Graphite potential in Greenland

GEOLOGY AND ORE

Exploration and Mining in Greenland

Graphite potential in Greenland

Graphite is the most common naturally occurring form of crystalline carbon. It has special characteristics due to its crystallographic structure, making graphite a very important industrial mineral with many applications including refractories, electrodes and crucibles, brake linings, lithium-ion batteries, etc. The production of total graphite in 2017 was 1.2 mio. tonnes. A conservative prediction is that the demand for flake graphite will rise 50% by 2025 to about 900,000 tonnes per year, especially due to the production of lithium batteries for electric cars.

In November 2017, a workshop on the 'Assessment of the graphite potential in Greenland' was arranged jointly by the Geological Survey of Denmark and Greenland (GEUS) and the Ministry of Mineral Resources (MMR), Government of Greenland. This workshop deviated from the standard resource assessment procedures applied in previous workshops, because no statistic grade/tonnage model has been established. Instead the focus of the workshop was to present and discuss: 1) the graphite value chain, 2) the Nordic graphite projects and operations, 3) the crucial parameters for graphite occurrence evaluation, and 4) known graphite occurrences in Greenland and their potential.

This edition of Geology and Ore provides an overview of: 1) the sources of graphite and the deposit types, 2) the graphite products, and 3) known graphite occurrences in Greenland. A GEUS report documenting results from the workshop is available.

Sources of graphite

Graphite deposits can be derived from biogenic, magmatic or carbonatitic sources.

Biogenic sources of graphite are restricted to sedimentary environments and the accumulation of algae, phytoplankton, humic or organic material. These syngenetic deposits yield either microcrystalline or flake graphite (see section on types of graphite), depending on the metamorphic grade of the host rock. In low-grade rocks, graphite deposits occur as black shales, graphitic slates or graphitised coal. For high-grade rocks, graphite deposits occur in gneisses, quartzites or granulite facies rocks.

Magmatic sources of graphite are carbon-bearing fluids (or, less commonly, melts). The graphite deposits form through rapid depressurisation and quenching of CO_2/CH_4-rich fluids, which trigger rapid crystallisation of fine-grained graphite within breccia matrixes and fractures in the walls. These deposits yield vein graphite.

Carbonatitic sources of graphite are limestones, marbles and calc-silicate rock. These rock types can undergo decarbonation reactions and thereby form carbonate rocks with graphite deposits. These deposits yield either microcrystalline or flake graphite, depending on the metamorphic grade of the host rock.

Types of graphite

Natural graphite

Microcrystalline graphite (also known as amorphous)

Microcrystalline graphite is the most abundant form of graphite but also the lowest-priced graphite. This form of graphite commonly occurs as micro-crystalline particles fairly uniformly distributed in weakly metamorphosed rocks, such as slates, or graphite beds of sedimentary origin. The grade varies and reflects the carbon content of the original sediment. Some microcrystalline graphite deposits are formed from contact metamorphism, whereas others are a result of regional metamorphism. Micro-crystalline graphite is mainly used for lubricants, refractory products, paints, drilling mud etc.

Crystalline flake graphite

The crystalline flake graphite is the commercially most important form of natural graphite. It occurs less commonly in nature than microcrystalline graphite but more commonly than vein graphite. It occurs in metamorphic rocks such as marble, gneisses and schist. It consists of many graphene sheets stacked on top of each other with weak bonds holding them together and therefor occurs as separate flakes. The flake size and crystallinity depends on the grade and temperature of the metamorphism, with amphibolite to granulite facies metamorphism producing the important economic deposits. The large crystals allow it to be used in more high-valued applications, such as refractories, foundries and, to some extent, in lithium-ion batteries and other battery types.

Vein graphite

Vein graphite is the rarest, most valuable and highest-quality type of natural graphite. It occurs in solid lumps in veins along intrusive contacts. Vein graphite results from deposition of carbon-bearing fluids (or melts) that are channelled through fracture systems. The most economic significant vein deposits are from high-grade upper amphibolite to granulite facies environments. Vein graphite is a niche market of *c.* 5,000 tonnes/year. It is used for electrical applications, friction products and powdered metal.

Synthetic graphite

Synthetic graphite is manufactured from calcined petroleum coke, coal tar pitch, anthracite, recycled synthetic graphite or natural graphite. It is very costly to produce synthetic graphite as its precursor material has to be baked at high temperatures of >2500°C for several days. The synthetic graphite is of very high quality and has a purity of 99.99%. It is used in high-end products such as electrodes in steel production, and in aluminium production, in lithium-ion batteries for electric vehicles and in the electrical, chemical, nuclear, mechanical and aerospace industries.

