DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 2018/53

Graphite potential in Greenland

Reporting on the 9th Greenland mineral resource assessment workshop, November 2017

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GEUS

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Executive summary

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.

The purpose of the workshop was to present and discuss 1) the sources of graphite and the deposit types 2) value chain of graphite and 3) known graphite occurrences in Greenland. All these topics will be covered in this report.

The standard concept for the ’Global Mineral Resource Assessment Project’ (GMRAP) as applied in previous assessment workshops held by GEUS and MMR was not applicable for graphite occurrences, as they are normally rated, based on parameters related to the quality of the graphite, rather than grade. As a substitute, a scoreboard was introduced for this workshop, allowing a systematic discussion of the known graphite occurrences in Greenland and revealing the current status of their commercial potential.

A list of 12 graphite occurrences in Greenland were selected for scoreboard assessments, out of which only seven occurrences were assessed. Occurrences not encompassed in the scoreboard assessment, were all occurrences from which very little information is recorded.

The conclusion, based on the parameters for the seven occurrences in the survey, was that no adequate and/or convincing data were presented regarding neither the quality of the graphite nor the volume of the occurrence, and, therefore, the viability of the occurrence.

The recommendations for future work on the occurrences also reflect the low level of knowledge of the graphite potential in Greenland. The recommendations for most of the projects focus on early-stage traditional geological knowledge build up, including fieldwork such as mapping, sample collection and geophysics. Complementarily, more laboratory analyses (geochemistry, petrography, etc.) of the collected samples, are recommended, followed by trenching and drilling and metallurgical tests. Only for the more advanced projects, especially Akuliaruseq but also Amitsoq, was fieldwork not considered such a high priority as this has already been carried out. Metallurgical tests and laboratory studies are prioritised instead.

Introduction

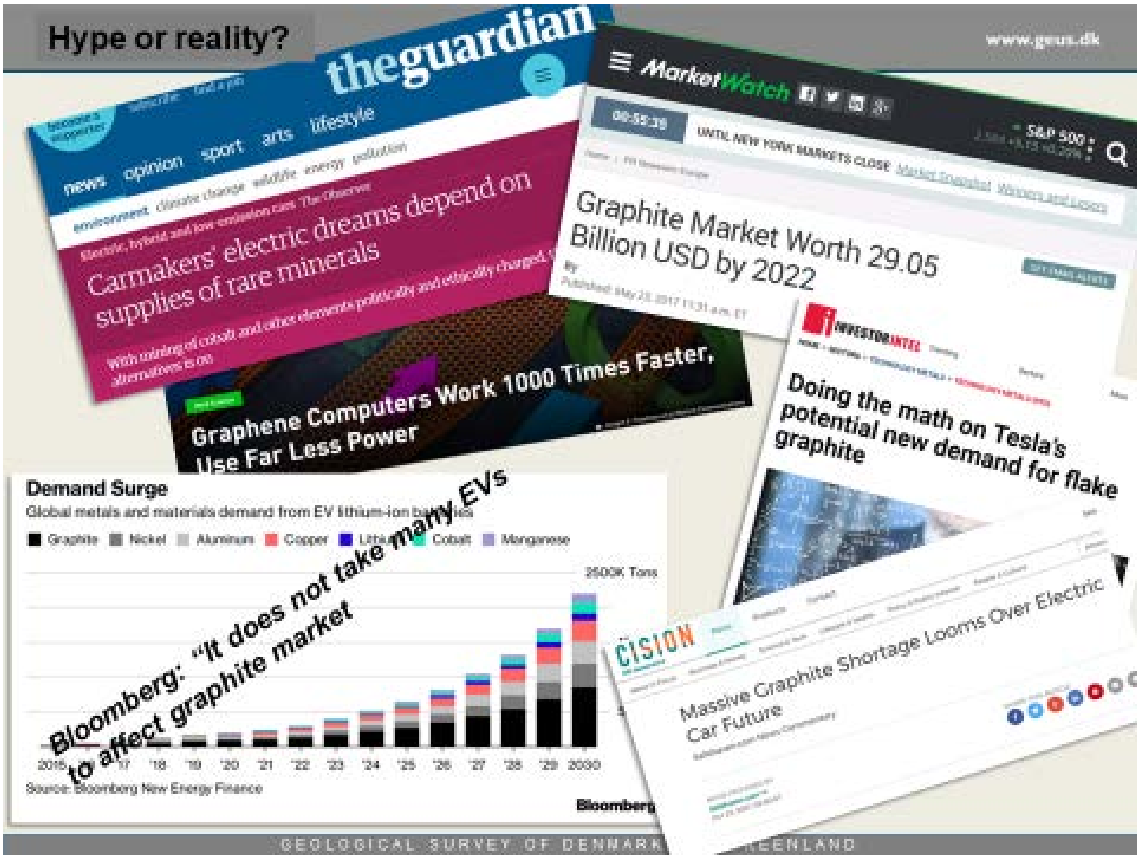

Figure 1. *Graphite – hype or reality? Does Greenland have a role to play?*

Over the past decade graphite has attracted a lot of attention in the press due to it's vital role as one of the key elements in the battery industry, and is at the same time considered to possess a high supply risk (Figure 1). Additionally, the promising results in the graphene industry, which is expected to find a wide range of technical applications in the near future, may increase the supply-demand imbalance even further.

