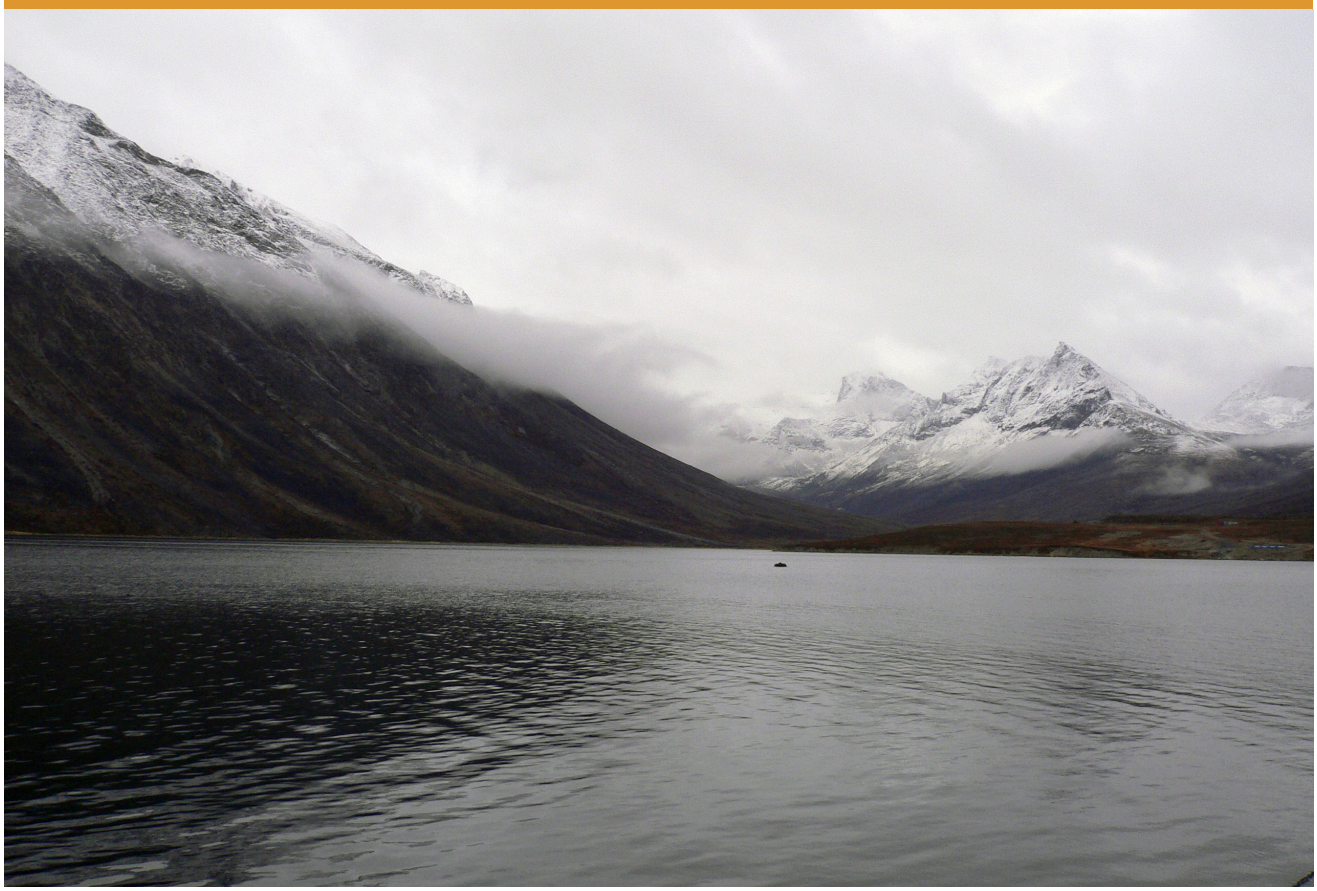
12th SGA Biennial Meeting
12–15 AUGUST 2013, UPPSALA, SWEDEN

Mineral deposit research for a high-tech world

EXCURSION GUIDEBOOK GRE1

Geological excursion to South Greenland



SGU
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Cover photograph: The view from Saqqaa Fjord in northerly direction into the Kirkespiret valley. The Nalunaq deposit is located approximately 5 km to the north. Photo: Jochen Kolb.

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Layout: Jeanette Bergman Weihed, SGU

EXCURSION GUIDEBOOK GRE1

Geological excursion to South Greenland

Organised by the Geological Survey of Denmark and Greenland (GEUS)
Excursion leader: Prof. Dr. Jochen Kolb
Guides:
Dr. A. Bartels (GEUS)
A.M. Borst (GEUS)
H. Bohse (geologist)
R.-M. Bell (GEUS)

Excursion held 16–24 August 2013

Dear field trip participant

You are holding in your hand a guidebook for one of several field trips offered in conjunction with the 12th SGA biennial meeting held in Uppsala, Sweden 12–15 August 2013. As president of The Society for Geology Applied to Mineral Deposits (SGA) I welcome you to the field trip and hope that it will be rewarding with interesting geology and stimulating discussions. The field trips organised in conjunction with the SGA biennial meetings have, so far, been a success and are regarded as an important part of the science SGA offers to its members and other interested geoscientists.

As a scientific society, we are proud to be able to offer the field trips this time in northern Europe in the Fennoscandian Shield and Greenland. The trips offered deal with ore deposits in Precambrian shield areas and thus reflect the metallogeny of the Precambrian. In the Fennoscandian shield, the main economic deposits are hosted in Palaeoproterozoic rocks, not in Archaean. This will be further explained during the individual trips.

The field trips organised will visit many different deposit types, e.g. mafic-ultramafic hosted Ni-Cu-PGE, IOCG, orogenic gold and VMS, in the main metallogenentic belts.

SGA would like to acknowledge the hard work done by the local organising committee in general and especially the Geological Survey of Sweden which is the main organiser of the 12th Biennial meeting and which has compiled all the field trip guidebooks. Dr Magnus Ripa and the technical editors from the Geological Survey of Sweden are especially acknowledged as responsible for the field trip programme. Their colleagues from the Geological Survey of Denmark, Prof. Jochen Kolb, the Geological Survey of Finland, Prof. Raimo Lahtinen, and the Geological Survey of Norway, Dr Rognvald Boyd, are all thanked for working hard to realise the field trip programme.

I would also like to express SGA's sincere gratitude to all the individual field trip leaders and contributors: Tobias Bauer (Luleå University of Technology), Holger Paulick (Boliden AB), Benno Kathol (Geological Survey of Sweden), Iain Pitcairn (Stockholm University), Erik Jonsson (Geological Survey of Sweden), Rodney Allen (Boliden AB), Nils Jansson (Boliden AB), Magnus Ripa (Geological Survey of Sweden), Michael Stephens (Geological Survey of Sweden), Christina Wanhainen (Luleå University of Technology), Olof Martinsson (Luleå University of Technology), Ingmar Lundström (formerly Geological Survey of Sweden), Per Nysten (Geological Survey of Sweden), Karin Högdahl (Uppsala University), Sten Anders Smeds (formerly Geological Survey of Sweden), Eero Hanski (Oulu University), Wolfgang Maier (Oulu University), Yury Voytekhovsky (Kola Science Centre), Pasi Eilu (Geological Survey of Finland), Tero Niiranen (Geological Survey of Finland), Asko Kontinen (Geological Survey of Finland), Jukka Kousa (Geological Survey of Finland), Peter Sorjonen-Ward (Geological Survey of Finland), Hannu Makkonen (Geological Survey of Finland), Terje Bjerkgård (Geological Survey of Norway), Sven Dahlgren (Buskerud, Telemark and Vestfold counties), Henrik Schiellerup (Geological Survey of Norway), Are Korneliussen (Geological Survey of Norway), Pål Thjøemøe (Magma Geopark), Jan Sverre Sandstad (Geological Survey of Norway) and Espen Torgersen (Geological Survey of Norway).

With these words, I welcome you to northern Europe and the fantastic geology both in the Fennoscandian Shield and on Greenland. Enjoy!

Pär Weihed
President SGA

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"Bohses hytte" Kringlerne, Camp site in the eastern part of the Kangerlusarsuq Fjord.



Hotel Kap-Farvel, Isua B 304, P.O. Box 104,
3922 Nanortalik, Phone: +299 61 32 94,
E-mail: kapfarvel@greennet.gl
Website: www.kapfarvel.gl/info



Transport in the field

MOTORBOAT

The main part of the transport in connection to the excursion will be the motorboat Juvel – a 40 footer Jupiter, which is approved by the Danish authorities to accommodate 27 passengers. Cruising speed is 15 km per hour. Juvel is well-equipped with all modern nautic- and communication gear, safety gear and dry-suits for all passengers. Toilet is available. Berths for 8 persons.
Satellite phone (Irridium) contact:
+88 1631 5564 66
Mobile phone: +299 532414
E-mail: juvel@greennet.gl or
qaamasoq@gmail.com



HELICOPTER

A Eurocopter EX 120b helicopter, the ice-patrol helicopter, based in Nanortalik will be chartered to lift the participants to the Motzfeldt Intrusion (locality 19).

Excursion programme

Due to the relatively unique situation in Greenland, it is ambitious to organise a field trip and to allocate exact timing for the different parts. We will be more weather-dependent than many of you have experienced before and delays of up to several days are not rare. Weather can change very fast from nice to very unpleasant with rain and gale-force winds, and even snow is possible. We will always take care for the safety of the group and changes to the program may apply. Since we have a boat, we are relatively flexible, but please do not expect everything to work out as smoothly as it may look from the list below. The stops are marked with numbers on the two maps Figures 1 & 2.

16 AUGUST

Leave Stockholm early in the morning on a complicated tour through Copenhagen and Greenland. Prepare for a long trip. You will be provided with the travel information and tickets in advance. Make sure that you are there in time!

Arrival at Narsarsuaq and the hotel late in the afternoon. Joined dinner in the hotel and introduction to the tour. Possibly a late walk to the Inland Ice.

17 AUGUST

Breakfast in the hotel will be followed by the helicopter excursion to sites at the Motzfeldt Intrusion (locality 19). We will return in the late afternoon and having dinner at the hotel. This tour is depending on good weather conditions. Alternatively, we will visit outcrops in Narsarsuaq and take a walk to the Inland Ice. Your guide will be Alexander Bartels.

18 AUGUST

Starting from Narsarsuaq Hotel at 8:00 a.m. with our boat Juvel, we will visit several localities of intrusions from the Gardar Province and rocks of the Eriksfjord Formation (localities 1–5, Fig. 1).

Locality 1: Qassiarsuk (2–3 h)

The cultivated lowlands around the village of Qassiarsuk, are underlain by carbonatitic volcanic rocks and consolidated volcanic tuff of Gardar age (1.2 Ga) and the older Eriksfjord Formation. Brattahlid was Erik the Red's estate in the Eastern Settlement Viking colony, established toward the end of the 10th century. Guide: A. Bartels.

Locality 2: Sillisit (c. 1 h)

On the northern side of the Tunulliarfik, the sandstone of the Eriksfjord Formation is exposed with gently dipping bedding planes, locally it is developed as a spotted reddish sandstone with light coloured spots that represent reduction halos. Guide: A. Bartels.

Locality 3: Strygejernet / East Nunasarnaq (c. 1 h):

The Eriksfjord Formation is cut by red dykes. Guide: A. Bartels.

Locality 4: West Nunasarnaq

View from Tunulliarfik to the southern contact between the Eriksfjord Formation and the Ilimaussaq Intrusion. Guides: A. Bartels and A. Borst.

Locality 5: Narsaq township

Optional – if time allows: Geological tour around Narsaq, visiting the granitic rocks of the Julianehåb Batholith, and the Eriksfjord Formation sandstone, volcanic rocks, and the gabbro and ultramafic rocks of the Narsaq-Dyrnæs Complex. Guides: J.Kolb, A. Bartels and A. Borst.

Evening program: Presentation of the geology of the Gardar Province, and the ongoing REE, Nb, Zr, Zn, F and U exploration activities by A. Bartels, A. Borst, and H. Bohse.

Accommodation: Hotel Narsaq. Dinner at the hotel.

19 AUGUST

Starting from Hotel Narsaq at 08:00 a.m. after breakfast. Transport to the Kvanefjeld Deposit, locality 6, by car.

The deposit is hosted by the Ilimaussaq Intrusion and we will be visiting the northern part of the agpaitic, peralkaline intrusion, with main focus on the lujavrite and associated mineralogy. This will take several hours and may involve presentations by Greenland Minerals and Energy Ltd, but confirmation on this is pending. Guide: A. Borst and A. Bartels.

In the afternoon, departure with destination Kringlerne, locality 7, the southern part of the intrusion by boat.

Accommodation: Tent camp around Lakseelv, in the bottom of Kangerluarsuk (one tent per person, sleeping bags provided). Hot shower is available. Dinner served in the camp.

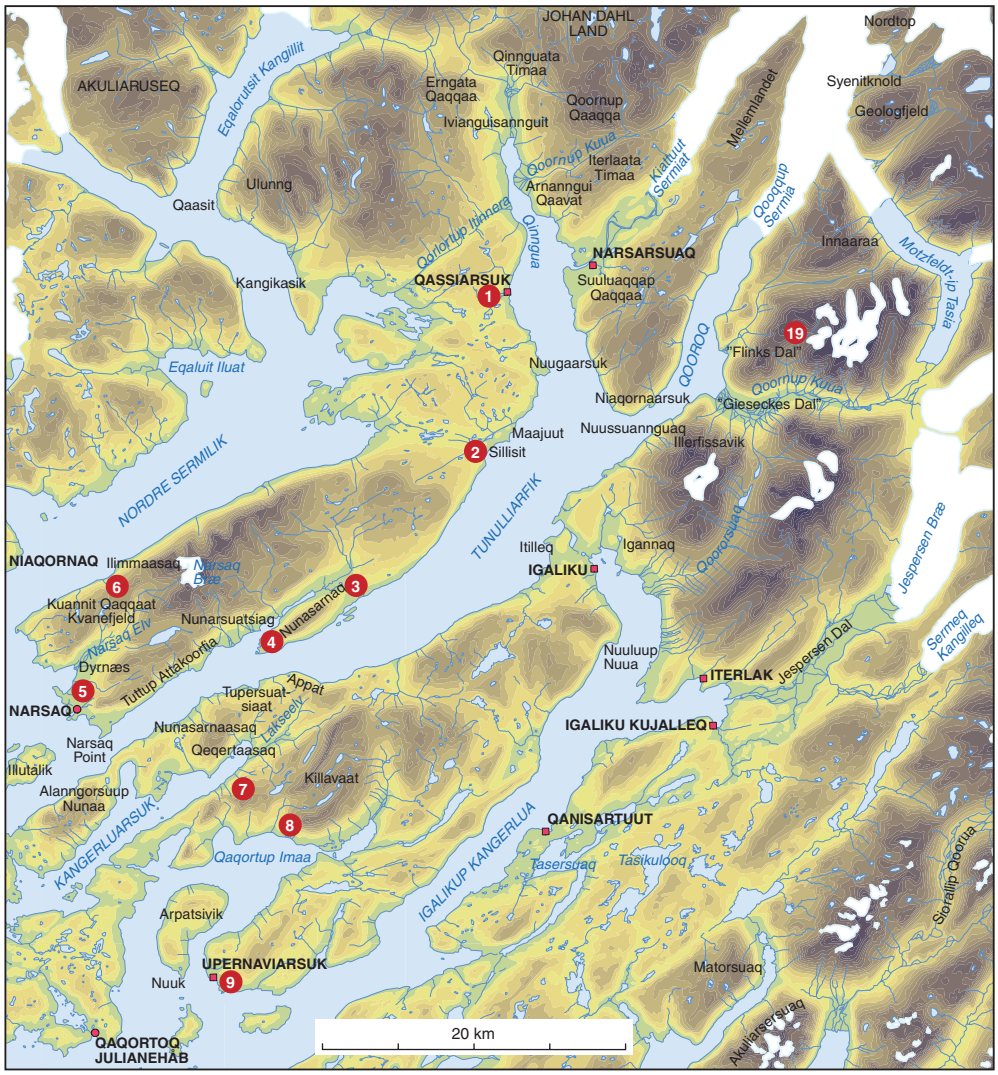


Fig. 1. Topographic map of the excursion area during the first days of the excursion, which will start at Narsarsuaq. The numbers refer to the locations described in the text.

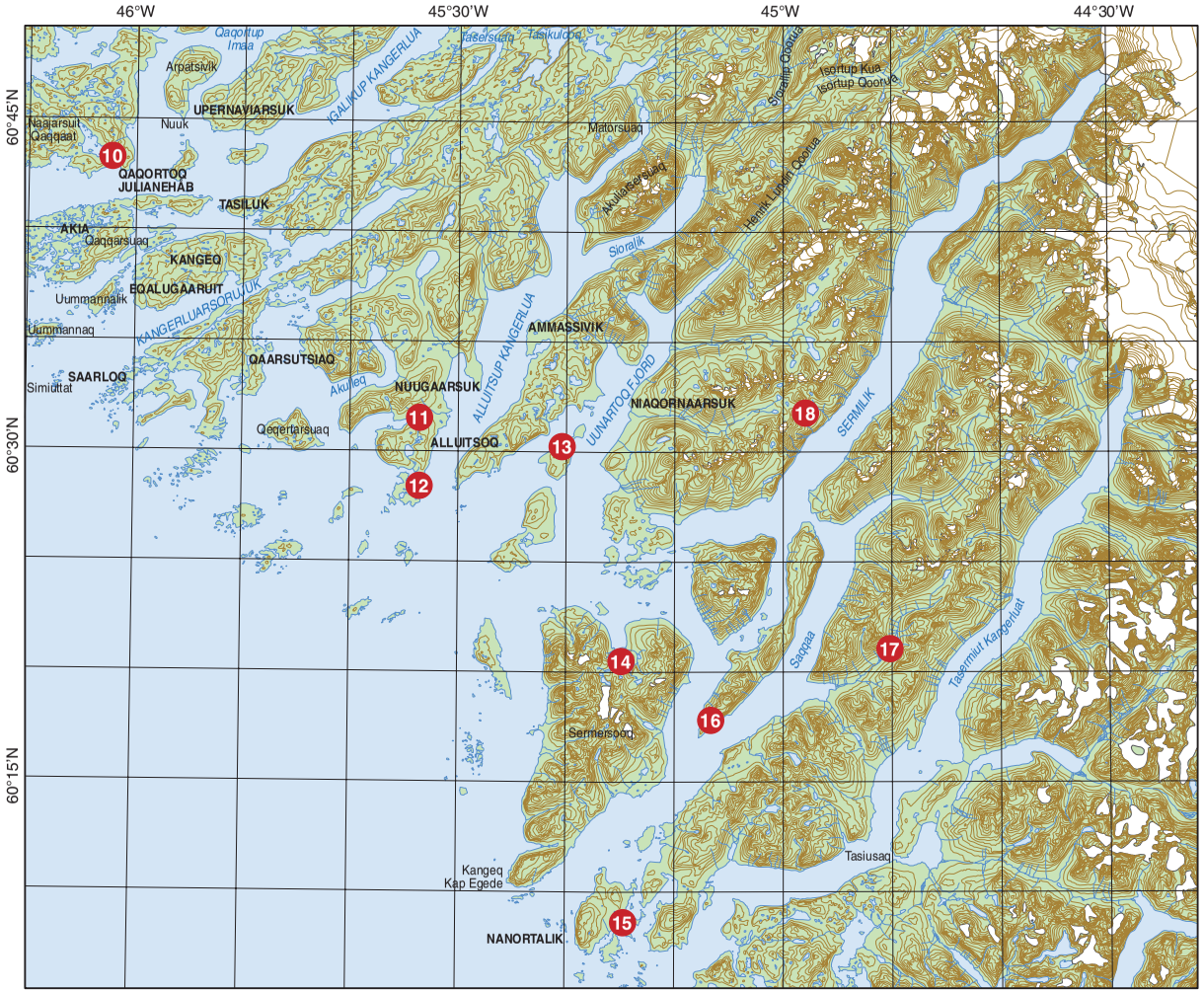


Fig. 2. Topographic map of the southern part of the excursion area visited later during the excursion. The numbers refer to the locations described in the text. Location 15 is the town of Nanortalik for orientation.

