphide body in excess of 20 million tons of zinc ore. Limited follow-up of the anomaly located graphite rich layers as conductors only.

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Figure 44. *Nuluk gold locality within the greenstone of the 'Tartoq Group' south of the fjord Sermiligaarsuk, South-West Greenland.*

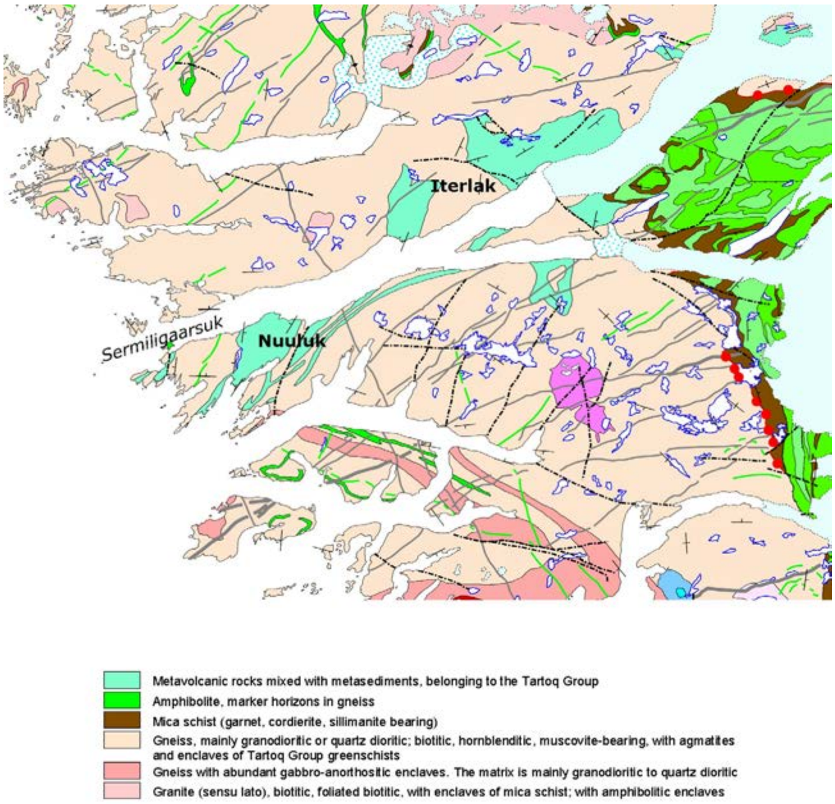

Figure 45. *Geological map of the Sermiligaarsuk gold area, South Greenland. Map area 80 x 55 km.*

7f

Locality name: **Nalunaq**

Area: **Nanortalik**

GSC deposit type: **15.2 – Quartz-carbonate vein gold**

Commodities: **Gold**

Geological characteristics:

Description of occurrence: Two major gold-bearing veins occur. They strike along a NE ductile thrust zone that dips 40^o to 55^o SE. The structure is compatible with a NNE trending regional sinistral shear that controls the location of gold mineralisation on the Niaqornarsuk peninsula to the north (Coller et al. 1995). The gold mineralisation is epigenetic and occurs in quartz veins and in calc-silicate altered shears sub-parallel to the foliation. The gold mineralised vein system is 1700 m long and 0.1 to 2 m wide (Fig. 46; Gowen 1994; Gowen et al. 1993; Petersen et al. 1997; Petersen and Pedersen 1995; Lind *et al.* 2001).

Geotectonic setting: The vein system is part of the of the history development of the Ketilidian orogen with quartz veins formed in the late stages of the Julianehåb batholith formation (Fig. 5). The Nalunaq gold prospect is hosted in meta-pelites and meta-mafic rocks of Ketilidian age (1850–1800 Ma) at the Nanortalik peninsula. Post-kinematic biotite granites intrude the supracrustal succession. Subsequently anorogenic rapakivi granites at c. 1750 Ma (Kalsbeek and Taylor 1985) intrude the same package.

Depositional environment/Geological setting: The supracrustal rocks of the Psammite and Pelite zones comprise voluminous metamorphosed feldspatic sandstones and siltstones and minor conglomerates, mudstones, and mafic volcanic rocks. Psammitic rocks predominate in the northwest clost to the batholith, whereas (meta-) siltstones and mudstones are widespread in the southeast (Garde *et al.* 2002; McCaffrey *et al.* 2004).

Age of mineralisation: Pb isotopes of different mineralisations in South Greenland mainly 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 up-concentrated into shear zones and vein-systems. The source indications for Pb in these occurrences is compatible with a juvenile c 2 Ga old source compatible with that of the direct supracrustal host rocks to these occurrences (Stendal & Frei 2000). A second stage of gold deposition seems time-wise related to late stages of the emplacement of the Julianehåb batholith. The source of the slightly more evolved Pb in these mineralisations is difficult to assess, but a mixture of juvenile Pb from the batholith with some contributions from the host rocks may readily explain the scatter of data around a 1.78 Ga reference line.

Host/Associated rock types:
Fine-grained mafic volcanic rocks: The mafic volcanic rocks hosting the Au-As mineralisation association are tholeiites formed over an oceanic crust.

Deposit form: Thin sheet like quartz vein - Main Vein (Fig. 46).

Texture/Structure: Quartz vein system.

Ore mineralogy: Gold (Fig. 47) is associated with löllingite and traces of Bi-Sb.

Gangue mineralogy: Quartz

Weathering: Insignificant.

Ore controls: The gold mineralisation hosted by meta-volcanic and meta-sedimentary rocks are formed during regional deformation and metamorphism. The hydrothermal system, where the fluid inclusions in quartz vein at Nalunaq vary in composition from the predominant aqueous saline fluids to CO2-CH4 – aqueous mixtures. Salinities are high with 17–38 wt % NaCl. Preliminary interpretation of the fluid inclusion data suggests precipitation of gold at 525–575^{o}C and about 2.5 kb (Kaltoft et al. 1998).

Genetic models: Quartz vein system in a thrust zone environment. The host rocks represent a thrust sheet overlying molasse-type sediments deposited in a marginal basin in the Ketilidian orogen (Petersen *et al.* 1997).

Analytical data:

Gold production from Nalunaq is expected to be approximately 130,000 oz/yr, from 2004 onwards. The latest reserves are given by Crew Development at their homepage December 2004 as follows:

Measured & Indicated Mineral Resources (M & I)	Over 1.0 meters		Over 1.2 meters		Over 1.5 meters		Ounces
	tonnes	g/t	tonnes	g/t	tonnes	g/t	
Main Vein (including Stockpiles)	352,100	30.3	414,200	25.8	508,300	20.9	343,700
South Vein	58,000	28.3	69,700	23.6	88,300	18.7	52,900
Total	410,100	30	483,900	25.5	596,600	20.6	396,600

Inferred Mineral Resources	Over 1.0 meters		Over 1.2 meters		Over 1.5 meters		Ounces Gold
	tonnes	g/t	tonnes	g/t	tonnes	g/t	
Main Vein	200,000	24.7	240,100	20.6	326,000	15.9	159,100
South Vein	34,000	22.4	41,200	18.7	52,000	14.8	24,800
Total	234,000	24.4	281,300	20.3	378,000	15.7	183,900

Exploration:

Nunaoil A/S has conducted mineral exploration since 1990 at Nalunaq/Kirkespirdalen where the Nalunaq prospect was located in 1992 (Gowen et al. 1993). In 1993 Nunaoil A/S & Cyprus Greenland Corporation recovered 10 exploration drill cores - totalling 2950.5 m (Guy 1993). A 300 m long drift was constructed in 1998. Bulk samples were collected for production tests (Mindex 1997). Mindex A/S and Nuna Minerals have continued exploration drilling and mine development throughout 1999. In the autumn 1999 Mindex ASA merged with Crew Developement Corp. The Crew Development and Nunaminerals (17.5% share) got the exploitation rights in 2004.

Figure 46. *Kirkespirdalen with Nalunag gold mine. Red line outlines the gold-bearing Main Quartz Vein.*

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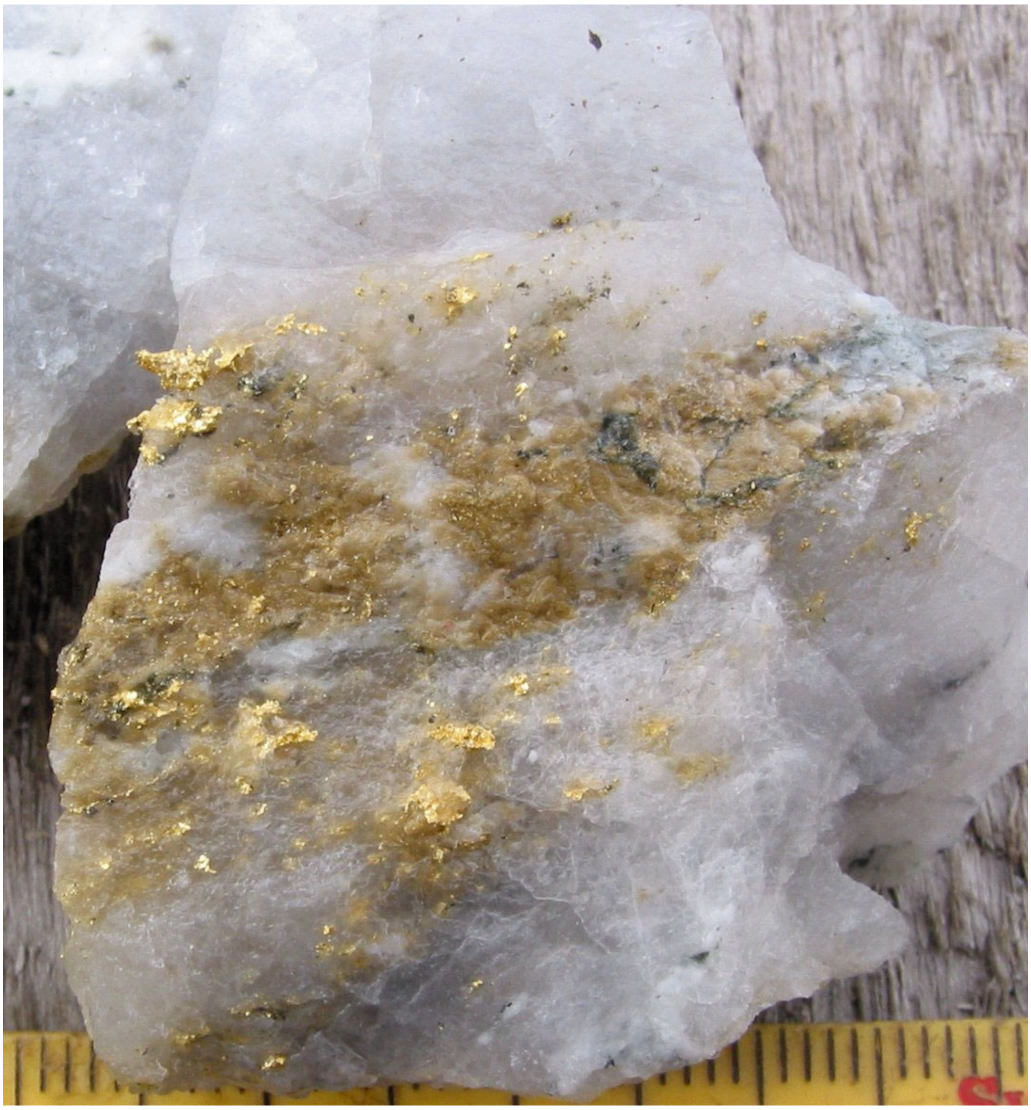

Figure 47. *Visible gold in quartz vein, Nalunag gold mine. Size of figure 4 x 5 cm.*

Locality name: **Eqalussuit**

Area: **Nassuttooq**

GSC deposit type: **6.3 – Volcanic-associated massive sulphide base metals**

Commodities (minor): **Graphite**

Geological characteristics:

Description of occurrence: Graphite accumulations occur in a supracrustal sequence composed of foliated biotite garnet ± graphite ± sillimanite gneiss, locally interlayered with amphibolite and marble bands and ultrabasics (Fig. 48). The metamorphic grade is upper amphibolite facies. The supracrustal rocks in the area have an overall strike of 265° and dip 60°N, parallel to the Nordre Strømfjord (Nassuttooq) steep belt. Graphite schists are known from observations further inland to the east, but apparently without substantial accumulation of graphite.

Geotectonic setting: In “greenstone belts” believed to be developed in the transition platform/volcanic environment.

Depositional environment/Geological setting: Sedimentary and submarine volcanic sequences with pelitic sediments, exhalites and mafic rocks.

Age of mineralisation: The graphite rich schist is probably Palaeoproterozoic in age, but precise data are not available.

Host/Associated rock types: Graphite, together with pyrite/pyrrhotite lenses is hosted in pelitic sediments (paragneisses).

Deposit form: The occurrences are found within two parallel schist layers (supracrustals), up to 20 m thick and traceable for tens of kilometres along strike. Individual graphite rich lenses may reach 1 x 20 m, and are found scattered within the schist. Horizons, where the graphite accumulation is observed, are locally due to shearing and internal folding (Platou 1969; Bondam, 1992).

Texture/Structure: The graphite occurrences are generally of a disseminated type of fine-grained flake graphite, and locally developed in lenses with more or less massive graphite (Fig. 49), interlayered with pyrrhotite/pyrite, quartz, biotite and garnet. Foliation-parallel pegmatites contain minor amounts of coarse-grained flake graphite (Pedersen 1992).

Ore mineralogy: Graphite. Associated pyrite and pyrrhotite.

Gangue mineralogy: Quartz, biotite, garnet.

Weathering: Graphite sequences are turned into gossans and rust zones due to weathering of the sulphides.

Ore controls: Graphite is considered to represent a primary carbon content within the supracrustals.

Genetic models: Metamorphosed counterpart to primary bituminous sediments.

Analytical data: Not applicable.

Exploration:

Exploration of the graphite deposits in the area has been carried out since the beginning of the 20th century (Ball 1923). Graphite attracted economic interest as one of the first commodities in West Greenland, and the activity increased around 1900, partly because of the demand from the growing electrical industry and partly from the use in the foundry and moulding industry. In the actual area the activity in 1903, 1912 and again in 1916 went as far as to primitive exploitation on a pilot scale. In 1916 a complete plant layout including a miner's accommodation village was presented by the Grønlandsk Minedrift A/S. However, proper exploitation was not brought to the practical step (Lindås 1916).

The activity was based on a licence granted in 1904 and later extended to 1933. The locality was later renamed 'Akuliaruseq' and was a target for renewed evaluation from 1982–86 by the Kryolitselskabet Øresund A/S. Geophysical surveys, drillings and flotation tests were carried out during this campaign (Keto et al, 1987). In 1992–93 NunaOilA/S undertook additional investigations (Pedersen 1992). The exploration has at the time of writing ceased.

Resource estimates are primarily based on the data from the Kryolitselskabet Øresund A/S. According to these data the total volume of graphite ore, calculated down to 40 m below surface, is 5.3 million t with an average C-content of 9.5% as flake graphite. At least 1.6 million t of this resource is representing an average of 14.8% C. About 50 wt% of the flake graphite are in the +100 mesh category (Pedersen 1992).

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Figure 48. *Old pits from graphite mining at Eqalussuit.*

Figure 49. *Close-up of graphite ore sample (scale is indicated by green label to the right, 1 cm).*

8b

Locality name: **Amitsoq**

Area: **Nanortalik**

GSC deposit type: **6.3 – Volcanic-associated massive sulphide base metals**

Commodities (minor): **Graphite**

Geological characteristics:

Description of occurrence: The graphite deposit is hosted in graphitic schists embedded in strongly sheared cordierite-sillimanite-biotite gneisses. A steep fault separates the gneisses from aplitic granite and meta-arkoses found in the northern part of the island. The graphite layer can be followed over 400 metres along strike with a graphite content of 20-24 vol. %. The layer reaches a maximum width of c.13 metres, but generally pinches out to 3,5 metres or less (Bondam 1992; Mosher 1995).

Geotectonic setting: The supracrustal rocks comprise voluminous metamorphosed feldspatic sandstones and siltstones and minor conglomerates, mudstones, and mafic volcanic rocks. Psammitic rocks predominate in the northwest closet to the Julianehåb batholith, whereas (meta-) siltstones and mudstones are widespread in the southeast of the Ketilidian Psammite and Pelite zones (Garde *et al.* 2002; McCaffrey *et al.* 2004).

Depositional environment/Geological setting: Sedimentary and submarine volcanic sequences with pelitic sediments and mafic rocks. Later metamorphism is at high grade (amphibolite to granulite facies) and the rocks are generally strongly migmatised.

Age of mineralisation: The supracrustal rocks hosting the graphite deposit are from the Early Proterozoic (the Ketilidian orogeny) and dated at 1810±35 Ma (Pedersen *et al.* 1974).

Host/Associated rock types: Graphite, together with pyrite lenses is hosted in cordierite-sillimanite-biotite gneisses.

Deposit form: The ore consists of finely disseminated crystalline graphite flakes in a quartz rich groundmass, accompanied by pyrite and some biotite. The metamorphic nature of the deposit is accentuated by crenulated slabs of biotite gneiss, irregularly incorporated in the main graphite schist. Four graphite ‘veins’ were delineated, of which one, called the 'main vein', was subsequently quarried (Bondam 1992).

Texture/Structure: The ore consists of finely disseminated crystalline graphite flakes in a quartz-rich groundmass, accompanied by pyrite and biotite. The graphite flakes are up to 15 mm in size.

Ore mineralogy: Graphite and associated pyrite.

Gangue mineralogy: Quartz and biotite.

Weathering: Graphite sequences are turned into gossans and rust zones due to weathering of the sulphides.

Ore controls: Graphite is considered to represent a primary carbon content within the supracrustal sequences.

Genetic models: Metamorphosed counterpart to primary bituminous sediments.

Analytical data:

Ball (1923) reports the grade to be 20-24% graphite. Although a large number of samples have been investigated there is no record of proper assays. The only available analyses of "average ore grade" is given by Høeg (1915) as 21.0% C, 6.0% S and 0.2% H_20, based on ore quarried in 1914.