This has also lead the EU Commission to consider graphite to be one of the critical materials for the EU, which is supported by various market intelligence data pointing to a future with strong global demand for graphite, playing a crucial role in the electrification of the energy sector. Based on these facts, the Ministry of Mineral Resources of Greenland (MMR) and the Geological Survey of Denmark and Greenland (GEUS), jointly organised a workshop aiming at discussions on the status of the Greenland graphite resource potential.

GEUS and MMR have previously organised 'Global Mineral Resource Assessment Project' GMRAP workshops, along the lines laid out by USGS in 2002. The primary aim of GMRAP is to identify the main areas in the world with potential for undiscovered mineral resources, down to a depth of one kilometre. The GMRAP makes use of available information about geology, geochemistry, geophysics, and previous exploration results in the context of modern quantitative grade/tonnage statistical models. The GMRAP is being conducted on a regional-multinational basis for selected deposit models and commodities.

MMR and GEUS initiated the Greenland 'Mineral Resource Assessment Workshop' project in 2009 as part of the GMRAP activities. Since then, annually workshops have been held at GEUS for the assessment of the Greenlandic potential for copper, rare-earth elements, sediment-hosted zinc, magmatic nickel, tungsten, orogenic gold, Ti-V and uranium, in 2009-2016 respectively.

The GMRAP concept works very well for the metal occurrences, for which the grade and mineralisation types are the paramount parameters. However, assessment of graphite occurrences is characterised by being based on parameters related to the quality of the graphite flakes, rather than grade, so that relevant tracts delineating these parameters cannot be made. Consequently, the standard concept for the GMRAP is not applicable, and this workshop is not considered as a contribution to the GMRAP.

Instead, a scoreboard was introduced for this workshop, allowing a systematic discussion of the known graphite occurrences in Greenland and revealing the current status of their commercial potential. Moreover, it was the aim of the workshop to present and discuss 1) key parameters for graphite occurrence evaluations, 2) the graphite value chain in general, and 3) the development of the Nordic graphite projects and operations.

It is the hope of the organizers that the outcome of the workshop, summarised in this report, will constitute a useful tool for understanding the graphite exploration challenges and provide useful information about the graphite occurrence potential in Greenland.

Graphite

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 graphitized 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 triggers 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 rocks. 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 (Simandl et al. 2015). 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 on the carbon content of the original sediment. Some microcrystalline graphite deposits are formed from contact metamorphism, whereas others are a result of regional metamorphism. Microcrystalline graphite is mainly used for lubricants, refractory products, paints and 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, gneiss and schist. 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 (Simandl et al. 2016). 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 (Simandl et al. 2016). Vein graphite is a niche market of approximately 5000 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 it's precursor material has to be baked at high temperatures of >2500ºC 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, 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, 2.27 g/cm^3 and 3.5 g/cm^3, respectively (Taylor 2006). 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 ºC (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. It consists of many graphene sheets stacked on top of each other with weak bonds holding them together and therefore it occurs as separate flakes. 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.

Value chain

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 micron) to +32 mesh (500 micron).

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 (category 1 and 2). Mines typically have their own advanced screening plant and convert their concentrate directly into standard products. If the graphite is subsequently milled to a so called micronized 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.

Main applications

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

Historic background

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. The Danish government prohibited this mining. In the beginning of the 19^{th} century the mining company Grønlands 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 (Figure 2). It was in operation between 1914 and 1924, where it produced c. 6000 tonnes of ore at an average grade of 21 % Cg (graphitic carbon) (Nielsen 1973).

Figure 2. *Historic Amitsoq graphite mine (Source: Nanortalik Museum).*

Methodologies

This workshop deviated from the standard resource assessment procedures applied in previous workshops. No tracts were defined prior to the workshop and instead of evaluating all of Greenland, the know occurrences of graphite in Greenland were described and evaluated according to a list of questions listed prior to the workshop. The main purpose of this workshop was to enhance our knowledge on 1) the graphite value chain 2) the Nordic graphite projects and operation, 3) the crucial parameters for graphite occurrence evaluation, and 4) to present and discuss known graphite occurrences in Greenland and their potential.

Participants

At the workshop, 42 geologists participated (Table 1). They came from geological surveys, government institutions, universities and private exploration- and consulting companies, and collectively covered expertise related to the value chain of graphite, graphite deposit types, and graphite deposits in Greenland (Table 1). Given that the workshop did not follow the guidelines set out in the GMRAP an assessment expert panel was not appointed; all participants were free to vote in the scoreboard exercise if they felt comfortable.