20 AUGUST

Starting from the Kringlerne camp site at 08:30 a.m. after breakfast.

Locality 7: Kringlerne

Hiking tour to the layered kakortokite, the roof-rock units and the pegmatites, visits to some of the world-famous mineral localities. We have several hours for that and will go into a detailed investigation of the intrusion and its mineral wealth. Guides: H. Bohse and A. Borst

In the afternoon, we depart by Juvel heading for some touristic sites on the way to Qaqortoq, via Hvalsey church ruin and Upernaviarsuq, some of the Viking age localities on the way to Qaqortoq.

Locality 8: Hvalsey church ruin (c. 1 h)

The Hvalsey church is the ruin of an old Norse church, constructed when the Vikings settled in Greenland in around 985, and was still in use in 1408. The government of Greenland has applied to have the Hvalsey church approved as a UNESCO world heritage site.

Locality 9: Upernaviarsuq (c. 1 h)

Upernaviarsuk is the Greenlandic government's research and training center for the agricultural sector in Greenland. Upernaviarsuk grows potatoes, turnips and a wide variety of other vegetables such as iceberg lettuce, cabbage, tomatoes etc. In addition to the vegetables production, Upernaviarsuk grows trees and bushes that are especially adapted to the arctic climate.

Locality 10: Qaqortoq quarry (c. 1 h)

Outcrop of a biotite-hornblende-bearing, porphyritic granite, which belongs to the Julianehåb Batholith. The characteristic lithology of this zone of the Ketilidian Orogen. Guide: J. Kolb.

Accommodation: Hotel Qaqortoq, dinner at the hotel. Presentation on the geology of the Ketilidian Orogen by J. Kolb.

21 AUGUST

Starting from Hotel Qaqortoq at 09:00 after breakfast with the boat, making stops at several outcrops on the way to Nanortalik.

Locality 11: East of Saarloq (c. 1 h)

Mixing and mingling structures of gabbro–diorite and granite that belong to the Julianehåb Batholith and sheared lithologies of the Sårdloq shear zone. Guide: J. Kolb.

Locality 12: Sydprøven settlement (c. 1 h)

Rapakivi granite, marking the end of the Palaeoproterozoic activity of the Ketilidian Orogen. The rapakivi texture is particularly well-developed, where the K-feldspar megacrysts grew in basic or monzonitic members of the suite. Guide: J. Kolb.

Locality 13: Uunartoq hot springs (c. 1 h)

Guide: J. Kolb.

Locality 14: Samersoq North (view)

Rapakivi granite – optional – view from boat. Guide: J. Kolb.

Locality 15: Nanortalik (c. 2 h)

Psammite Zone metasedimentary rocks (metagreywacke, metasiltstone, metamudstone), metamorphism and structure. Guide: J. Kolb.

Accommodation and dinner at Hotel Kap Farvel.

22 AUGUST

Starting from: Hotel Kap Farvel at 08:00 a.m., after breakfast.

Locality 16: Amitsoq graphite deposit (c. 2 h)

We will visit the abandoned underground mine site, from which approx. 6 000 t of graphite have been produced 1915–1924. Guide: J. Kolb.

Locality 17: Nalunaq gold mine (c. 4 h)
Presentations and safety procedures followed by an underground visit of Greenland's only active mine. Guide: R.-M. Bell.

Locality 18: Vagar
Optional visit to the Vagar gold project of NunaMinerals A/S. Guide: J. Kolb.

Arrival at the hotel in Nanortalik late in the afternoon, dinner.

23 August
Starting from Nanortalik by boat bound for Narsarsuaq. On this trip, we can visit outcrops or tourist places that we have missed earlier. It is basically a travelling day, but we want to make sure that you won't miss your flight home.

Accommodation: Hotel Narsarsuaq. Evening: Dinner and farewell at Hotel Narsarsuaq. Jochen, Leon and Robin-Marie will continue field work, as will Alexander and Thomas.

24 AUGUST
Travelling back home via Iceland to individual destinations.

The Ketilidian orogen

Jochen Kolb, Department of Petrology and Economic Geology,
Geological Survey of Denmark and Greenland, Copenhagen, jkol@geus.dk

South Greenland is underlain by the Palaeoproterozoic Ketilidian orogen that is interpreted to continue in the Makkovik orogen in Canada, whereas the continuation to the east is not clear (St-Onge et al. 2009). The Ketilidian orogen has been subdivided into five lithological and structural domains by Garde et al. (2002a), which are: (1) the Archaean foreland in the north, (2) the Border zone, (3) the Julianehåb batholith, (4) the Psammite zone, and (5) the Pelite zone in the south (Fig. 3). During this field trip, we will have the chance to see rocks of the Julianehåb batholith and the Psammite zone. The other zones are only briefly described in the following in order to give a comprehensive overview of the orogen.

The Archaean foreland is represented by orthogneisses, greenstone belts and higher grade metamorphic equivalents, and granite (Kolb 2011, Kolb et al. 2013, Szilas et al. 2013, Kisters et al. 2012, Friend & Nutman 2001). Palaeoproterozoic deformation is recognised in a conjugate set of west-south-west and north-west trending faults, suggesting east-south-east–west-north-westerly compression (Bondesen 1970, Higgins 1970).

The Border zone is characterised by granite intrusions and sedimentary rocks unconformably overlying Archaean rocks (Fig. 3). Three main deformation stages are distinguished (Fig. 4, Bondesen 1970, Higgins 1970). The D_1 stage is characterised by folds and thrust zones with several hundred metres displacement to the south-west, which is correlated with sinistral shearing in the Qoornoq and Kobberminebugt shear zones (Fig. 3) that is contemporaneous to c. 1 845 Ma granite intrusions (Garde et al. 1998). The D_2 deformation is characterised by north-vergent fold and thrust structures that thrust higher metamorphic rocks on top of lower metamorphic to unmetamorphosed rocks (Figs. 3 & 4). The D_3 deformation refolded earlier structures into minor folds with gently inclined axial planes. The Kobberminebugt shear zone system was reactivated by highly localised dextral transpression shortly before 1 800 Ma, as indicated by the intrusion of the 1 805±2 Ma Sâtukujôq granite (Garde et al. 2002a). The Palaeoproterozoic strata contain a set of mafic dykes, meta-sedimentary and meta-volcanic rocks, which grade from unmetamorphosed in the north to amphibolite facies in the Kobberminebugt shear zone area (Bondesen 1970, Higgins 1970). The sedimentary rocks were deposited between c. 1 880 and 1 850 Ma (Fig. 4, Berthelsen & Henriksen 1975). The volcanic rocks are interpreted to be formed during rifting in a back-arc setting (Garde et al. 2002b).

The Pelite zone grades from the Psammite zone to the north and is characterised by meta-pelites, migmatites and granites. The Pelite zone is extensively intruded by a suite of c. 1 755–1 723 Ma Rapakivi granites during late open folding (Garde et al. 2002b).

THE JULIANEHÅB BATHOLITH

The Julianehåb batholith is 100–200 km wide and has a tectonic contact in the north to the Border zone with the Kobberminebugt shear zone, and to the south to the Psammite zone with the Niaqornaarsuq shear zone that continues eastward north of Kangerluluk (Fig. 3). The rocks are dominated by calc-alkaline granite and granodiorite, with subordinate tonalite, hornblende diorite and gabbro. Most granodiorites and granites are medium-grained and weakly porphyritic. Dioritic enclaves in granite and synplutonic dyke swarms (appinite) are common (Chadwick & Garde 1996). U-Pb zircon and titanite geochronology suggest that the granitoids

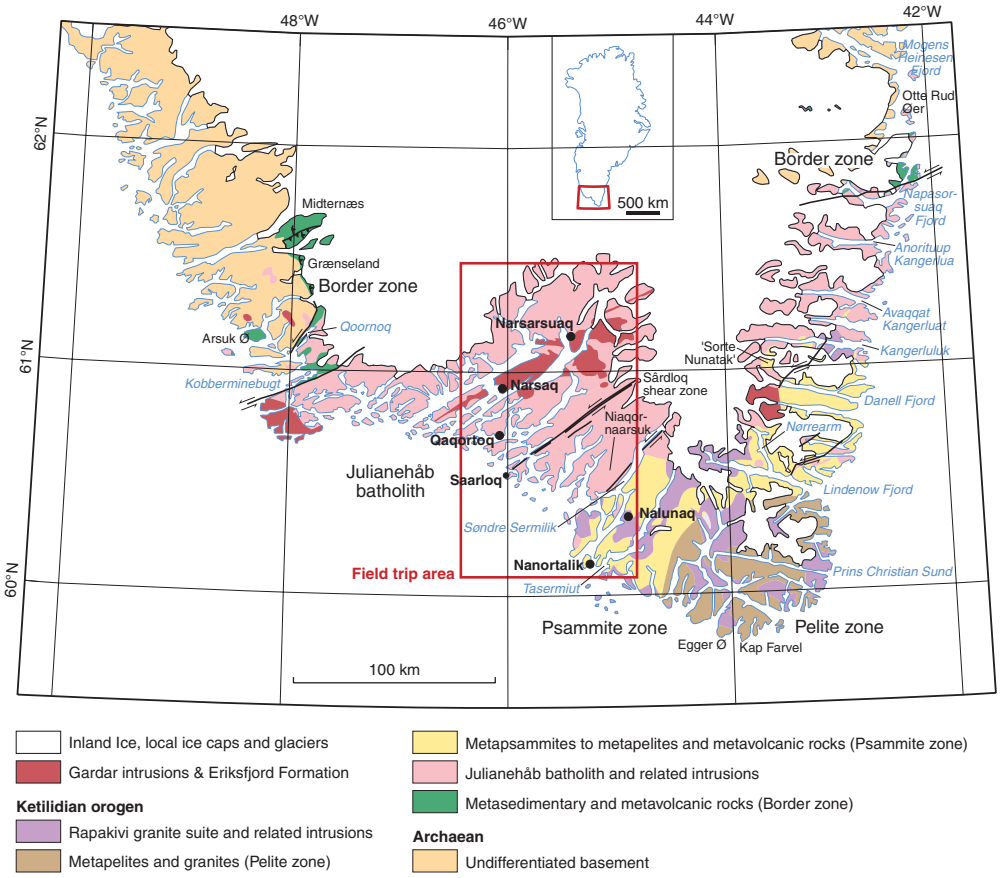


Fig. 3. Geological map of South Greenland and the Ketilidian orogen (modified after Garde et al. 2002a).

were emplaced in two major pulses between 1 854–1 836 Ma (JBI) and 1 818–1 799 Ma (JBII, Fig. 4, Garde et al. 2002b). The geochemical signature indicates that the rocks represent a largely juvenile Palaeoproterozoic magmatic arc batholith (Patchett & Bridgwater 1984, Garde et al. 2002b).

The granitic rocks have a near-vertical magmatic foliation, trending north-east, and shallow lineations. Steeply dipping, north-east-trending sinistral shear zones are a few centimetres to c. 1.5 km wide and are characterised by high-temperature crystal-plastic fabrics and shallow lineations (Chadwick & Garde 1996). A syn-kinematic aplite intrusion into the sinistral Sårdloq shear zone was dated at 1 816 Ma, and post-tectonic intrusions were emplaced at c. 1 800 Ma, dating the sinistral transpression for the Julianehåb batholith (Garde et al. 2002a).

THE PSAMMITE ZONE

The Psammite zone is underlain by meta-sedimentary and meta-volcanic rocks of variable metamorphic grades. The meta-sedimentary rocks consist of feldspathic arenites, lithic arenites, shales and rare polymict conglomerates (Garde et al. 2002a). In the Danell Fjord area, they are interpreted as turbidites (Fig. 3). The provenance was dominated by rocks of the Julianehåb batholith, but also older Palaeoproterozoic units and

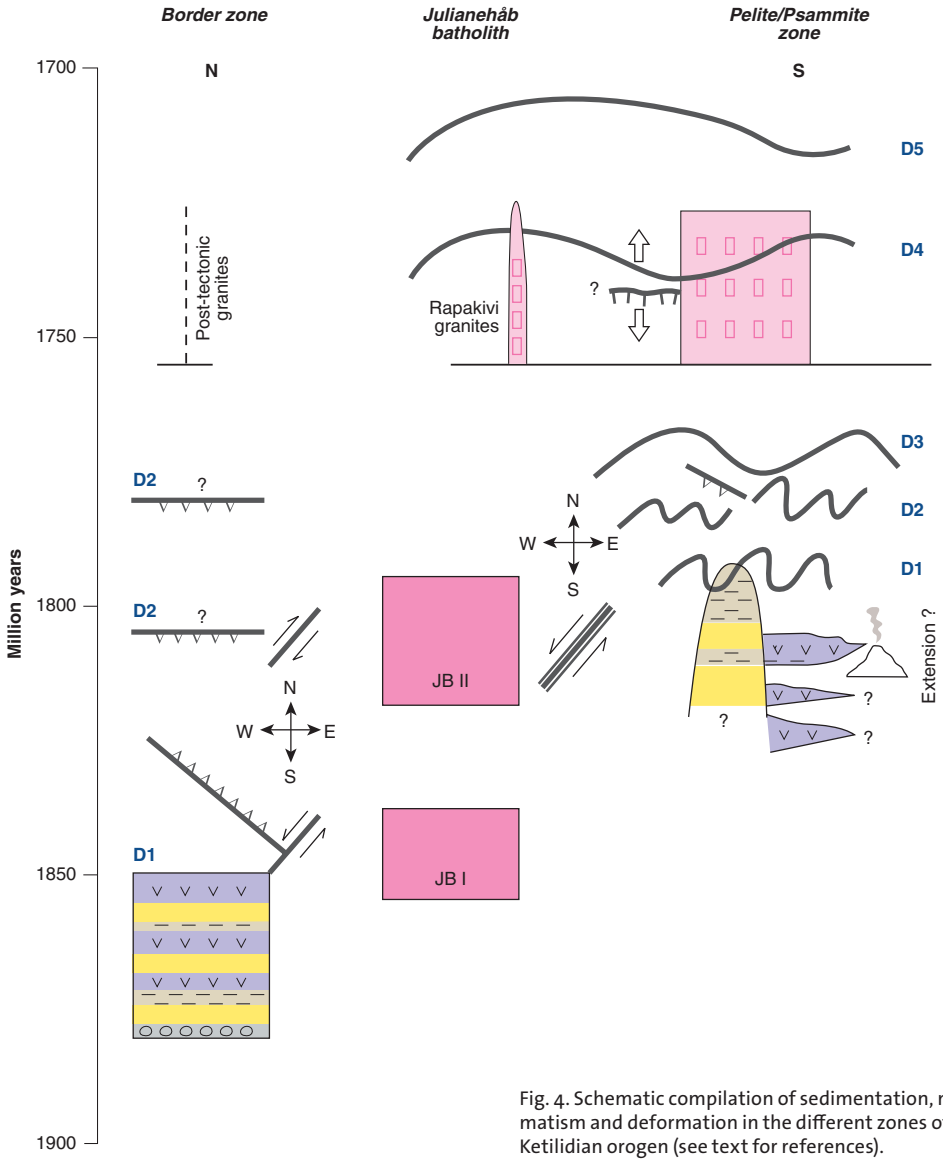


Fig. 4. Schematic compilation of sedimentation, magmatism and deformation in the different zones of the Ketilidian orogen (see text for references).

Archaean rocks have been in the source area (Garde et al. 2002b). Sedimentation ceased at c. 1793 Ma (Fig. 4, Garde et al. 2002a). The meta-volcanic rocks of the Sorte Nunatak and Kangerluluk areas include c. 1808 Ma tholeiitic lava flows and subaqueous pyroclastic rocks probably formed during rifting in an island-arc setting (Figs. 3 & 4, Mueller et al. 2000, 2002).

Five deformation stages are distinguished in the Psammite zone (Fig. 4, Garde et al. 2002a). During D_1 tight, upright, north-east-plunging folds and an axial planar foliation containing andalusite porphyroblasts formed. The folds are south-east vergent and interpreted to be formed by south-east directed deformation. The D_2 stage is characterised by a foliation and mineral

stretching lineation plunging gently south-west and north-east due to later folding. The intensity of D_2 fabrics increases eastward together with the metamorphic grade, reaching anatexis of meta-pelitic rocks south of Danell Fjord. In general, D_2 fabrics formed during north-east vergent deformation in the Psammite zone of eastern South Greenland. Syn-kinematic sills date the D_2 stage at c. 1 792 Ma (Garde et al. 2002a). D_3 formed large-scale, close to tight, north-east trending folds overturned to the north-west still at high metamorphic grades. Syn-kinematic intrusions are dated at 1 786–1 778 Ma (Garde et al. 2002a). D_4 folds are kilometre-scale open to tight, upright folds with north-easterly trends and they formed c. 1 736 Ma. D_5 folds are open, kilometre-scale, basin-like fold structures. Rapakivi granites were emplaced between 1 755 and 1 723 Ma at approximately 2 kbar (Garde et al. 2002b, van Breemen et al. 1974, Windley 1991, Hutton & Brown 2000, Hutton et al. 1990), mainly as extensive flat-lying sheets within the Psammite zone and along its boundary with the Julianehåb batholith during north–south extension and normal south-vergent deformation (Hutton & Brown 2000, Hutton et al. 1990).