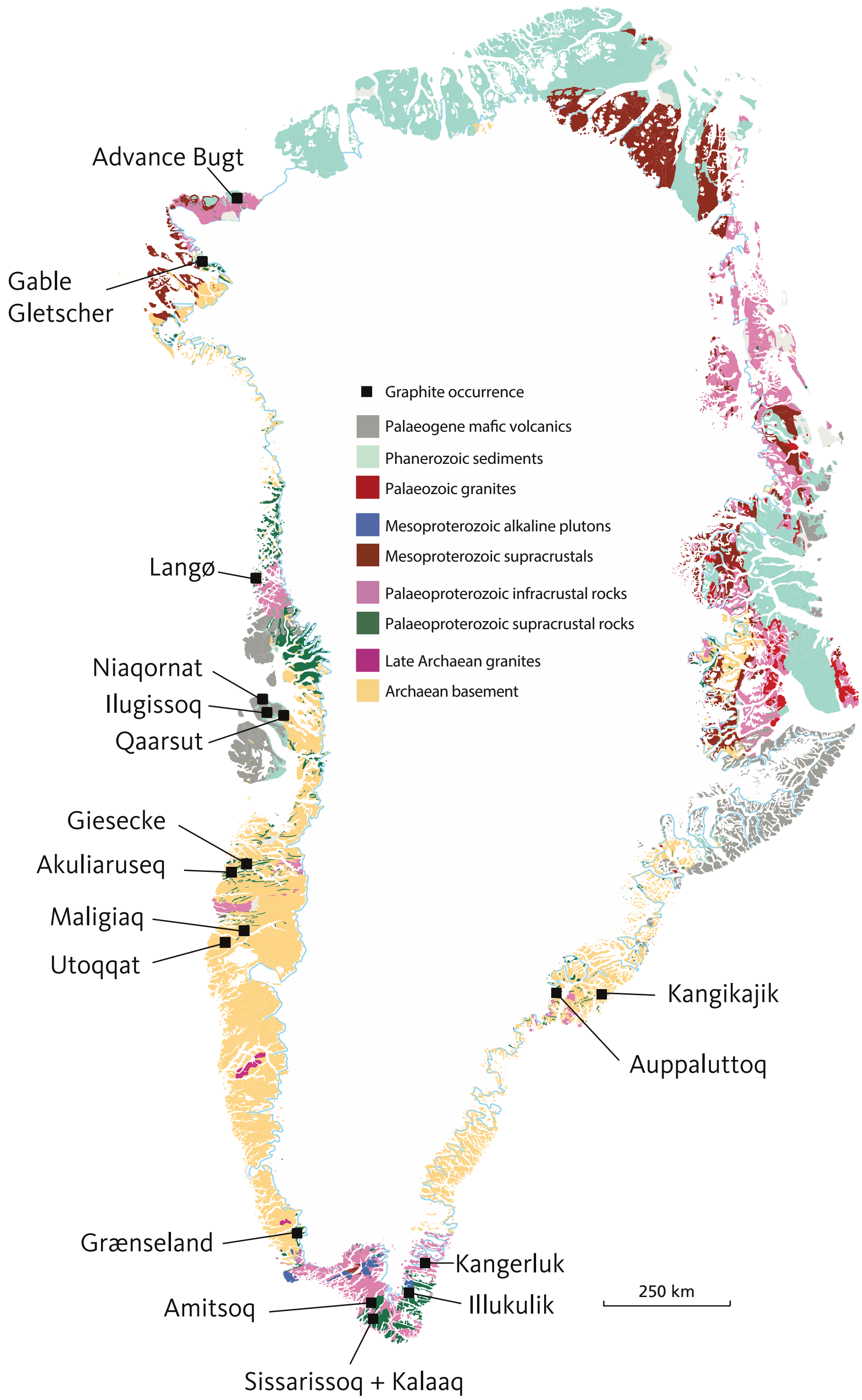
Physical and chemical properties

The three forms of carbon (charcoal, graphite and diamond) are distinguished by chemical and physical properties. The gravities of charcoal, graphite and diamond are 1.3 – 1.9 g/cm^3, 2.266 g/cm^3 and 3.5 g/cm^3, respectively. Graphite has a hardness of 1 to 2 (Mohs scale), which makes it a soft and flexible material. It is heat resistant to about 3000°C (in a reducing atmosphere) and it is an excellent conductor of heat and electricity. Graphite is chemically inert, environmentally friendly, resists chemical attack by most reagents and is infusible in most common fluxes. Flake graphite has a very high crystallinity and a strong anisotropy along the graphene layers causing lubricity. Other molecules can intercalate between the graphene layers and give it expandable properties.

Graphite products

Natural graphite is characterised by many parameters, the two most important ones for commercially traded flake graphite being purity (carbon content) and particle size distribution (PSD). High carbon content products have been processed in several steps for purification and are, therefore, more expensive. Large flakes are more rare and, therefore, attracts higher prices. In contrast, smaller sizes of screened product are cheaper as this material is more abundant. Typically, screened products are commercially available in classes from –200 mesh (75 microns) to +32 mesh (500 microns).