Table 1. *Participants attending the workshop.*

Anders Lie, 21st North	Karsten Secher, GEUS
Anna Varga Vass, MMR	Katrine Baden, GEUS
Bjørn Thomassen, GEUS	Kristine Thrane, GEUS
Bo M. Stensgaard, EIT RawMaterials	Lars Brunner, Golder
Casper Mejer, Ofoten Minerals	Lotte Melchior Larsen, GEUS
Christoph Frey, Pro-Graphite	Mark Saxon, Leading Edge Materials
Claus Østergaard, 21st North	Martin Ghisler, GEUS
Diogo Rosa, GEUS	MikkelVognsen, Scandinavian Highlands
Edward Lynch, SGU	Nanna Rosing, UiO
Elin Ryösä, Leading Edge Materials	Nynke Keulen, GEUS
Fiona Reiser, Pro-Graphite	Ole Christiansen, Consultant
Graham Banks, Consultant	Panu Lintinen, GTK
Henrik Stendal, MMR	Per Kalvig, GEUS
Håvard Gautneb, NGU	Rasmus Blomqvist, Beowulf Mining
Jan Steinar Rønning, NGU	Sam Weatherley, GEUS
Janja Knezevic, NGU	Sasha Kerkhof, Acutier
Janne Kuusela, GTK	Sauli Raunio, Beowulf Mining
Jens Gothenborg, Consultant	Stefan Bernstein, GEUS
Jeroen van Gool, Consultant	Timo Ahtola, GTK
John Pedersen, Consultant	Trond Abelsen, Skaland
Jonas Petersen, MMR	Wolfgang Lämmerer, Leoben University

Key literature

Key literature on the deposit models covered by this assessment and on the assessment procedure, were forwarded to the team members prior to the workshop, and is included in the reference list.

Workshop presentations

The first half day of the workshop was used to present and discuss the different types of graphite, the graphite market and the value chain; the afternoon was spend on graphite mines and projects in Scandinavia. The presentations were given by selected speakers and are listed in Appendix A and included as PDF files on the CD-ROM accompanying this report.

Scoreboard approach for the assessment of the Greenland graphite occurrences

The second workshop day was dedicated to discuss the current knowledge of graphite occurrences in Greenland. A scoreboard evaluation was used to assess the progress of each of the occurrences discussed, and replaced the previously undiscovered mineral potential assessment using the USGS approach.

The scoreboard - principles

The graphite occurrences in Greenland encompass both licensed and non-licensed sites. The aim of this workshop was to facilitate a general discussion of the graphite mineral potential in Greenland, but at the same time avoiding to affect the licensed exploration projects. Consequently, the scoreboard does not include any ranking, recommendations nor views on the prospectivity of the occurrences. Thus, the scoreboards are designed to provide information about '*what we know – and what we would like to know in the event we would like to advance the project'*.

Two scoreboards were developed by GEUS prior to the workshop, to be filled in by the workshop participants:

(i) **Progress assessment scoreboard (Table 2):**
The purpose of the progress assessment scoreboard, was to provide a state-of-the-art picture of the known graphite occurrences in Greenland, which should form basis for the discussions on the Greenland graphite resource potential.

The scoreboard includes five parameters: ore quality, ore quantity, beneficiation, market, and plans for exploitation. The main parameters" were broken down into a number of sub-parameters, as shown in Table 2. Background information for this assessment stems from public available information, and presentations given at the workshop. A maximum of 3 points could be allocated to each of the parameters; a zero for no info available and 3 points for advanced information available. For each occurrence, nine parameters/sub-parameters had to be evaluated, consequently a maximum total of 27 points could be achieved. Average figures are presented to overcome the effects of the fluctuation in the number of voting participants. Consequently, a high total score expresses high confidence in the project and vice versa.

Table 2. *Scoreboard parameters applied for the progress assessment*

Aggregated parameters	**Scoreboard parameters**
Ore quality	Grain-character
	Crystallinity
Ore quantity	Grade
	Depth/shape
	Tonnage
Beneficiation	By-products/penalties (chem/phys)
	Beneficiation amenability
Market	Market solutions
Exploitation	Exploitation plans

(ii) **Prioritised recommendations to advance the project (Table 3):**
This scoreboard contained 22 predefined options, but participants were invited to suggest additional tasks (However, only trenching was added to the list during the workshop). The following overall options were available: 1) Laboratory studies such as data integration, petrographic- and chemical analyses; 2) Field campaigns encompassing sampling campaign, geophysics, remote sensing and 3D-modelling; 3) Resource data from trenching and drilling; 4) Metallurgical studies; 5) Market assessments and 6) Economic analyses. Each participant was requested to distribute a total of 10 points to one or more prioritised activities.

Table 3. *Scoreboard parameters applied for the prioritised recommendations*

Aggregated classes	**Scoreboard parameters (filled in by participants)**
Laboratory analyses	Data-integration Petrography SEM XRD Image analyses Chemistry Thermal analysis
Fieldwork / geophysics	Sampling campaign Field mapping Photo-geology/3D model Geophysics Remote sensing
Resource data	Trenching Drilling
Metallurgical tests	Bench scale metallurgical studies Pilot scale metallurgical studies Beneficiation flowsheet optimisation
Market assessments	Market study Marketing of products
Economic analyses	PEA/scoping study Mining engineering study Pre-feasibility study Feasibility study

This progress evaluation approach was meant to be instrumental for MMR and GEUS to provide a status of the graphite exploration projects and to point to relevant actions that could ultimately lead to exploitation. Therefore, the floor was open for discussions prior and after each voting-session.