Exploration:

The graphite occurrence on the island Amitsoq was located in 1911 after prospecting, and mining operations were carried out 1915 to 1924 by Grønlandsk Minedrift A/S in co-operation with the Grønlands Grafit Company A/S. The activity was based on a licence granted in 1911 and later extended to 1933. An ore reserve was estimated at 250 000 tons. The mining history is based on the descriptions of Ball (1923, Lindaas(1914 and Bondam 1992). The graphite mine produced a total of 6.000 t graphite averaging 21% graphite. The Amitsoq graphite mine is located near the southern tip of Amitsoq island in the Saqqaa fjord at N 60°17´ - W 45°07´ (Schjøth *et al.* 2000, Secher & Burchardt 2000).

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Figure 50. *Open pit mining at the Amitsoq graphite mine 1915.*

Figure 51. *Old mining equipment at the abandoned Amitsoq graphite mine, 1992.*

9a

Locality name: **Skaergaard**

Area: **Kangerlussuaq**

GSC deposit type: **27.2 – Magmatic platinum group elements**

Commodities: **Palladium, gold, platinum**

Geological characteristics:

Description of occurrence: The noble metals are located in special layers of the Kangerlussuaq intrusion e.g. Triple Group (Fig. 52), which contains the Platinova reef. This reef is a strata-bound resource of Pd and Au in the well-known Skaergaard intrusion (Fig. 54).

Geotectonic setting: Magmatic layered intrusion.

Depositional environment/Geological setting: The Platinova reef appears to have formed in response to silicate-sulphide liquid immiscibility in the basaltic magma. However, in contrast to classic PGE reefs, there is no evidence for magma replenishment and/or magma mixing associated with the reef. Instead, it appears that the immiscibility was reached entirely through magmatic differentiation by fractional crystallisation. A simple model of PGE fractionation by silicate-sulphide liquid immiscibility, however, fails to explain the repetitive nature of the reef and the separation of Pd, Pt, Au and Cu. Repeated sulphur saturation in intercumulus melt concentrations followed by bulk magma sulphur saturation is offered as an explanation for the layered nature of the mineralisation and the separation of Pd, Pt, Au and Cu.

Age of mineralisation: 55-54 Ma

Host/Associated rock types: Gabbroic rocks.

Deposit form: The Platinova Reef structure includes at least five levels of Pd-concentration and is 45 meters thick. All levels are perfectly concordant with the magmatic layering in the host rocks. They form a large basin shape, which in an E-W cross section is 7 km wide with a central depression of c. 700 meters. From the lower to the upper level the economic levels of Pd are concentrated towards the centre of the mineralisation as a stack of bowls with decreasing size. Au is concentrated at the rims of these bowls. The reef accordingly displays a variable stratigraphic separation between the main lower Pd5 Pd-level and Au across the intrusion.

Texture/Structure: Minor faulting and southward rotation of the intrusion.

Ore mineralogy: Palladium and gold minerals are dominated by alloys that are intimately associated with Fe-poor, Cu sulphide minerals dominated by bornite and chalcosine group minerals. The dominant precious metal minerals are skaergaardite (PdCu), zvyagintsevite (Pd_3Pb), vysotskite (PdS), tetraauricupride (AuCu). Skaergaardite is a new mineral and of major importance. It dominates the Pd-rich levels in the central parts of the mineralisation. It is estimated that the mineralisation contains > 1000 tons of Skaergaardite with 60% Pd. Zvyagintsevite is the dominant phase in Pd-rich levels at the margin of the intrusion. Vysotskite is important in some central parts of the mineralisation. The investigated Au-rich rims and levels of the mineralisation are dominated by tetraauricupride.

Gangue mineralogy: Not applicable

Weathering: None

Ore controls: Igneous layering.

Genetic models: Orthomagmatic: formation of immiscible sulphide melt droplets due to S-saturation in response to fractional crystallisation in S-undersaturated basaltic magma.

Analytical data:

The lower Pd5 of a series of levels enriched in Pd is suggested to contain >300 million tons of gabbro, which averages 2 g/t precious metals. Pd5 is at 1 g/t cut-off app. 5 m thick. Estimates by the current holder of the concessions suggest a global resource of 1.8 billion tons. This estimate includes all the Pd-levels of the intrusion, the gold rich parts of the intrusion and the host rocks between levels enriched in Pd and/or Au. The host rock is believed to be a resource in itself, being an ilmenite-rich gabbro with ilmenite and magnetite concentrations of economic interest.

Exploration:

The Platinova reef was discovered in the late 1980´ies during a regional exploration program for platinum-group elements (PGE) in Palaeogene intrusions in East Greenland. The initial exploration programme conducted by Platinova Resources Ltd. and Tech Corporation in 1986 focused on the large layered igneous complexes with demonstrated events of magma replenishment, in particular the Kap Edvard Holm complex. Unexpectedly, anomalously high concentrations Au were found in stream sediments and whole rock samples from the Skaergaard intrusion. Later exploration by traditional methods of drilling, channel sampling (Fig. 53) and assaying identified a stratabound zone rich in Pd and Au in the upper 100 meters of the Middle Zone in the Layered Series of the intrusion. This zone, subsequently known as the Platinova reef, can be traced in outcrop as well as underground across 2/3 of the area of the intrusion. Metallurgical tests indicate flotation, cyanidation, and selective leaching to be effective extraction methods. Recoveries of 90% are shown.

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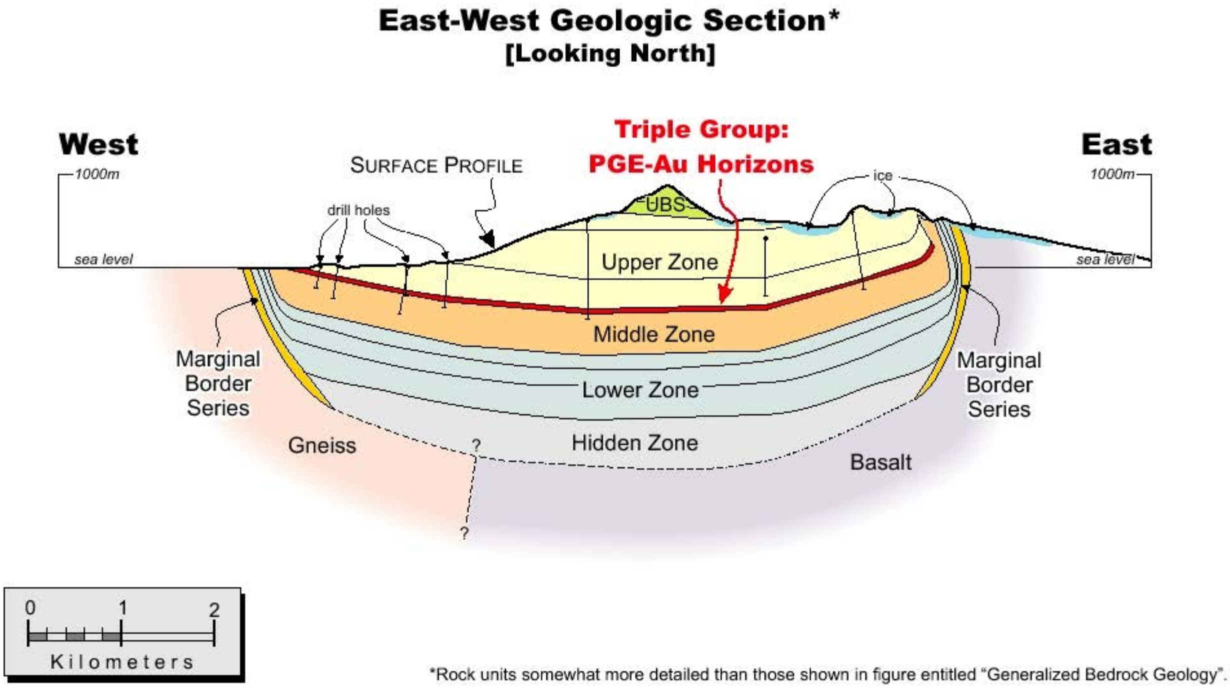

Figure 52. *Simplified section of the Skaergaard intrusion with the mineralised layers (PGE-Au horizons). The figure is provided by Troels Nielsen.*

Figure 53. *Channel sampling at Skaergaard.*

Figure 54. *View of the Skaergaard intrusion.*

Locality name: **Hammer Dal**

Area: **Disko**

GSC deposit type: **27.2 – Igneous platinum group elements**

Commodities: **PGE, Nickel**

Geological characteristics

Description of occurrence: The Hammer Dal complex on Disko belongs to a mineralised dyke swarm of sediment contaminated lava, which has a number of attractive characteristics. It is the richest metallic iron deposit exposed in the region and the strongest hydrothermal alteration field on Disko is exposed close to the complex, which may imply the existence of a larger intrusion at depth. Additionally the complex is accessible to ground geophysics, which has revealed a conductor 400-500 m below the present surface with much larger dimensions than the outcrops (Ulff-Møller 1977).

Geotectonic setting: During the opening of the Davis Strait in late Mesozoic to early Palaeogene basins were formed by subsidence and block faulting of the basement and were filled with continental and marine sediments. The Nuussuaq Basin extends onshore from Disko to Svartenhuk Halvø and is part of a series of linked basins extending offshore along the west coast of Greenland. Onshore volcanism commenced early in the Paleocene. The volcanic rocks erupted into a marine embayment that was gradually filled out laterally by progradation from west to east. The net result is a very complex facies architecture of the lavas, hyaloclastites and contemporaneous sediments (Clarke & Pedersen 1976; Pedersen 1985).

The oldest volcanics are voluminous picrites that formed from very Mg-rich and very hot magmas. Some of the magmas reacted with coal-bearing sediments and became so reduced that they precipitated native iron. The reactions also led to formation of Cu- and Ni-depleted lavas, and accumulations of these elements and PGEs are inferred to be present at depth (Ulff-Møller 1977).

Depositional environment/Geological setting: The occurrences in the Disko region are hosted in presumably sediment-contaminated lava and dykes at the base of the basalt sequence. The prospective area on north-west Disko is defined by a swarm of NW-SE to N-S striking contaminated dykes and subvolcanic intrusions. Many of these were probably feeders to extensive contaminated lavas - now strongly eroded. The intrusions host deposits of metallic iron and sulphides many of which are modest from a direct economic point of view. "Branched iron bodies" dominate the iron cumulates and were deposited along contacts sloping up to 70° by a mechanism that is not completely understood. The presence of iron cumulates is thus evidence of considerable magma transport capability, whereas the amount of iron typically reflects the local conditions of deposition rather than the general potential of an intrusive system (Pedersen 1978; Ulff-Møller 1977).

Age of mineralisation: Most of the voluminous onshore volcanics were deposited in a short period at c. 61-59 Ma (Henriksen *et al.* 2000).

Host/Associated rock types: Tholeiitic and picritic lavas.

Deposit form: Dykes and irregular subvolcanic intrusions.

Texture/Structure: "Branched iron bodies" dominate the iron cumulates, which together with sulphide accumulations were deposited along contacts.

Ore mineralogy: Native (metallic) iron (and alloys), pyrrhotite and pentlandite.

Gangue mineralogy: Not applicable.

Weathering: Sulphides create rust zones/rusty areas within the basalts.

Ore controls: Sediment contaminated dykes and subvolcanic intrusions in the Hammer Dal show signs of sulphide enrichment (together with metallic iron as cumulate).

Genetic models: The metallic iron and sulphides occur in contaminated volcanic rocks, which were derived from ultrabasic parent magmas by reaction with carbonaceous, sulphurous sediments.

Analytical data

Sulphide enriched basalt (together with metallic iron as cumulate) carry at least 1% Ni and shows elevated PGE contents of up to 0.5 ppm.

Exploration

Economic considerations regarding the metallic iron have been promoted since the discovery in the mid-1800, as reviewed by Ball (1922) and Bøggild (1953).

In the 1980's renewed interest in the area in general and the Hammer Dal area in particular commenced with the aim of locating Norilsk-type intrusions on the boundary between sediments and overlying plateau basalts. An extensive nickel exploration programme was carried out by Greenex/Cominco Limited from 1985. From 1991 to 1996 a Platinova A/S–Falconbridge Greenland A/S joint venture conducted an extensive exploration programme for Ni, Cu and PGEs that included regional geology, mapping and sampling, plus follow-up diamond drilling. In 2003 Vismand Exploration Inc. undertook a geophysical survey using the 'Titan 24'- technology within a new exploration licence, which is continued.

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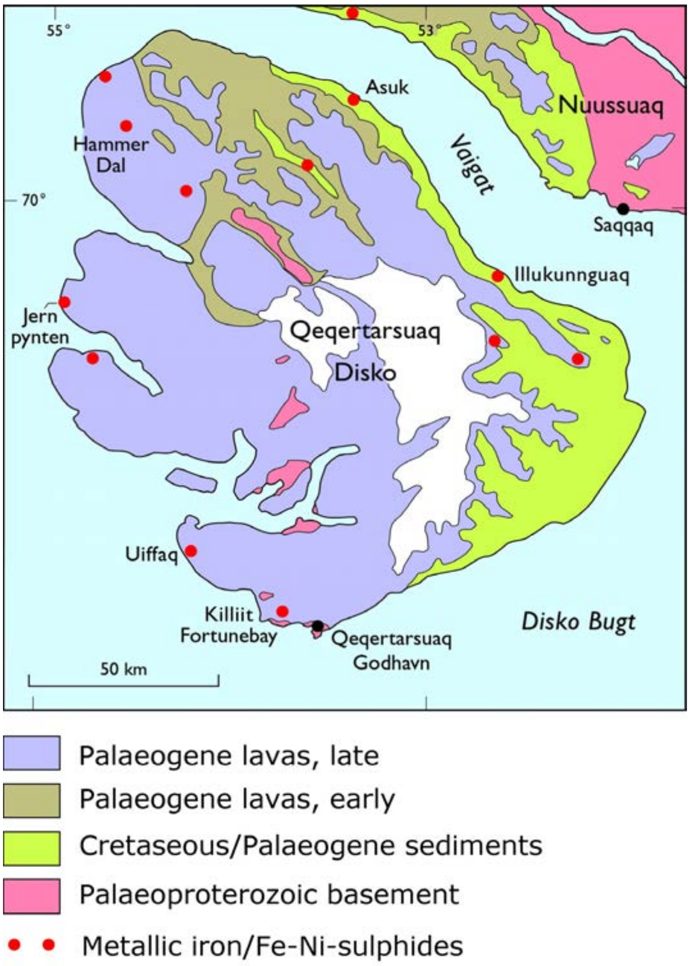

Figure 55. *Geological map of the Disko Bugt area, West Greenland.*

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Locality name:	**Malmbjerg**
Area:	**Mesters Vig**
GSC deposit type:	**19 – Porphyry deposit**
Commodities:	**Molybdenum, tungsten**

Geological characteristics:

Description of occurrence: In the Werner Bjerge Alkaline Complex molybdenite mineralised areas are known such as the Malmbjerg porphyry molybdenum deposit (Figs. 56 & 57). The Complex is nearly circular with a diameter of about 17-km. Syenites and granites are the dominant rock types of the intrusive centres. The Werner Bjerge Complex comprises the porphyry Mo deposit, Malmbjerg, which is a Climax type deposit.

Geotectonic setting: The Palaeogene igneous province of the Mesters Vig area forms a prominent NE-SW trending line of plutonic-subvolcanic centres traceable for approximately 125 km from the Werner Bjerge Complex in the SW to Kap Parry in the NE (Schønwandt 1988).

Depositional environment/Geological setting: Three types of mineralisation are associated with the Malmbjerget granite stock: 1) molybdenite mineralisation, 2) greisen mineralisation, and 3) base.metal mineralisation. Molybdenite occurs in a large inverted bowl-shaped body. Greisen appears as flat-lying veins of up to one meter in thickness and locally makes up more than 10% of the volume. Base-metal occurs as vertical up to 30-cm thick argillitized fracture zones, but represent only a minor mineralising event (Harpøth *et al.* 1986).

Age of mineralisation: Radiometric dating of the syenite yields a whole rock Rb/Sr age of 30±2 Ma (Rex *et al.* 1979). The granite stock is a little bit younger given by K-Ar ages of 26±1.1 Ma to 21.1±0.9 Ma (Schønwandt 1988). The Malmbjerget molybdenum deposit is dated to have been emplaced at 25.8±0.1 Ma based on Re-Os and ^{40}Ar/^{39}Ar methods (Brooks *et al.* 2004).

Host/Associated rock types: Granite and syenites.

Deposit form: Stockwork mineralisation around a granite body.

Texture/Structure: Disseminated ore and veinlets.

Ore mineralogy: In the Mo-ore zone the following mineral assemblages occur: 1) biotite-quartz-magnetite±fluorite±siderite; 2) biotite-molybdenite; 3) molybdenite-quartz; and 4) fluorite-molybdenite±quartz. Pyrite is disseminated in all mineral assemblages. In the greisen zone open-space fillings are dominated by columnar quartz with minor topaz, wolframite, fluorite, coarse-grained molybdenite and locally beryl, cassiterite, siderite, pyrite, sphalerite,chalcopyrite, bismuth, and bismuthinite. The base metal occurrences have two mineral-assemblages: 1) quartzbiotite-sphalerite-chalcopyrite-galena$\pm$pyrite$\pm$siderite, and 2) dolomite/ankerite-fluorite-sphalerite$\pm$pyrite (Harpøth *et al.* 1986).

Gangue mineralogy: Quartz, biotite, sericite and argillite.

Weathering: Rusty appearrance.

Ore controls: Malmbjerg is a typical porphyry Mo deposit of Climax type.

Genetic models: The Malmbjerg Mo deposit and the Mellempas occurrence are temporally and spatially related to the syenite-granite unit.

Analytical data:

The porphyry system has an orebody of 150 million tons with 0.23% MoS_2 at a cut-off of 0.16% MoS_2 and 0.02% WO_3 (Harpøth *et al.* 1986; Schønwandt 1988).