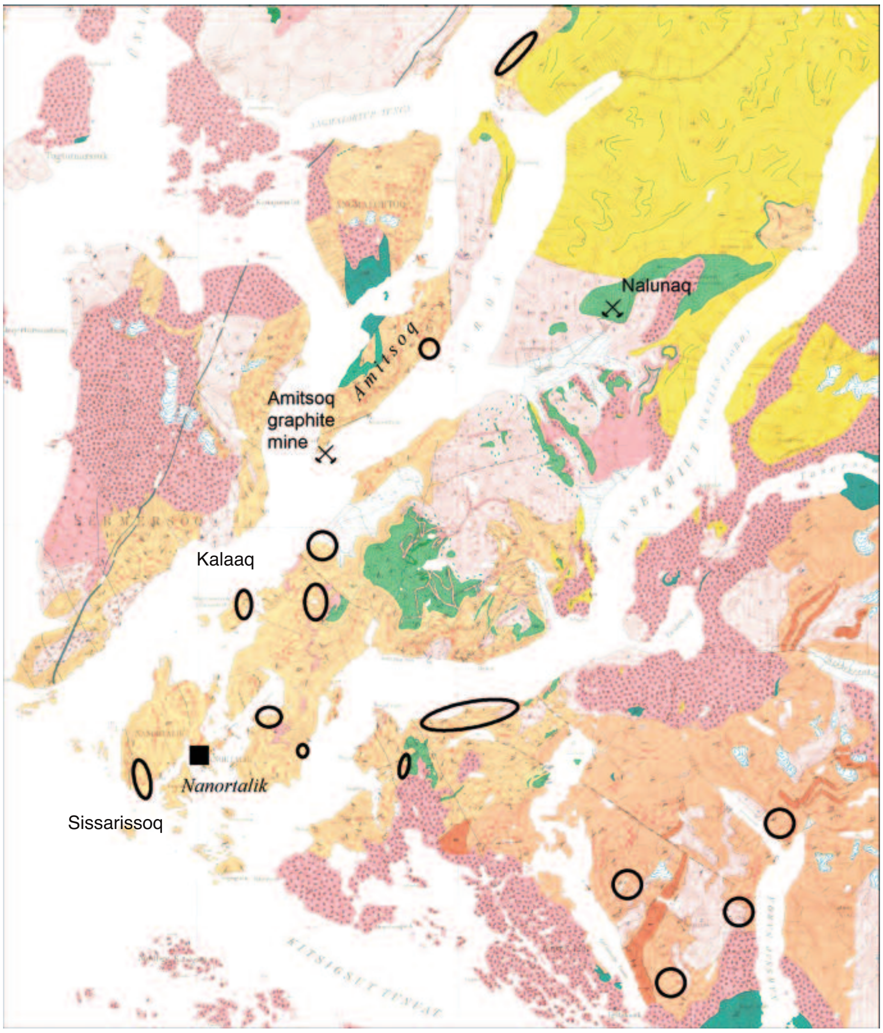
Graphite concentrate, called category 0 product, is usually not sold on the market. Instead, the concentrate is screened into standard products of different mesh grades (categories 1 and 2). Mines typically have their own advanced screening plant and convert their concentrate directly into standard products.



Main lithostratigraphic units in Greenland with location of known graphite occurrences.

If the graphite is subsequently milled to a so-called micronised product, it is classified as a category 3 product.

Special-value added products such as expandable or expanded graphite, spherical graphite, lubricants and graphene have a more complex production process. These category 4 products are the most expensive. Prices are typically opaque and individually agreed to between processor/ trader and customers.



Geological map of known graphite occurrences in the Nanortalik region (Source: Jeroen van Gool).

Main applications

Graphite is a very important industrial mineral with many applications in both low-tech industries (lubricants, paints, drilling mud, brake linings, pencils, etc.) and in high-tech industries, such as electrical, chemical, nuclear, mechanical and aerospace (refractories, electrodes, cathodes and anodes in aluminium, etc). In particular, the market for graphite anode-material in lithium-ion batteries is expected to grow, reflecting the changes induced by expansion of the carbon-free transport sector. Additionally, graphite as a raw material for graphene, which carries the potential to be used as electrical conductors and for construction material, is considered to have a substantial growth potential.

Historic graphite mining in Greenland

Graphite has been known to Greenlanders for several hundreds of years. They showed specimens to English whalers, which lead to a British expedition to Greenland in 1845, where 100 tonnes of graphite were quarried from shallow pits at Langø, West Greenland. Later the Danish government prohibited this mining. In the beginning of the 19th century the mining company Grønlandsk Minedrifts Aktieselskab carried out exploration for graphite in Greenland. A number of graphite occurrences and deposits were prospected by the company and described by Ball (1923) with other occurrences described by Bøggild (1953). The first and only real graphite mine in Greenland was situated at Amitsoq near Nanortalik, South Greenland. It was in operation between 1914 and 1924 and it produced c. 6,000 tonnes of ore at an average grade of 21% Cg (graphite in carbon).

Graphite occurrences in Greenland

Occurrences of graphite and graphite schist are reported from many localities in Greenland.

South Greenland

Amitsoq

The Amitsoq Island north of Nanortalik, in South Greenland, encompasses the former Amitsoq graphite mine. Several graphite showings are also reported in the surrounding Nanortalik region (see below). The graphite at Amitsoq is hosted by graphitic schists embedded in strongly-sheared cordierite-sillimanite-biotite gneisses. The host rocks are Palaeoproterozoic high-grade metamorphic gneisses of the Ketilidian Psammite zone. The graphite content ranges from c. 20–35%, with an overall mean graphitic carbon content of 28.7%. The graphite exists in various morphologies, ranging from fine-grained specular forms to large discrete crystals, to agglomerations, which span areas of up to 15 m in size. The average flake size is 0.2–0.3 mm, but large flakes up to 15 mm have been reported. The ore genesis is associated with volcanogenic massive sulphide (VMS) formation, as a result of syngenetic deposition of organic material from bacteria that thrive in hot sulphide exhalations. Subsequent deformation and metamorphism transformed the organic material into flaky graphite. The old ore-reserve figures indicated that the occurrence contained 250,000 tonnes of graphite (non-compliant estimate). The current licence holder of the area is Alba Mineral Resources.