Scoreboard exercise - participants

As opposed to the GMRAP workshops, in which an expert panel is assigned, all workshop participants were invited to fill in the two scoreboard forms. This approach was chosen because, assessment and development of graphite occurrences depends on an adequate and wide range of expertise, which only rarely are represented by individuals; we consider the workshop participants to collectively accommodate such a pool of relevant expertise. Participants who find themselves not qualified were free to abstain from voting. The number of experts diminished in course of the workshop due to fixed transport itineraries, forcing some participants to leave the workshop before all scoreboard exercises were concluded. Therefore the number of expert assessments varies between 24 and 10. Individual scores were provided anonymously.

Occurrences assessed

Prior to the workshop, a list of 12 graphite occurrences were selected for scoreboard assessments, out of which only seven occurrences were assessed, due to time constraints (see Table 4). Occurrences not encompassed in the scoreboard assessment, are all occurrences from which very little information is recorded.

Table 4. *Greenlandic graphite occurrences, selected for the scoreboard exercise. Time limitations prevented assessments of all sites.*

Graphite occurrence	Presenter	Scoreboard
Auppaluttoq	A. Lie	Yes
Akuliaruseq	C. Østergaard	Yes
Amitsoq	J. van Gool	Yes
Giesecke (also called: Eqalussuit E)	C. Østergaard	Yes
Illukulik	O. Christiansen	Yes
Kangerluk	O. Christiansen	No
Kangikajik	N. Rosing-Schow	Yes
Langø	B. Thomassen	No
Niaqornat	L.M. Larsen	No
Qaarsut	L.M. Larsen	No
Sissarissoq	J. van Gool	Yes
Thule- Inglefield Land	B. Thomassen	No

Scoreboard results

Progress evaluation

The scores for the seven Greenland graphite occurrences included varies between 1.9 for the Illukulik and up to 10.9 for the Akuliaruseq occurrence, which for the latter is about 40 % of the maximum score (Figure 3). These fairly low scores, aligns very well with the views expressed by geologists over the past decades – that there are many indications about graphite in Greenland, but the knowledge on each of the occurrences is rather limited.

Based on the aggregated parameters for the seven occurrences included in the survey (Table 2), it can be concluded that the participants did not find that adequate and/or convincing data were presented regarding neither the quality of the graphite nor the volume of the occurrence, and, therefore, were uncertain about the viability of the occurrence.