GEODYNAMIC INTERPRETATION

The calc-alkaline Julianehåb batholith is interpreted to represent a continental-arc system that evolved during northward oblique subduction of an oceanic plate under the North Atlantic craton. The Psammite and Pelite zones represent the fore-arc of the orogen and the Border zone the back-arc region (Fig. 5, Garde et al. 2002b). A similar interpretation is based on the geology and geochemistry around Kangerluluk, where subduction is related to magmatism in the Julianehåb batholith, but c. 1 808 Ma volcanism is interpreted to be caused by subsequent rifting of the magmatic-arc represented by the Julianehåb batholith (Fig. 6, Mueller et al. 2002, 2000).

These models are in contrast to earlier interpretations of the Ketilidian orogen as a Himalaya-type collisional orogen (Windley 1991). The Border zone is interpreted as continental shelf on Archaean basement and the Kobberminebugt shear zone in the south as the suture zone of the orogen (Fig. 7). The Julianehåb batholith represented an island-arc with a back-arc shear belt, the Sârdloq shear zone, in the southern margin. The Psammite and Pelite zones represent nappe stacks in the back-arc setting (Windley 1991).

OPEN QUESTIONS FOR DISCUSSION IN THE EVENINGS

- How does the c. 1 845 Ma south-west vergent thrusting in the Border zone in the early stages of arc magmatism fit into the plate tectonic models for the orogeny?

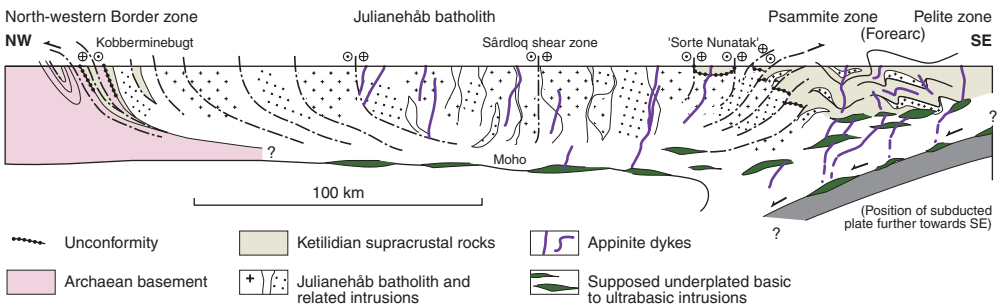


Fig. 5. Schematic cross section through the Ketilidian orogen and interpreted position of subduction (modified after Garde et al. 2002b).

- If the Border zone represents a back-arc setting, how can the rocks largely be older than arc magmatism in the Julianehåb batholith?
- Which role do the shear zones play at the contact between Julianehåb batholith and Psammite zone?
- Why is there sinistral shearing in the Sårdloq shear zone and dextral shearing in the largely parallel Kobberminebugt shear zone between c. 1 816 Ma and 1 800 Ma, directly following a 18 million year gap of continuous magmatism in the Julianehåb batholith?

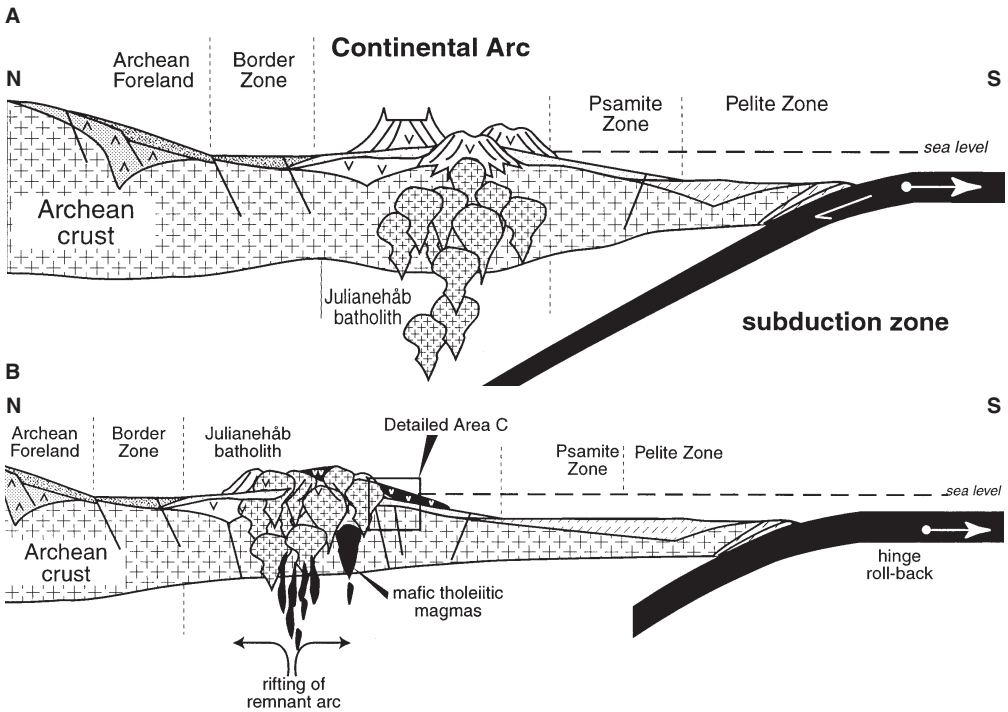


Fig. 6. Schematic cross section through the Ketilidian orogen in eastern South Greenland around Kangerluluk (Mueller et al. 2002).

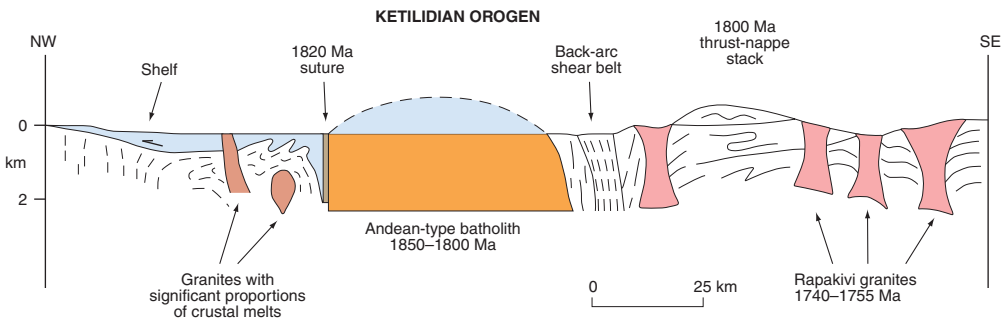


Fig. 7. Schematic cross section through the Ketilidian orogen in western South Greenland with the Kobberminebugt shear zone as the suture of the orogen (Windley 1991).

- How can there be Archaean zircons in the meta-sedimentary rocks of the Psammite zone, if there is an arc separating the fore-arc basin from the Archaean hinterland?
- Why is the grade of metamorphism in the Psammite zone increasing away from the Julianehåb batholith? Shouldn't the opposite be expected?
- How does folding and extension during Rapakivi granite intrusion relate?

METALLOGENY OF THE KETILIDIAN OROGEN

Two abandoned mines, Josva mine and Lilian mine, and one active mine, the Nalunaq gold mine, are situated in rocks of the Ketilidian orogen. We will visit the Nalunaq gold mine and, therefore, a separate chapter introduces the geology of this orogenic or intrusion-related gold deposit. The Josva and Lilian mines produced approximately 60 tonnes of Cu, 50 kg Ag and 0.5 kg Au in 10 years of mining until they were closed in 1914.

The deposits are hosted in Palaeoproterozoic meta-sedimentary and meta-volcanic rocks in the Kobberminebugt shear zone (Fig. 3). Copper sulphides are hosted in veins, breccias, foliation-parallel stringers and vugs. The mineralised shear zone is characterised by an early albite alteration followed by a proximal garnet-calcite-ore ± epidote ± diopside ± actinolite ± apatite ± titanite assemblage and a distal hornblende-biotite-epidote assemblage (Harry & Oen 1964). The ore assemblage is bornite-chalcocite-ilmenite-magnetite-hematite-chalcopyrite ± wittichenite ± electrum ± pyrite ± galena (Harry & Oen 1964).

The mineral assemblages indicate hydrothermal mineralisation at temperatures between 475 and 660 °C (Harry & Oen 1964). These authors relate the hydrothermal mineralisation to alkali-enriched fluids derived from intrusions belonging to the Gardar province. The structural setting, the probable syn-metamorphic nature of mineralisation and the magnetite-hematite-copper sulphide ± gold assemblage are the basis for a reinterpretation as a metamorphic IOCG mineral system similar to Tennant Creek deposits in Australia (Stensgaard et al. 2011).

The Palaeoproterozoic units of the Border zone host syngenetic mineralisation, such as banded iron formation and disseminated sulphides, mainly pyrite and chalcopyrite, in mafic and felsic (meta)volcanic rocks (Secher & Kalvig 1987). The mafic–felsic association together with the geochemical rift or back-arc signature (Garde et al. 2002a) may be regarded as favourable for VMS-like mineral systems. Additionally, galena and sphalerite have been described from marble, which may be indicative of Mississippi Valley Type systems. The sulphide occurrences are relatively small at the surface and only weakly explored. VMS-like Cu-Au mineralisation has also been identified in the Psammite zone at Kangerluluk and Sorte Nunatak (Stendal & Frei 2000).

Quartz vein hosted sulphide mineralisation with a Au ± Bi-Ag-As-W-Cu-Mo metal association has been identified at several places in the Border zone, the Julianehåb batholith and the Psammite zone (Secher & Kalvig 1987, Higgins 1970, Stendal & Frei 2000). The veins have hydrothermal alteration halos of fuchsite, epidote, clinozoisite and pyrite at lower metamorphic grades, and clinopyroxene, plagioclase, amphibole and pyrrhotite at higher metamorphic grades. The veins are spatially associated with the major shear zones, i.e. Kobberminebugt, Sârdloq and Niaqornaarsuq shear zones. Their formation is, thus, probably related to regional deformation and metamorphism, representing either an orogenic, intrusion-related mineralisation or an IOCG setting (Stendal & Frei 2000, Stensgaard et al. 2011). Economic gold quartz veins are mined at the Nalunaq gold mine, and exploration focusses on similar gold-quartz vein mineralisation on Niaqornaarsuk peninsula, the Vagar deposit of NunaMinerals A/S.

The Amitsoq graphite deposit

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The Amitsoq graphite deposit is located near the southern tip of Amitsoq Island in the Saqqaa Fjord. The graphite deposit was found in 1911. Mining by Grønlandsk Minedrifts A/S in co-operation with the Grønlands Grafit Company A/S started in 1915 and lasted until 1924. The ore reserves were calculated at 250 000 tonnes, and only 6 000 tonnes of graphite ore averaging 21% graphite were produced (Bondam 1992).

The graphite deposit is hosted in graphitic schists in cordierite-sillimanite-biotite gneiss wall rocks of the Psammite zone. A fault in the northern part of the island marks the deposit limit in the north (Fig. 8). Three parallel graphite-bearing horizons have been identified, where the main horizon is <15 m wide and c. 600 m along strike (Fig. 8). The two minor horizons are 4 m wide and have a strike extent of c. 100 m (Bondam 1992). The ore consists of finely disseminated crystalline graphite flakes in a quartz-rich groundmass with minor pyrite and biotite. The graphite flakes are up to 15 mm in size and the graphite content varies between 20 and 24 vol.% (Bondam 1992). Only one geochemical analysis of an average ore grade was published as 21.0 wt.% C, 6.0 wt.% S and 0.2 wt.% H_20 (Høeg 1915). The foliation-parallel nature of the ore horizons and the association with amphibolite facies metamorphic wall rocks suggests that the graphite deposit formed by metamorphic or hydrothermal processes, but no specific scientific studies on the deposit are available.

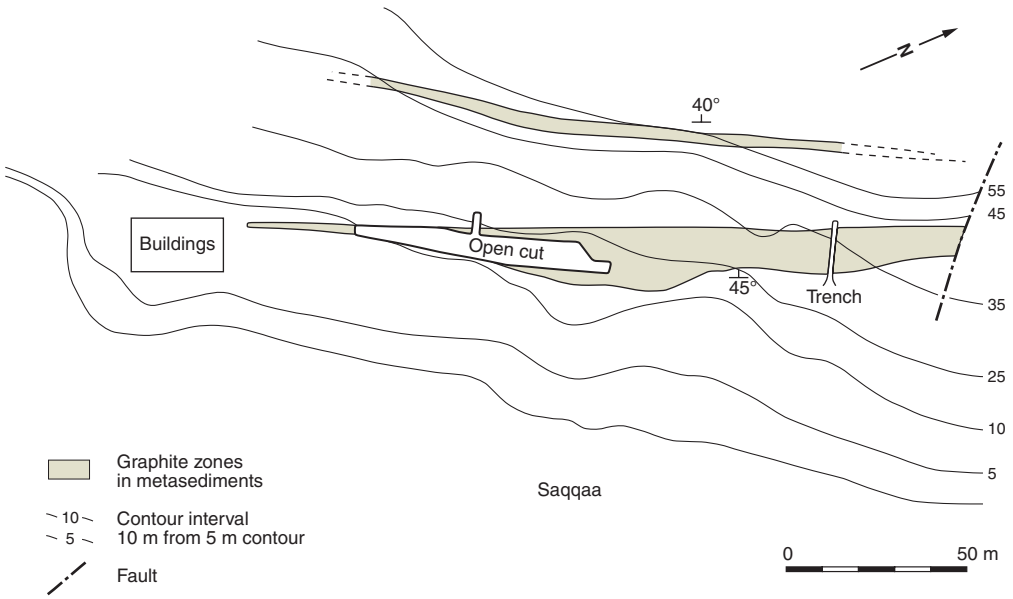


Fig. 8. Schematic map of the Amitsoq graphite deposit (Bondam 1992).

The Nalunaq gold deposit

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The Nalunaq gold mine is the site of a quartz-hosted gold deposit, located on the southern tip of Greenland within the Ketilidian orogen. The deposit has been commercially mined since the early 1990's with production expected to cease within the next 18 months. Despite this, there is still a large amount of interest in the Nalunaq gold deposit, as both an indicator for potential gold in the surrounding area, and as Greenlands only currently operating mine. The current gold grade is unusually high for a gold deposit at 14.04 g/t average and the mine recovers 1 682 oz of gold per month (September–December 2011, Angel Mining Operations update report 2012, www.angelmining.com).

Another deposit with significant gold grades has not been found elsewhere, but it would be unusual for the Nalunaq gold deposit to be an isolated occurrence in the Ketilidian orogen. A thorough constraint on the genesis of the Nalunaq gold deposit may aid in the discovery of comparable deposits within southern Greenland.

LOCAL AREA GEOLOGY

The Nalunaq gold deposit is located within the Nanortalik nappe of the Psammite zone, a sequence of overthrust meta-basalts and meta-dolerites, which have since been largely eroded with the exception of three klippes, Lake 410, Nalunaq and Ippatit (Fig. 9, unpublished report by Petersen & Pedersen 1995, Petersen et al. 1997). The Nanortalik nappe overthrust a sequence of meta-arkoses and meta-pelites, which are thought to represent metamorphosed detritus eroded from the Julianehåb batholith, (Garde et al. 2002b). The contact between the Julianehåb batholith and the Psammite zone is located several kilometres to the north and the west of the Nalunaq gold deposit. In the north, the rocks of the Psammite zone unconformably overlie the granitic rocks of the Julianehåb batholith, whereas the western contact is probably tectonic (Fig. 9). The Nanortalik peninsula is an area of elevated gold, with visible gold recorded at Ippatit and Lake 410 (Fig. 9, Petersen et al. 1997).

The quartz-gold veins are hosted by coarse-grained meta-dolerites and fine-grained meta-basalts, which have undergone metamorphism to amphibolite facies. This metamorphism predates all hydrothermal alteration within the Nalunaq gold deposit (Porritt 2000, Schlatter & Olsen 2011). The rocks generally contain hornblende, plagioclase and minor quartz and are often black in colour, but can be dark grey or green due variable mineralogy. The majority of host rock observed hosting the quartz-gold veins is fine-grained.

Additional rock types are observed in outcrop at the surface of Nalunaq Mountain. These include fine- to medium-grained meta-volcaniclastic rocks and meta-basalts with ellipsoidal bleached areas. These structures have been previously interpreted as pillow structures (unpublished report by Petersen 1993). Also observable on the surface of Nalunaq Mountain are bands of rusty coloured rocks. These rocks are highly distinctive and clearly visible from a distance. However, in hand specimen a fresh surface does not appear different from surrounding rocks. These rocks may be the pyrrhotite-cherts described in past papers (Kaltoft 2000, Schlatter & Olsen 2011), but they do not have a chert-like texture.

DEPOSIT TYPE AND LOCAL STRUCTURES

The gold is hosted in mineralised ductile shear zones. There are three zones of quartz mineralisation present in Nalunaq Mountain, however only one of these contains significant economic

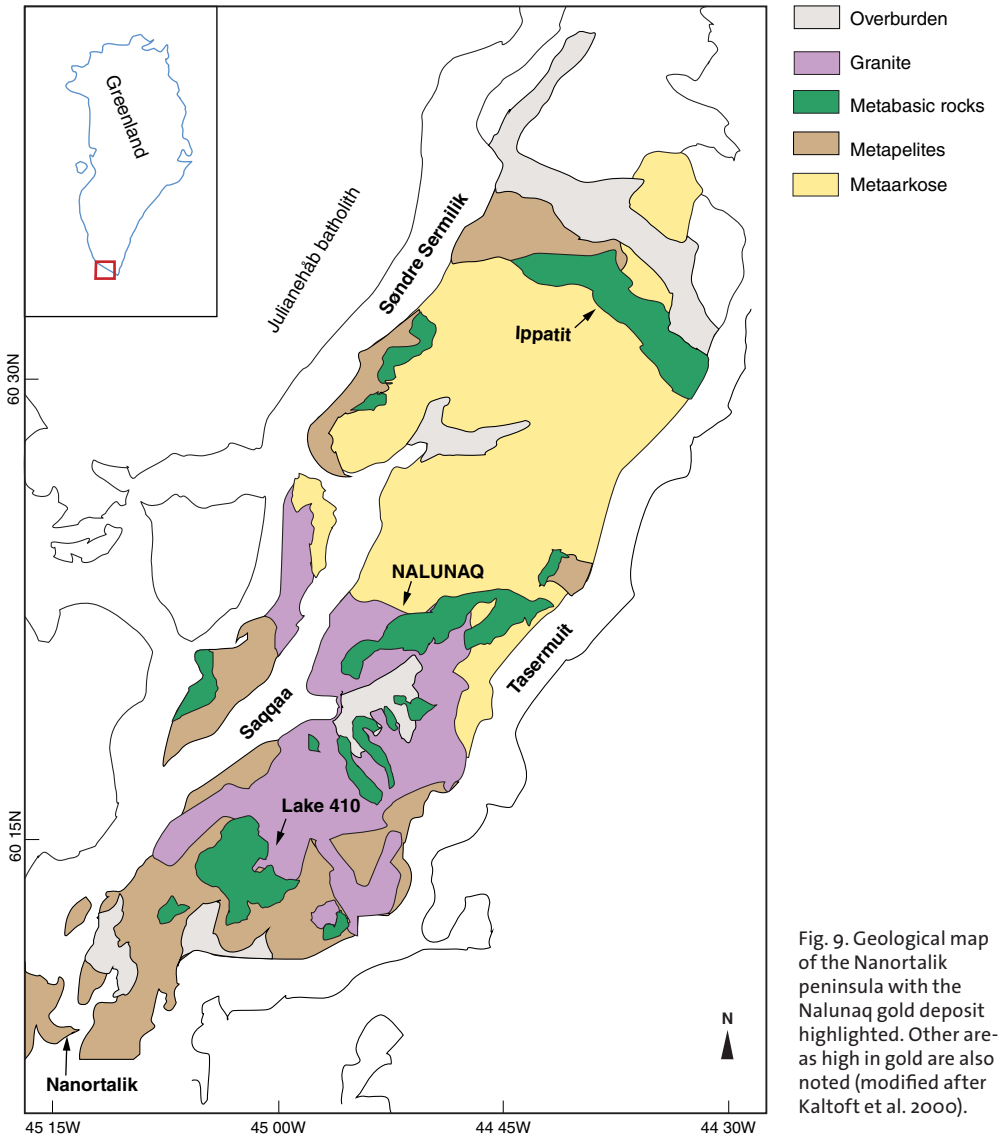


Fig. 9. Geological map of the Nanortalik peninsula with the Nalunaq gold deposit highlighted. Other areas high in gold are also noted (modified after Kaltoft et al. 2000).

gold grades. This is the Main vein (MV), which consists of a single sheet of slightly undulating quartz that dips 35–40° south-east and has a roughly north-easterly strike (unpublished report by Goddard 2009 to Angel Mining), that has been mined commercially since the mid 2000's (Secher et al. 2008). There are two smaller veins above and below the MV, Upper vein and Lower vein, which are more discontinuous and contain lower levels of gold. The MV is a narrow structure, generally 0.8–2 m in width, with an average of c. 1.5 m. The lateral extent of the sheet is c. 1 300 m vertically and 800 m horizontally (Kaltoft et al. 2000, Secher et al. 2008). The emplacement of the gold has been constrained to metamorphism and deformation

between c. 1 792 Ma and 1 785 Ma, with a Palaeoproterozoic Pb-source outside the Julianehåb batholith rocks, based on whole rock and sulphide Pb-isotope data the later stages of the emplacement of the Julianehåb batholith (Stendal & Frei 2000).