Nanortalik region incl. Sissarissoq and Kalaaq

The Nanortalik region surrounding Amitsoq hosts laterally extensive systems

From the closed Amitsoq graphite mine (Photo: Nanortalik Museum).

of graphite occurrences that can potentially be traced for many kilometres within the same tectonostratigraphic level. This area is considered to carry a high potential for undiscovered occurrences. At Sissarissoq, west of Nanortalik, a graphite-rich lens, 30 m long and 1.5 m wide, is hosted in biotite-garnet-schist. Chemical analyses yielded 22–25% Cg and 7–12% S, with a ratio of flake to amorphous graphite of 3:7. The current licence holder of the area is Alba Mineral Resources. In 2017, Alba Mineral Resources discovered a new showing at Kalaaq. It is situated between Amitsoq and Sissarissoq, and consists of multiple thick graphite layers that extend for more than 460 m. The grade averages 25% Cg with a maximum of 29% Cg. Exploration is ongoing.

Illukulik and Kangerluk

At Kangerluk, sheared semi-massive graphite lenses are common in rust zones. A 30 m long and 9 m wide semi-massive graphite lens with up to 60% graphite occurs on the north shore of Kangerluk Fjord hosted by a micaschist. South of Kangerluk, at Lindenow Fjord, graphite occurs in the Illukulik area both as low grade graphite schist and higher grade graphite veins that intrude the schist.

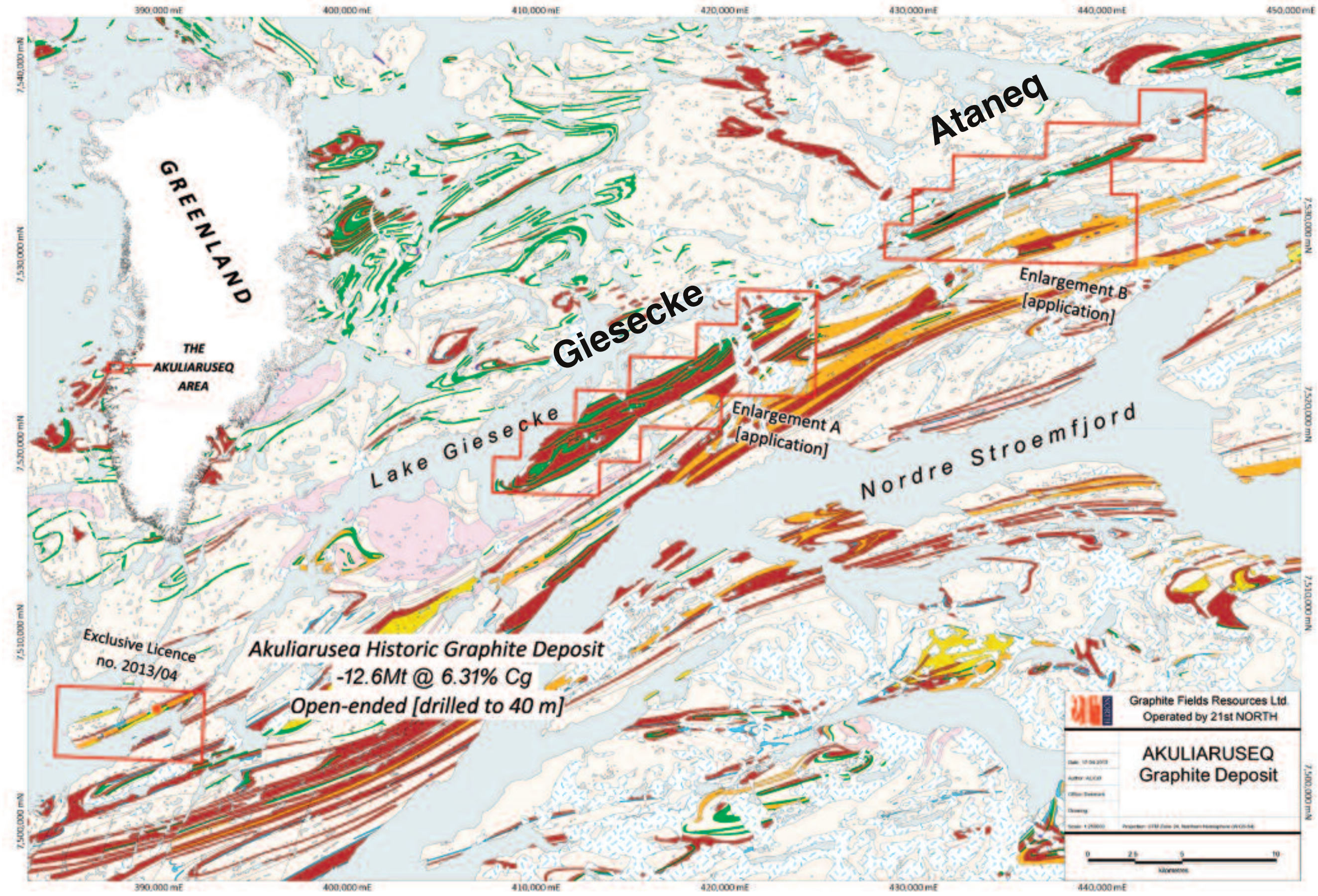
Grænseland

Coal, anthracite and graphite occur in a thin sedimentary unit in the Foseelv Formation near the base of the Ketilidian Sortis Group in Grænseland, South-West Greenland. Carbonaceous material was altered to almost pure graphite during contact metamorphism caused by intruding mafic dykes. The amount of graphite has reported to be 10,000 tonnes (non-compliant resource). The southern part of the occurrence is graphite schist whereas the northern part is an anthracite coal layer.