Exploration:

The Palaeogene porphyry molybdenite deposit was found at Malmbjerg in 1954 (Bearth 1959). Nordisk Mineselskab A/S and AMAX INC. carried out the major investigations of the deposit (Brinch 1969). From 1954 to 1979 a total of 22877 m was drilled and 1329 m of adit has been excavated to investigate the deposit (Harpøth *et al.* 1986; Schønwandt 1988).

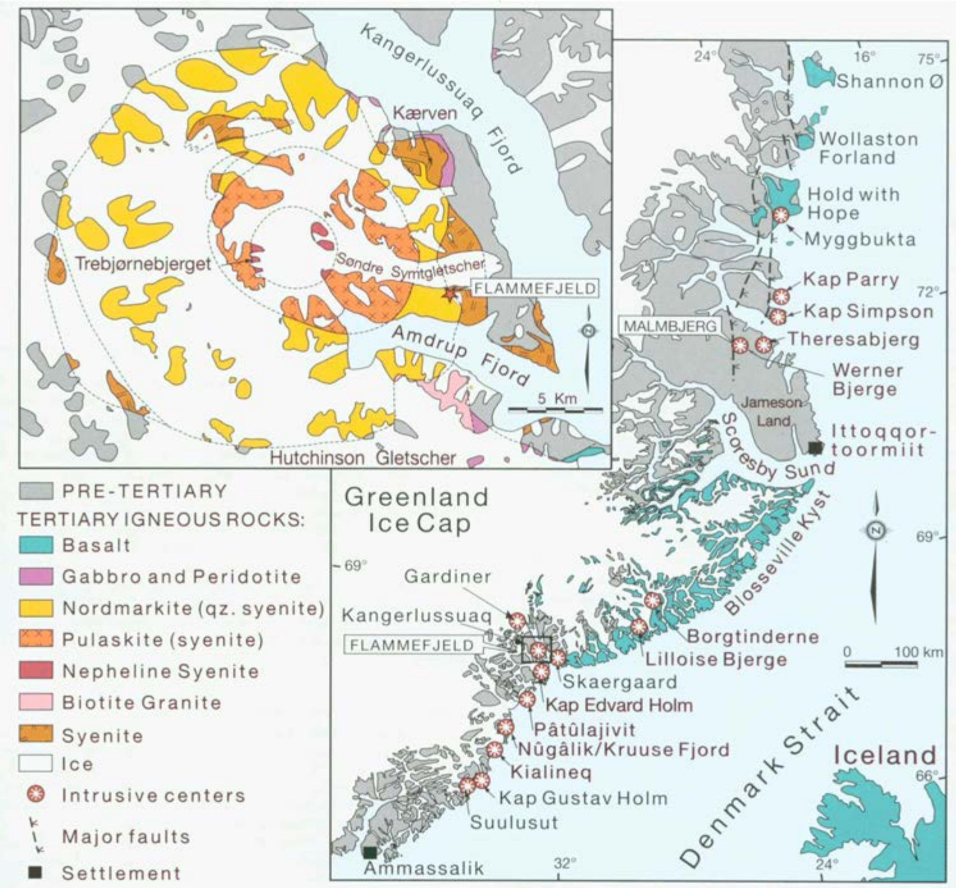

Figure 56. *Distribution of Palaeogene igneous rocks in East Greenland. From Brooks et al. (2004).*

Figure 57. *Alkaline granite intrusion, Malmbjerg Mo- deposit.*

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11a

Locality name:	**Flammefjeld**
Area:	**Skaergaard region**
GSC deposit type:	**15.1 – Epithermal gold**
Commodities:	**Gold, silver, molybdenum**

Geological characteristics:

Description of occurrence: A zone of hydrothermal veins occurs in the Kangerlussuaq region, southern East Greenland. The veins are gold-silver bearing in Precambrian and Palaeogene rocks north of Amdrup Fjord (Fig. 56; Thomassen & Krebs 2001). The mineralised veins generally have widths in the cm–dm range. However, a few vein systems have widths in the metre range, and can be followed over distances of several hundreds of metres. The wall rocks exhibit silicification, carbonatisation, kaolinisation and phyllic alteration, with propylitic alteration of the mafic dykes.

Geotectonic setting: A igneous system with hydrothermal veins formed in a Palaegene environment. The Kangerlussuaq region of southern East Greenland is underlain by a Precambrian crystalline basement intruded by igneous rocks generated during the continental break-up of the North Atlantic in the Early Palaeogene (Wager 1934; Brooks & Nielsen 1982).
The vein-type mineralisation centred on Flammefjeld is confined to brittle structures and shows similarities with epithermal gold-silver veins of low-sulphidation type generated at shallow depths, i.e. within *c.* 1.5 km of the Earth's surface (see e.g. Sillitoe 1993).

Depositional environment/Geological setting: The following geological description is adopted from Thomassen & Krebs (2001). The crystalline basement consists predominantly of quartzo-feldspathic gneisses formed during a major late Archaean episode of sialic crust formation between 3.0 and 2.8 Ga ago (Taylor *et al.* 1992). The Palaeogene magmatic rocks include extensive plateau basalts, several felsic and mafic alkaline intrusions and a major coast-parallel dyke swarm. The largest of the intrusions is the Kangerdlugssuaq complex (50 Ma). The *c.* 700 km^2 Kangerdlugssuaq alkaline intrusion consists of concentric zones with gradational contacts of quartz syenite at the outside through syenite to nepheline syenite at the centre. The satellite intrusions include a variaty of syenites and granites. The presumed youngest intrusive rocks comprise the 500 x 800 m sub-volcanic Flammefjeld complex.

Age of mineralisation: Palaeogene age based on Re-Os dating of molybdenite yielding 39.6$\pm$0.1 Ma (Brooks *et al.* 2004).

Host/Associated rock types: Alkaline granitic/syenitic intrusions.

Deposit form: Veins.

Texture/Structure: The veins are typically developed as breccia fillings and crustifications of epithermal character, often displaying vuggy and colloform structures (cockade structures).

Ore mineralogy: Galena is the most common ore mineral, followed by pyrite and sphalerite. Copper minerals (chalcopyrite and tetrahedrite-tennantite) are less common and arsenopyrite occurs sporadically.
The vein mineralisation can be grouped into three types according to their dominant sulphides:

1. Pyrite-bearing veins with typical widths in the cm–dm range. These predominate along the coast.
2. Galena-sphalerite-pyrite veins. This is the most common type.
3. Chalcopyrite-tetrahedrite-tennantite-pyrite±galena±sphalerite veins. These are not so common.

Gangue mineralogy: Quartz, calcite, Fe-Mn-Mg-carbonates and occasionally fluorite and barite.

Weathering: Yellow, brown and red oxidation colours (Fig. 58).

Ore controls: Hydrothermal system associated by alkaline granitic/syenitic intrusions.

Genetic models: The Flammefjeld complex comprises a breccia pipe intruded by quartz porphyries and surrounded by a halo of hydrothermal alteration displaying vivid yellow and red oxidation colours (Fig. 58); the name Flammefjeld translates as 'flame mountain' (Geyti & Thomassen 1984).

Analytical data:

The highest *in situ* gold values (up to 7.5 ppm) stem from vein types (1) and (3). Silver concentrations above 50 ppm occur in 25% of the samples, values above 100 ppm in 15% and above 200 ppm in 8%; the maximum value recorded is 1193 ppm Ag. Silver correlates well with lead and is most common in vein types (2) and (3).

Exploration:

Mineral exploration by Nordisk Mineselskab A/S in 1970 and 1982 east and north of Flammefjeld revealed a number of base metal-bearing hydrothermal veins with enhanced silver and gold concentrations as well as stockwork-type molybdenum mineralisation in granitic breccia fragments of the Flammefjeld breccia pipe (Brooks 1971; Thomassen 1971; Geyti & Thomassen 1983, 1984; Brooks *et al*. 1987). The existence of a blind 'Climax-type' porphyry molybdenum deposit at 300–500 m a.s.l. below Flammefjeld, and 1–2 km below the palaeosurface, has been suggested (Geyti & Thomassen 1983; Stenstrop 1987). Hydrothermal veins of quartz-carbonate cemented breccia are widespread in the Kangerlussuaq region, but tend to be barren outside the Amdrup Fjord area (Brooks 1972; Geyti & Thomassen 1983; Brooks *et al.* 1987).

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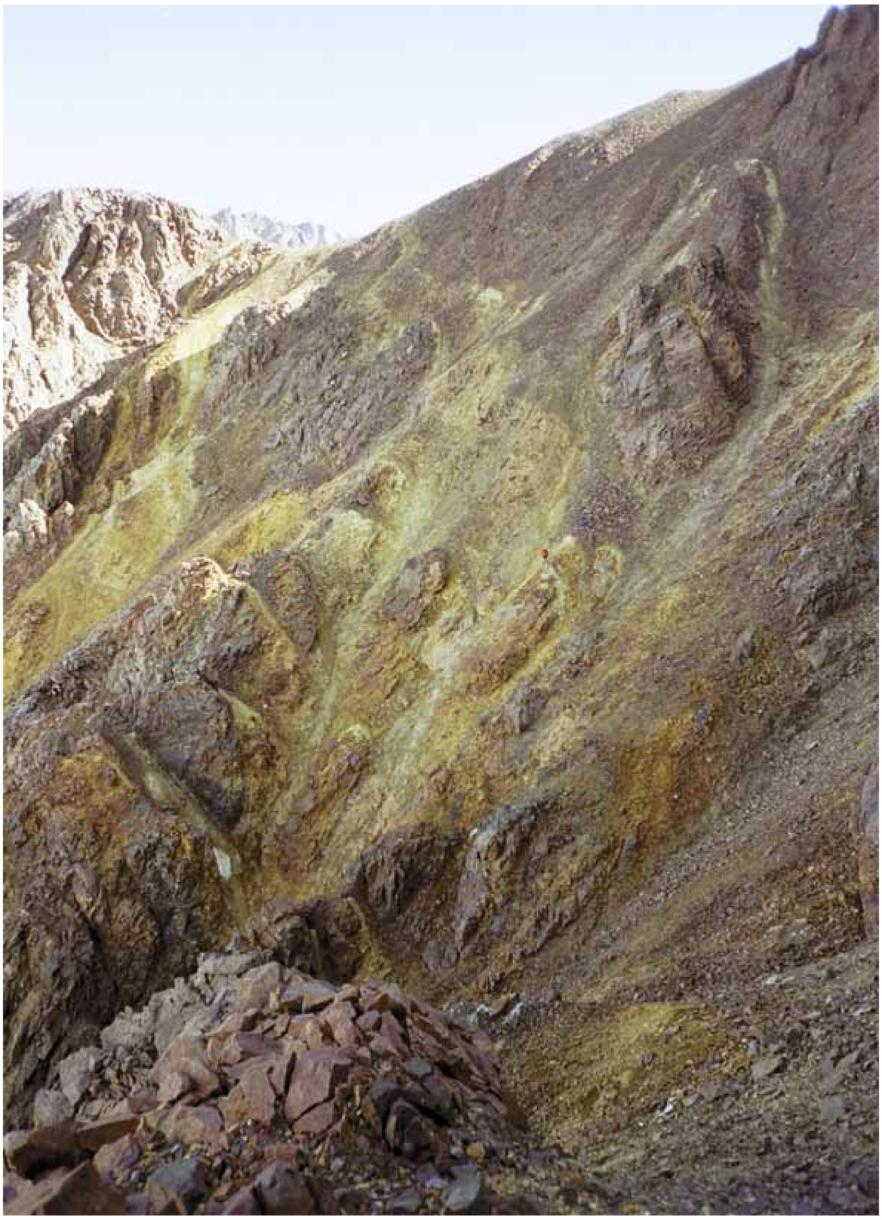

Figure 58. *Typical weathering colours from the Flammefjeld deposit.*

11b

Locality name: **Niaqornaarsuk/Qoorormiut**

Area: **Nanortalik**

GSC deposit type: **15.2 – Quartz-carbonate vein gold**

Commodities: **Gold**

Geological characteristics:

Description of occurrence: The gold bearing vein system is part of the Julianehåb batholith formation. The hydrothermal alteration halo of the granitoids is bleaching, silicification, and albitization, often associated with traces of Fe-sulphides (sulphidation) and locally arsenopyrite or magnetite containing 1-5 ppm Au. The quartz/granitic veins are 0.5 – 5 m wide and can discontinuously be followed up to 200 m, but the individual quartz/granitic veins rarely exceeds 10 m.

Geotectonic setting: The gold mineralisation is related to the Julianehåb Batholith (Niaqornaarsuk and Igusait; Fig. 5) and occurs in quartz veins, in aplites, in sheared metabasic rocks, and hydrothermal altered granitic batholith rocks (Stendal & Grahl-Madsen 2000; Stendal *et al.* 1995). For the evolution of the Ketilidian orogen and the Julianehåb batholith see Garde *et al.* (2002) & McCaffrey *et al.* (2004).

Depositional environment/Geological setting: The gold mineralisation is related to the Julianehåb Batholith (Niaqornaarsuk and Igusait) occurs in quartz veins (Fig. 59), in aplites, in sheared metabasic rocks (Fig. 60), and hydrothermal altered granitic batholith rocks. The hydrothermal alteration halo of the granitoids is bleaching, silicification, and albitization, often associated with traces of Fe-sulphides (sulphidation) and locally arsenopyrite or magnetite.

Age of mineralisation:
Pb isotopes of mineralisation in South Greenland mainly 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 up-concentrated into shear zones and vein-systems. The source indications for Pb in these occurrences is compatible with a juvenile *c*. 2 Ga old source compatible with that of the direct supracrustal host rocks to these occurrences (Stendal & Frei 2000). A second stage of gold deposition seems time-wise related to late stages of the emplacement of the Julianehåb batholith. The source of the slightly more evolved Pb in these mineralisations is difficult to assess, but a mixture of juvenile Pb from the batholith with some contributions from the host rocks may readily explain the scatter of data around a 1.78 Ga reference line.

Host/Associated rock types: Granites, mafic rocks, aplites, and quartz veins.

Deposit form: Sheet like quartz and aplite veins.

Texture/Structure: Vein system of quartz and/or granite.

Ore mineralogy: Several stages of parageneses are identified. (1) a first stage with pyrite (I) + arsenopyrite (I) and (2) second stage with gold, electrum, galena, chalcopyrite, pyrite (II), and arsenopyrite (II+III). They were later followed by sphalerite mineralisation (Dyreborg 1998).

Gangue mineralogy: Quartz and albite.

Weathering: Common rusty appearrance of sulphide-bearing rocks.

Ore controls: The structure of the second order shear zones and control of gold mineralisation is compatible with the regional sinistral NNE-NE shear movement (Coller *et al.* 1995). The gold mineralisation in second order structures is located near the roof of the Julianehåb Batholith and is characteristic for the element association Au-Bi-(As-Mo-W).Fluid inclusion studies show aquaceous-CO_2 with salinities from 6-20 wt.% NaCl and CO_2-CH_4 inclusions with up to 15-mole% CH_4 in the late mineralised fluids. The temperature formation of the mineralisation is 200-400^{o}C and a pressure from 0.5-1.5 kbar (Dyreborg 1998; Fougt *et al.* 1995).

Genetic models: Hydrothermal gold occurrences related to late stage formations of the Julianehåb batholith. Gold- mineralisation in quartz veins is associated with the latest undeformed quartz veins (Dyreborg 1998).

Analytical data:

Typical gold values vary generally from 1-5 ppm. However, quartz veins can have erratic values e.g. Qoorormiut. The gold concentration varies significantly in this type of mesothermal gold mineralisation and reaches 380 ppm Au in thin silicified shear zones (<1 m wide). One 6 metre chip sample in a vein of milky quartz gave 114 ppm Au and a second 6 metre chip sample in rusty and locally carbonated amphibolite with small quartz veinlets gave 147 ppm Au (Olsen 1995). Re-sampling by GEUS did not reproduce these results.

Exploration:

Nunaoil A/S has conducted mineral exploration in the beginning of the 1990's. Crew Development and Nunaminerals have the concession in the target area (2004).

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Figure 59. *Rusty gold-bearing quartz vein in bleached granodiorite.*

Figure 60. *The 'Amphibolite Ridge' at Niaqornaarsuk, hosting mineralised quartz veins. Mountaineer for scale.*

Locality name: **Ymer Ø**

Area: **Central East Greenland**

GSC deposit type: **18 – Vein-stockwork tungsten**

Commodities: **Tungsten and antimony**

Geological characteristics:

Description of occurrence: Tungsten mineralisation (Hallenstein & Pedersen 1983; Hallenstein *et al.* 1981; Pedersen & Stendal 1987) occurs as scheelite (Fig. 73). Hallenstein & Pedersen (1983) group the scheelite occurrences into three main geological settings: (1) scheelite in metasediments often associated with granodiorite or granite intrusions. Scheelite occurs in this type as calcareous quartzite (garnet-hornblende quartzite) also called skarnoid (Hallenstein and Pedersen1983). This type is often associated with minor tin occurrences. (2) Scheelite associated with granite, pegmatite and quartz veins are only found in the Lower Eleonore Bay Supergroup. (3) Scheelite in sediments without direct igneous association is distributed along the extensional fault zone between the Eleonore Bay Supergroup and Devonian sediments on Ymer Ø, where several levels of the Ymer Ø carbonates are mineralised (Pedersen & Stendal 1987).

Geotectonic setting:

Depositional environment/Geological setting: Mineral occurrences related to Caledonian intrusions and lineaments comprise arsenic, tungsten and stibnite occurrences. Arsenic is found at several places and is particularly concentrated in the Alpefjord region as arsenopyrite (Stendal 1981). The arsenopyrite is hydrothermal formed and distributed in fracture and vein systems closely related to the contact, which separates the Eleonore Bay Supergroup from the older metamorphic crystalline complex (Stendal 1981). Fluid inclusions in the arsenopyrite-bearing veins yield homogenisation temperatures of boiling CO_2-bearing water of moderate salinity are from 225^o to 260^{o}C with a pressure of approximately 1 kb (Stendal & Ghisler 1984).

The scheelite and stibnite occurrences are hosted in brecciated carbonates in minor fault zones and the grade of tungsten is high. The mineral occurrences on Ymer Ø reflect a crude zonation with scheelite and stibnite at a higher stratigraphic level than pyrite, galena, sphalerite, chalcopyrite and locally arsenopyrite with gold at lower levels of the Upper Eleonore Bay Supergroup.