The gold has a high nugget effect, which has made estimating overall gold content and therefore the longevity of mining operations very difficult. The majority of the gold is native (98%), but it can also occur in maldonite (Au_2Bi) and a number of other gold-bearing minerals (Kaltoft et al. 2000). Additionally, there appears to be no clear relation between vein thickness and gold concentration (Kaltoft et al. 2000). Conversations with Christiansen (2011, 2012) have shown that there may be a slight correlation between wider (>0.5 m) quartz veins and lower gold grade.

There are a series of faults that run through the Main vein: Clay fault, Your fault, Fault 210 and the Pegmatite fault (Christensen pers. comm. 2011). Because of this, the deposit has been divided into three separate sections: the Target block, the South block and the Mountain block (Figs. 10 & 11). The Pegmatite fault has displaced the South block 240 m laterally and 60 m vertically (Kaltoft et al. 2000, Stendal & Frei 2000). Clay fault, Your fault and Fault 210 show much less displacement. None of the faults appear to have an effect on the gold grade.

ALTERATION TYPES

The major indicator used by previous authors for the location of gold within the Nalunaq gold deposit has been the presence of a 1–5 m thick halo of yellow-green-brown alteration termed 'calc-silicate alteration' (Kaltoft 2000, Porritt 2000,

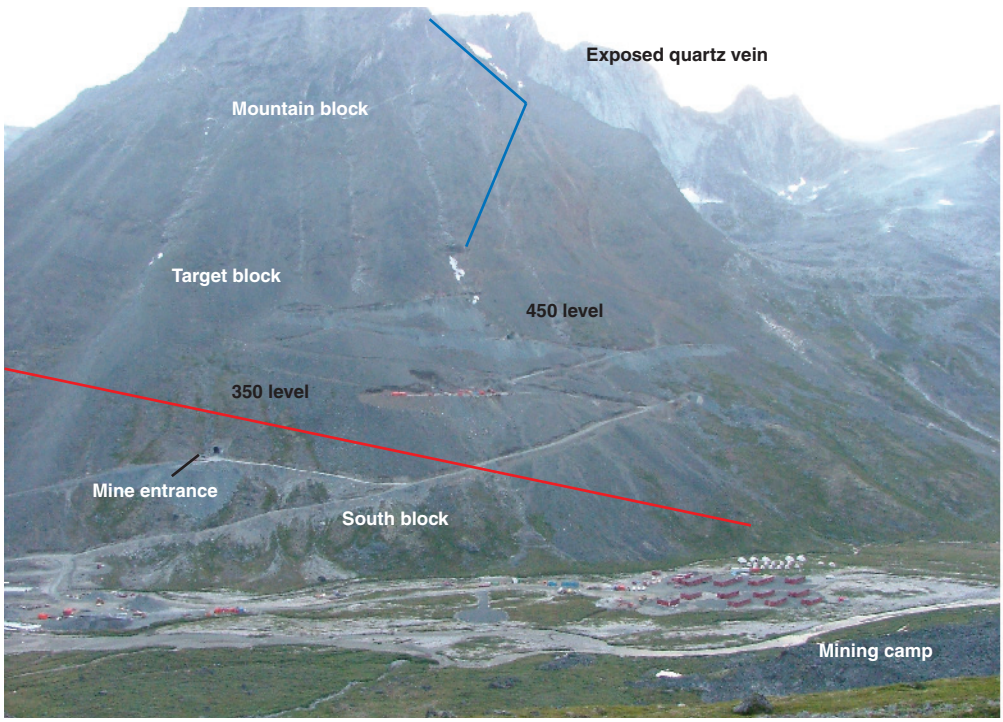


Fig. 10. Photograph of the exterior of Nalunaq Mountain. The structural blocks within Nalunaq gold deposit are noted as well as the main entrances to the mine (mine entrance, 350 level and 450 level). The Pegmatite fault is marked by the red line. The mine camp is shown in the bottom right corner. Modified after Secher et al. 2008.

Grammatikopoulous et al. 2004). However, recent observations have shown that a minimum of four separate hydrothermal alteration events affected the Nalunaq gold deposit, with up to six currently identified. Additionally, these separate hydrothermal events both pre- and post-date the emplacement of the gold-bearing quartz veins. These events and their distinguishing features are described below, in their currently assumed chronological order.

Splayed discolouration of host rocks

Pale grey or green vein-like bands of discoloured host rock can be observed, usually situated 1–2 m

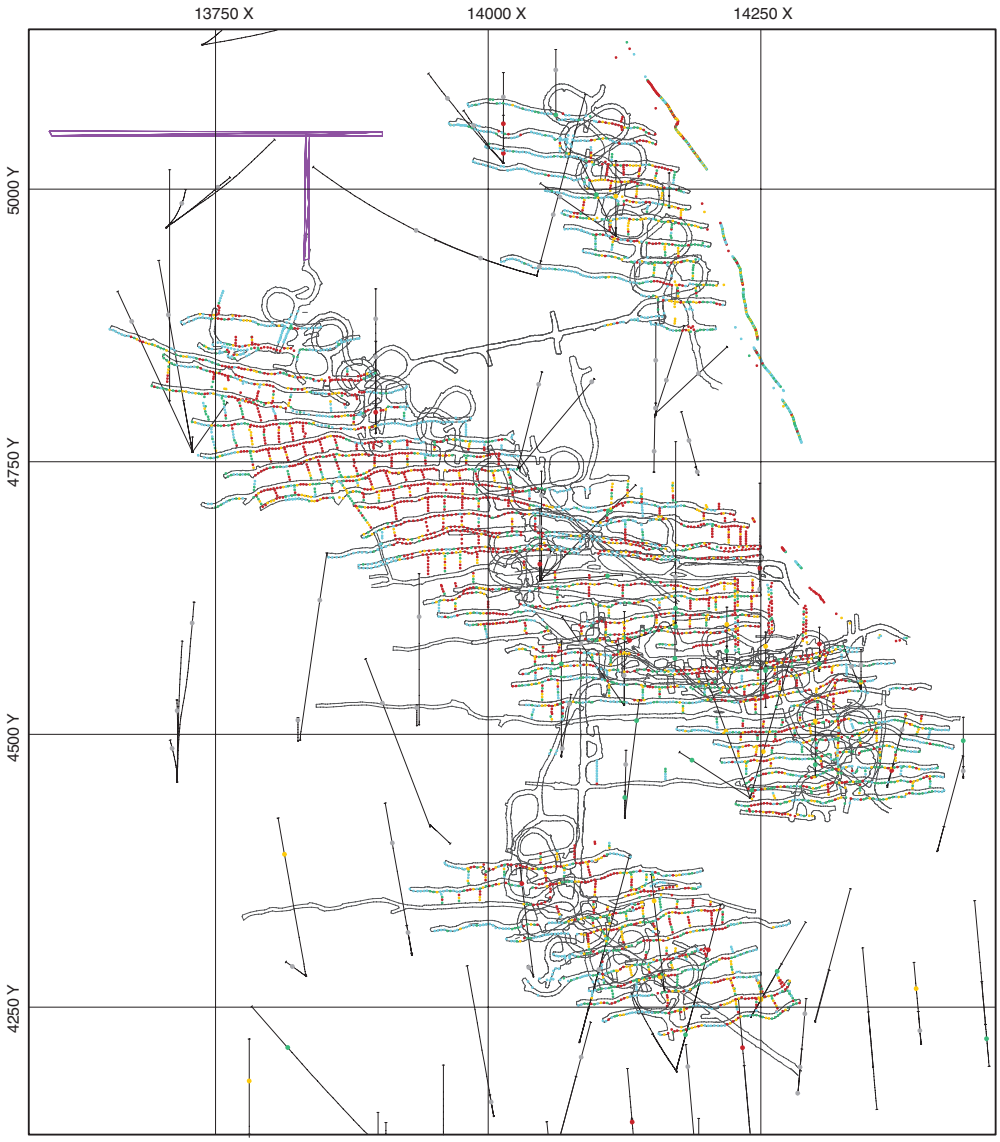


Fig. 11. Interior development plan for Nalunaq gold mine. The colour reflects different gold grades from red (high-grade ore) to blue (low-grade ore). Site visits can be marked on this (with permission from AngelMining A/S).

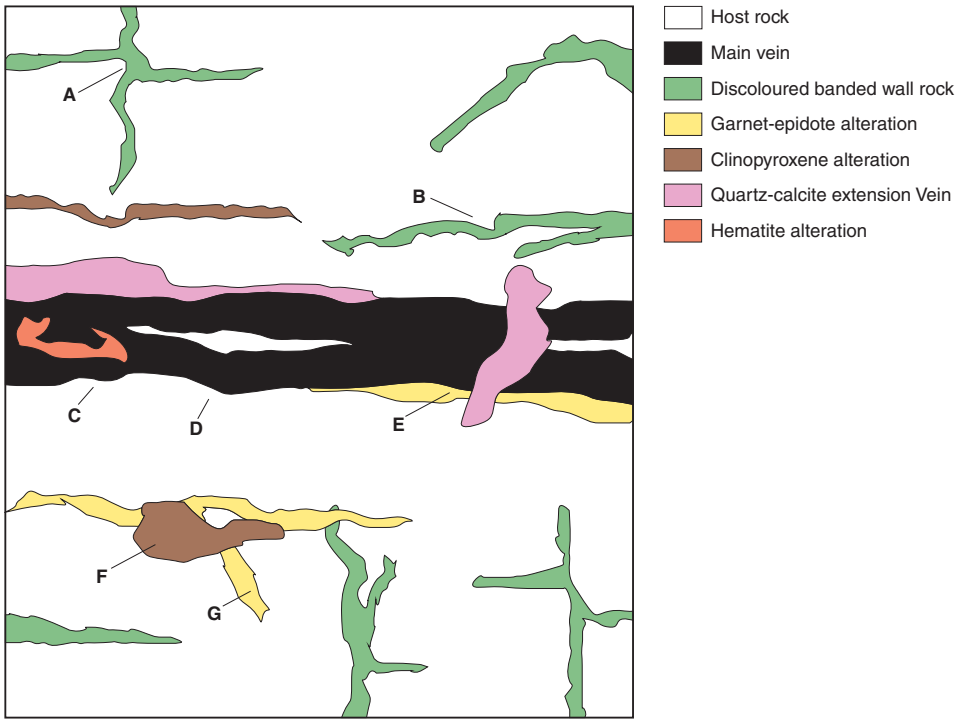


Fig. 12. Schematic diagram of the alteration features observed with the Nalunaq gold deposit. Not all alteration types are visible in all areas. The information presented is only recently gathered, and the relationships are still poorly understood. **A.** Disjointed bands of discoloured wall rock. **B.** These bands are often transposed parallel to the MV nearer to the MV-host rock contact. **C.** Hematite alteration. This can often be observed by staining of the quartz. **D.** The MV. This often incorporates fragments of the host rock. **E.** The quartz-calcite veins are both overprinting and being overprinted by the MV. **F.** Barren clinopyroxene alteration is observed both as circular blebs and sheared sections parallel to the MV. It can be observed overprinting the garnet-epidote alteration. **G.** Garnet-epidote alteration can be observed both in disjointed bands within the host rock and horizontal bands close to the MV.

from MV. These bands can often be seen forming a discordant set, with one band running parallel to the MV, and another set at c. 80° to the MV. These discordant bands are more prevalent further from the MV whereas closer to the MV, the bands are mostly parallel (Fig. 12). These bands have undergone intense deformation, with some bands displaying isoclinal folding, placing them early in the alteration history.

Garnet-epidote alteration

Garnet-epidote (GE) alteration has affected the Nalunaq gold deposit (Fig. 13A). This alteration is bright green in colour and often features clusters of 0.25–1 cm large garnets. Large (up to 1 cm) crystals of pyrite and chalcopyrite are also present. The texture of this alteration varies from replacement to strong veining in lower mine areas. This alteration is not observed on all levels, and it is more prevalent at the peripheries of the deposit. There is an apparent relationship between the presence of GE alteration and low gold grades.

Clinopyroxene alteration

The clinopyroxene alteration stage can be identified by 0.25–5 cm large pockets of 0.25–2 mm biotite and feldspar crystals, and a green coloured clinopyroxene-quartz granular halo which is 2–30 cm in width (Fig. 13B). With the exception of the biotite-feldspar pockets, the grain size

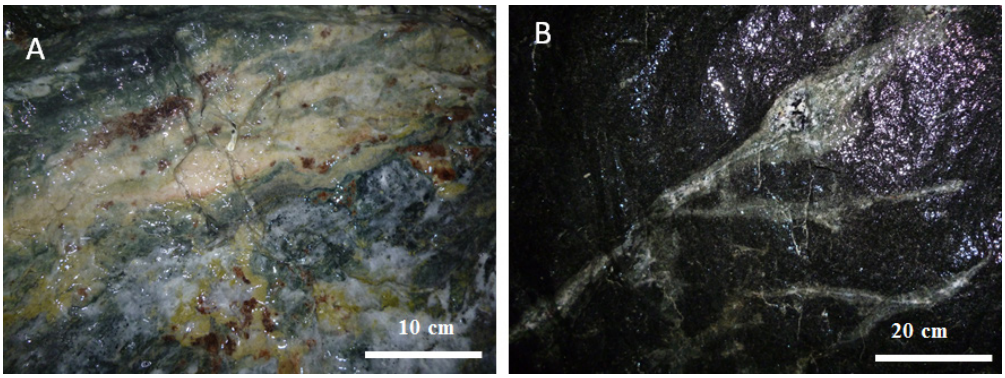


Fig. 13. **A.** Photograph of the garnet-epidote alteration. This host rock is almost completely overprinted in this section, and the gold grade of this area is very low. **B.** Photograph of the clinopyroxene alteration. It is usually darker green than the garnet-epidote alteration, and does not contain garnets. It is observed in streaks and blebs.

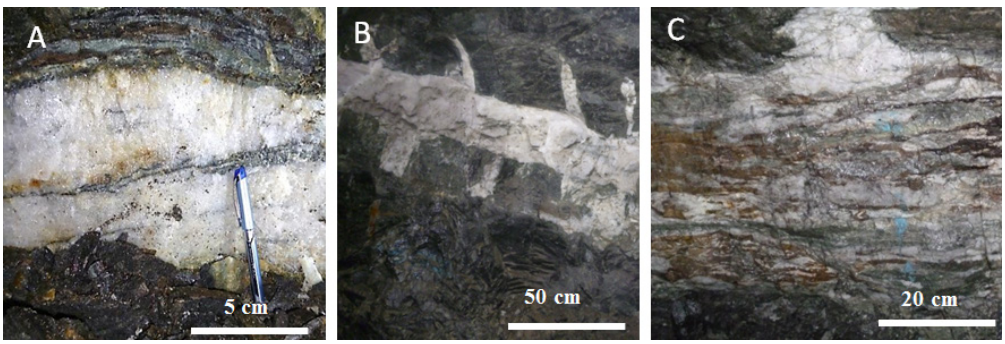


Fig. 14. **A.** Photograph of a high-grade section of the gold-bearing quartz vein. Typical mineralogy of a high-grade area includes biotite and arsenopyrite. Slivers of the host rock within the quartz vein can also be observed. **B.** Extension veins pre-date the formation of the gold bearing quartz veins and have been cross cut and slightly offset by them. **C.** Photograph of typical hematite alteration. This is observed in both the quartz vein and the host rock, but often ceases suddenly at the contact (highlighted here).

is fine and comparable with the host rock. Arsenopyrite and pyrrhotite are associated with this alteration. This alteration assemblage overprints the GE alteration (Fig. 12). Both the GE and clinpyroxene alteration have been termed by previous authors as 'calc-silicate alteration' (Kaltoft 2000, Porritt 2000, Grammatikopoulous et al. 2004).

Quartz and calcite veins

The MV can be primarily identified as a 0.25–2 m wide vein of mainly quartz (>90%) with transparent to translucent quartz grains and host rock slivers incorporated within it (Fig. 14A). This stage hosts the bulk of gold within the Nalunaq gold deposit. On the eastern face of the Nalunaq Mountain, the MV is displaced by a later fault-hosted pegmatite and is not observed again. Towards the west, the vein thins, and the gold grades become lower. The highly complex overprinting by different alteration assemblages means that it is difficult to accurately determine the presence of an alteration halo specifically related to the MV. Gold is primarily observed on the surface of slivers of host rock that have been incorporated into the MV. This pattern is not repeated at the host rock/MV boundary.