West Greenland

Utoqqat and Maligiaq

At Utoqqat, graphite occurs in Archaean gneisses and schists. Seven horizons of graphite-bearing schists extend for 1.2 km and have widths between 1 and 10 m. In the beginning of the 1900, 80 tonnes of sample material from two closely spaced graphite-bearing zones, sampled at regular intervals, are reported to yield 21% Cg and 5.5% S. Farther to the east, at



Geological map of the Nordre Strømfjord region with the Akuliaruseq occurrence to the left. The Giesecke occurrence in the middle and Ataneq to the right (Source: 21st North 2013).

Maligiaq, graphite-bearing mica schists have been sampled over a distance of 800 m with carbon content in graphite ranging from 5% to 25% Cg.

Akuliaruseq

In the Nordre Strømfjord region, West Greenland, graphite is abundant in Palaeoproterozoic sulphide-rich supracrustal rocks. The Nordre Strømfjord supracrustal belt is particularly enriched. Here, the graphite is accumulated in a supracrustal sequence composed of foliated biotite garnet ± graphite ± sillimanite gneiss, locally interlayered with amphibolite, marble bands and ultramafic rocks. The metamorphic grade is upper amphibolite facies. The graphite is considered to represent metamorphosed bituminous and sulphide-rich strata deposited in a volcanic arc or back-arc environment, associated with subduction related to the *c.* 1.85 Ga Nagssugtoqidian Orogeny.

At Eqalussuit, just north of Nordre Strømfjord, the graphite mineralisation occurs as layers and lenses. This mineralisation, called the Akuliaruseq occurrence, is hosted in schists, amphibolites and ultramafic rocks, which form a narrow, steeply-dipping synform. The graphite occurrence was investigated by Kryolitselskabet Øresund A/S between 1982 and 1986. They reported that the graphite was confined to three separate horizons in the northern limb and is predominately hosted by sillimanite schists that could be followed along strike for about 6 km. Graphite occurs as two different types: 1) disseminated graphite flakes, grading 6–8% graphite, occurring as both large lumpy flakes and small flakes, none of which contain impurities; and 2) massive graphite in intensely deformed parts of the schist, grading up to 20–24% Cg. The thickness of the graphite-bearing rocks varies between 35 and 60 m, but they contain numerous 1–20 m wide low-grade zones. Resource estimate data based on in-fill drill holes (down to 40 m), carried out by the current licence holder, Graphite Field Resources Ltd., predict a graphite resource of 12.6 million tonnes grading 6.3% Cg including a high-grade zone encompassing 2.8 million tonnes grading 12% Cg.

Giesecke

The sequence of felsic garnet ± graphite ± sillimanite gneiss at Akuliaruseq can be followed along strike to the north-east to Lake Giesecke and Ataneq, and makes this area prospective for graphite. The graphite is not evenly distributed in the gneisses but is concentrated in strata-bound layers of 0.5–20 m width. The graphite concentration in this area varies from 0.5–7%.

Sampling at the Akuliaruseq occurrence, carried out by Graphite Field Resources (Photo: Claus Østergaard, 21st North).

Qaarsut, Niaqornat and Ilugissoq

At Nuussuaq, West Greenland, three occurrences of graphite have been registered. Two of the occurrences, Qaarsut and Niaqornat, are early Cretaceous to Palaeocene bituminous shales containing graphite. The third occurrence is the Ilugissoq graphite andesite volcano that produced pyroclastic rocks and lava flows at Nuuk Killeq. The amount of outcrop for the latter is very large, however, the graphite content of 2% is very low. The sediments at Qaarsut and Niaqornat were intruded by Palaeogene mafic dykes, which caused the carbonaceous matter in the sediment to be metamorphosed to amorphous graphite. At Qaarsut, quartzitic bituminous shales are metamorphosed over a zone of 3–5 m on both sides of an ultramafic dyke. Three samples from the Qaarsut occurrence were collected and analysed. The results are reported to yield 93 to 95% Cg and 3.6–4.9% ash. These numbers, however, most likely represent ore concentrates or very-rich graphite-bearing samples or even massive graphite or graphite flakes. As such, they are probably not representative of the entire occurrence. Small-scale mining activities were undertaken occasionally between 1908 and 1924, in a 0.2 m thick graphite layer hosted in a sandstone and shale sequence.