Age of mineralisation: The ultimate source of Pb (and by inherence that of W) in scheelite indicates isotope data points to be a mixing sources of granite and sediments contemporaneously with the emplacement of the Caledonian granite (Stendal pers.com.).

Host/Associated rock types: Limestones.

Deposit form: Lenses in veins.
Texture/Structure: Veins and veinlets.

Ore mineralogy: Scheelite and stibnite are the main ore minerals but accessories such as arsenopyrite, pyrite and chalcopyrite occur.

Gangue mineralogy: Calcite and dolomite.

Weathering: None.

Ore controls: Faults in a carbonate sequence.

Genetic models: Hydrothermal veins probably related to Caledonian granites.

Analytical data:
The average of the best prospect is 0.7% tungsten and 3.5% antimony (Harpøth *et al.* 1986).

Exploration:
In the period from 1979 to 1984 Nordisk Mineselskab carried out a tungsten exploration programme supported by the Commission of the European Communities (Hallenstein & Pedersen 1983; Hallenstein *et al.* 1981; Pedersen & Stendal 1987). During this campaign several vein-type occurrences were located such as fluorite and base metal mineralization, precious- and base metal mineralization, tungsten-antimony mineralization, antimony-gold and bismuth-gold mineralisation. Diamond drilling of one of the scheelite and stibnite veins indicate a deposit of 42000 Mt with 0.7% W and 108,000 Mt with 3.5% Sb (Harpøth *et al.* 1986). Locally this vein-type mineralization, especially the arsenic-bearing vein, has gold contents up to a few parts per million (Pedersen 1993).

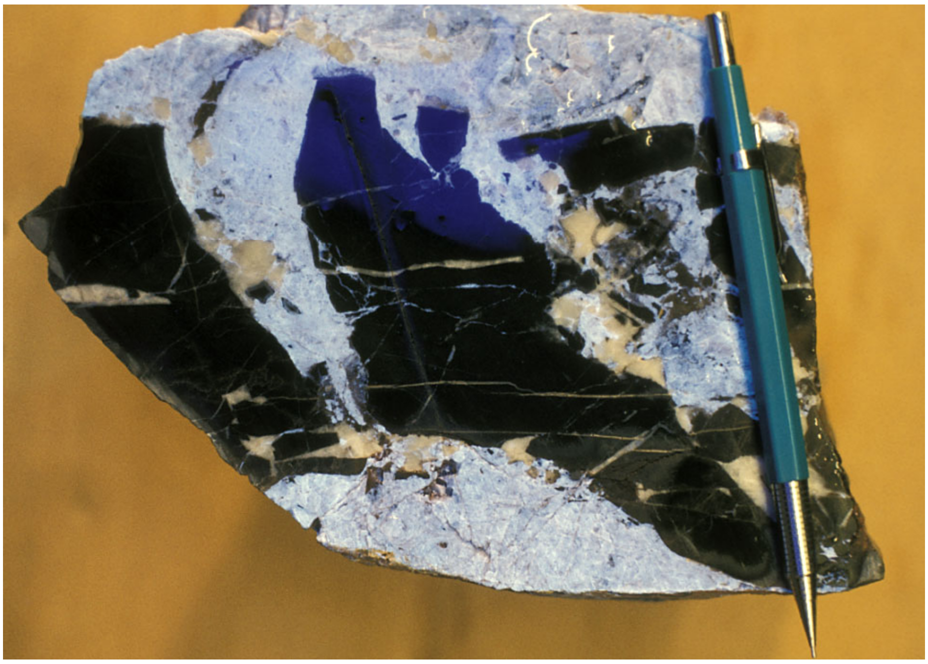

Figure 61. *Massive scheelite in limestone breecia (UV-light) – see Figure 62.*

Figure 62. *Scheelite-bearing limestone breccia with scheelite (see Figure 61) from Ymer Ø.*

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13

Locality name: **Ivittuut**

Area: **Arsuk Fjord**

GSC deposit type: **23.0 Peralkaline rock-associated commodity**

Commodities: **Cryolite**

Geological characteristics

Description of occurrence: The Ivittuut cryolite deposit is hosted in an intrusive complex, located within the roof zone of a 300 m wide pipe-like granite stock. The cryolite deposit is divided into a siderite-cryolite, a pure cryolite, a fluorite-cryolite and a fluorite-topaz unit, which is located above a large siderite and quartz rich unit. The genesis of the cryolite deposit is described in (Pauly 1992; Pauly and Bailey 1999).

Geotectonic setting: Syenite, nepheline syenite, and granite complexes are emplaced in the Mesoproterozoic Gardar province in South Greenland (Kalsbeek *et al*. 1990)

Depositional environment/Geological setting: The Ivittuut granite stock contained and retained F-rich fluids that formed the ore body of the cryolite deposit. The deposit was formed when F-rich post-magmatic fluids from deeper parts of the Ivittuut granite intensively percolated the top of the central part of the granite stock to form a homogeneous supercritical fluoride-rich melt (Pauly and Bailey 1999).

Age of mineralisation: The Ivittuut cryolite granite has been Rb-Sr age dated at 1171±10 Ma (unpublished data from J.C.Bailey), which places the deposit close to the group of Late Gardar intrusive Centres at 1159-1118 Ma (Blaxland *et al*. 1978).

Host/Associated rock types: Granite and greisen of the Ivittuut granite intrusion.

Deposit form: The Ivittuut cryolite deposit is composed of irregular mineralised layers (units) within a 300 m wide pipe-like granite stock.

Texture/Structure: The deposit consists of coarse-grained pegmatitic rock at the top of an intrusive stock.

Ore mineralogy: Cryolite, fluorite, siderite and topaz.

Gangue mineralogy: Quartz.

Weathering: The cryolite is generally unaffected by weathering. Secondary alteration due to circulating water locally creates a suite of rare unique minerals of the cryolite-family (e.g. cryolithionite, thomsenolite, pacnolite) (Petersen & Secher 1993).

Ore controls: The deposit is formed by F-rich post-magmatic fluids from deeper parts of the Ivittuut granite, which intensively leached, metasomatised and eventually remobilised the top of the central part of the granite stock to form the cryolite-rich deposit.

Genetic models: Alakline igneous intrusion.

Analytical data

Not applicable.

Exploration

Mining activities directed at cryolite exploitation were initiated in 1854 and lasted until the open pit operations finally stopped in 1987. After a temporary closing of the pit in 1962, the concessionaire, Kryolitselskabet Øresund A/S, decided in 1983 to make a final effort to localise more cryolite ore and to re-open the pit for further exploitation of remaining high-grade reserves. Exploration activities from 1984 to 1987 included re-evaluation of the mineral reserves through development drilling, exploration drilling, geophysical, and environmental surveys. During this drilling investigation a possible new ore body was encountered c. 800 m below the surface, but no further drilling was carried out and exploration ceased. In total nearly 19 km of drill core have been collected by Kryolitselskabet Øresund A/S up to 1987. Further surveys were carried out in 1989 under a separate concession granted to Platinova Resources Ltd. For 1991 a concession was granted to the municipality of Ivittuut and from 2001 a new exploration licence was granted to New Millennium Resources NL. (Bondam 1991).

The remaining in situ reserve of probably usable ore is calculated to be at least 22,000 t of cryolite ore (average 45.9% cryolite), 501,000 t of fluorite ore (average 49,9% F) and 691,000 t of siderite ore (average 65% siderite) (Bondam 1991).

The cryolite deposit originally contained 3.8 million tons of ore with 58% cryolite, including the fluorite-topaz unit underlying the western part of the deposit. To this is added an underlying mass of quartz with siderite of 8.5 million tons to a total tonnage of the mineralisation of 12.3 million tons (Pauly and Bailey 1999).

The position of the abandoned open pit mine at Ivittuut is 61^{o}14´N and 48^{o}10´W, on the northwest coast of the Ivittuut peninsula at the shore of Arsuk Fjord.

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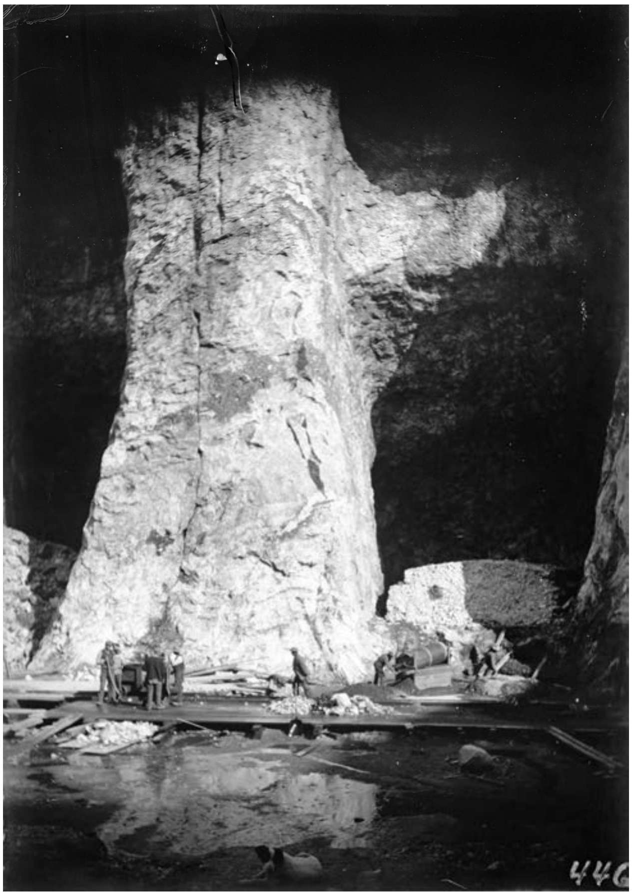

Figure 63. *Mining of cryolite in the Ivittuut mine 1898. Pillars of solid cryolite are left along the side of the open pit.*

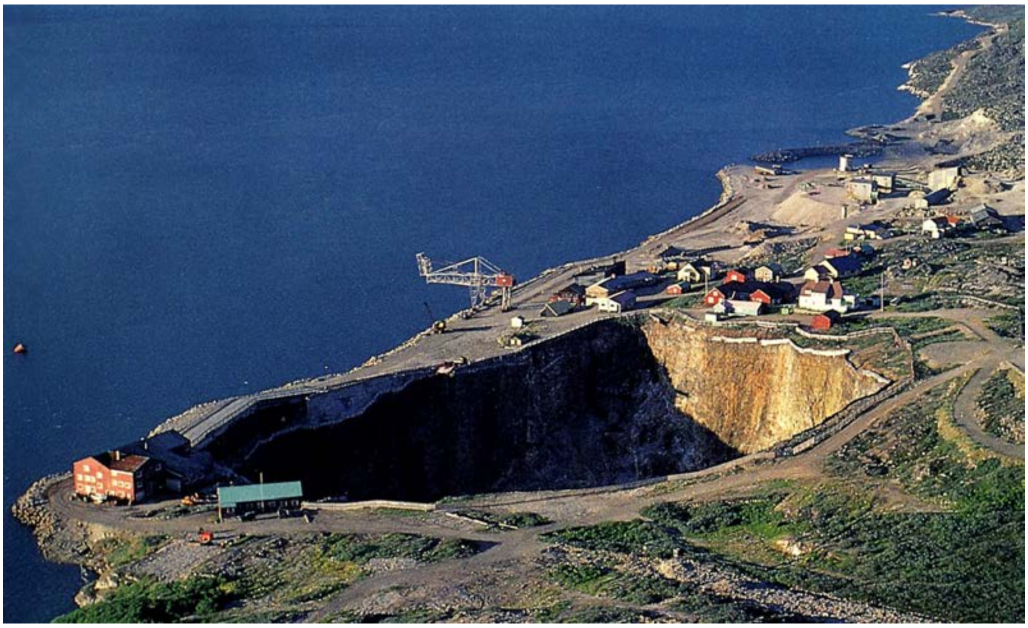

Figure 64. *Aerial view of the abandoned cryolite mine in Ivittuut, 1987. The open pit has the shape of the now exploited cryolite body.*

Locality name: **Kangerluarsuk**

Area: **Narsaq**

GSC deposit type: **23.0 Peralkaline rock-associated commodity**

Commodities: **Zirconium, REE**

Geological characteristics

Description of occurrence: Within the Ilimmaasaq intrusion the floor sequence of the agpaitic nepheline syenite, called kakortokite, represents an accumulation of the zirconium-rich mineral. In the Kangerluarsuk area the layered kakortokite contains repetitive banding of black, red and white layers in which the varying concentrations of the main constituents arfvedsonite, eudialyte and alkali feldspar result in the banded appearance (Bohse *et al.* 1971, Johnsen *et al.* 2001; Sørensen 2001). The Kangerluarsuk area covers an area of at least 2 x 3 km from sea level to c. 400 m asl. and this area represents the Zr-deposit, named 'Kringlerne' (pretzel in English).

Geotectonic setting: The mid-Proterozoic Gardar Province encompasses episodes of faulting, sedimentation and alkaline igneous activity. A NE-SW trending continental rift is developed in the region in which a sequence of sandstones and lavas (the Eriksfjord Formation) is accumulated. Within and outside the rift major central intrusions and numerous generations of dykes were emplaced. Upton & Emeleus (1987) have reviewed the Gardar Province.

Depositional environment/Geological setting: The Ilimmaasaq intrusion has an outcrop area of 17 x 8 km, and is built up of an outer discontinuous envelope of augite syenite and a central series of conformably layered, strongly peralkaline (agpaitic) nepheline syenites. Additionally a small sheet of alkali granite occurs beneath the roof. The nepheline syenites are divided into a roof sequence (pulaskite, foyaite, sodalite foyaite and naujaite) that crystallised downwards, and a floor sequence (kakortokite and lujavrite) that accumulated upwards (Ussing, 1912; Bailey *et al.,* 1981).

Age of mineralisation: The rocks yielded a Rb-Sr isochron age at 1143±21 Ma (Blaxland et al. 1976), which places the intrusion in the late part of the Gardar period.

Host/Associated rock types: Agpaitic nepheline syenites.

Deposit form: The layered kakortokite contains repetitive banding of black, red and white layers, in total 29 units with varying thickness from 1–20 m.

Texture/Structure: The complex is made up of a group of layered nepheline syenites. These are rich in Na and comparatively poor in Si and they were formed from aluminous alkali basalt magmas, which during ascent from the mantle were strongly modified through fractional crystallisation processes. At the same time they were enriched not only in Na but also in volatile components as F, Cl and S together with a wide range of rare elements such as Li, Be, Nb, Zr, REE, U and Th.

Ore mineralogy: The Ilimmaasaq complex is a unique igneous complex because of its extreme enrichment in a number of rare elements expressed in more than 225 different minerals. Thirty minerals were first discovered and described in the complex and twelve are only known from this place. Eudialyte is the main ore mineral (Johnsen *et al.* 2001).

Gangue mineralogy: Arfvedsonite, sodalite and alkali feldspar.

Weathering: The kakortokite disintegrates into rough gravel of the main mineral components.

Ore controls: Sequences in layered igneous rocks.

Genetic models: Cumulate from a layered igneous intrusion. The layering may be a result of sorting of minerals after density in the consolidating magma and successive deposition of layers on the floor of the magma chamber, but the origin of this spectacular layering is still under debate (Sørensen 2001).

Analytical data

Average ZrO_2 contents of the three different Zr-rich layers are: Black kakortokite 1.1%; Red kakortokite 3.8 %; White kakortokite 1.3% (Bohse et al. 1971).

Exploration

K.L. Giesecke has carried out exploration in the Kangerluarsuk area several times since the discovery in 1806. K.J.V Steenstrup, who made a pilot mining of eudialyte ore in 1888-89 on the small island Qeqertaasaq, carried out the first commercial investigation on behalf of the Cryolite Company. During field work in 1900 and 1908 N.V.Ussing of the Geological Museum made a thorough mapping of the complex (Ussing 1912). The Cryolite Company revisited the Kangerluarsuk area in 1939 and 1946 (Bøgvad 1950) but concluded that mining was not feasible at that time.

A modern geological map of the complex was produced by GEUS (Ferguson 1964). Ferguson also presented a detailed examination of the geochemistry of the kakortokites (Ferguson 1970). In 1988 a revised geological map of the southern half of the complex including the kakortokites was published (Andersen *et al.* 1988). From 1968–76 Superfos A/S, who developed methods for extracting Zr from eudialyte concentrates, however without finding a market for the commodity, carried out 76 exploration. A/S Carl Nielsen, who carried out drillings of high-grade kakortokite areas, resumed the exploration in 1985. Highwood Resources and partners entered exploration in the area in 1987 and in they 1988 made a joint venture with A/S Carl Nielsen. The activity resulted in extended drilling and mapping programmes until 1992, when the operations ceased.

Based on the work carried out by GEUS and partners a preliminary reserve estimate of a single 3.5 m thick layer of red kakortokite indicated a total of 61 000 tons ZrO_2 and 6500 tons Nb_2O_5, with an average grade of 4% ZrO_2. A geometric mean of 1.2% ZrO_2 is found for the entire kakortokite rock suite (Bohse *et al.* 1971; Andersen *et al.* 1988).

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Figure 65. *Sequences of zirconium rich rocks (kakortokites) in the layered Ilimmaasaq igneous intrusion at 'Kringlerne'. The top of the cliff face is c. 350 m above sea level.*

15

Locality name: **Motzfeldt Sø**

Area: **Narsarsuaq**

GSC deposit type: **23.0 Peralkaline rock-associated commodity**

Commodities: **Tantalum, Niobium**

<u>Geological characteristics</u>

Description of occurrence: The Ta-Nb deposit within the Motzfeldt centre crops out locally over an area of about 20 X 15 km. The formation of the Motzfeldt centre, which is made of multiple intrusions of syenites with a wide range of textural and compositional characteristics, can be resolved into three major and several minor intrusive phases (Emeleus & Harry, 1970; Tukiainen *et al.,* 1984). Nepheline syenites of the second phase, the Motzfeldt Sø formation, are peralkaline and volatile-rich, and some are strongly enriched in Zr, Nb, Ta, REE, U and Th, locally forming deposits of economic interest (Thomassen 1988; Tukiainen 1988).