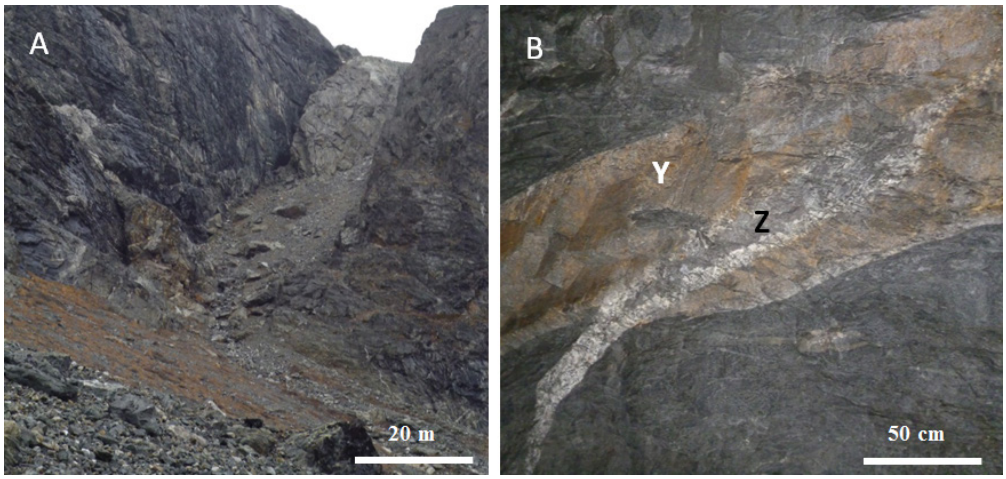


Fig. 15. **A.** The pegmatite dyke, exposed at the surface. This rock is also exposed in the main mine entrance. **B.** A biotite-rich dyke (Y) crosscut by a lens of coarse-grained aplite (Z).

The MV both cross cuts and is cross cut by a set of barren quartz-calcite veins (Fig. 14B). These veins form a network of extension veins adjacent to the MV in a cross hatched pattern parallel to the plane of MV formation. They are composed to 99–100% of calcite and quartz. Both these veins and the MV have no apparent associated alteration zone.

Hematite alteration

A final stage of alteration post-dating the formation of the MV is observed in some areas. This stage is classified by the presence of hematite and an orange-brown rust-like staining of the quartz within the MV (Fig. 14C). One of the major diagnostic features used by the geologists at the Nalunaq mine is a rusty coloured staining of the quartz veins and alteration zones. Areas with this type of alteration often correlate with high gold grades. The hematite alteration shows strong replacement textures. It is thought that this replacement is the result of infiltration of surface-derived meteoric waters causing the breakdown of sulphides. This later alteration may have caused gold remobilisation into high grade ore shoots.

GRANITIC INTRUSIONS

The area surrounding the Nalunaq gold mine is dominated by several generations of later granitic intrusions. There are several distinctive granite types, including pegmatites (Fig. 15A) and a biotite-aplite dyke (Fig. 15B). A large pegmatite, associated with the Pegmatite fault, cross-cuts the Nalunaq gold deposit, offsetting it significantly. Additional rock types include fine-grained granite dykes and quartz-feldspar intrusions. It is unlikely that the presence of the dykes has an effect on the levels of gold within Nalunaq. However, age dating of them will produce some minimum absolute ages for the formation of the gold deposit.

DISCUSSION TOPICS

- The gold deposit is generally described as orogenic (Kaltoft et al. 2000, Grammatikopoulous et al. 2004, unpublished report by Goddard 2009 to Angel Mining). This would be consistent with the gold deposits' orogenic setting, but fluid inclusion studies show that it may have a magmatic source. What is the source of the gold and hydrothermal alteration? Is there any evidence for their source in the field?

- The discoloured bands are a point of contention. They clearly predate all other alteration within the Nalunaq gold deposit, and although classified in this guide as an alteration stage, they have also been explained as either a metamorphic feature or as primary compositional banding of the host rock. However, the observation of discordant sets of veins makes the latter interpretation unlikely. What is the mineralogy of these bands? Are they a metamorphic feature?
- The hydrothermal history of the Nalunaq gold deposit is far more complex than originally thought. Has one alteration stage or a combination of stages produced a favourable environment for the precipitation of gold? Has a later stage encouraged gold remobilisation?
- There appears to be a negative correlation between the garnet-epidote alteration stage and gold deposition. What has caused this?
- What causes the rusty-coloured weathering seen in some surface samples? Why is it so pronounced? What differentiates these from the surrounding rocks?

The Gardar province

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The rock units of South Greenland can be subdivided into three major geological groups: the North Atlantic craton in the north, the Palaeoproterozoic Ketilidian orogen in the south and the geographically much more restricted magmatic bodies and contemporaneously formed lavas and sediments belonging to the Mesoproterozoic Gardar province, which intruded into the Archaean as well as into the Ketilidian rocks (Fig. 16).

These rocks formed in an extensional environment of the crust around 500 Ma after the Ketilidian orogeny and can be related to two main magmatic events around 1 280 Ma and 1 160 Ma and a contemporaneously formed alternate sequence of lava flows and sediments. Wegmann (1938) adopted the term Gardar rocks from the old Norse bishopric of Garður, where the present village of Igaliku is located today (Fig. 17). The Gardar rocks consist of essentially unmetamorphosed and undeformed alkaline intrusive rocks and successions of sediments with interbedded lavas, called the Eriksfjord Formation (EF), which are mainly exposed on the Ilimaussaq peninsula. The intrusions can principally be subdivided into dykes and dyke swarms as well as subcylindrical plutons (Upton et al. 2003).

MAGMATIC CHRONOLOGY

All Gardar intrusions as well as the extrusive EF are Mesoproterozoic in age, ranging from 1 350 to 1 160 Ma.

Within this period, two main magmatic events can be distinguished (Fig. 18): the "Older Gardar magmatism" (OGM) occurring between 1 300 and 1 250 Ma and the "Younger Gardar magmatism" (YGM) occurring between 1 180 and 1 140 Ma. The OGM comprises mainly east-striking olivine dolerite dykes, the Kûngnât, Ivigtut, Grønnedal-Ika, North Qôroq and the Motzfeldt complexes as well as some associated carbonatites and lamprophyres. This magmatic period is concentrated within the northern parts of the province and intruded into the Archean as well as the Ketilidian basement (Fig. 19). The YGM is characterised by the emplacement of two main south-west trending dyke swarms in the Nunarssuit–Isortoq and the Tugtutoq–Ilimaussaq zones, respectively. Contemporaneously, the Nunarssuit, Puklen, Tugtutoq central,

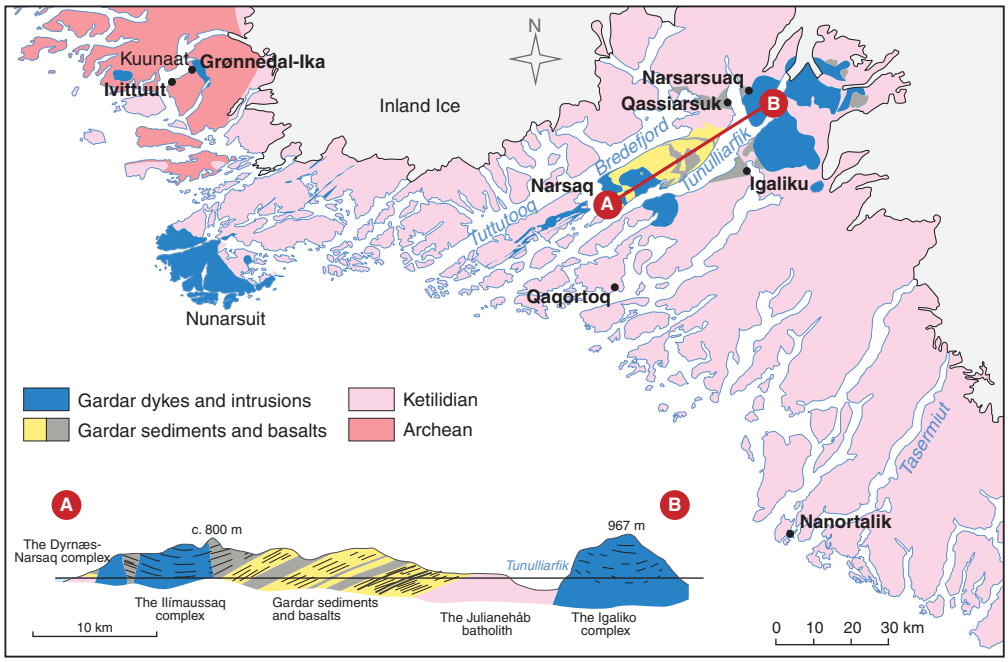


Fig. 16. Geological map of the Gardar igneous province (from Sørensen 2006).



Fig. 17. Ruins of the Norse cathedral built of red sandstone from the Eriksfjord Formation. In the middleground: Illerfissalik mountain.

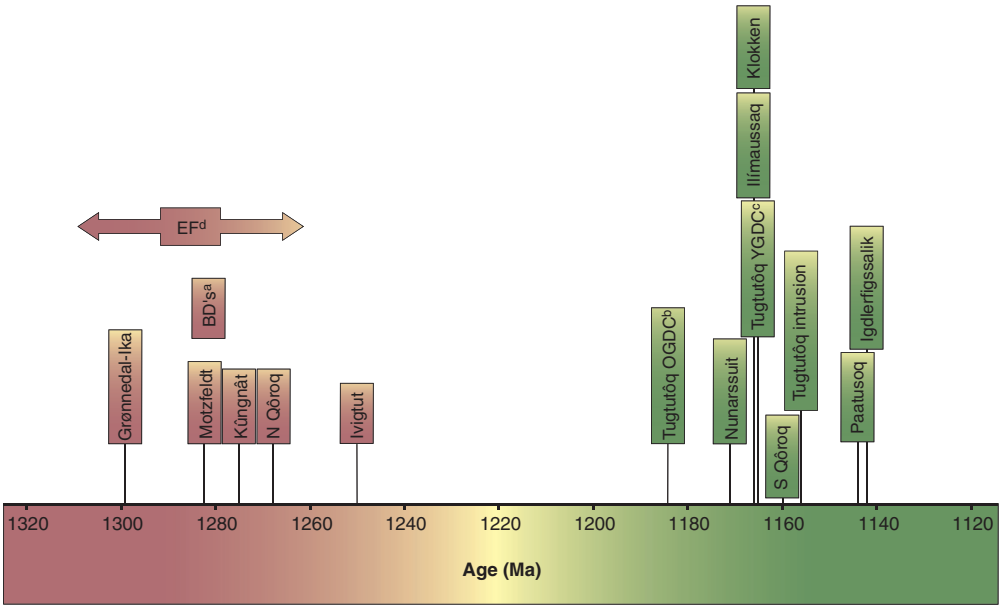


Fig. 18. Chronology of Gardar magmatic events (ages from Upton et al. 2003). Abbreviations: a – brown dykes, b – Older giant dyke complex, c – Younger giant dyke complex, d – Eriksfjord Formation.

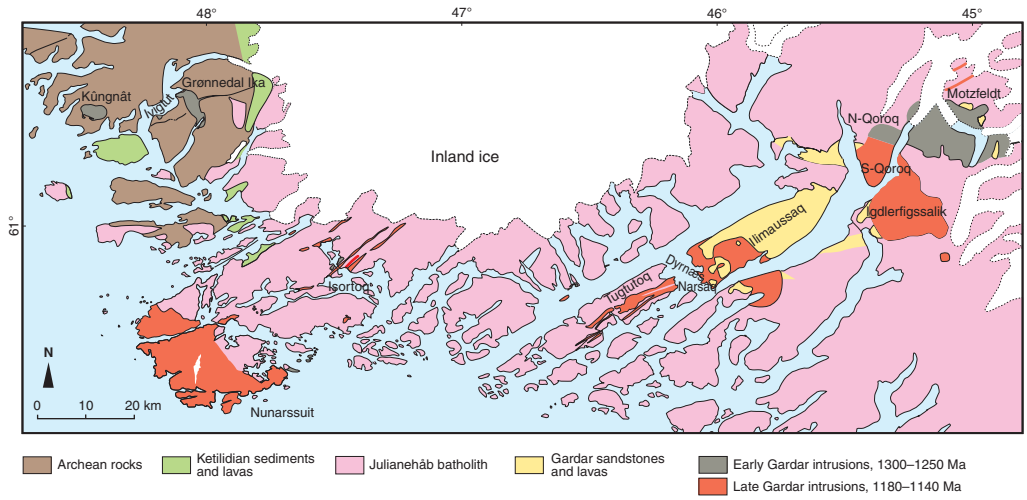


Fig. 19. Geological map of the Gardar province including the chronological classification of individual intrusions (see text for details).



Fig. 20. The Eriksfjord Formation at the south coast of Sermilik Fjord: Succession of sandstones and interbedded laves.

Ilímaussaq, Dyrnæs-Narssaq, South Qôroq, Iglerfigssalik, Klokken and Paatusoq plutons were formed. These later intrusions are concentrated in the southern and eastern parts of the province and solely intruded into Ketilidian basement rocks (Fig. 19).

Supracrustal rocks of the Eriksfjord Formation

The Eriksfjord Formation (EF) represents a c. 3 500 m thick, alternate sequence of supracrustal rocks consisting of lavas, sediments and pyroclastic rocks lying unconformably on the Ketilidian granite (Fig. 20).

The name Eriksfjord Formation was first proposed by Poulsen (1964) referring to the Tunugdliarfik Fjord which was formerly named Eriksfjord, related to Erik the Red, by the early Norse settlers. The type locality for this sequence is located on the Ilimaussaq peninsula (Fig. 21, no. 1) where it has been subdivided into six stratigraphic members: three sedimentary members (Mâjût, Naujarssuit and Nunasarnaq) interbedded with three volcanic members (Mussartût, Ulukasik and Ilímaussaq, Poulsen 1964). Additional localities, where parts of the sequence could be observed, are between Tunugdliarfik and Kangerdluarssuk Fjord east of the Ilímaussaq intrusion (2), in the area around Igaliko (3), in the Qassiarsuk reagion (4), in the vicinity of Narsarsuaq (5) and in small outliers around the Motzfeldt intrusion (6, Fig. 21).

Evidence in the form of xenoliths in some of the Gardar intrusions and clasts from glacier moraines demonstrates that the EF covered a much more widespread area within the Gardar province than indicated by the observed occurrences in these days. Thickening and an increase in number of lava flows within this formation to the north and east suggests that the former eruption site could be located between the Nordre Sermilik and the eastern Tunulliarfik Fjord (Larsen

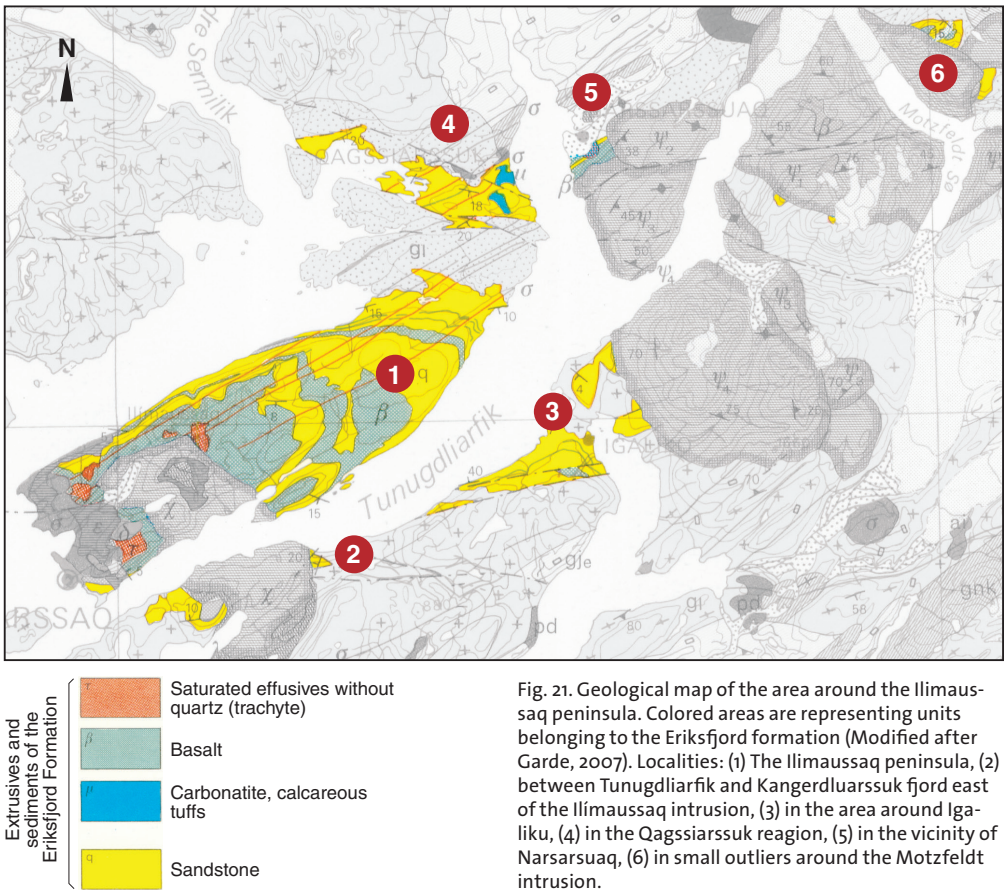


Fig. 21. Geological map of the area around the Ilimaussaq peninsula. Colored areas are representing units belonging to the Eriksfjord formation (Modified after Garde, 2007). Localities: (1) The Ilimaussaq peninsula, (2) between Tunugdliarfik and Kangerdluarssuk fjord east of the Ilímaussaq intrusion, (3) in the area around Igaliku, (4) in the Qagssiarssuk reagion, (5) in the vicinity of Narsarsuaq, (6) in small outliers around the Motzfeldt intrusion.

1977). Isotope ages between 1.2 and 1.17 Ga for the Mussartut and Ulukassik members of the formation are in disagreement with palaeomagnetic data indicating an age of 1.35–1.31 Ga for the complete formation and the exact age of the EF is yet unresolved (Upton et al. 2003).

Sedimentary rocks

The major part of the sedimentary layers consists of rather uniform medium- to fine-grained sandstones. These are mostly white or grey quartzites although red and orange quartzites also can be observed in several places (Emeleus & Upton 1976). Bleaching of the sandstones is a commonly observed phenomenon in the vicinity of dykes, along joints, fissures and bedding planes as for example in the section exposed at the cliffs near Sillisit (Fig. 22).

The sedimentary rocks are described as unfossiliferous. Common structures which can be discovered are cross-bedding and ripple-marks, sand dunes, preserved sun-cracks and rain pits as well as wind-blow fillings on the surface of lava flows. According to these structures, the sediments are interpreted to be formed in a continental environment as fluviatile, lacustrine or aeolian deposits (Emeleus & Upton 1976). The sediments mainly consist of quartz, feldspar and granitic fragments and lack basaltic fragments from the contemporaneous lavas. Therefore the surrounding granitic highland has been inferred as a source area for the sediments.