Langø, Upernavik

South of Upernavik, graphite occurs as lenses and veins in pelitic and garnet-bearing schist at the island Langø and adjacent areas. The host rock is a pegmatite intruding the Palaeoproterozoic Karrat Group at the end of the *c.* 1.85 Ga Nagssugtoqidian–Rinkian Orogeny. The area experienced high-grade metamorphism during the Nagssugtoqidian–Rinkian Orogeny. The graphite is crystalline occurring locally as fibrous crystals up to 2 cm long. Bulk-sampling and bench testing in the early 20th century yielded high grades of up to 81% C. However, samples are not documented to be representative and, despite the good quality of the samples, the occurrence is small and not considered to have economic importance. Today, five abandoned pits are still visible. They are 1-3 m wide and 5-15 m long and a couple of meters deep.

North Greenland

Gable Gletscher, Thule District,

The Palaeoproterozoic Prudhoe Land supracrustal complex hosts hydrothermally overprinted, pyrite- and graphite-rich schists with large rust zones estimated to contain 10–20% of graphite. However, the area is underexplored and needs closer investigation to study the potential for graphite. A section at Gable Gletscher was studied for graphite and returned values of 8.5 and 3.9% Cg, which are considered as minimum values.

Advance Bugt, Inglefield Land,

The Palaeoproterozoic Etah Group of Inglefield Land also hosts graphite-rich supracrustal rocks and large rust zones. A 2–3 km long and 500 m wide conformable rust zone is present in the northern part. The rust zone contains disseminated and semi-massive Fe-sulphides ± graphite. The graphite content ranges from less than 0.5 to 5% Cg. Three samples were measured and contain 2.4% Cg. The occurrence, Advance Bugt, was found by Rio Tinto Mining and Exploration Ltd. in 1991 and studied further by GEUS in 1995.

Old graphite pit at Langø (Photo: Bjørn Thomassen, GEUS).

East Greenland

Auppaluttoq

The Auppaluttoq area is located in the Palaeoproterozoic mobile belt of Ammassalik, about 60 km north-west of Tasiilaq. Graphite-bearing supracrustal rocks, including biotite and quartzitic schists, outcrop along the coast west of the Sermilik Fjord. The schists are brownish to greenish grey and fine to medium grained. The graphite occurs as millimetre-thick layers and films alternating with biotite. The flakes range in length from 1 to 6 mm, with the most common size being 3–4 mm. In the most distinct mineralised area, the supracrustal schist is between 50 m and 100 m thick, and may contain several graphite layers. The graphite-rich layers vary in width from 5 m to 15 m and are discontinuously traceable along three separate ridges for *c.* 750–1,000, 1,500 and 2,000 m. The last licence holder, Graphite Field Resources Ltd., made two new profiles 400 m apart. The analyses yielded a weighted average of 2.3% Cg over 13.2 m. and 7.6% Cg over 14.5 m. High-grade grab samples of semi-massive graphite-schist yielded 10.4 to 30.4% Cg.

Kangikajik

Kangikajik peninsula, 100 km north-east of Tasiilaq, is also part of the Palaeoproterozoic mobile belt of Ammassalik. Five graphite-bearing supracrustal units in Archaean gneisses were identified. Graphite occurs mainly as flake graphite (0.2–3 mm) hosted in schists. The graphite-bearing zones extend along strike for several kilometres and individual zones are typically about 100 m long and 5 m wide.

The graphite is hosted in shear zones and folds where the graphite content decreases outwards from the shear zones and the highest concentrations occur in the largest shear zones. Reconnaissance prospecting programmes in the late 1980s and early 1990s estimated that the potential graphite resource is *c.* 500,000 tonnes of graphite (non-compliant resource). Metal-

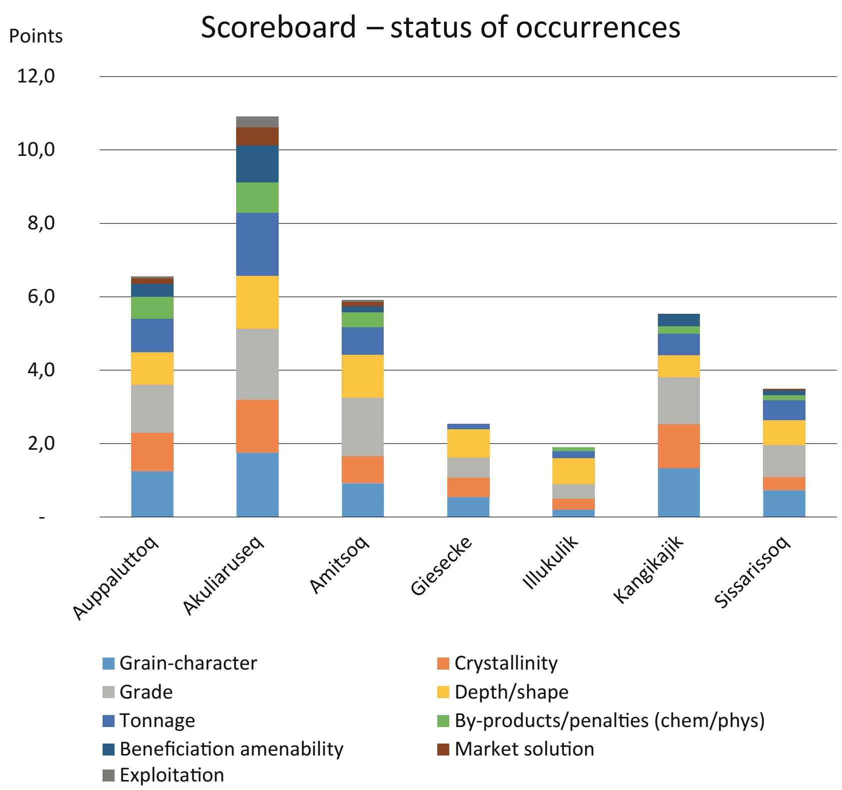
Typical colour anomaly in the Prudhoe Land supracrustal complex. View eastwards with Gable Gletscher in the background (Photo: Thomassen et al. 2002).