Geotectonic setting: The mid-Proterozoic Gardar Province encompasses episodes of faulting, sedimentation and alkaline igneous activity. A NE-SW trending continental rift is developed in the region in which a sequence of sandstones and lavas (the Eriksfjord Formation) is accumulated. Within and outside the rift major central intrusions and numerous generations of dykes were emplaced. The Gardar Province has been reviewed by Upton & Emeleus (1987).

Depositional environment/Geological setting: The Motzfeldt Centre of the Igaliko Nepheline Syenite complex, one of the major central complexes in the Gardar province of alkaline igneous activity, is the oldest centre in complex and its formation can be resolved into three major and several minor intrusive phases (Emeleus & Harry, 1970; Tukiainen *et al.,* 1984).

The so-called Motzfeldt Ring Series constitutes four major, steep sided, outward dipping intrusions of predominantly peralkaline syenite and nepheline syeinite which young inwards.The peralkaline residua gave rise to a complex of late peralkaline sheets of microsyenite and pegmatite and hydrothermal alteration with associated Th-U-Nb-Ta-Zr-REE mineralisation.

Age of mineralisation: Rb-Sr isotope data yield an age of 1310±10 Ma (Tukiainen 1988), which places the centre in the very early part of the Gardar period.

Host/Associated rock types: Nepheline syenites and syenites.

Deposit form: The mineralisation and the accompanied hydrothermal alteration is thought to have been formed by an upwards migrating volatile phase rich in alkalis, fluorine and incompatible elements. The pyrochlore enrichment at Motzfeldt Sø is characterised as a 'low grade - large tonnage' deposit.

Texture/Structure: The pyrochlore content increases outwards and upwards towards the roof of the syenite unit of the intrusion.

Ore mineralogy: Pyrochlore (Nb, Ta, U, REE), thorite (Th), zircon (Zr), and bastnaesite (REE, Th) (Tukiainen 1986).

Gangue mineralogy: Alkali feldspar.

Weathering: The ore minerals are not affected.

Ore controls: Magmatic fractionation and subsequent hydrothermal alteration. The pyrochlore at the deeper levels is enriched in Ta and Ca, whereas that of the higher levels of the igneous column is more enriched in Nb, U and REE.

Genetic models: Igneous intrusion related hydrothermal mineralisation. The apparent intrusion mechanism was a combination of ring fracture and block subsistence.

Analytical data

The Ta content in the pyrochlore vary from 1.3% to 8.3%. The general Nb/Ta ratio is 11. The Nb-Ta resource estimation indicates a mineralised rock volume of more than 500 million tons with average 0.14% Nb, 120 ppm Ta, 60 ppm U and 90 ppm Th. High grade zones carries up to 426 ppm Ta. With the cut-off grade at 250 ppm Ta, the estimated reserve is at least 30 million tons. Additionally a Nb resource of at least 130 million t with 0.4-1.0% Nb_20_5 is known (Thomassen 1988; Tukiainen 1988).

Exploration

The Motzfeldt Centre has been mapped geologically 1961-1970 by GEUS, and again in the period 1979-1985, partly funded by the European Economic Community. During the latter activity GEUS conducted a regional airborne radiometric survey and discovered and investigated widespread pyrochlore mineralisation (Armour-Brown *et al.* 1980; Tukiainen 1988; Tukiainen *et al.* 1984). In 1987-1988 a new programme was carried out as a joint venture between GEUS and Nunaoil A/S (Thomassen, 1988). The UK company Angus & Ross Pl. continued exploration under a new exploration licence from 2000, including drilling and detailed investigation of mineralised areas of what the company believes to be one of the largest Ta-deposits in the World.

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Figure 66. *Climbers sampling on an outcrop at a steep cliff face within the Motzfeldt Centre.*

Figure 67. *Close up of the pyrochlore mineralisation in syenite of the Motzfeldt Sø formation .*

Locality name: **Sarfartoq**

Area: **Kangerlussuaq region**

GSC deposit type: **24.0 – Carbonatite-associated deposits**

Commodities: **Niobium and tantalum**

Geological characteristics:

Description of occurrences: The pyrochlore deposit was formed during one of several magmatic phases of the Sarfartoq carbonatite intrusion (Secher & Larsen 1980). The pyrochlore is accumulated late in the igneous history as vein shaped bodies in a marginal zone surrounding a central carbonatite mass. The mineralisation is located in a tangential set of cataclastic fractures believed to be generated during the emplacement of the intrusion. Several of these fractures are later mineralised and those in the south-eastern part of the complex are the most prominent examples. However, only two occurrences (named 'Sarfartoq 1' and 'Sarfartoq 2') seem at present to be of economic interest. Unlike other known carbonatite complexes, the Nb content of the main Sarfartoq carbonatite is very low, thus explaining the late stage accumulation and precipitation of pyrochlore.

Geotectonic setting: The Sarfartoq carbonatite, together with kimberlitic rocks from the region, belongs to the well-known and widespread 'North Atlantic alkaline province', which has representatives in both eastern Canada and Scandinavia (Secher & Larsen 1980). It is believed that this province was formed in a rift system during the opening of the Iapetus Ocean (Larsen *et al.*1983; Larsen & Rex 1992).

Depositional environment/Geological setting: The Sarfartoq carbonatite complex is emplaced in the transition zone between the Archaean granulite facies craton to the south and the Palaeoproterozoic Nagssugtoqidian orogen to the north (Secher 1986). The complex is ellipsoidal at the surface and covers about 90 km^2, of which 10 km^2 are intrusive carbonatites (Secher & Larsen 1980).

Two major stages of igneous activity introduced Fe/Mg-carbonatite rocks, leading to the formation of a steeply dipping conical body (the core) of concentric sheets of carbonatite, followed by a series of concentric and radial dykes and agglomerates emplaced in the surrounding marginal shock-zone. Hydrothermal activity gave rise to several phases of Nb and REE- mineralisation in carbonate veins and shear zones. The accompanying fenitisation is of the Na-type.

The carbonatite core is divided into three zones based on the proportion of carbonatite to fenite. The inner core (>50% carbonatite) is only approximately 1 km^2 in area; the outer core (<50% carbonatite) forms a 1–3 km broad ring, occupying around 9 km^2. A narrow rim of fenite (about 5 km^2) surrounds this.

Age of mineralisation: The age of the Sarfartoq carbonatite complex is around 600 Ma, based on K/Ar age determinations (Larsen *et al.* 1983; Larsen & Rex 1992). The complex is thus of late Proterozoic age.

Host/Associated rock types: The dolomitic magmas of the carbonatite intrusion were poor in SiO_2, Al_2O_3 and K_2O, as well as Nb compared to other carbonatites. There is a marked trend in the increasing Nb content during the progress of the emplacement with a late stage culmination of the pyrochlore deposition. The host rock is gneiss with amphibolite schlieren, altered by a slight K-feldspar fenitisation and hematite staining.

Deposit form: The occurrence is located on the southern mountain slope of the valley Arnangarnup kua in an altitude of 640 m a.s.l. ('Sarfartoq 1'). The pyrochlore-mineralised structure is a steep to vertical dipping lens measuring 10 x100 m. The mineralisation strikes roughly E-W and has a sharp contact to the hosting gneiss. The western part of the mineralised lens has been displaced approximately 17 m towards NE by a 132° striking fault. The lens is pinching out laterally and gradually fading out into the host rock. The radiometric map shows very steep gradients in cps-values (counts per second, total gamma-radiation), which indicates a mineral occurrence with sharp contacts (Secher 1986).

Other known pyrochlore showings in the area ('Sarfartoq 2') of the same type are found to be much smaller and with lower grades.

Texture/Structure: Pyrochlore is typically deposited as granular to dense aggregates with size of individual grains in the range of 0.1–2 mm. Modal compositions of mineralised lenses shows up to 70 % pyrochlore. Single grains are often euhedral with a pronounced zonarity due to compositional variations. An accumulation of U and Ta in grain cores is not unusual. Cavities occur within the aggregates and can locally be up to walnut size. Hematite and mm-sized octahedrons of pyrochlore are observed in the cavities.

Ore mineralogy: The central part of the lens consists of 95 vol% pyrochlore giving the occurrence a nearly monomineralic character. The remaining 5 vol% comprises hematite, K-feldspar and aegirine. Thin section studies show that pyrochlore is strongly zoned generally with an irregular and inclusion filled core surrounded by alternating layers of fresh looking pyrochlore in varying shades of yellow brown. No sign of metamictisation has been observed.

The Nb-content varies from 40 % (Table 1) in the central part of the lens to 5 % at the contact to the host rock. In general it is estimated that the lens averaging approximately 10 % Nb equivalent to 15 % Nb_2O_5.

Analyses of pyrochlore are shown in Table 1. The Nb/Ta ratio increases from core to rim in the grains, whereas LREE seems to decrease. It is estimated that the high Ta-U cores of the pyrochlore represent 5–10 vol% of the mineralisation. The cores are probably remnants of earlier formed pyrochlore.

Gangue mineralogy: The main rock-forming minerals are dolomite, ankerite, calcite, apatite, phlogopite, richterite-arfvedsonite and magnetite. Important accessories are *pyrochlore, zircon and niobian rutile*.

Weathering: None.

Ore controls: Tangential cataclastic zones as well as the fenitisation within the marginal area around the Sarfartoq i complex is probably generated during the emplacement. Pre-hydrothermal Nb-deposition is observed only as Nb-rutile within the carbonatite proper. The initial pyrochlore crystals of the mineralised veins were deposited as open space fillings in cataclastic zones as isolated euhedral grains. During successive pyrochlore deposition the earlier deposited pyrochlore crystals were partly digested and U, Ta and REE redistributed. Together with fractionation of the fluid, this created changes in composition of later deposited pyrochlore.

Genetic models: The Nb-enriched hydrothermal phase terminating the carbonatite magma activity resulted in several stages of pyrochlore accumulation and deposition in veins and shear zones within the fenitised zone of the marginal part of the complex (Secher 1986, 1987, 1989).

The described pyrochlore occurrence is of an extremely unique type, so far not observed elsewhere. The geochemical, spatial and chronological evolution observed in the Sarfartoq complex is outlining a typical trend for carbonatite complexes, where the deposition of pyrochlore has developed into an extremely rich type of mineralisation (Secher & Larsen 1980; Wolley 1987).

Analytical data:

Chemical analyses (Secher 1987):

Sam-ple%	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	FeO	MgO	CaO	Na_2O	K_2O	P_2O_5	Nb_2O_5	RE_2O_3	UO_2	Volat	Sum	Ta_2O_5	ThO_2
1	8.32	2.57	0.63	3.10	0.63	1.11	12.50	5.27	0.36	0.11	58.20	1.67	0.92	5.28	100.67	0.58	0.01
2	1.07	3.10	n.d.	n.d	n.d.	n.d	13.24	5.29	0.06	0.11	63.49	0.79 *	1.72	-	88.95	0.64	0.27

*Includes only Ce and La

1 Rock: GGU No 253678, from the central part of mineralised zone. Chemical analyses based on XRF (GEUS/GGU) supplemented by results from EDX and INAA (RISØ-NL), recalculated and matrix corrected with heavy elements.
2 Mineral: Geometric mean based on 70 point analyses, representing several pyrochlore grains within the mineralisation. Analyses obtained by microprobe (University of Copenhagen) on single mineral grains.

Exploration:

The exploration of the Sarfartoq carbonatite complex has been based on the use of airborne gamma-ray spectrometry (Secher 1976). Stream sediment geochemistry has assisted in localising the Nb-enriched sections. The first showing ('Sarfartoq 1'), discovered in 1978, demonstrates a high grade, low tonnage type of deposit. There is an expected minimum of 0.1 x 10^6 ton of mineralised rock, calculated to a depth of 50 m, carrying 15 % Nb_2O_5 and 0.18 % Ta_2O_5. Maximum values are as high as 58 % Nb_2O_5 and 0.58 % Ta_2O_5. This calculation is based only on surface observations.

The pyrochlore potential within the Sarfartoq complex has been evaluated and drilled by two companies: In 1989 Hecla Mining Company drilled 568 m of core at the occurrence 'Sarfartoq 1', and based on that the company estimated 25,000 t –30,000 t of ore with a cut off at 10% Nb_2O_5. The company concluded that the mineralisation pinched-out laterally as well as at depth and accordingly ceased exploration at the licence (Druecker 1990). In 1998 New Millennium carried out 800 m of diamond drilling and after that calculated a measured resource at 35,000t at 11.3 % Nb_2O_5 and additional 100,000 tonnes at 4.6% Nb_2O_5 in the indicated category.

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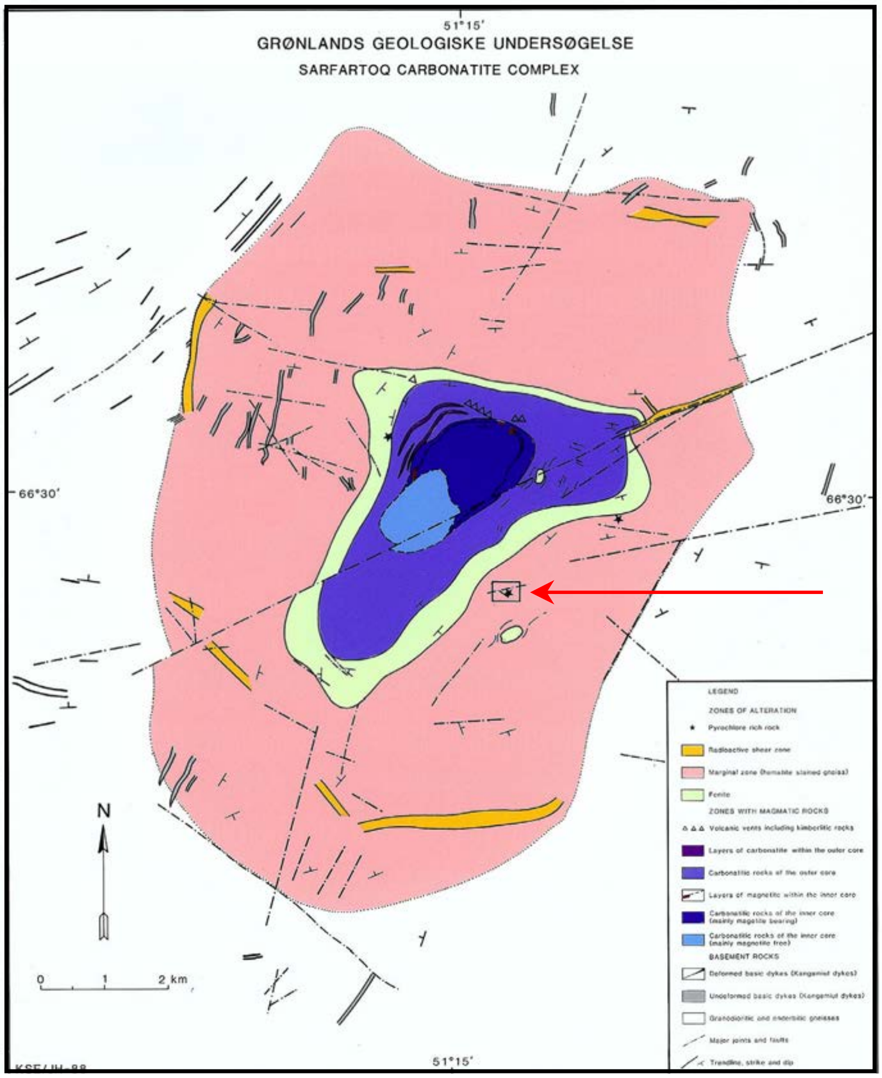

Figure 68. *Geological map of the Sarfartoq carbonatite complex . The pyrochlore mineralisation ("Sarfartoq 1") is outlined by a box (end of red arrow). After Secher (1986).*

Figure 69. *Close-up of pyrochlore lens at the southern margin of the Sarfartoq complex.*

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Locality name: **Kangerlussuaq**

Area: **Kangerlussuaq**

GSC deposit type: **25.0 – Primary diamond deposits**

Commodities: **Diamond**

Geological characteristics:

Description of occurrence: Diamonds have been found within some of the many kimberlitic dykes in the area. The dykes commonly contain numerous mantle xenoliths ranging in size from a few millimetres to several decimetres. A majority of the xenoliths have peridotitic or pyroxenitic composition. Kimberlitic or lamproitic boulders in sizes from a few centimetres to 2 metres across are ubiquitous, often in cluster or train several hundreds of metres long.

Geotectonic setting: Alkaline ultramafic dykes in the Sisimiut–Kangerlussuaq and Sarfartoq areas intrude the border zone between the Archaean craton and the Palaeoproterozoic Nagssugtoqidian orogen (Secher & Larsen 1980). The alkaline rocks were indeed intruded along the Archaean border zone during continental rifting following the opening of the Iapetus sea at the dawn of the Cambrian (Secher & Larsen 1980).

Depositional environment/Geological setting: The region hosts several clusters of kimberlitic dykes and sills (more than 600 outcrops), which appear to be controlled by pre-existing joint systems or concordant with the enclosing gneiss. A large number of dykes are located in the vicinity of the Sarfartoq carbonatite complex. The Kangerlussuaq region has the largest concentration of kimberlitic dyke and boulder occurrences within the West Greenland alkaline province (Larsen 1991, Jensen *et al.* 2002, 2004).

Age of mineralisation: Dykes in the adjacent Sisimiut region are around 1.2 Ga old, and the kimberlitic dykes in both the Sarfartoq and Sisimiut regions have ages of around 0.6 Ga (Larsen & Rex 1992). A new age dating programme involving the kimberlitic rocks is in progress at GEUS.

Host/Associated rock types: Southern West Greenland hosts an alkaline province with a variety of ultramafic alkaline rocks, including swarms of dykes traditionally described as kimberlites and lamproites. The classification of these rocks has been disputed and they are considered to be ultramafic lamprophyres. The term ‘kimberlitic’, however, is still in common use in Greenland and is applied here.