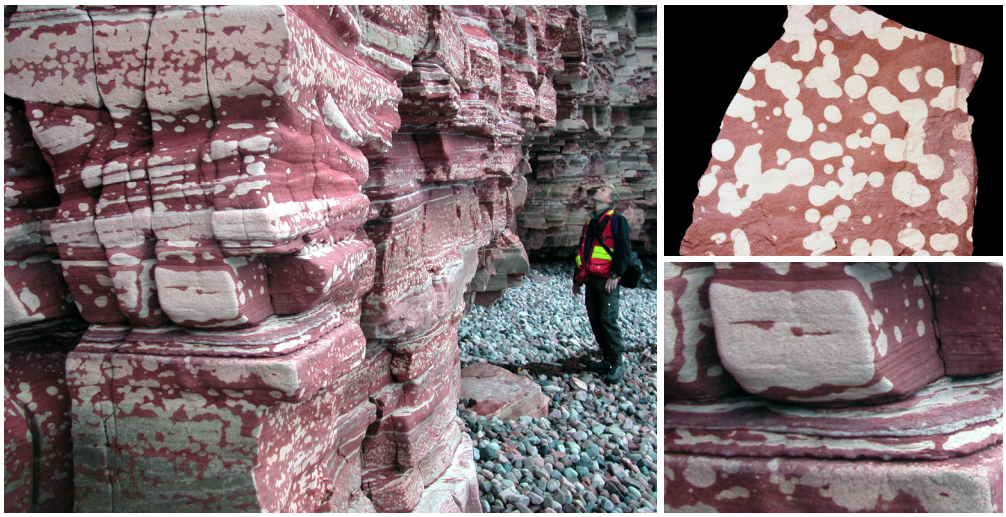


Fig. 22. Red-coloured sandstone with bleached areas along joints, fissures and bedding planes exposed in the coastal cliff at Sitdlisit. Red coloring due to hematite content. Bleaching due to circulating water.

Lavas

The lavas are commonly of basaltic composition although mochiquites, trachytes and carbonatites are also described (Stewart 1970), the latter solely in the area around Qassiarsuk where they can be correlated with local unusual alkaline ultrabasic diatremes.

The majority of lava flows are described to be erupted in a lowland, sub-aerial environment although some pillow lavas can be observed in the lower parts of the sequence indicating occasional sub-aqueous conditions. Most of the lavas are olivine basalts with plagioclase phenocrysts. The main minerals are olivine (often replaced by iddingsite), sericitised plagioclase, pink augite and opaque oxides (Emeleus & Upton 1976).

Pyroclastic flows

Layers of bedded ashes and agglomerates are well known from several regions within the Eriksfjord Formation but probably best known in the area around Qassiarsuk (Fig. 21), where the former volcanism was dominated by carbonate-rich magmas (Stewart 1970). Associated intrusive rocks are exposed in the form of carbonatites or CO_2-rich ultrabasic diatremes. The approximately 370 m thick volcanic succession is composed of thin carbonated lavas, overlain by bedded tuffs and agglomerates (Emeleus & Upton 1976).

Dykes

A large number of dykes of various compositions intruded into the Archean and Ketilidian basement during Gardar time. The compositions of these dykes vary from olivine gabbros and dolerites to nepheline syenite, syenite and alkali granite (Upton et al. 2003). Lamprophyric and carbonatitic dykes are less common but also occur, mainly in the area towards the Archean craton. The earliest generation of dykes belongs to a regional swarm in the area around Ivittuut, striking west or even north-west. The latter can be tracked in south-easterly direction more than 200 km parallel to the coast. These dykes are typical olivine dolerites known as "brown dykes", ascribed to their brown weathering colour. The term has been abbreviated as BD in the literature with different suffixes indicating relative ages of the dyke swarms (Emeleus & Upton 1976). During the late Gardar period, two major dyke

swarms were emplaced into the Ketilidian basement in the Nunarssuit–Isortoq and the Tugtutoq–Ilimaussaq zones along a south-westerly trend (Fig. 19), tracing an intercontinental rift geometry. The Nunarssuit–Isortoq swarm contains several generations of basic (gabbro and dolerites) dykes together with microsyenites and culminates in four major, up to 500 m thick, giant dykes which are characterised by granitic or syenitic centers enclosed by syenogabbroic margins (Upton et al. 2003). The Tugtutoq–Ilimaussaq zone, which is parallel to the Nunarssuit–Isotoq dyke swarm, is dominated by two major giant dykes, the Older giant dyke complex (OGDC) and the Younger giant dyke complex (YGDC) with the fullest development of magmatism in the latter. Although both systems were formed within a comparatively short interval and in the same geological setting, their internal petrology is rather different. Whereas the OGDC is characterised by separated marginal gabbroic to ferro-syenogabbroic, up to 100 m wide zones enclosing an axial zone of salic rocks (augite syenite to peralkaline sodalite foyaite), the YGDC is characterised by massive gabbro with only localised pods of more fractionated material (ferro-syenogabbroic, Upton et al. 2003, Upton in press).

Plutons

Throughout the Gardar magmatic activity, 14 major alkaline igneous complexes with various sizes intruded within and adjacent to the Gardar rift. With a few hundred metres up to around 50 km in diameter, Ivigtut being the smallest and Nunarssuit being the largest intrusion of the province, respectively. The central parts of the intrusions are commonly dominated by alkaline and peralkaline rocks, with syenites and nepheline syenites as the most abundant rock types. However, alkali granites, gabbros and syenogabbros can also be present (Upton & Emeleus 1987, Upton et al. 2003). With the exceptions of the Ilímaussaq and the Dyrnæs-Narssaq intrusions, which are dominated by both SiO_2 over- and undersaturated rocks, the intrusions in the south of the province are characteristically SiO_2 oversaturated whereas the intrusions in the north are mostly SiO_2 undersaturated (Derry 2012). Layered cumulates, coarse grain sizes and strong in situ crystal fractionation are typically observed in most of the Gardar intrusions and have been related to very low viscosities of the parental magmas, probably caused by a high content of fluorine in these melts (Upton 1996, Upton et al. 2003). In the following, the main features of the individual plutons are described in more detail and the individual ages are given in parenthesis (from Upton et al. 2003).

Grønnedal-Ika (1.299 Ga)

The heavily faulted Grønnedal-Ika intrusion originally measured 6.0 × 3.5 km and consists of a nepheline syenite dominated centre, which was then partly replaced by a central plug of carbonatite and breccia. Several doleritic dykes crosscut the intrusion. Layering is a common feature and is made of cumulates, formed by gravity settling of alkali feldspar, nepheline, aegerine-augite and apatite (Emeleus 1964, Emeleus & Upton 1976).

Kûngnât (1.275 Ga)

Composed of highly weathering resistant rocks, the Kûngnât intrusion forms a prominent elevation in the western coastal regions of the Gardar province. It is a comparably small complex (5.0 × 2.5 km) consisting of two syenite stocks which were later intruded by a mafic troctolitic to syenogabbroic ring dyke. These three intrusions were emplaced successively with progressively more primitive compositions. The syenitic stocks show magmatic layering. Gravitational differentiation has taken place by the settling of alkali feldspar, olivine, clinopyroxene and Fe-Ti oxides, leading to the evolution of peralkaline granitic residua (Upton et al. in press).

Ivigtut (1.250 Ga)

In terms of public, economic and strategic interests, although the smallest, the Ivigtut intru-

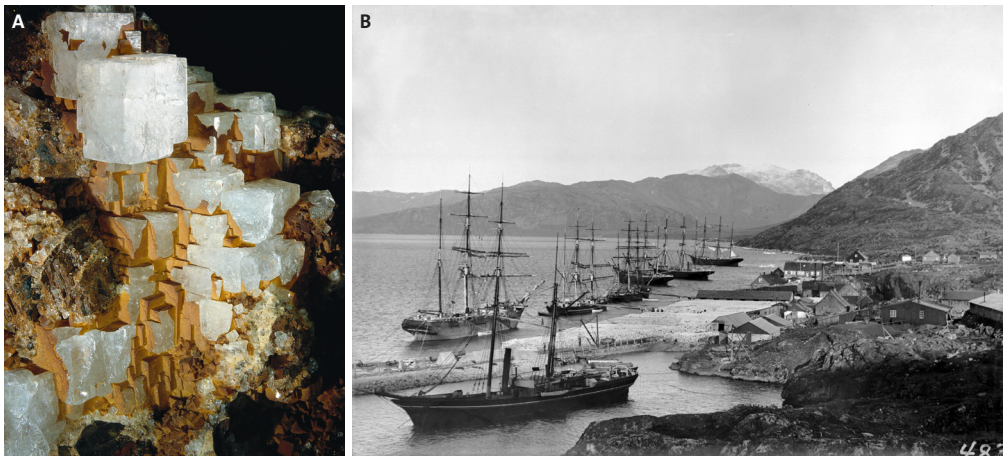


Fig. 23. **A.** Cryolite crystals from the Kryolit mine. **B.** Historic photograph of the Kryolit mine.

sion is probably the most prominent within the Gardar province. The world-wide unique occurrence of cryolite (Fig. 23A) in that complex, discovered in 1799, gave rise to extensive mining which started in 1859 (Fig. 23B). The use of cryolite in the aluminium industry increased the importance of this deposit and it became a strategic area for the American Army during the Second World War. The Ivigtut intrusion is one of the most evolved complexes in the Gardar province and consists of a central peralkaline granitic stock, roughly around 300 m in diameter, hosting the cryolite deposit at the top. This unit is surrounded by a thin intrusion breccia. A second associated cylindrical breccia is located in close vicinity to the main intrusive body (Goodenough et al. 2000). Today, the cryolite deposit is mined out completely and the former open pit is filled with water.

Nunarssuit (1.171 Ga)

With an outcrop area of 45 × 25 km, the Nunarssuit intrusion is one of the largest in the Gardar province. It consists mainly of syenitic rocks which can be internally subdivided into five main types representing a regular differentiation sequence. In parts, these syenites show spectacular layering that can be seen in the south-western coastal regions of the complex. In the south-east, the syenite develops a suite of late-stage peralkaline granites which geochemically show the continuous trend, already observed within the syenitic rocks (Emeleus & Upton 1976).

Puklen (1.171 Ga)

The small Puklen intrusion is about 4 × 2 km in size and closely associated with the much larger Nunarssuit intrusion. It was formed by two magma pulses, the first producing a slightly SiO_2 oversaturated augite syenite followed by a coarse-grained, peralkaline granite which grades locally into fine-grained, leucocratic microgranite (Marks et al. 2003, 2004a, Emeleus & Upton 1976).

Klokken (1.166 Ga)

The Klokken intrusion in the south-east of the big Igaliko intrusive complex consists of a marginal syenogabbroic unit which encloses a spectacular central series of layered larvikites and quartz syenites. Locally, this layered series is cut by small sheets of microsyenites and quartz-microsyenites (Upton in press).

Central Tugtutôq complex (1.156 Ga)

With comparable size to Puklen, the Central Tugtutôq complex intruded the main Tug-

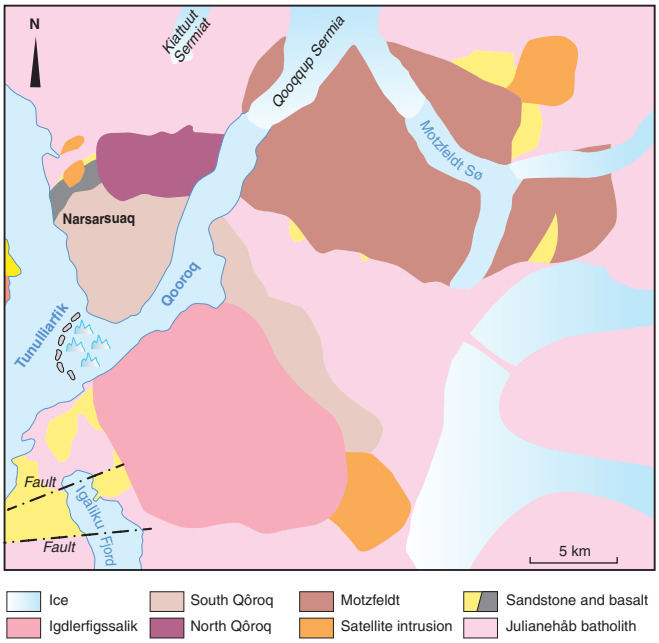


Fig. 24. Sketch map of the four centers of the Igaliko complex: Motzfeldt, North Qôroq, South Qôroq and Igdlerfigssalik.

tutôq–Ilímaussaq dyke swarm and cuts the Older and Younger giant dyke complexes in the central region of the Tugtutoq island. It is composed of syenites, quarz syenites and peralkaline granites (Upton 1962, 1964).

Paatusoq (1.144 Ga)

First discovered in the 1990's within the Paatusoq Fjord on the east coast of South Greenland, the Paatusoq intrusion represents the youngest described for the Gardar magmatic period. Although mostly covered by glaciers, the visible outcrops lead to the assumption that it is one of the biggest plutons within the Gardar province. The intrusion is at least 2 000 m thick although neither the roof nor the floor facies are exposed and it consists of megacrystic syenite (Grocott et al. 1999). The locality of the intrusion is far off a hypothetical prolongation of the main Gardar rift zone and its relation to this magmatism is still under debate.

The Igaliko complex, as well as the Dyrnæs-Narsaq and the Ilímaussaq intrusion, which will be visited during the excursion, are described in more detail in the next chapter.

DETAILED GEOLOGY OF CHOSEN LOCALITIES

Igaliko complex

Beside Nunarssuit and probably Paatusoq, the Igaliko complex is the largest within the Gardar complex and consists of four main and several smaller satellite intrusive bodies (Fig. 24, Emeleus & Upton 1976).

The Igaliko complex shapes the landscape to the east of Narsarsuaq and Igaliku. The mineralogy and texture of the individual intrusions vary significantly and each of the four main bodies is described in order of decreasing age in the following.

The Motzfeldt intrusive body, approximately 20 × 15 km in size, is located in the north-east of the Igaliko complex and offers an excellent three dimentional exposure in steep glacial valleys (McCreath et al. 2012). It comprises mainly nepheline syenite in which a number of fragments, belonging to the Eriksfjord Formation,

are embedded (Schoenenberger 2008). These supracrustal series of sediments and lavas are interpreted to build up the former cover of the intrusion and could explain the relatively flat landscape of the Motzfeldt roof zone. Based on cross-cutting relationships, six different intrusive units, SM1–SM6 were distinguished by Emeleus & Harry (1970). This classification was revised by Bradshaw (1985, 1988) and Tukiainen et al. (1984) who divided the central part of the Motzfeldt intrusion into the Geologfjeld (GF), Motzfeldt Sø (MFS) and Flinks Dal Formation (FDF), each of which has several subdivisions (Fig. 25).

The magmatic activity in that complex is interpreted to start in the regions to the north and east. During that period, the Geologfjeld Formation, which is dominated by nepheline syenite and the Motzfeldt Sø Formation, which consists of nepheline syenite, altered nepheline syenite and a marginal arfedsonite syenite, were emplaced. During a younger magmatic event,

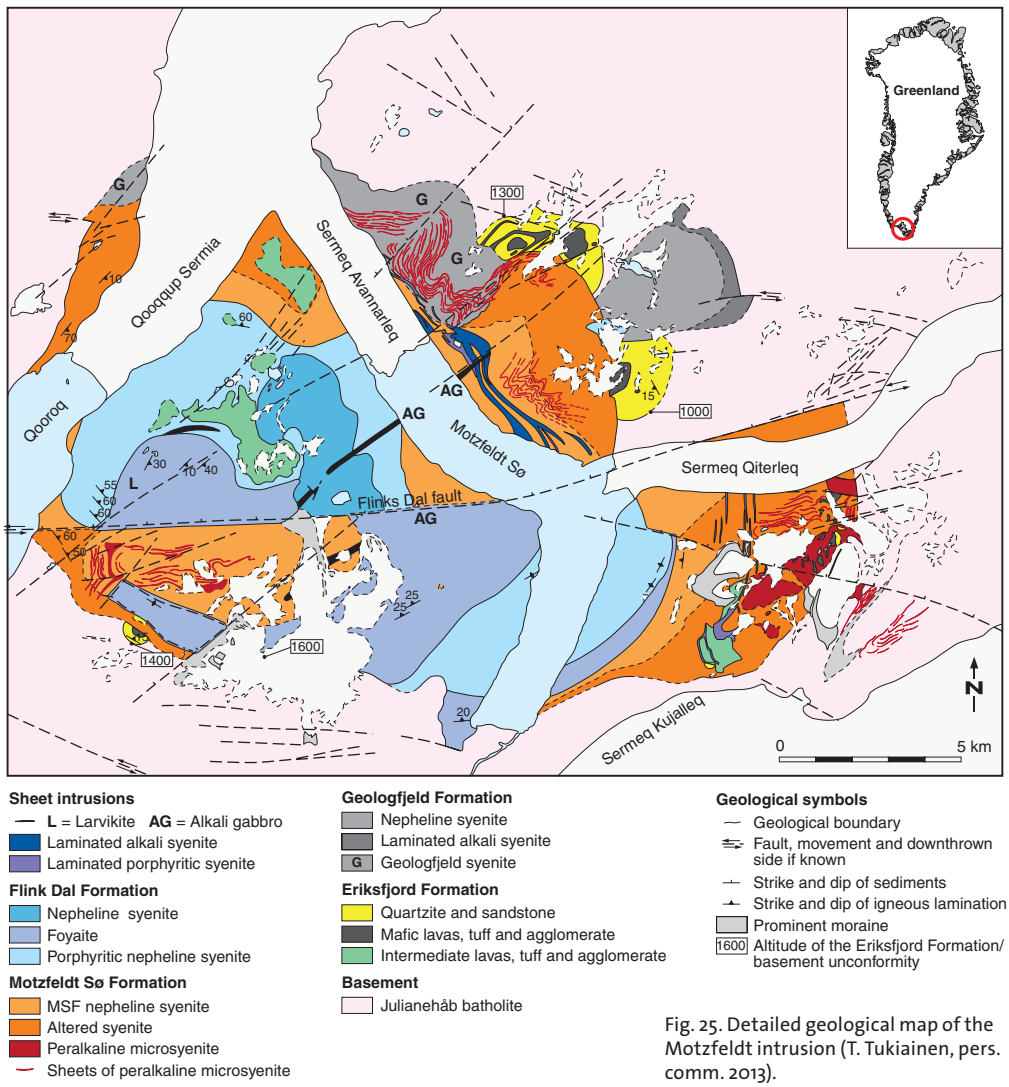


Fig. 25. Detailed geological map of the Motzfeldt intrusion (T. Tukiainen, pers. comm. 2013).

the older central syenites were cored out and replaced by the Flinks Dal Formation, which consists of nepheline syenite, porphyric syenite and foyaite. This formation also builds up the western and southern parts of the complex. The youngest activity is dominated by the intrusion of sub-horizontal peralkaline sheets and syenogabbroic as well as larvikitic giant dykes (McCreath 2012, Fig. 25). The whole complex is cross-cut by several faults, the most important being the east-striking Flinks Dal fault which offsets the southern parts of the intrusion by c. 6 km (Fig. 25).