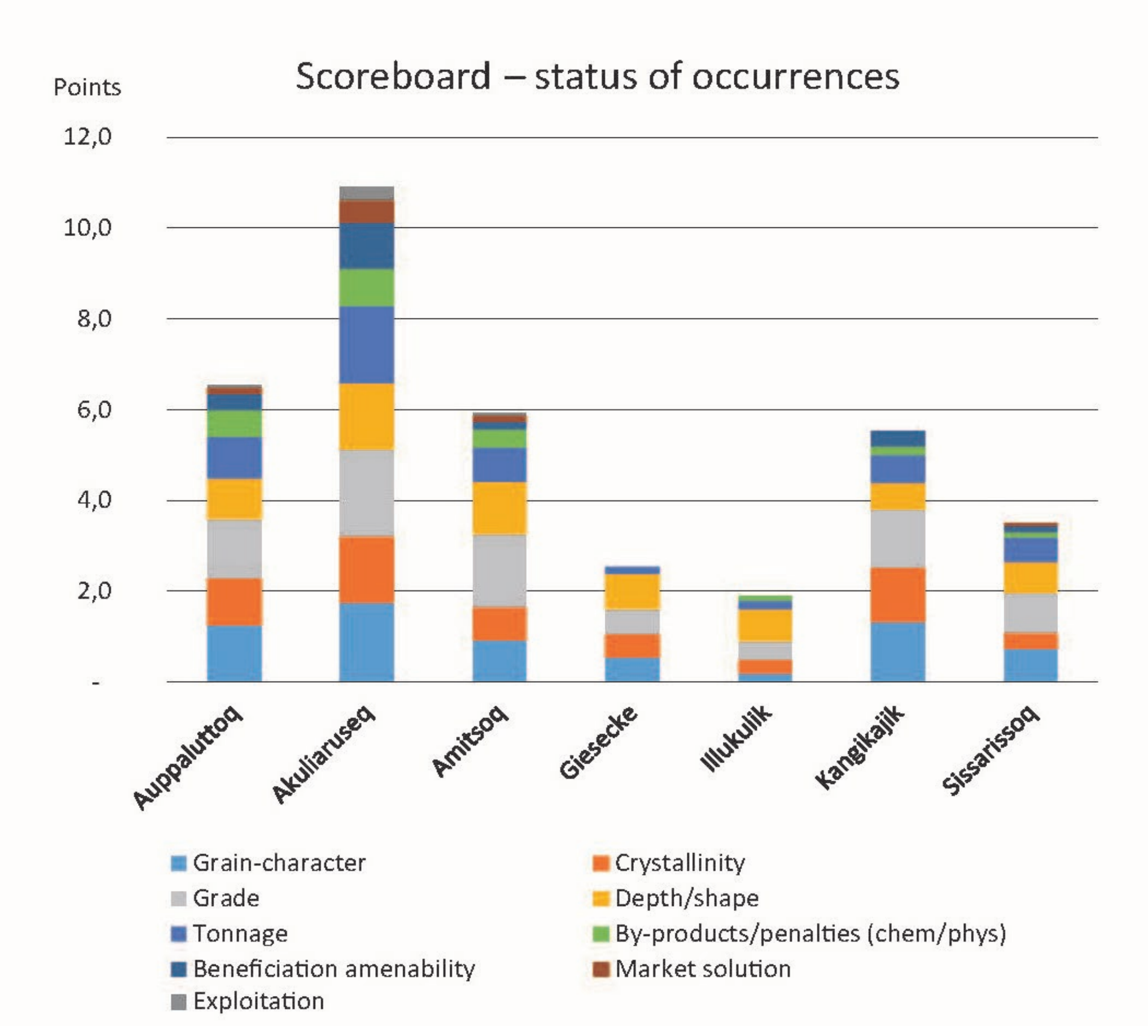

Figure 3. *Average scoreboard points obtained for each occurrence, showing how the knowledge status was evaluated for the seven occurrences included in the assessment.*

Recommendations

The recommendations (Table 5 and Figure 4) reflect the low level of knowledge of the graphite potential in Greenland. The recommendations for most of the projects follow the traditional geological knowledge build up, starting with fieldwork such as mapping, sample collection and geophysics. Secondly, more laboratory analyses of the collected samples such as geochemistry, petrography etc. Followed by trenching and drilling and metallurgical tests. For the more advanced projects, especially Akuliaruseq but also Amitsoq, the fieldwork is not such a high priority as this has already been carried out. Metallurgical tests and laboratory studies are prioritised instead.

Table 5. *Scoreboard recommendations – Conclusions; aggregated data (see Table 3)*

	Aup-paluttoq	Aku-liaruseq	Giesecke	Amitsoq	Sissarissoq	Kangikajik	Illukulik
	%	%	%	%	%	%	%
Lab studies	14	17	36	29	27	19	14
Fieldwork /geophys	55	7	46	31	64	58	84
Resource data	15	18	4	17	2	3	-
Metallurgical tests	12	26	10	17	3	12	2
Market assess-ments	-	15	-	1	1	1	-
Economic studies	4	17	4	4	3	7	-

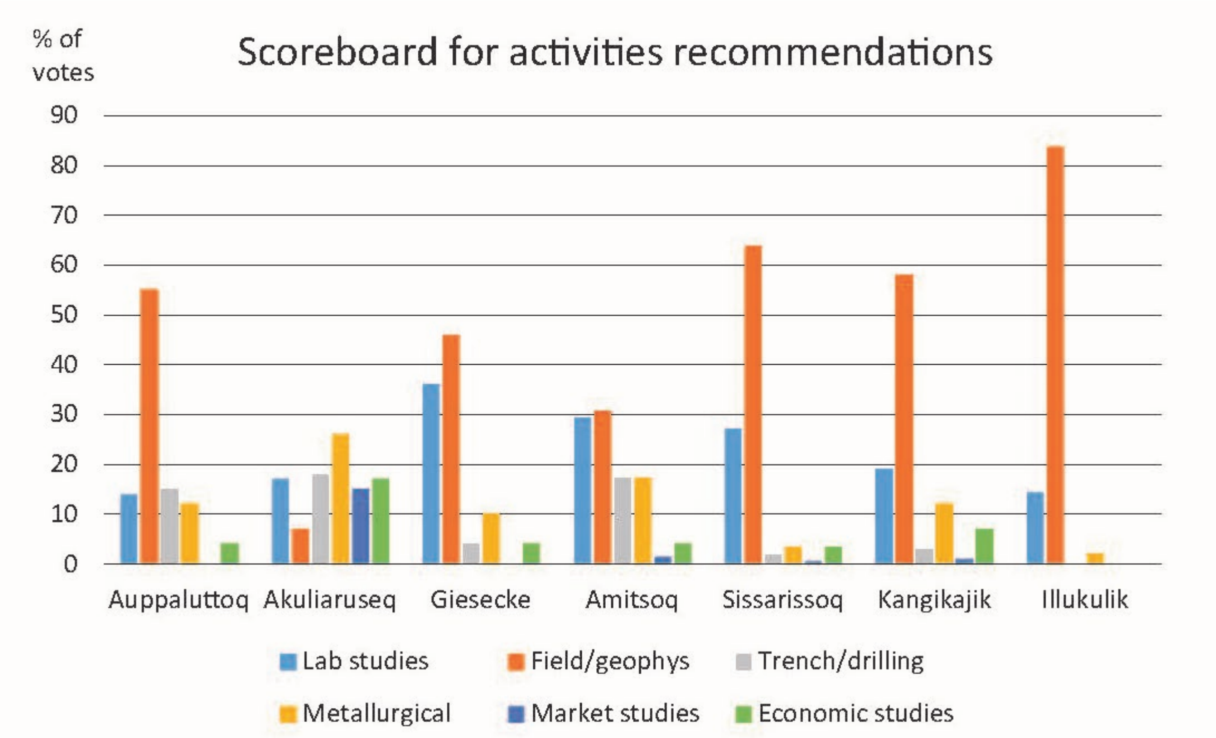

Figure 4. *Scoreboard showing which activities the participants recommended for the seven occurrences included in the assessment.*