Deposit form: In total around 900 diamonds (microdiamonds and a few macrodiamonds) are found in outcropping dykes. Only dykes located within the unreworked Archean craton are sofar known to be diamondiferous. The dykes are often subvertical, 1–2 m wide, and traceable for many hundreds of metres. Others are shallow dipping, rarely over 1 m wide, and exposed over tens of metres.

Texture/Structure: Two clusters of dykes have been recognised within the region in the last 20–30 years (Scott 1977, 1981; Larsen 1980, 1991). Dykes of the Sisimiut swarm (20 x 60 km), consisting mainly of 1287 Ma lamproites and 587 Ma kimberlites, generally have vertical E–W/SE–NW striking orientation. The structure of the Sarfartoq swarm with mainly 615 Ma kimberlites appears to be dominated around a N-S corridor of steeply dipping dykes (Jensen *et al*. 2003) A number of kimberlitic dyke orientations follow the trends of the Palaeoproterozoic Kangâmiut dolerite dykes in reworked as well as unreworked parts of the Archaean basement. Information from magnetic field data lend support to the hypothesis that kimberlitic dyke emplacement may be controlled by such structures of more regional character.

Ore mineralogy (principal and *subordinate*): Diamond. Kimberlite indicator minerals: pyrope garnet (G10 and eclogitic), chrome diopside, ilmenite, chromite, olivine and phlogopite.

Gangue mineralogy (principal and *subordinate*): Kimberlitic rock.

Weathering: Development of secondary monohydrocalcite coating on boulders and cliff surfaces. On a local scale kimberlite indicator minerals from till samples are distributed due to complex glacial dynamics having characterised the formation of till deposits. The most diamond-favourable indicator minerals are distributed far beyond the areas with known diamonds. This observation, together with the postulated regional structural control, suggests that the potential for diamonds is not restricted to the known occurrences.

Ore controls: Not applicable.

Genetic models: Diamond is transported from the mantle's diamond stability field (180–200 km's depth) to the recent position during kimberlite dyke intrusion.

Analytical data:
Not applicable.

Exploration:
The kimberlites have been a target for commercial diamond exploration since the mid-1990s. The first (micro) diamonds recorded from the area were collected from stream sediments in the valley of Sarfartoq in 1973. Since the mid 1990s exploration companies have reported in situ micro and macro diamonds in kimberlitic dykes and sills from several localities within the area (reviewed by Jensen *et al*. 2004). Indicator minerals from till are reported from 8000 localities within the area. The study of indicator minerals is regarded as a key method for localising kimberlitic rocks. Company exploration is ongoing.

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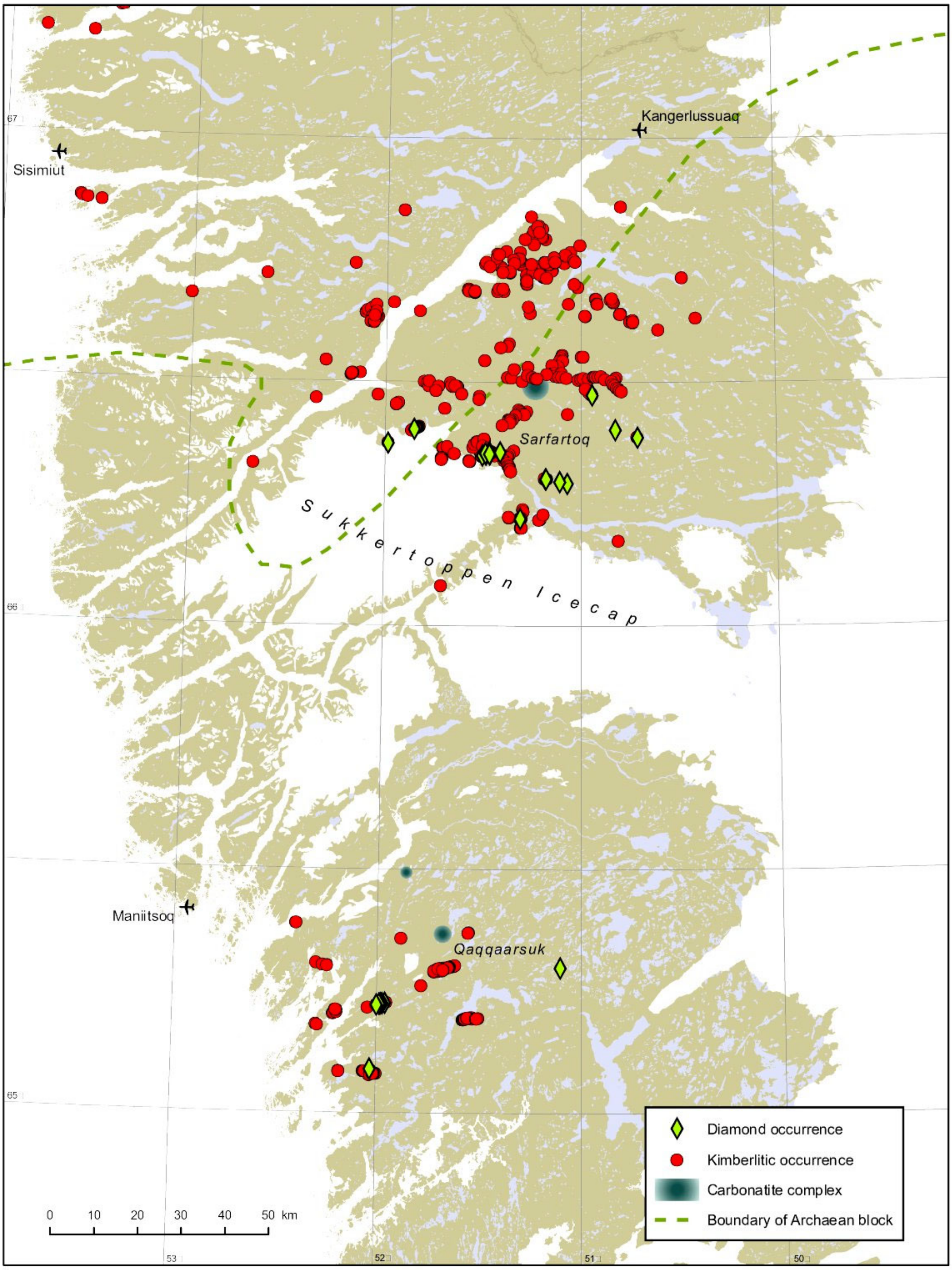

Figure 70. *Map of kimberlitic and diamond occurrences in the Kangerlussuaq – aniitsoq region, West Greenland.*

Figure 71. *Typical diamondiferous kimberlitic dyke exposure in the Maniitsoq region.*

Figure 72. *Largest macrodiamond recovered during recent exploration in the Kangerlussuaq region (Hudson Resources press release January 2005).*

18

Locality name: **Broget Dal, Strindberg Land**

Area: **Central East Greenland**

GSC deposit type: **8.3 – Sediment-hosted stratiform copper**

Commodities: **Copper**

Geological characteristics:

Description of occurrence: The strata-bound copper mineralisation 0.2 to 2 m thick is found at different stratigraphic levels in Neoproterozoic shale and quartzite and extends over a distance of 275 km. Eight levels of strata-bound occurrences are recorded (Table below; Fig. 73).

Stratigraphy	Lithostrati-graphy	Age (Ma)	Lithology	Thickness (m)	Sulfide mineralization (Cu grade - %)
Riphean	Ymer Ø Group	700	1.3 km sandstones, mudstones and carbonates	0.1 – 0.25	Pyrite-chalcopyrite- bornite-chalcocite
				0.1 – 0.25	Chalcocite (<0.1)
				1.0 – 2.0	Chalcocite (0.1 – 0.5; max. 6)
	Lyell Land Group		2.8 km sandstones and mudstones	0.2 – 1.0	Pyrite-chalcopyrite-tetrahedrite (0.1 – 1.35)
				0.2 – 2.0	Pyrite-chalcopyrite-bornite-chalcocite (0.1 – 1.25)
				0.2 – 2.0	Pyrite-chalcopyrite (0.1)
	Nathorst Land Group	900	9 km sandstones, mudstones and carbonates	0.2 – 1.5	Pyrite-chalcopyrite-(pyrrhoteite)-cobaltite (0.25 – 2.5)
				0.2 – 5.0	Pyrrhotite-pyrite-chalcopyrite (0.1)

The two lowest levels are found in the top of the of the Nathorst Land group in metamorphosed quartzitic shales. The lowest level is some 150-m below the top of the sequence and the upper copper bearing layer in transition zone between the Nathorst Land Group and the Lyell Land Group. The Lyell Land Group is dominated by sandstone/quartzite and quartzitic shale and comprises three levels with copper. The first level is in the middle of the group and the two other levels are found in the top of the group.

Epigenetic overprinting resulted in adding antimony to the upper copper bearing layers on Strindberg Land. Three more strata-bound copper bearing layers are found in the lower part of the Ymer Ø Group, which is dominated by red and green shales at the bottom and upwards the sediments are being more dolomitic shales and ends with dolomite.
Near Holmesø in Broget Dal, Strindberg Land (Figs. 24 & 74) a copper occurrence occurs in an open, SSE-NNW anticline with intense faulting (Katz 1952). Near the core of the anticline, malachite-azurite-stained outcrops of white quartzite occur inside a 500 x 1000-m area. The mineralized outcrops occur in the top of the *c.* 100-m thick quartzite bed (Harpøth *et al.* 1986).

Geotectonic setting: In the Neoproterozoic basins of central East Greenland strata-bound copper occurrences are located in the Eleonore Bay Supergroup (Ghisler *et al.* 1980a; Ghisler *et al.* 1980b; Ghisler *et al.* 1980c; Stendal 1979, 1980; Stendal & Hock 1981; Stendal & Ghisler 1984). The Eleonore Bay Supergroup comprises an up to 16-km sedimentary succession.

Depositional environment/Geological setting: The Neoproterozoic Eleonore Bay Supergroup comprises an up to 16-km sedimentary succession. The sediments are shallow water deposits in a major sedimentary basin extending between 72^{o} and 76^{o}N latitudes in the central part of the region (Fig. 1) except for an outlier at Canning Land (C) (Higgins & Soper 1994; Sønderholm & Tirsgaard 1993). Siliciclastic-carbonate rocks evolved from siliciclastic deposits over mixed siliciclastic-carbonate sediments to carbonate deposits dominate the lithologies. The Eleonore Bay Supergroup is unconformably overlain by the Tillite Group of a 700-800 m thick succession of Vendian age (610-570 Ma and includes two glacigene diamictite formations (Hambrey & Spencer 1987).

Age of mineralisation: Neoproterozoic probably with remobilization during the Caledonian orogeny.

Host/Associated rock types: Sandstone and shale.

Deposit form: Strata-bound.

Texture/Structure: In the quartzites chalcopyrite occurs interstitially to the detrital quartz grains.

Ore mineralogy: The mineral assemblages are in the shales dominated by an iron-poor paragenesis represented by chalcocite-(bornite) and an iron-rich consisting of pyrite-chalcopyrite. Chalcopyrite is dominant in the coarse-grained laminae together with pyrite-(pyrrhotite). In addition strata-bound sulfide-bearing veins occur with chalcopyrite-pyrite-(tetrahedrite).

Gangue mineralogy: Quartz.

Weathering: Malachite staining.

Ore controls: The strata-bound copper sulphides were probably concentrated mainly by diagenetic processes but later modified by metamorphic mobilisation and locally enriched by hydrothermal solutions.

Genetic models: Sedimentary-diagenetic processes in a sedimentary basin.

<u>Analytical data:</u>
The grade of copper in the mineralised zones is in general low (Table above).

<u>Exploration:</u>
In the 1970's strata-bound copper occurrences were found and explored be Nordisk Mineselskab A/S in the Neoproterozoic sedimentary sequence between 72°N to 74°N (Ghisler *et al.* 1980a; Ghisler *et al.* 1980b; Ghisler *et al.* 1980c; Stendal 1979, 1980, 1981, 1982; Stendal & Hock 1981; Stendal & Ghisler 1984).

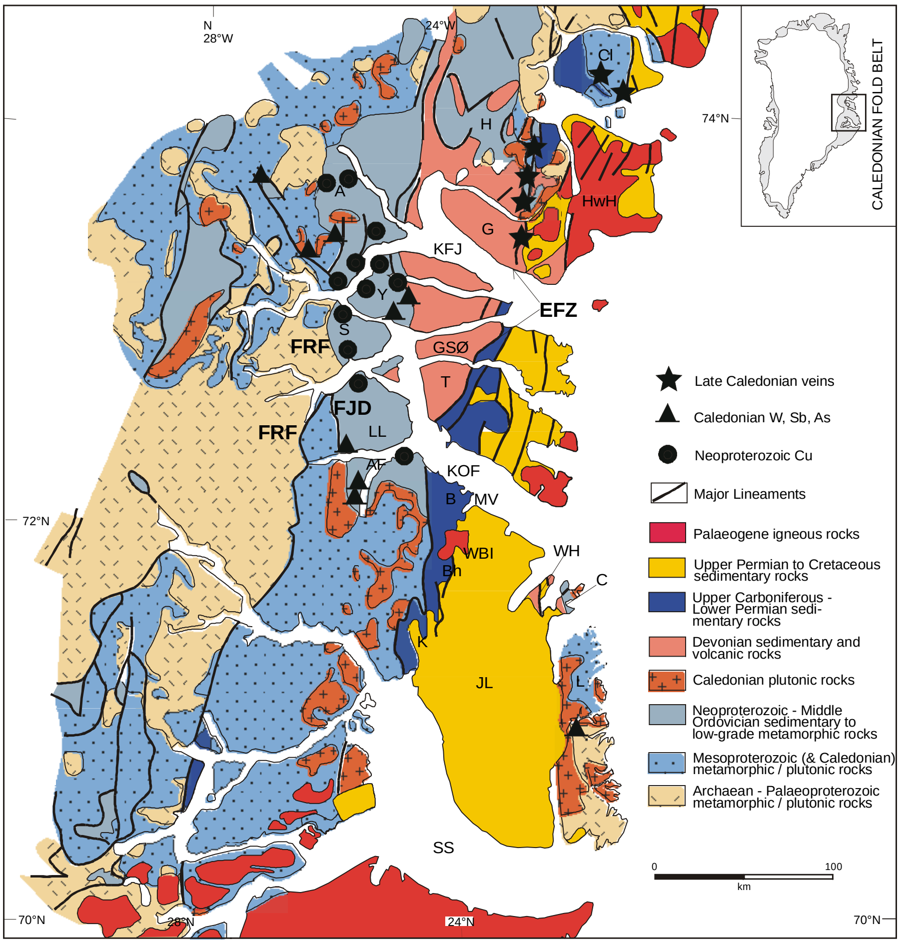

Figure 73. *Simplified geological map of central East and North-East Greenland showing the lineaments and localities mentioned in the text. The figure is modified from Harpøth et al. (1986) and Pedersen and Stendal (2000). EFZ = Eastern Fault Zone; FJD = Franz Joseph Detachment; FRP = Fjord Region Fault; A = Andreé Land; AF = Alpefjord; B = Blyklippen; Bh = Bredehorn; C = Canning Land; Cl = Clavering Ø; G = Gauss Halvø; GS = Geographical Society Ø; H = Hudson Land; HwH = Hold with Hope; JL = Jameson Land; K = Karstryggen; KFJ = Kejser Franz Joseph Fjord; KOF = Kong Oscar Fjord; LL = Lyell Land; MV = Mesters Vig; S = Suess Land; SS = Intrusives; WH = Wegener Halvø; Y = Ymer Ø.*

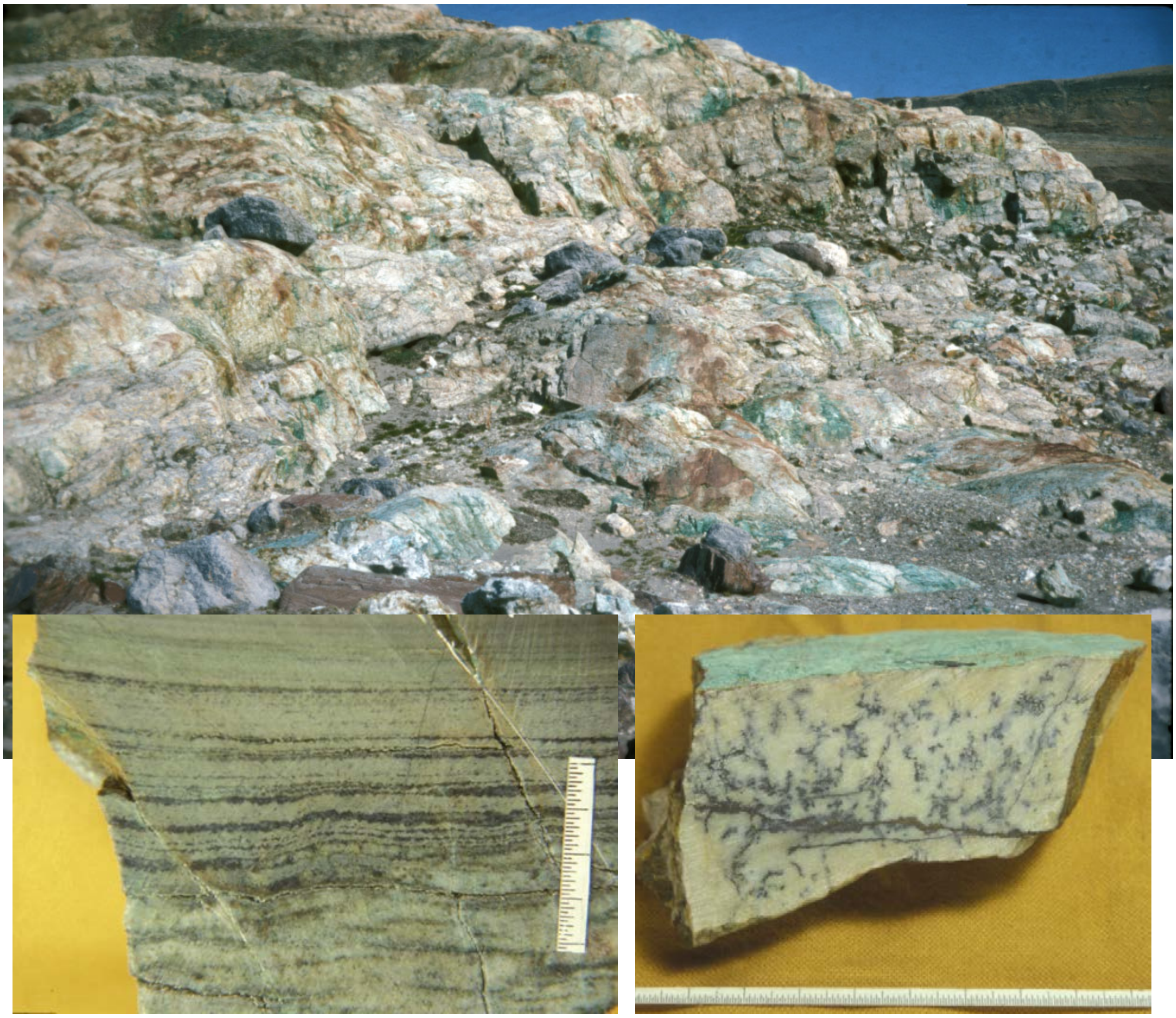

Figure 74. *Copper occurrence in white quartzite, Holmesø, Strindberg Land. Inserts: Left - Strata-bound copper bearing layers (chalcocite, bornite, chalcopyrite); right – veinlets with chalcocite, bornite and tetrahedrite in white quartzite.*

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Locality name: **Citronen Fjord**

Area: **Peary Land**

GSC deposit type: **6.1 – Sedimentary exhalative sulphides (SEDEX)**

Commodities: **Zinc, lead**

Geological characteristics:

Description of occurrence: In the Franklinian basin a major Lower Palaeozoic zinc-lead deposit occur. The deposit is hosted in argillaceous lithologies, which is deposited just north of the carbonate platform margin in Peary Land. The Cironen Fjord deposit (Fig. 12) is a SEDEX-type, shale-hosted massive sulphides (Fig. 75) comprised of massive and bedded pyrite that contains variable amounts of sphalerite and minor amounts of galena (Fougt 1997, 1998a, b; Fougt *et al.* 1999; Kragh 1997, 2000; Kragh *et al.* 1997; van der Stijl & Mosher 1998). The proven ore is continuos over a strike length of at least 3-km with a maximum width of 500-m; an additional 5-km of mineralisation along the same trend is suggested by geological mapping and gravity survey (van der Stijl & Mosher 1998).