The North Qôroq intrusive body is located to the north-west of the Igaliko complex. Today, it comprises an area of about 7 × 4 km but it was originally much larger (Emeleus & Upton 1976). Most of the southern parts of the intrusion are cut and replaced by younger syenites belonging to the South Qôroq complex. The North Qôroq centre is devided into six major syenite units (Emeleus & Harry 1970). Although they are thought to be synchronous, they comprise significant differences in composition reaching from marginally undersaturated augite syenite, through more highly evolved nepheline syenites to, locally, peralkaline lujavrites (Coulson 1997, Coulson et al. 2003). This variation has been interpreted to be caused by in situ crystal fractionation (Chambers 1976).

The South Qôroq complex (Fig. 26) is located in the west of the Igaliko complex and is around 10 × 26 km in size (Emeleus & Upton 1976). Most of the southern parts are cored out and replaced by the rocks of the later Igdlerfigssalik intrusion. The South Qôroq complex is built up by several concentric stocks and ring intrusions. The first three units were emplaced in rapid succession from a common foyaitic magma source. Later, a probably former ring-dyke of au-



Fig. 26. View on the South Qôroq intrusive complex north of Gieseckes Dal. The mountain summit (Qooqqup Qaqqai, 1510 m) is composed of Julianehåb granite. The mountain wall consist of nepheline syenite of the South Qôroq intrusion. A black trachyte dyke can be seen beneath the summit (from Sørensen 2006).

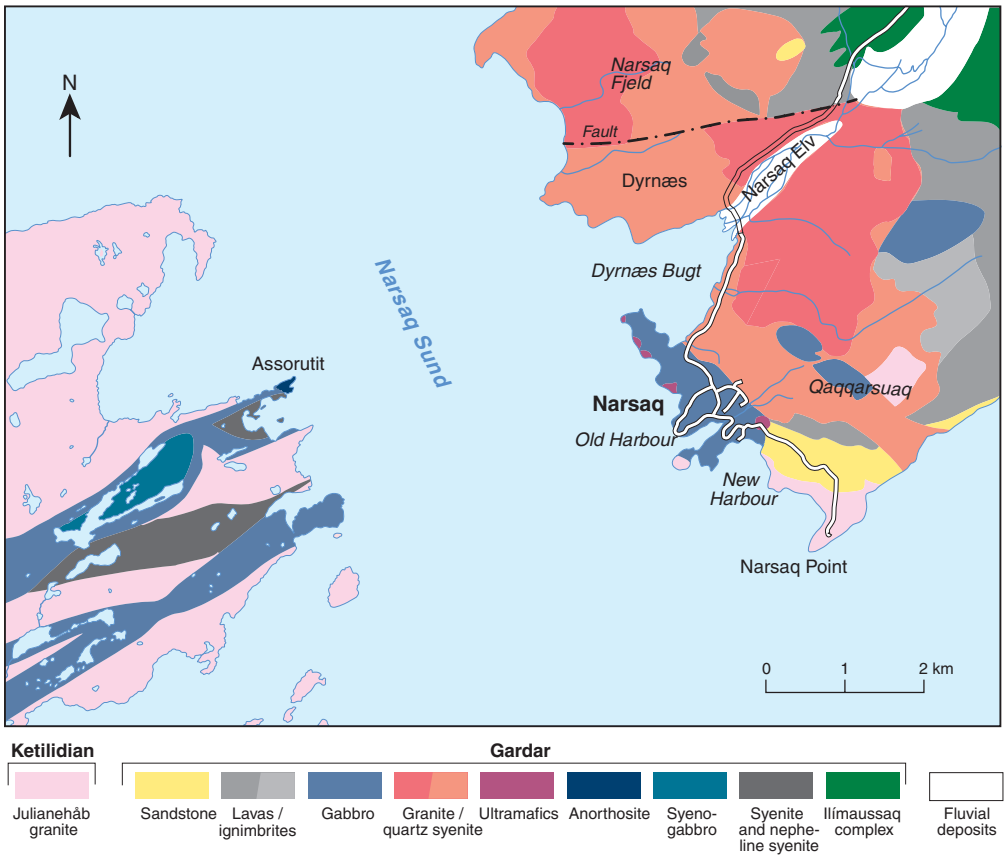


Fig. 27. Geological map of the Narsaq area and of the north-east coast of Tugtutoq (from Sørensen 2006).

gite syenitic composition intruded the foyaites in at least two emplacement steps. Minor satellite intrusions of nepheline syenite in the north-west of the complex predate the main units described above but are most likely directly related bodies (Stephenson 1976).

The Igdlerfigssalik igneous complex is located in the southern parts of the Igaliko complex. It is one of the younger intrusions within the Gardar magmatic period and approximately 16 × 11 km in size (Emeleus & Upton 1976). Emeleus & Harry (1970) subdivided the intrusion into two main groups, the earlier one dominated by the emplacement of augite syenites with only small proportions of nepheline syenite, and the later one dominated by nepheline syenites. In the latter group, local layering can be identified within the syenites. Both groups are separated in time by the intrusion of a regional dyke swarm.

Dyrnæs-Narssaq

The Dyrnæs-Narssaq intrusion is located on the west end of the Ilimaussaq peninsula and consists of syenites, augite syenites as well as quartz syenites. To the east and north, several sheets of alkali granite intruded these units (Fig. 27).

To the south-west of the Dyrnæs-Narssaq intrusion on the south-western tip of the Ilimaussaq peninsula, a suite of ultramafic rocks intruded the gabbro which is related to the YGDC (Fig. 27). These rocks strongly contrast most

other rocks of the Gardar province. According to the classification of Rock (1991), they can be defined as aillikites, a variety of ultramafic lamprophyres. Upton et al. (2006) suggested that they may be related to low degree melting of mantle metasomatites.

The Ilímaussaq complex

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INTRODUCTION TO THE GEOLOGY

The Ilímaussaq complex is one of the youngest intrusions of the Gardar igneous province and contains some of the chemically most evolved rock types in the world. The complex consists of a series of nepheline syenites, which intruded the Ketilidian basement between 1 130 and 1 160 Ma (Blaxland et al. 1976). It is the type locality for agpaitic rocks, defined by their peralkaline character (molar (Na+K)/Al >1) and the presence of complex Na-Zr silicates, such as eudialyte and rinkite. The complex also forms a classic example to study magmatic layering, which is exceptionally well developed in most parts of the intrusion (Sørensen & Larsen 1987). The intrusion has an oval shape and measures 17 by 8 km (Fig. 28). The term agpaitic was introduced by Ussing (2012), who first studied and mapped the complex in detail, after Appat (formerly spelt Agpat) on the south coast of Tunulliarfik (Fig. 28).

The extreme enrichment in alkalis (especially Na), volatiles (especially F and Cl) and generally incompatible elements (e.g. Li, Be, Zr, Nb, Ta, REE, Y, U and Th) and the complementary depletion in otherwise compatible elements (e.g. Mg, Ni and Cr) led to very unusual mineral assemblages in the various rock types. As a consequence, the intrusion has received great interest from geologists and mineral collectors in the past two centuries. Over 225 minerals have been identified from Ilímaussaq, thirty of which were first discovered there (e.g. sodalite, eudialyte and arfvedsonite) and twelve which are unique to the complex (e.g. naujakasite and sørensenite, Table 1). Furthermore, many of the rock types have economically relevant concentrations of critical elements, like Zn, Zr, REE, U, Nb and Ta. Recent developments on the REE market have led to active exploration in the complex (the Kvanefjeld deposit is owned by Greenland Minerals and Energy Ltd and the Kringlerne deposit by Tanbreez A/S) and mining activities are likely to begin in the near future (see Metallogeny of the Gardar province).

The main process leading to the extreme composition of the magma is thought to have occurred through extensive fractional crystallisation of alkali basaltic and nephelinitic magmas during their long ascent through the lithosphere (Larsen & Sørensen 1987, Marks et al. 2011). Estimates on the depth of emplacement suggest shallow emplacement, only 3 to 5 km below the contemporary surface. Despite a relatively thin lid on the magma chamber in relation to its width (8–17 km), the system seems to have remained closed, as suggested by the large amounts of volatiles and alkalis retained in the magma during the final stages of crystallisation (Larsen & Sørensen 1987) and Nd-, O- and H-isotope compositions (Marks et al. 2004b).

STRUCTURE OF THE INTRUSION

Three intrusive phases are distinguished in the complex (Sørensen 1968, Nielsen & Steenfelt 1978). The first stage consists of augite syenite, which is exposed as a discontinuous marginal shell around the complex and in the roof in the northern part of the complex (Figs. 28 & 29). It was chilled against the country rocks and crystallised successively inwards from the walls.

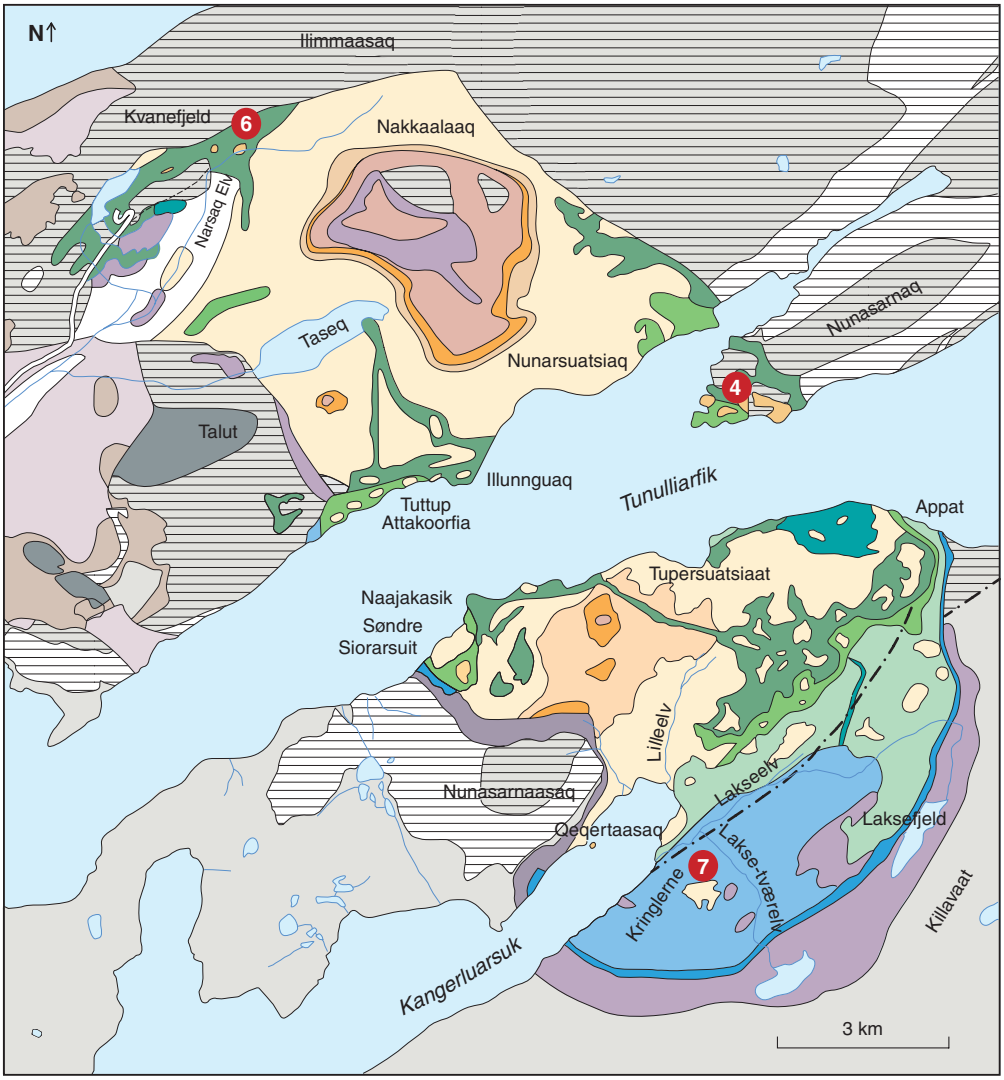


Fig. 28. Geological map of the Ilímaussaq complex and surroundings (modified after Ferguson 1964 by Upton & Garde 2013). Excursion localities 4, 6 and 7 indicated at Nunasarnaq, Kvanefjeld and Kringlerne, respectively.

Table 1. List of minerals likely to be found during a field excursion to the complex. Minerals printed in bold are type localities from Ilimaussaq, minerals listed in bold and italics are unique to Ilimaussaq. An asterisk (*) indicates minerals that are typical in the most evolved hyper-agpaitic lujavrites (Sørensen & Larsen 2001). Note that the mineral occurrences are not necessarily restricted to the rock types.

Mineral	Pulaskite/ Foyaite	Sodalite Foyaite	Naujaite	Lujavrite	Kakortokite	Chemical Formula	Colour in hand specimen
Aegirine	✓	✓		✓	✓	$NaFeSi_2O_6$	Green to black
Aenigmatite	✓	✓	✓		✓	$(Na,Ca)_4(Fe,Ti,Mg)_{12}Si_{12}O_{40}$	Dark red to black
Albite				✓	✓	$NaAlSi_3O_8$	White
Analcime				✓*	✓	$NaAlSi_2O_6{\cdot}H_2O$	Colourless to white
Arfvedsonite			✓	✓	✓	$Na_3(Fe,Mg)_4FeSi_8O_{22}(OH)_2$	Bluish black
Augite	✓	✓				$(Ca,Na)(Mg,Fe,Al,Ti)(Si,Al)_2O_6$	Black
Chkalovite				✓*		$Na_2BeSi_2O_6$	White
Eudialyte		✓	✓	✓	✓	$Na_{15}Ca_6(Fe,Mn,Na)_3(Zr,Ti)_3(Si,Nb)Si_{25}O_{72}(O,OH,H_2O)_3(Cl,OH)_2$	Pink to red
Fluorite	✓	✓	✓		✓	CaF_2	Colourless, purple
Microcline				✓	✓	$KAlSi_3O_8$	White
Naujakasite				✓*		$(Na,K)_6(Fe,Mn,Ca)(Al,Fe)_4Si_8O_{26}$	Grey, silvery white
Nepheline	✓	✓	✓	✓	✓	$(Na,K)AlSiO_4$	White to grey
Neptunite				✓		$KNa_2Li(Fe,Mg,Mn)_2Ti_2Si_8O_{24}$	Dark red, near black
Polylithionite			✓	✓		$KLi_2AlSi_4O_{10}(OH)_2$	White to light green
Pyrochlore				✓		$(Na,Ca)_2Nb_2O_6(OH,F)$	Yellow
Rinkite			✓	✓	✓	$(Na,Ca)_3(Ca,Ce)_4(Ti,Nb)(Si_2O7)_2(O,F)_4$	Yellow-brown
Sodalite		✓	✓	✓	✓	$Na_4Al_3Si_3O_{12}Cl$	Green, grey, blue, yellow
Sørensenite				✓		$Na_4Be_2Sn(Si_3O_9)_2\,H_2O$	Silky white to pink
Steenstrupine				✓*		$Na_{14}REE_6(Mn,Fe)_3(Zr,Th)(OH)_2(PO_4)_7Si_{12}O_{36}\,3H_2O$	Brown to black
Tugtupite				✓*		$Na_4BeAlSi_4O_{12}Cl$	White to carmine red
Ussingite				✓*		$NaAlSi_3O_8NaOH$	White to violet
Villiaumite			✓	✓		NaF	Deep red

The major minerals are ternary feldspar, augite, fayalite, titanomagnetite and apatite, and the rock has a relatively coarse-grained texture. The second phase consists of a single layer of alkali granite and quartz syenites, which are exposed in the roof and occur as xenoliths in rocks of the third intrusive phase. These alkali acid rocks carry alkali feldspar, aegirine augite and quartz as typical minerals. The third intrusive phase is volumetrically dominant and consists of a series of conformably layered agpaitic nepheline syenites (Fig. 28).

THE AGPAITIC SUITE

The agpaitic sequence is made up of roof cumulates, layered floor cumulates and a 'sandwich' horizon containing the most evolved rock types, which intruded and brecciated the earlier crystallised roof cumulates. The roof series crystallised from the top downwards, successively forming pulaskite, foyaite, sodalite foyaite and naujaite. Upon crystallisation, the initially phonolitic magma was progressively enriched in alkalis and volatiles. The various units show a gradual change in mineral assemblage. Sodalite appears first as an interstitial phase in the foyaite stage and becomes a common phase in the sodalite foyaite. Eudialyte also occurs interstitially in the foyaite. The appearance of eudialyte marks the transition from peralkaline to agpaitic conditions. In the naujaite, sodalite is a major component of the liquidus assemblage, where they constitute 40–50% of the rock volume.

The lowermost exposed units of the intrusion consist of a thick series of rhythmically layered kakortokites (Figs. 29–30). The kakortokites are exposed in the southern part of the intrusion in the Kringlerne area (Fig. 28, Locality 7). The main minerals are alkali feldspar, nepheline,

eudialyte and arfvedsonite. The exposed thickness is approximately 280 m. The kakortokites

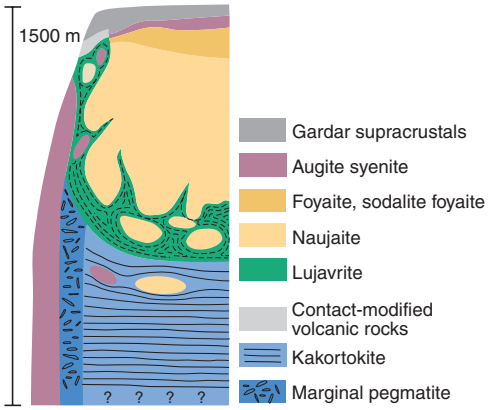


Fig. 29. Schematic cross section through the Ilímaussaq intrusion showing the stratigraphic positions of the various units (modified after Andersen et al. 1981).

are overlain by an intermediate sequence of lujavrites formed during the final stages of crystallisation. These lujavrites are meso- to melanocratic agpaitic nepheline syenites, rich in either aegirine (lower lujavrites) or arfvedsonite (upper lujavrites). The lujavrite magma was particularly enriched in volatiles and alkalis, leading to the most extreme mineral assemblages with respect to the other Ilimaussaq rock types (Table 1).

During the excursion we will mainly look at the three main agpaitic rock types, which will be described in further detail below.