Graphite occurrences

Occurrences of graphite and graphite schist have been reported from many localities in Greenland (Bondam 1992, Stensgaard et al. 2016).

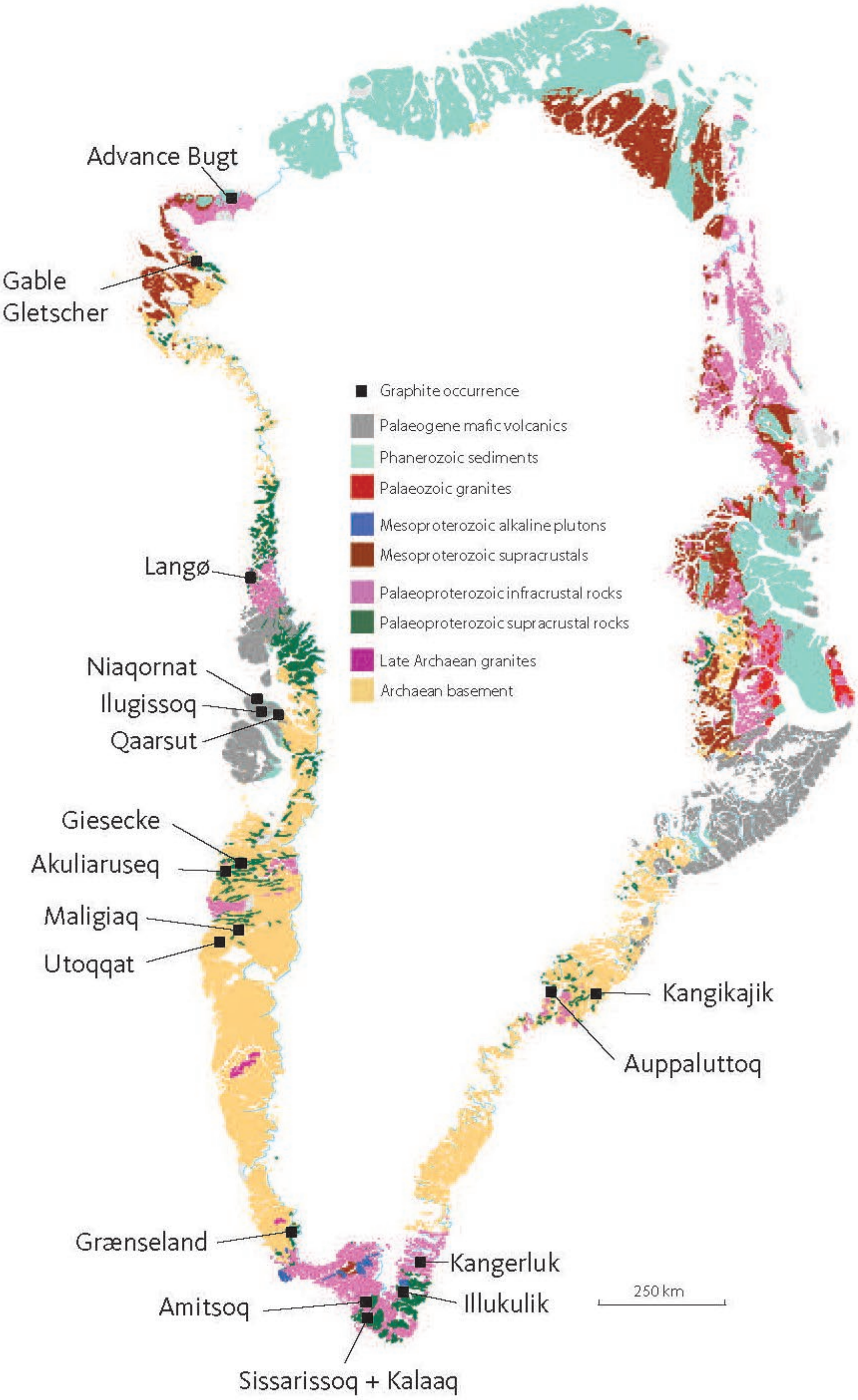

Figure 5. *Main lithostratigraphic units in Greenland with location of known graphite occurrences.*

South Greenland

Amitsoq

The Amitsoq Island north of Nanortalik, in South Greenland, hosts the former Amitsoq graphite mine. Several graphite showings are also reported in the surrounding Nanortalik region (Figure 6). The graphite at Amitsoq (Figure 7) 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 c. 29 %. 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 (Ball 1923 and Bondam 1992). 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.