Graphite mineralisation at Kangikajik (Photo: Rosing-Schow et al. 2017).

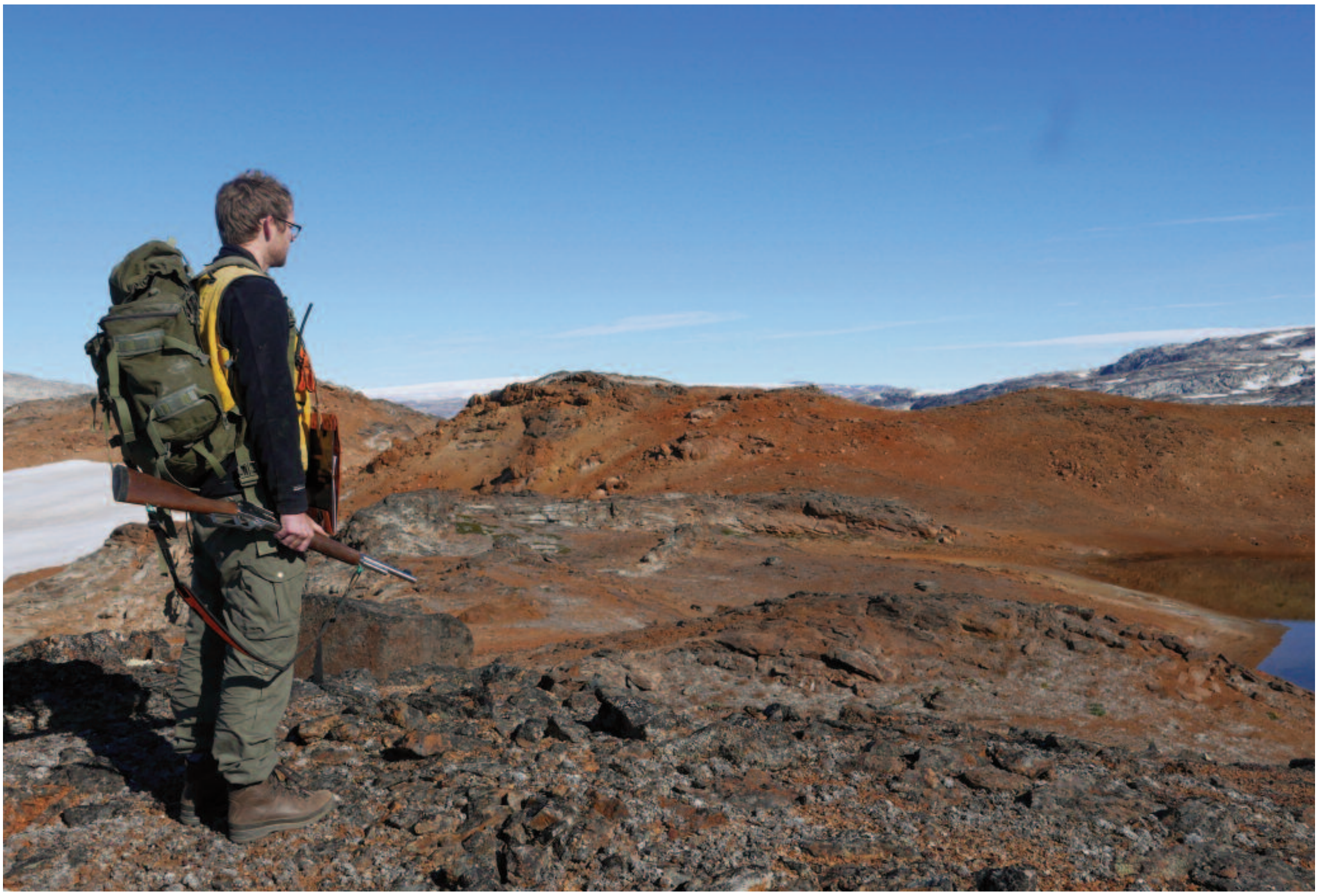
lurgical tests yield 9% Cg in the crude ore with 74% of the flakes above 100 mesh. The grade of the graphite concentrate was about 92% Cg with some impurities.