THE NAUJAITE

Naujaite is a sodalite nepheline syenite and is the most pervasive rock type in the northern part of the complex, with a vertical exposure of about 400 m. It is coarse-grained and relatively



Fig. 30. Layered kakortokites at the southern part of the complex, as seen from the Kangerluarsuk Fjord, in westerly direction. The brownish unit in the center, behind the layered kakorktokites, is part of the marginal augite syenite. The high ranges in the background are the Killavaat (Redekammen), consisting of Julianehåb granite (Photo: K. Secher).

light-coloured in outcrop and displays a vivid range of green, blue, red, white and black colours in hand specimen (Fig. 31). The sodalite generally occurs as dodecahedral or hexagonal prisms, ranging up to 1 cm in size and make up almost 50 vol.% of the naujaite. The other minerals, mainly white alkali feldspar, nepheline, black arfvedsonite, green aegirine and red eudialyte, may grow over 10 cm in size. Sodalite was the first mineral to crystallise and due to its low density relative to the magma it floated upward in the magma chamber. The naujaite is thus described as a floatation cumulate, where large quantities of sodalite collected at the roof of the magma chamber, which were subsequently overgrown by minerals crystallising from the interstitial melt (Ussing 1912).

Additional minerals you may find in the naujaite are fluorite (NaF), villiaumite (CaF), rinkite, polylithionite and pectolite (Table 1, Fig. 31). The naujaite exhibits macroscopic layering, visible as horizontal layers of pegmatitic (coarse-grained) naujaite, alternating with metre-thick 'normal' naujaite. In some places, pegmatites occur as lenticular bodies containing enriched zones of minerals like eudialyte and polylithionite, e.g. at the Qeqertaassaq island on the north coast of the Kangerluarssuk Fjord (Fig. 28).

A good place to observe the texture of the naujaite and the thin pegmatitic layering is along the southern coastline of the Tunulliarfik Fjord, west of Tupersuatsiaat bay (Fig. 28). The pegmatite layers are c. 0.5 m thick and consist of the same minerals as the naujaite, but the sodalite appears as large prismatic crystals (>20 cm) rather than as small rounded crystals. The sodalite grows downward from the upper boundary of the pegmatite layers, perpendicular to the contact with the overlying naujaite.



Fig. 31. **A.** Red villiaumite (c. 4 cm). **B.** Perfect crystal of steenstrupine in albite (c. 1×0.5 cm). **C.** Naujaite sample showing its typical coarse texture with poikilitic grey-blue sodalite enclosed in black arfvedsonite, alkali feldspar, nepheline and red eudialyte. Size of sample c. 4×12 cm. **D.** Pink tugtupite in white chkalovite and albite from late stage albite vein enriched in Be (8×5 cm). **E.** Perfect crystal of eudialyte surrounded by sodalite (c.1×0.8 cm). Photographs: Ole Johnsen.

The Lujavrite

The lujavrites are the youngest and most evolved rocks in the Ilímaussaq intrusion and are emplaced between the kakortokites and the naujaites. Mineralogically speaking, lujavrites are very similar to kakortokites, but they have a different texture and a higher modal abundance of aegirine and arfvedsonite. Lujavrites are meso- to melanocratic, fine-grained and laminated (Fig. 32), with a strong horizontal alignment of the prismatic minerals. They are subdivided into a series of aegirine-rich lujavrites and arfvedsonite-rich lujavrites, respectively coloured dark green and black. The main exposures of lujavrite are in the north-west corner at Kvanefjeld (Fig. 33, locality 6), at the eastern contact of the complex along the northern coast of the Tunulliarfik Fjord and north-east of the Lakseelv Valley in the southern part of the complex (Fig. 28).

A strong upward fractionation trend is observed in Zr, Nb, Ta, REE, Y, Th and U (Andersen et al. 1981, Bailey et al. 2001). The most evolved lujavrites are therefore of major economic interest (Sørensen 1992). They contain many complex and rare minerals, such as steenstrupine, naujakasite, neptunite, sørensenite, ussingite, tugtupite and lovozerite (Fig. 31 & Table 1). This more evolved stage is also referred to as 'hyper agpaitic', characterised by, among others, steenstrupine substituting for eudialyte and naujakasite substituting for nepheline (Sørensen & Larsen 2001). At this stage, the lujavrite magma was strongly enriched in volatiles, making it highly mobile and allowing the magma to penetrate and intrude the overlying naujaite body as well as the marginal augite syenite and country rocks. Large rafts and xenoliths of naujaite and, to a smaller extent, augite



Fig. 32. Black and finely laminated lujavrites, draped over large blocks of naujaite. North coast of Tunulliarfik at Tuttup Attakoorfia.

syenites are enclosed within the lujavrite, which show complex reaction rims from interaction with the lujavrite magma (Fig. 32).

The Kakortokite

The lowermost exposed part of the complex consists of a series of rhythmically layered agpaitic nepheline syenites – the lower layered kakortokites (LLK). Bohse et al. (1971) identified and mapped 29 individual units, and numbered them from –11 to +17 (Fig. 34). Most units consist of three separate layers: a basal layer of black kakortokite, dominated by arfvedsonite, a thin red layer of eudialyte-rich kakortokite and a thicker white layer dominated by alkali feldspar and nepheline (Fig. 35). Yellow rinkite, a Ca-, REE-, Ti- and Nb-bearing mineral, is also common in the white layers (Table 1). The red layer is absent in some units. The transitions from one layer to another within a given unit are mostly gradual, while the contacts between the consecutive units often, but not always, are sharp. The units dip gently towards the centre of the intrusion and steepen towards the margin of the complex, from c. 10° to 50°.

The layering stands out clearly from a distance (Fig. 34), but may be hard to see when standing right on top of the outcrop. In those cases, aerial photographs are of great help determining the exact number of the units you are looking at. Each unit has slightly different characteristics, such as more or less pronounced mineral grading, lamination, thickness of its layers and the nature of its contacts, which may also help in recognising consecutive units (Bohse et al. 1971). Laterally, the units are very homogeneous and little or no variation in texture, thickness and mineralogy is observed (Bohse et al.



Fig. 33. Kvanefjeld seen from Narsaq Elv valley (Fig. 28, Locality 6). The grassy area at the upper right of the Kvanefjeld plateau consists of the volcanic rocks of the Eriksfjord Formation. The dark coloured rocks are the lujavrites, which intruded into the roof of the Ilímaussaq complex. The road leads up to the entrance of the mine adit, used for uranium exploration in the 70's (photo H. Friis).

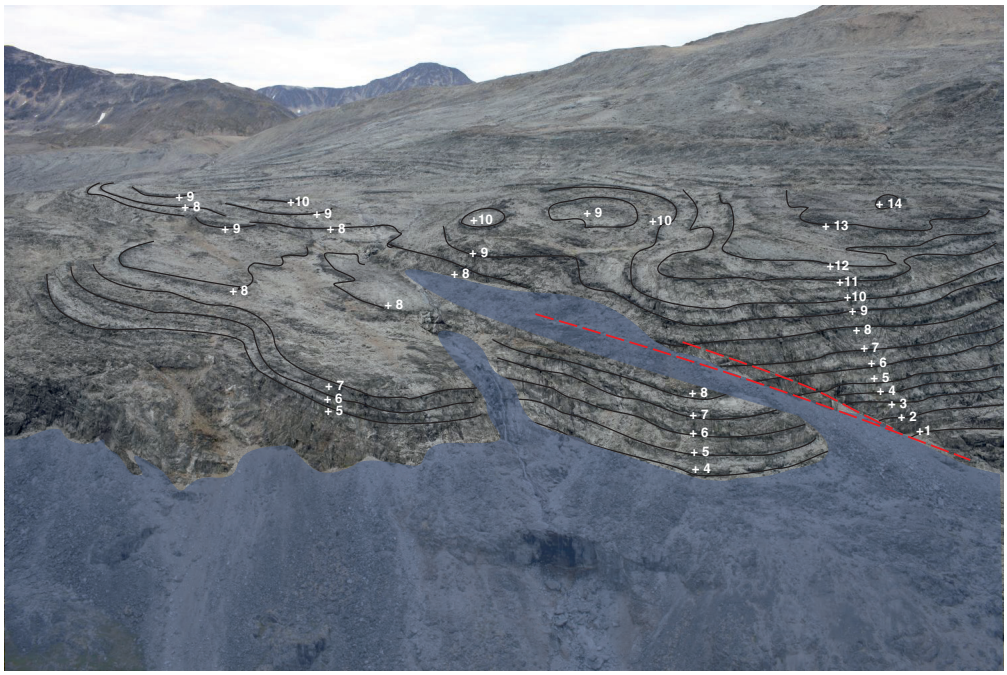


Fig. 34. Magmatic layering in the kakortokites as seen on the south coast of the Kangerluarsuk fjord at Kringlerne (locality 7). The layers are annotated according to the unit numbers given by Bohse & Brooks (1971). Each numbered unit consists of a black, red and upper white kakortokite layer. Red lines indicate minor faults and the blue zone is poorly exposed or covered with debris.

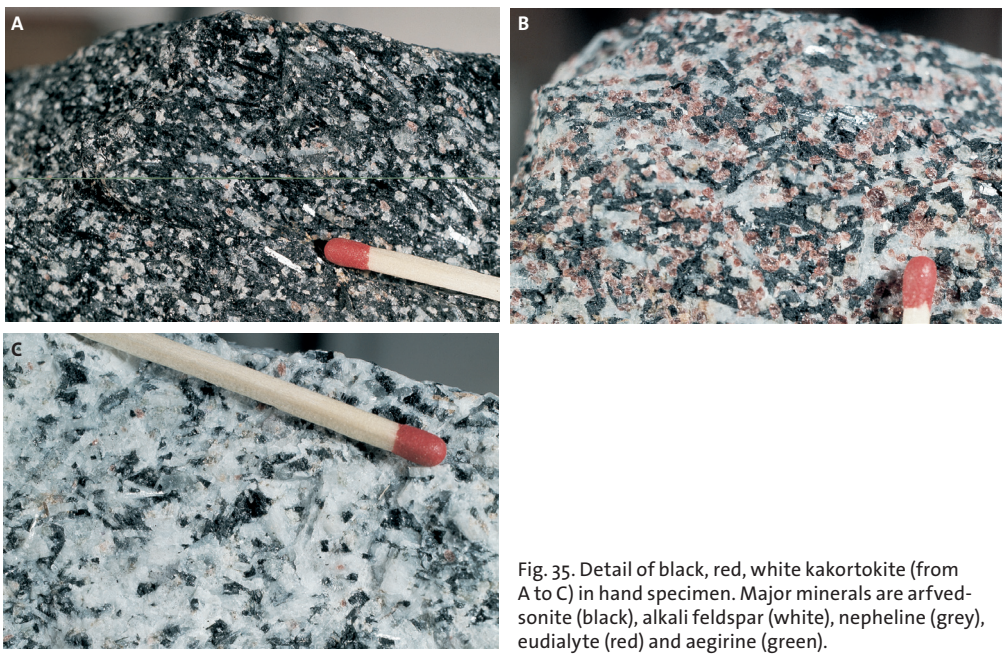


Fig. 35. Detail of black, red, white kakortokite (from A to C) in hand specimen. Major minerals are arfvedsonite (black), alkali feldspar (white), nepheline (grey), eudialyte (red) and aegirine (green).

1971, Andersen et al. 1981). One specific unit (+3) contains numerous large inclusions of earlier rock types (augite syenites, naujaite and sodalite foyaite), indicating that the relative timing of crystallisation post-dated the formation of the roof series. The blocks of naujaite are interpreted to have 'fallen' into the partially solidified kakortokite series, during a proposed roof collapse (Bohse et al. 1971). A 50 m thick sequence of so-called slightly layered kakortokites (SLK) lies concordantly above the last recognisable three-layered unit (+17).

In the Lakseelv Valley, the kakortokites are covered by alluvial deposits, obscuring the stratigraphic contacts between the SLK and the rocks on the northern side of the valley (Fig. 34). A large south-east oriented normal fault was suggested to run through this valley by Bohse et al. (1971), which down-set the northern block by several hundreds of metres. The offset along the fault increases to the west and dies out to the east. North of the Lakseelv fault, another zone of layered kakortokites of about 40 m is exposed, and these are referred to as the transitionally layered kakortokites (TLK). On mineralogical and textural grounds, Bohse et al. (1971) correlated these kakortokites to the highest kakortokites exposed just south of the fault, thereby stratigraphically placing the TLK above the SLK and implicating a downward offset of up to c. 350 m along the Lakseelv fault.

Marginal pegmatite

At the contact between the kakortokite and the surrounding augite syenite and country rocks, a zone of kakortokite cut by a network of pegmatite veins occurs (Fig. 36). This zone is referred to as the marginal pegmatite. The pegmatites contain minerals that are over a metre in size. The zone is thought to have formed by late-stage



Fig. 36: A network of small pegmatite veins with large crystals of arfvedsonite (black) intersecting fine-grained and internally deformed kakortokite.

melts, highly enriched in volatiles and rare elements, which escaped the crystallising kakortokite mush along the margins of the magma chamber.

KAKORTOKITE LAYERING

The mechanisms responsible for the repetitive layering still remain a matter of debate. Proposed models include magma chamber recharge, gravitational crystal settling, compositional layering in the magma, oscillatory changes in the liquidus temperature, mat formation, convective overturns and more (Larsen & Sørensen 1987, Pfaff et al. 2008). A combination of two or more mechanisms may be responsible for the spectacular recurrence of the units, while gravitational settling is generally proposed to have caused the differentiation into a black, red and white layer within a given unit.

A systematic chemical study of eudialyte and amphibole in the kakortokite–lujavrite sequence by Pfaff et al. (2008) revealed a strikingly uniform composition of these minerals in the kakortokites. On the other hand, a strong fractionation trend is observed in the overlying lujavrites. A few compositional jumps between units in the lujavrite sequence are suggested to indicate at least two stages of magma replenishment during the lujavrite stage (Pfaff et al. 2008). Evidence for feeder conduits or other field observations to support magma recharge have, however, not been identified to date.

OPEN QUESTIONS FOR DISCUSSION IN THE FIELD

- What is the relation in time and emplacement of the lujavrite relative to the overlying roof sequence?
- What mechanisms led to the formation of the spectacularly uniform and repetitive layering in the kakortokites?
- How did the magma become so enriched in incompatible elements and volatiles?
- Do field observations support crystallisation from a single batch of agpaitic magma or is there any evidence for multiple injections of magma in the lujavrite–kakortokite sequence?
- What is the relation between Ilímaussaq and other intrusions in the Gardar province with respect to magma evolution?
- Is there any field evidence to support the presence of the Lakseelv fault, placing the kakortokites south of the Lakseelv Valley next to higher levels of kakortokites and lujavrites north of the valley?

Metallogeny of the Gardar province

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KVANEFJELD, ILIMAUSSAQ

Two companies are currently operating and exploring for REE, U, Zn, Zr and other elements in the Ilímaussaq complex. The Kvanefjeld deposit in the north-westernmost part of Ilimaussaq is licensed by Greenland Minerals and Energy Ltd (GME) and is classified as one of the world's largest resources of rare earth elements and the sixth largest deposit of uranium. Kvanefjeld has a long history of uranium exploration (unpublished report by Makovicky et al. 1980), but for several political and (socio-) economic reasons it was never developed into a project. A recent relaxation of the Greenlandic regulations for uranium exploitation now allows GME to initiate large-scale mining. The overall resource inventory comprises 956 million tonnes of ore containing 575 million lbs U_3O_8 (average grade 400 ppm U), 10.33 million tonnes of TREO and 2.25 million tonnes of Zn. The target ore

material is the (hyper-agpaitic) lujavrite in the agpaitic nepheline syenite suite of the intrusion. The main REE, U and Zn bearing minerals are steenstrupine, britholite (Na, REE, phosphate silicates), monazite, vitusite, xenotime (REE-phosphates) and various Na-Zr silicates like eudialyte and lovozerite. Pilot tests of extraction by froth floatation and atmospheric leaching have proven successful (GME announcement 2012).

KRINGLERNE, ILIMAUSSAQ

The Kringlerne deposit in the southern part of the Ilímaussaq intrusion is owned by TANBREEZ Mining Greenland A/S. The company name reflects its focus on the elements Ta, Nb, REE and Zr. The ore is the kakortokite, containing variable amounts of Zr- and REE-rich eudialyte. The inferred resources are 4 340 million tonnes with an average grade of 1.8 wt.% ZrO_2, 0.2 wt.% Nb_2O_5, 0.04 wt.% HfO_2 and 0.5 wt.% TREO. An exceptionally high proportion of the total rare earth content comprises heavy rare earth elements (HREE), on average 27%. The company reports an expected construction phase throughout 2014, and the operation stage is expected to start at the end of 2015. The ore will be processed through simple magnetic separation, without the use of chemicals. The magnetic separates consist of three fractions: a red eudialyte concentrate (containing Ta, Nb, REE and Zr), a white non-magnetic feldspar concentrate and a black magnetic arfvedsonite concentrate. In contrast to the lujavrites, the kakortokites contain relatively low levels of uranium and thorium. The Kringlerne project is therefore independent of the Greenlandic regulations about exploitation of radioactive material.

KRYOLIT MINE

Large occurrences of cryolite (Na_3AlF_6) within the Ivigtut complex (see description above) were discovered in 1799, and mining started in 1859. Until the close down of the mine in 1987, around 3.5 million tonnes of cryolite were mined. Pauly and Baily (1999) proposed the following evolution model for the cryolite deposit: fluorine-rich, post-magmatic fluids caused an intensive metasomatism of the emplaced granite, leading to the recrystallisation of feldspar and the formation of a hydrous aluminofluoride melt, which later separated into fluoride and siliceous melt fractions (Koehler et al. 2008). The cryolite subsequently crystallised from the fluoride melt, forming this world-wide unique deposit.

MOTZFELDT

Occurrences of Th, U, Nb, Ta, Zr and REE mineralisation are dominantly hosted within the Motzfeldt Sø Formation. The most important economic mineral is pyrochlore, which is associated with zircon, carbonates and rare-metal silicates. Possible reserves of ore grade rock within this formation are estimated to be approximately 130 million tonnes. The mineralisation of economically interesting phases is concentrated within a 2 to 4 km wide side-wall and roof zone consisting of red hydrothermally altered syenite, which contains a number of pegmatitic segregations ranging from cavities up to extensive subhorizontal sheets (Bradshaw 1988).

DYKES

In the wider surrounding of the settlements of Narsaq, Narsarsuaq and Qaqortoq, several occurrences of pitchblende (UO_2) and secondary uranium minerals have been discovered. The mineralisation occurs in veins and salic dykes, which are crosscutting the Ketilidian granite, and is associated with minor sulphides, such as pyrite and chalcopyrite and typical gangue minerals such as calcite, quartz and fluorite. Ages of 1 180 Ma closely relate the formation of these veins and dykes to the Gardar province and they are probably formed by hydrothermal activity associated with this magmatism (Armour-Brown et al. 1982).

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