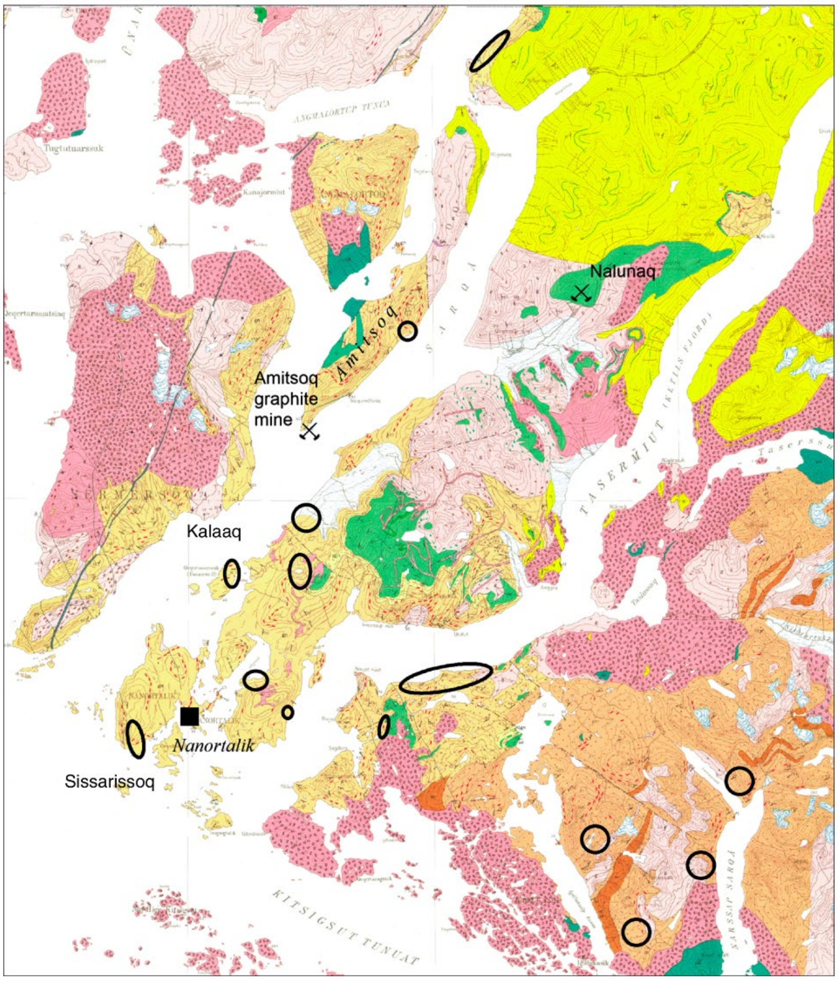

Figure 6. *Geological map with the location of the Amitsoq graphite mine and the additional 14 graphite occurrences discovered by Bernard (1915) in the Nanortalik Region. The new Kalaaq showing was discovered by Alba Resources. (From presentation by van Gool 2017).*

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.

Figure 7. *Amitsoq Island and Amitsoq graphite mine, near the shore. (Photo: van Gool)*

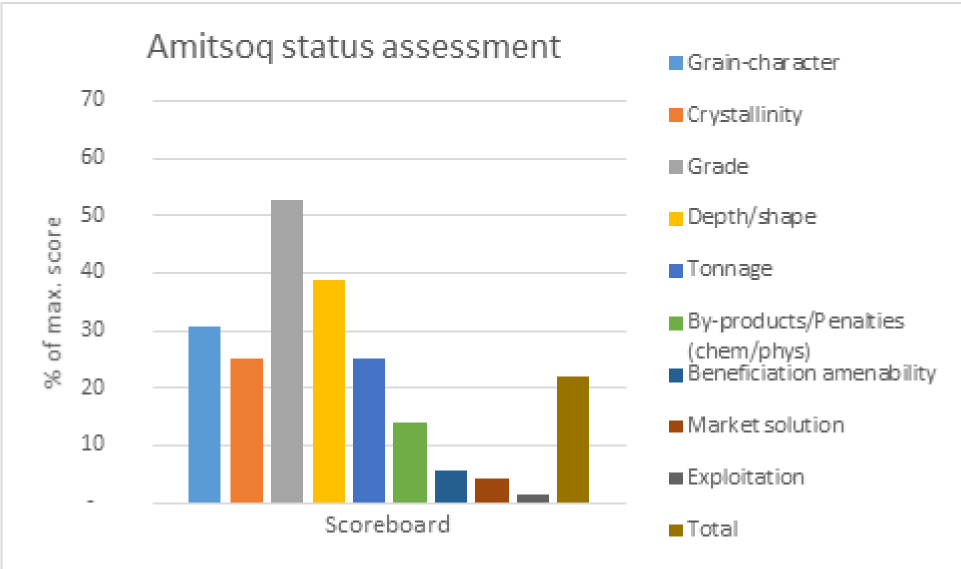

Figure 8. *Scoreboard results indicating the current progress for the Amitsoq occurrence. Average scores shown as % of total for each parameter.*

Results for the Amitsoq graphite occurrence (Figure 8) reflect the long history of the project, providing a relatively high score related to the ore quality and the volume of the occurrence, although the overall score is not significant. It should be noted, that the license holder did not participate in the workshop and thus it is likely that more detailed data/information would have changed the result.