Assessment results

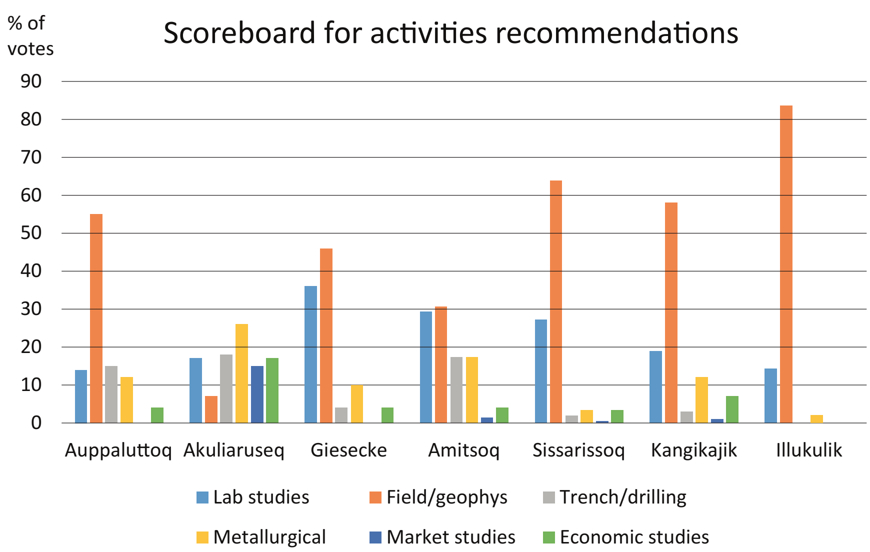
The graphite potential in Greenland is considered to be good, although, graphite is still an underexplored commodity. During the workshop, seven graphite occurrences were discussed using two different scoreboards filled out by the participants; some of the occurrences are licensed, some not. One scoreboard characterised the current knowledge and status of the individual occurrences. The result from this exercise aligns very well with the views expressed by geologists over the past decades – namely, that there are many positive indicators for graphite in Greenland, but that the technical knowledge of the quality of the graphite from the known occurrences is limited. The other scoreboard shows the activities the participants recommend to advance the knowledge of the occurrences. This scoreboard assessment resulted in a range of recommendations reflect-



Average scoreboard points obtained for each occurences showing how the knowledge status was evaluated for the seven occurrences included in the assessment.



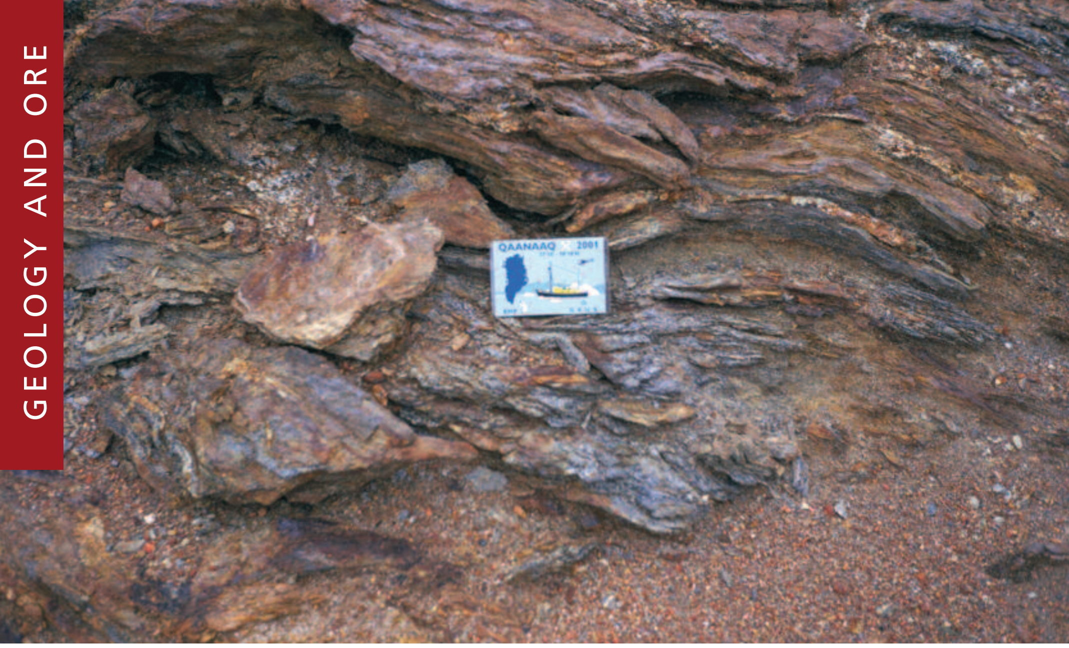
Outcropping semi-massive graphite-schist mostly rusty and coated by iron sulphate at Auppaluttoq (Photo: 21st North).



Scoreboard showing which activities the participants recommended for the seven occurrences.

ing the low level of knowledge. The recommendations for most of the occurrences follow the traditional geological knowledge build-up, starting with field-work such as mapping, sample collection and geophysics.

However, more laboratory analyses of the collected samples such as geochemistry and petrography were recommended reflecting the need to gain more data regarding the quality of the graphite, and thus, metallurgical tests were recommended. This was in particular the case for the advanced and licensed occurrences, such as Akuliaruseq and Amitsoq, for which metallurgical tests and laboratory studies are prioritised and investigations on defining the ore-body given lower priority.



Typical graphite-pyrite schist, west of Gable Gletscher. Logo is 8.5 cm (Photo: Thomassen et al. 2002).

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Front cover photograph
Auppaluttoq area
(21st North)

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Printed
January 2019,

Printers
Rosendahls A/S

ISSN
1602-818x (print)
2246-3372 (Online)