Geotectonic setting: The Ellesmerian Orogen (North Greenland Fold Belt) comprises a shelf sequence to the south, where Proterozoic and Palaeozoic sediments overlie a crystalline basement and a folded, deep-water sequence to the north, consisting of Phanerozoic sediments.

Depositional environment/Geological setting: The area around Citronen Fjord comprises Cambrian, Ordovician and Silurian sediments. These sediments are mainly sandstone turbidites and calcareous silstones. The ore mineralised area forms a well-exposed, conformable stratigraphic pile stretching from the Ordovician Amundsen Land Group to the Silurian Peary Land Group. This sequence comprises a starved basin sequence of cherts and shales with siltstones and mudstones, punctuated by carbonate debris flow conglomerates derived from the nearby southern carbonate shelf (van der Stijl & Mosher 1998).

Age of mineralisation: The age of the mineral occurrence is not known, but is believed to be contemporaneous with faulting of the Ellesmerian Orogen (North Greenland Fold Belt). The age of the hosting sediments are Ordovician (Amundsen Land Group). Evidence of post-sedimentary, epigenetic mineralisation is commonly seen in drill cores and rock exposures (van der Stijl & Mosher 1998).

Host/Associated rock types: Shales and mudstones.

Deposit form: The Citronen Fjord massive sulphides form a stratiform deposit displaying evidence of deposition on the sea floor contemporaneously with the enclosing sediments. In the Discovery, Beach and Esrum areas, three main sulphide levels occur within a 200-m thick stratigraphic interval. A fourth mineralised area is the West Gossan area where one level of ore is found although the ore minerals are disseminated.

Texture/Structure: The massive sulphides are generally fine- to medium-grained; some are weakly-bedded and laminated (Fig. 76), others lack sedimentary features (van der Stijl & Mosher 1998). There is a variation in the texture from massive to semi-massive to the intermittent presence of dendritic-textured pyrite to net-like texture (Kragh 1997, 2000; Kragh *et al.* 1997).

Ore mineralogy: Pyrite-dominated with variable contents of sphalerite and minor amounts of galena. Silver, barium, and copper are present in very minor quantities (van der Stijl & Mosher 1998).

Gangue mineralogy: Silt and clay from mudstones and some calcite infillings.

Weathering: Gossan weathering.

Ore controls: Sphalerite has clearly been deposited contemporaneously with the enclosing pyrite and it commonly forms laminae but rarely beds (van der Stijl & Mosher 1998). The site of ore deposition is probably structural controlled (faults).

Genetic models: SEDEX-type, shale-hosted massive sulphides: The zinc-lead deposit is interpreted to be of sedimentary-exhaltive origin formed by precipitation of sulphides from metal-bearing fluids introduced onto the sea-floor through underlying fractures (van der Stijl & Mosher 1998).

Analytical data:

The total tonnage of sulphides is estimated to exceed 350 million tons. The overall base metal resource is estimated at 20 million tons of 7% Zn, with a higher grade core of 7 million tons containing 9% Zn and 15 Pb (van der Stijl & Mosher 1998).

Exploration:

The first indication of actual mineralization in the Frederick E. Hyde Fjord region was reported in 1960 (van der Stijl & Mosher 1998). In 1992 Platinova A/S participated in a joint venture program with Nanisivik Mines Ltd. to explore for base metals in the western part of the Franklinian Basin. The following year the same party continued in the Frederick E. Hyde Fjord. The major zinc-lead discovery was made in 1993 based on observations from GEUS, north of the carbonate platform in Peary Land in the adjoining argillaceous lithologies south of Citronen Fjord. Diamond drilling (34 km) between 1993 and 1997 indicate a medium-sized deposit.

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Figure 75. *Gossans with exposures of massive sulphides from the Discovery area (from van der Stijl & Mosher 1998).*

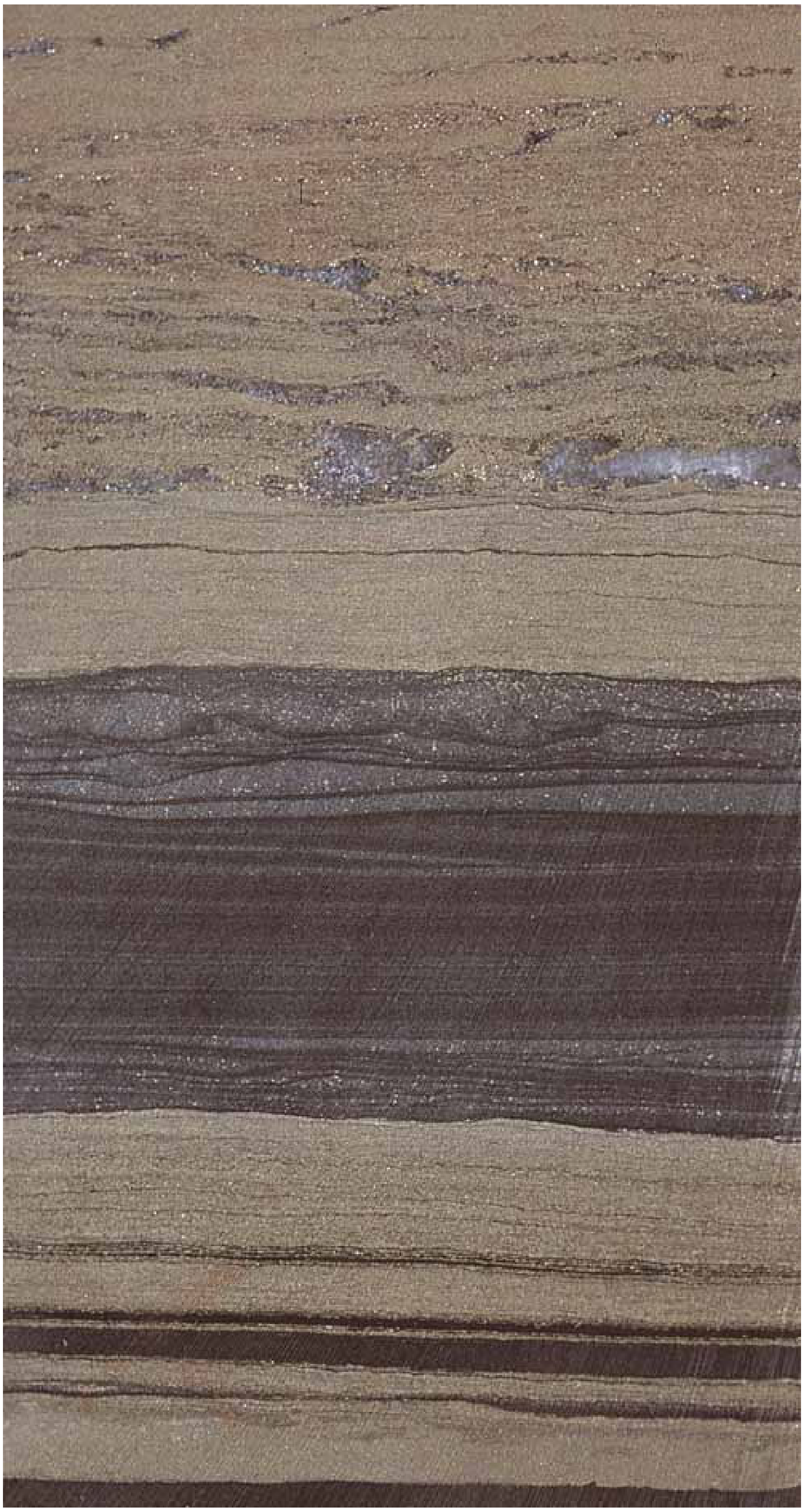

Figure 76. *Fine-grained laminated sulphides in black mudstone. The Zn-content in the upper sulphide layer is 25-30% and in the lower 1-3% (from van der Stijl & Mosher 1998). The core is 3.6 cm across.*

19b

Locality name:	**Washington Land**
Area:	**North Greenland**
GSC deposit type:	**10 – Mississippi Valley-type lead-zinc**
Commodities:	**Zinc, lead**

Geological characteristics:

Description of occurrence: The carbonate-hosted lead-zinc-silver deposit in Washington Land was discovered by the Geological Survey of Denmark and Greenland (GEUS) in July, 1997 (Jensen 1998; Jensen & Schønwandt 1998). The mineralisation is associated with strongly dolomitised carbonates with variable parageneses. The surface expression of the mineral occurrence is a float train of rusty weathering patches (Fig. 77). The train can be followed for 2.4 km long and approximately 100-m wide NE_SW trending zone (Fougt *et al.* 1999; Jensen 1998).

Geotectonic setting: The Ellesmerian Orogen (North Greenland Fold Belt) comprises a shelf sequence to the south, where Proterozoic and Palaeozoic sediments overlie a crystalline basement and a folded, deep-water sequence to the north, consisting of Phanerozoic sediments. Washington Land is made up of Cambrian – Lower Silurian carbonate platform and Lower Silurian reef belt successions of the Franklinian Basin (Fig. 12).

Depositional environment/Geological setting: The lead-zinc occurrences occur in the carbonate platform environment and the occurrences are fault-controlled and are characterised by relative high silver content.

Age of mineralisation: The age of the mineral occurrence is not known, but is believed to be contemporaneous within faulting of the Franklinian basin.

Host/Associated rock types: Dolomite and limestone.

Deposit form: Elongated boulder train.

Texture/Structure: Sphalerite aggregates up to 5-cm large in coarse-grained dolomite (Fig. 78).

Ore mineralogy: Both pyrite-dominated, sphalerite-galena-dominated and pyrite-sphalerite galena-rich mineralised rocks occur (Jensen 1998; Jensen & Schønwandt 1998)

Gangue mineralogy: Dolomite.

Weathering: Rusty appearance of mineralised floats.

Ore controls: The source of metals is suggested to have been the underlying Lower Cambrian siliciclastic sequence (Humboldt Formation) or perhaps the crystalline basement (Jensen 1998).

Genetic models: Mississippi Valley Type.

Analytical data:

Visually estimated Zn and Pb grades vary from close to nil to over 20% Zn and 10% Pb. Silver figures are normally anomalous up to *c.* 170 ppm (Jensen 1998).

Exploration:

The occurrence were investigated during the multidisciplinary project 'Resources of the sedimentary basins of North and east Greenland initiated in 1995 (Stemmerik *et al.* 1996). The investigations were carried out in Washington Land in 1997.

Figure 77. *Sulphide-rich, dolomitised limestone, Washinton Land (from Jensen 1998). Person for scale to the left.*

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Figure 78. *Coarse-grained dolomite with large sphalerite aggregates, Washinton Land (from Jensen 1998).*

19c

Locality name: **Navarana Fjord**

Area: **Freuchen Land, North Greenland**

GSC deposit type: **10 – Mississippi Valley-type lead-zinc**

Commodities: **Zinc, barium**

Geological characteristics:

Description of occurrence: In the Navarana Fjord Anticline, a vertical, 7-m-thick and 300-m long, brecciated calcite vein crosscuts the limestone of the Portfjeld Formation (Jakobsen 1989). Centrally in the calcite vein of a one-metre wide breccia zone epigenetic sphalerite occurs associated with barite, which constitute 60-70% of the matrix (Fig. 79). In addition to the vein type, another type of Ba-Zn occurrence is present in the area. This type is strata-bound occurrence within a carbonaceous shale and chert sequence (Jakobsen 1989).

Geotectonic setting: The Ellesmerian Orogen (North Greenland Fold Belt) comprises a shelf sequence to the south, where Proterozoic and Palaeozoic sediments overlie a crystalline basement and a folded, deep-water sequence to the north, consisting of Phanerozoic sediments (Fig. 12). The Navarana Fjord area belongs to deep-water sequence (Jakobsen 1989).

Depositional environment/Geological setting: The Navarana Fjord area (Fig. 12) in North Greenland is hosted in deep-water sequence at the eastern end of a 259-km long, folded zone consisting of a sequence of unmetamorphosed Lower Cambrian shelf sediments and Lower Silurian deep water sediments (Jakobsen 1989a; Jakobsen & Stendal 1987). The vein is emplaced in a fault fracture intersecting dolomites (Steenfelt 1991).

Age of mineralisation: The age of the mineral occurrence is not known, but is believed to be contemporaneous within faulting of the Franklinian basin.

Host/Associated rock types: Dolomite and limestone.

Deposit form: Vertical vein.

Texture/Structure: Veining and zonation in the vein.

Ore mineralogy: The vein comprises sphalerite, barite and minor galena, chalcocite, chalcopyrite, pyrite, and fluorite. In the strata-bound Ba-Zn occurrence hydrated Ba-silicates are described (Jakobsen 1990).

Gangue mineralogy: Calcite and quartz.

Weathering: Hydrated iron sulphate occurrences displaying a suite of rare sulphate minerals are known from the Navarana Fjord (Jakobsen 1989b).

Ore controls: Vein system in a fault zone.

Genetic models: Mississippi Valley Type.

Analytical data:
No average values is known. No tonnage estimation of the deposit is known.

Exploration:
Investigations carried out of the Geological Survey of Greenland in the 1980's.

Figure 79. *Navarana Fjord vein system – the red bar is c. 20 m.*

References:

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Jakobsen, U.H. & Stendal, H. 1987: Geochemical exploration in central and western North Greenland. Rapport Grønlands Geologiske Undersøgelse, 133, 113–121.

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Locality name: **Maarmorilik, Black Angel**

Area: **Uummannaq**

GSC deposit type: **Sedimentary exhalative deposits (SEDEX)**

Commodities: **Zinc-lead**

Geological characteristics:

Description of occurrence: The Black Angel mine took its name from a pelite outcrop that forms a
dark angel-like figure on a precipitous cliff face of marble above Affarlikassaa fjord. The mineralised zone actually crops out just above the angel figure about 700 m above fjord level. The 1100-m high Angel mountain is situated at the margin of the Greenland ice cap at 71°N lat. The peninsula across the fjord housed the mining camp, mill and all services and received its name Maarmorilik from a former marble quarry situated there from the 1930’s (Thomassen 2003).
Carbonate-hosted lead-zinc mineralisation is common in the Mârmorilik Formation and in the mine area stratabound sulphide mineralisation occurs at various levels. The main ore bodies are located 600–700 m a.s.l. in the upper part of the sequence, which is dominated by calcite marble. The ore forms flat lying, highly deformed massive lenses up to 30 m thick, of which ten reach economic size and were mined.

Geotectonic setting: The Black Angel lead-zinc mine is hosted in the Marmorilik Formation of the Palaeoproterozoic Karrat Group (Garde 1978; Henderson & Pulvertaft 1987). The formation rests unconformably on an Archaean gneiss complex and is overlain by semipelites of the upper Karrat Group. It consists of calcitic and dolomitic marbles with a basal quartzitic unit and intercalations of anhydrite-bearing marbles and semipelitic schists. The main ore bodies are hosted in calcitic marble and dolomite marble.

Depositional environment/Geological setting: The ores are hosted in the Mârmorilik Formation of the Palaeoproterozoic Karrat Group. This Group belongs to the Foxe– Rinkian mobile belt of NE Canada and central West Greenland, which constitutes a component of the Trans-Hudson Orogen of North America. In Greenland, exposures of the Karrat Group are known over a north–south distance of c. 550 km covering some 10,000 km2. The Group, that rests unconformably on an Archaean gneiss complex, is intruded by a major 1860 Ma syn-tectonic granite complex and is overlain by Cretaceous–Tertiary sediments and volcanics. The Karrat Group, several kilometres thick, is composed of lower shelf units of carbonates and quartzites, and an upper unit of deepwater turbidites and minor volcanic rocks. The basement and the cover sequence were subjected to several phases of strong folding and thrusting during the Rinkian Mobile Belt and variably affected by regional metamorphism. The Mârmorilik Formation consists of calcitic and dolomitic marbles with a basal quartzitic unit and intercalations of anhydrite- bearing marbles and semipelitic schists. In the mine area, where the formation has been tectonically thickened to c. 1000 m, three main phases of folding and thrusting have been distinguished, and metamorphism reached upper greenschist facies.

Age of mineralisation: The Mârmorilik formation have been deposited on a carbonate shelf in an epicontinental marginal basin *c.* 2 Ga ago. The ore is believed to be syn-sedimentary deposited as exhalative chemical sediments.

Host/Associated rock types: Calcite and dolomite marble.

Deposit form: The ore forms flat-lying, highly deformed, massive lenses up to 30 m thick, of which ten reach economic size and were mined.

Texture/Structure: Strata-bound.

Ore mineralogy: The massive ore consists of pyrite, sphalerite and galena with abundant rotated marble fragments and quartz inclusions. The main accessory ore minerals are pyrrhotite, chalcopyrite, tennantite and arsenopyrite. Cherty horizons and disseminated graphite are quite common in the wall rocks whereas minor fluorite and baryte are restricted to a few of the ore bodies.

Gangue mineralogy: Calcite and dolomite.

Weathering: None.

Ore controls: Sedimentary-exhalative processes.

Genetic models: SEDEX. Opinions on the genesis of the ores has varied from sabkha model to Mississippi Valley type (Carmichael 1988; Pedersen 1981) but at present the most likely model is a SEDEX-type model.

Analytical data:
The Black Angel deposit comprised ten ore bodies totalling 13.6 million tons grading 12.3% Zn, 4.0% Pb and 29 ppm Ag. Of these 11.2 million tons were extracted in the period 1973–90. The mining operations ceased when the extractable ore reserves were exhausted, leaving 2.4 million tons of ore tied up in pillars and other areas inaccessible to mining (Thomassen 1991).

Exploration:
Sulphide samples leading to the discovery of the Black Angel deposit were found in connection with marble quarrying in the 1930s and investigated by Danish geologists in the 1930s and 1940s. A syndicate led by Cominco Ltd. of Canada carried out commercial investigations including diamond drilling in the 1960s. In 1971 the Danish mining company Greenex A/S (established in 1964 and 62.5% owned by Cominco Ltd. through the subsidiary Vestgron Mines Ltd.) obtained a 25-year exploitation concession. Financial terms were favourable at that time, with only a resource tax of yearly earnings to be paid after recovery of all pre-production costs and capital investments. The investment of c. 333 mill. DKK had been recovered in 1977, after which the company started to pay concession fees. Underground exploration in 1971–72 indicated a probable ore reserve of 4.1 million

tons grading 15.0% Zn, 5.0% Pb and 28 ppm Ag. Based on this and after a hectic construction period of only 15 months, production started in 1973. During the mine's 17-year lifespan, it was possible to more than triple the original minable reserves (Thomassen 1991; 2003).

References:

Carmichael, A.J. 1988: The tectonics and mineralisation of the Black Angel Pb-Zn deposits, central West Greenland., 371. Unpublished Unpublished thesis, Goldsmith's College, University London.

Garde, A.A. 1978: The Lower Proterozoic Marmorilik Formation, east of Mârmorilik, West Greenland. Meddelelser om Grønland, 200, 71.

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Pedersen, F.D. 1981: Polyphase deformation of the massive sulphide ore of the Black Angel mine, central West Greenland. Mineralium Deposita 16, 157–176.

Thomassen, B. 1991: The Black Angel lead-zinc mine 1973-90. Rapport Grønlands Geologiske Undersøgelse 152, 46–50.

Thomassen, B. 1993: The Black Angel lead-ainc mine at Maarmorilik in West Greenland. Geology and Ore. Exploration and Mining in Greenland No. 2, 12p.

Figure 80. *The folded dark pelite in the marble cliff, known as the 'Black Angel' at the Maarmorilik mine, West Greenland. Cable-way and mine adits on the cliff face for scale.*

Figure 81. *“Buck shot ore” (massive sulphide) with marble rafts left in pillar in the underground mine area of the ‘Black Angel’ mine.*

20a

Locality name: **Milne Land**

Area: **Central East Greenland**

GSC deposit type: **1.1 – Palaeoplacer deposit**

Commodities: **Special metals and zirconium**

Geological characteristics:

Description of occurrence: The heavy mineral sands occur as irregularly distributed 10-40 cm thick lenses within a c. 20-m thick unit of arkosic sandstone (Harpøth *et al.* 1986). In 5 of 7 trenches a 10-40 cm thick layer of heavy mineral (zircon, monazite) sand was found and sampled. Shallow diamond drilling revealed that heavy mineral sands occur as irregularily distributed 10-40 cm thick lenses within a c. 20 m thick unit of arkosic sandstone and breccia.

Geotectonic setting: The Mesozoic clastic sediments are deposited from Middle Jurassic to Lower Cretaceous (Birkelund & Callomon 1985; Birkelund *et al.* 1978, 1984). The sediments rest on a basement of kaolinized, Mesoproterozoic migmatitic granite/gneiss, which forms an irregular erosional surface with a pronounced palaeorelief (Harpøth *ert al.* 1986).

Depositional environment/Geological setting: The sediments represent a marine transgression from east over a deeply eroded part of the Caledonian Fold Belt.

Age of mineralisation: Middle Jurassic.

Host/Associated rock types: Clastic sediments.

Deposit form: 10-40 cm thick lenses.

Texture/Structure: Stratiform palaeoplacer.

Ore mineralogy: The heavy mineral sands are rich in garnet, ilmenite, rutile, zircon, and monazite.

Gangue mineralogy: Quartz.

Weathering: None.

Ore controls: Synsedimentary deposit.

Genetic models: Detrital sedimentary placer deposit.

Analytical data:

The 20-m thick basal part of the sequence is estimated to contain 5 million tons with 1-3.8% Zr and 0.5%-1.9% REO (Harpøth *et al.* 1986). A *c.* 10 tons selective bulk sample from 5 pits was metallurgical investigated. The average heavy minerals was 33 wt.% and consists of 40-50 % TiO_2 minerals (anatase), 20-30 % zircon, 10-15 % monazite, and 10-30 % iron oxides and garnet.

Exploration:

Fossil zircon-monazite placers in Jurassic sandstones were detected as thorium anomalies during an airborne radiometric survey carried out by Nordisk Mineselskab A/S and the Research Establishment RISØ in 1970.

In five of seven trenches a 10-40 cm thick layer of heavy mineral (zircon, monazite) sand was found and sampled. Shallow diamond drilling revealed that heavy mineral sands occur as irregularily distributed 10-40 cm thick lenses within a c. 20 m thick unit of arkosic sandstone and breccia.

References:

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Birkelund, T., Callomon, J.H. & Fürsich, F.T. 1984: The stratigraphy of the Upper Jurassic and Lower Cretaceous sediments of Milne Land, central East Greenland. Bulletin Grønlands Geologiske Undersøgelse 147, 56.

Harpøth, O., Pedersen, J.L., Schønwandt, H.K. & Thomassen, B. 1986: The mineral occurrences of central East Greenland. Meddelelser om Grønland, Geoscience 17, 139pp.

20b

Locality name: **Moriusaq**

Area: **Thule**

GSC deposit type: **1.2 – Placer deposit**

Commodities: **Titanium**

Geological characteristics:

Description of occurrence: Ilmenite-rich placers occur at Moriusaq in the Thule (Pittuffik) region. Black sands occur along the entire coast in the region. The most conspicuous exposures occur on the active beaches. The darkest sands are concentrated in diffuse layers (up to 50-cm thick); lighter coloured sandy beaches can be streaked with concentrations of dense black sands. The black sands on the uplifted beaches are associated with much coarser material and in general, these deposits contain a smaller concentration of heavy minerals (Dawes 1989).

Geotectonic setting: Postglacial to recent beach sand deposit.

Depositional environment/Geological setting: The mineralogical composition of the heavy mineral fractions of sand samples from the Thule district reflect the local bedrock geology, which ranges from sedimentary rocks (Thule Group) over different types of gneisses to intermediate and basic intrusives (Dawes 1989; Ghisler & Thomsen 1971).

Age of mineralisation: Quaternary.

Host/Associated rock types: Beach sand and sand from raised beaches.

Deposit form: The best concentration of black sand is located immediately north-west of Thule Air Base. Here a flat uplifted plain up to 3-km wide, dominated by alluvial and littoral deposits, forms the outer coast for over 80-km, active sandy beaches are up 10-m wide (Dawes 1989).

Texture/Structure: Syn-sedimentary layers.

Ore mineralogy: Ilmenite, magnetite and titanomagnetite are dominating with accessories such as zircon, sphene, garnet and sillimanite.

Gangue mineralogy: Quartz, epidote, diopside, hypersthene, and hornblende.

Weathering: None.

Ore controls: Sedimentary processes such as tide, rivers and glaciation.

Genetic models: Synsedimentary deposit.

Analytical data:

Grades of the active beaches is high – up to 60% - with an average about 43% TiO_2; uplifted beaches have a larger tonnage potential but lower titanium values up to 23% TiO_2 with an average around 12% (Dawes 1989).

Exploration:

Lauge Koch reports 'iron sand' from the area already in 1916 (Dawes 1989). In 1950 and several times later the Geological Survey of Greenland carried out investigations of the area and did sampling of the heavymineral sand (Ghisler & Thomsen 1971). In 1985 Greenex A/S got a prospecting licence and sampled the Moriusaq heavy mineral sands (Dawes 1989).

References:

Dawes, P.R. 1989: The Thule black sand province, North-West Greenland: investigation status and potential. Open File Series Grønlands Geologiske Undersøgelse 89/4, 17.

Ghisler, M. & Thomsen, B. 1971: The possibility of ilmenite placers in the Thule district, North Greenland. A preliminary examination of the heavy fractions of some sands. Rapport Grønlands Geologiske Undersøgelse 43, 15.

Locality name: **Karstryggen**

Area: **Jameson Land**

GSC deposit type: **5 - Evaporites**

Commodities: **Celestite ($SrSO_4$)**

Geological characteristics:

Description of occurrence: Stratabound celstite ($SrSO_4$) mineralization in Upper Permian carbonates occurs at Karstryggen in Jameson Land (Fig. 82). The Karstryggen formation hosts the celestite deposit, is dominated by limestone and evaporites. In general, the intensity of the occurrence varies considerable both laterally and vertically. Mineralization occurs both in a lower 3–10 m thick algal-laminated limestone unit and in at least 50-m thick overlying karst breccia sequence. In the latter, celestite occurs for more than 50 m vertically, but in general in the lowermost 20 m of the section (Harpøth *et al.* 1986).

Geotectonic setting: The Jameson Land Basin forms the southern end of a *c.* 600 km long depositional basin that comprises the coastal region of central East and North-East Greenland. Basin formation was initiated as a result of post-Caledonian crustal collapse during the Middle Devonian and up to 17000 m of sediments ranging from Devonian to Cretaceous in age are present within the basin (Larsen & Marcussen 1992). The sedimentary pile is dominated by thick sequences of immature continental molasse sediments of Devonian to Lower Permian age, which are unconformably overlain by a succession of marine, lacustrine and continental deposits up to 5000 m thick. Up to 1500 m of flood basalt may have covered the area following the initial opening of the North Atlantic in the Tertiary, but have later been removed as a result of regional uplift (Larsen & Marcussen 1992).

Depositional environment/Geological setting: The Karstryggen formation is a marine marginal carbonate and evaporite sequence (Harpøth *et al.* 1986). The Karstryggen formation is dominated by limestone deposited in hypersaline shallow marine environment.

Age of mineralisation: Upper Permian.

Host/Associated rock types: Limestone.

Deposit form: The celestite deposit occurs in an 80-km^2 area with $SrSO_4$ content of 15-30% over several metres thickness. The occurrence occurs both as statabound in algal-laminated limestone and as veins in brecciated limestone.

Texture/Structure: Cement, **v**eins and cave fillings.

Ore mineralogy: Celestite.

Gangue mineralogy: Calcite.

Weathering: None.

Ore controls: The celestite mineralisation occurs as redeposited early diagenetic celestite from an underlying laminated limestone sequence, as celestite cement and fillings in the karst breccia and as pockets, lenses and veins of celestite in karst fractures and caves (Harpøth *et al.* 1986).

Genetic models: Strontium isotope data show that evaporites (gypsum) and primary precipitated calcite stem from seawater and the celestite of all types have a common origin in water derived from western highlands (surface and or subsurface water) (Harpøth *et al.* 1986).

Analytical data:

The total tonnage is 25-50 million tons with a grade of *c.* 50% $SrSO_4$ (Harpøth *et al.* 1986).

Exploration:

Nordisk Mineselskab A/S had until 1984 extensive exploration in the whole region.

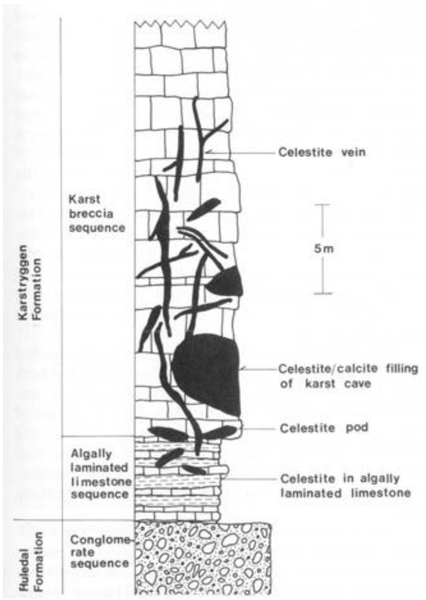

Figure 82. *Celestite occurrence in Upper Permian Karstryggen Formation (from Harpøth et al. 1986).*

References:

Harpøth, O., Pedersen, J.L., Schønwandt, H.K. & Thomassen, B. 1986: The mineral occurrences of central East Greenland. Meddelelser om Grønland Geoscience, 17, 139.

Larsen, H.C. & Marcussen, C. 1992: Sill-intrusion, flood basalt emplacement and deep crustal structure of the Scoresby Sund region, East Greenland. In: Storey, B.C., Alabaster, T. & Pankhurst, R.J. (eds): Magmatism and the causes of continental break-up. 68, 365–386.

Locality name: **Blyklippen**

Area: **Mesters Vig**

GSC deposit type: **8.2 – Sandstone lead**

Commodities: **Lead**

Geological characteristics:

Description of occurrence: Base metal-bearing quartz, fluorite, barite and/or calcite veins are found in several areas along the Stauning Alper Fault in West Jameson Land (Harpøth *et al.* 1986). Veins are usually parallel to the fault or to other important faults in the vicinity. The richest ore field with vein type mineralization is the Mesters Vig area, where the only exploited ore body - the Blyklippen Vein - is situated. The vein zones can be up to 1000 m long and 70 m wide. The vein occurs in intensely silicified sandstones that include numerous quartz veinlets, or as wider mineralized fissure-filling quartz veins (± ore minerals). Sulphides are normally concentrated in certain parts of the quartz vein zones. The mined-out sulphide lens was 2-10 m thick, 300 m long and 160 m high.

Geotectonic setting: The Mesters Vig area consists of Carboniferous, Permian and Triassic sediments intruded by Palaeogene doleritic dykes and sills. The Blyklippen vein-type lead-zinc deposit comprised a sulphide lens within a major quartz vein zone hosted by Carboniferous-Lower Permian continental clastic rocks in the western part of the basin.

Depositional environment/Geological setting: Base metal and barite occurrences within the Jameson Land Basin are confined to the Carboniferous through Triassic part of the stratigraphy (Fig. 83). A thorough description of the known mineral occurrences in the area was given by Harpøth *et al.* (1986). The Mesters Vig area is dominated by a 12-km long and 4-km wide graben structure, the Mesters Vig graben, outlined by a series of steeply-dipping N-S and NNW-SSE trending normal faults. Mineralization is confined to Pb and Zn (+/- Cu)-bearing quartz-barite vein zones along the faults that bound the graben and to a parallel-trending lineament (Nuldal line) c. 3 km to the east. (Pedersen 2000).

Age of mineralisation: Not known but probably Mesozoic or even Palaeogene age.

Host/Associated rock types: Sandstone.

Deposit form: Veins

Texture/Structure: Discordant veins.

Ore mineralogy: The veins consisted of 65% quartz, 15% sphalerite, 10% galena, 5-10% barite and trace amounts of chalcopyrite (Harpøth *et al.* 1986). The major ore minerals are associated with minor amounts of pyrite, marcasite, pyrrhotite, sulphosalts, bournonite and tetrahedrite.

Gangue mineralogy: Quartz

Weathering: None

Ore controls: Faults with veins.

Genetic models: Lead in sandstones in veins.

Analytical data:
Production totalled nearly 550,000 tons of ore grading 9.3% Pb and 9.9% Zn.

Exploration:
Veins were found and investigated from 1949 to 1951 by the Lauge Koch expeditions, and from 1952 the exploration were taken over by the Danish mining company Nordisk Mineselskab A/S (Brinch 1969; Kampmann 1953). In the Mesters Vig area a lead-zinc deposit was found in 1954 in quartz veins near Blyklippen (Witzig 1954). Mining from the Blyklippen mine was initiated in 1956 and lasted until 1962 (Fig. 84). Mesters Vig is the only area in central East Greenland where proper mining has taken place.

References:

Brinch, V. 1969: Er der økonomisk grundlag for minedrift i Østgrønland. Tidsskriftet Grønland, 171-179.

Harpøth, O., Pedersen, J.L., Schønwandt, H.K. & Thomassen, B. 1986: The mineral occurrences of central East Greenland. Meddelelser om Grønland Geoscience, 17, 139.

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Witzig, E. 1954: Stratigraphische und tektonische Beobachtungen in der Mesters Vig-region (Scoresby Land, Nordöstgrönland). Meddr Grønland 72, 26pp.

Figure 83. *The 'Blyklippen' mine area at Mesters Vig. Two mine adits are located at centre, left, viewed in 1982.*

Figure 84. *The main portal at the Mesters Vig mine, shortly after closing of operations in 1963.*