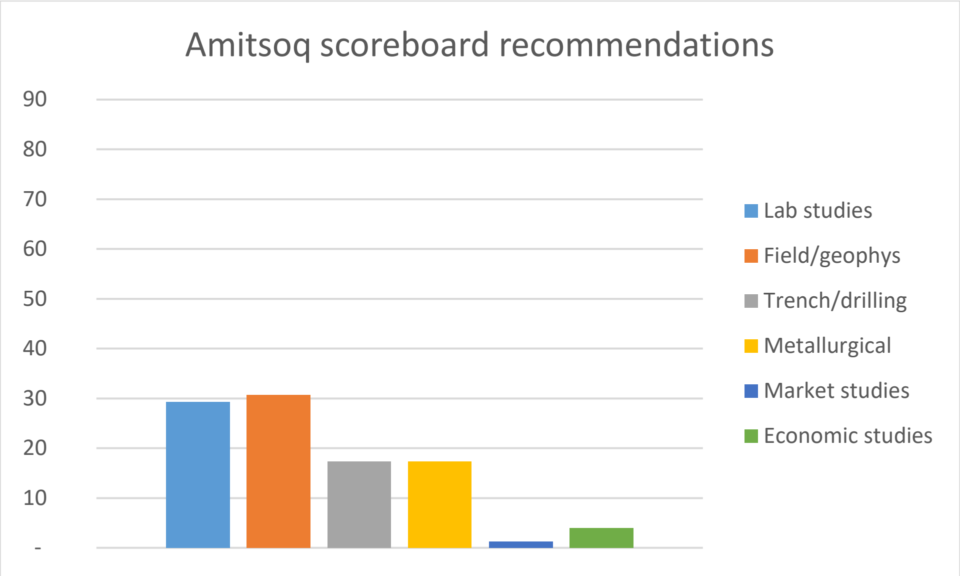

Figure 9. *The scoreboard of prioritised recommendations (% of the max. 10 points) for the Amitsoq occurrence.*

Recommendations for the Amitsoq occurrence (Figure 9) show that, in particular, additional work testing the quality of the graphite and additional field observations, in combination with more target drilling are recommended; further it is also recommended to gain more metallurgical information.

Nanortalik region incl. Sissarissoq and Kalaaq

The Nanortalik region surrounding Amitsoq hosts numerous laterally extensive systems of graphite occurrences (Figure 6), 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. One of the richest of the occurrences is Sissarissoq, west of Nanortalik. It is a graphite-rich lens, 30 m long and 1.5 m wide, 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 the new Kalaaq showing. 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.

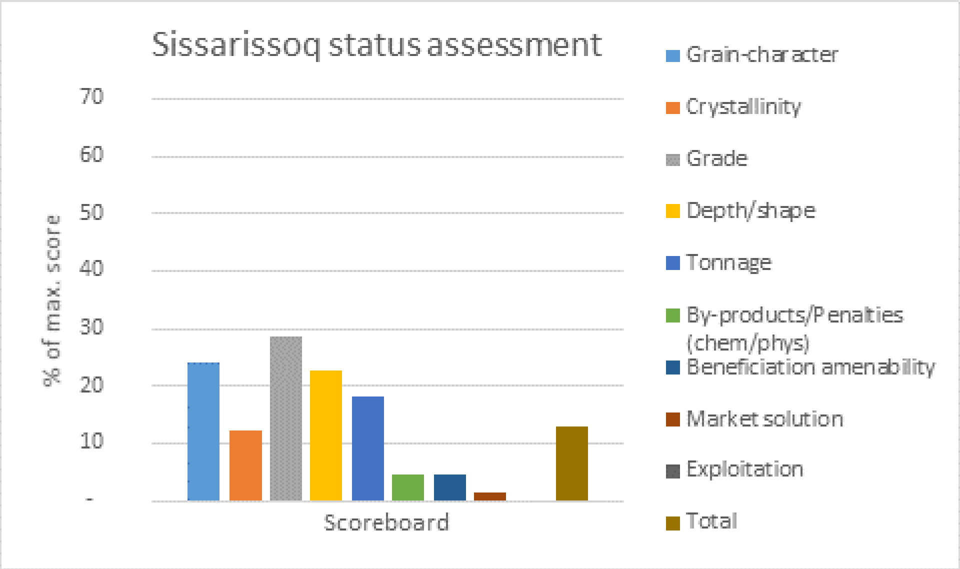

Figure 10. *Scoreboard results indicating the current progress for the Sissarissoq occurrence. Average scores shown as % of total for each parameter.*

Very little information was available for the assessing the current progress status of the Sissarissoq, which is also reflected in the low total score (Figure 10).

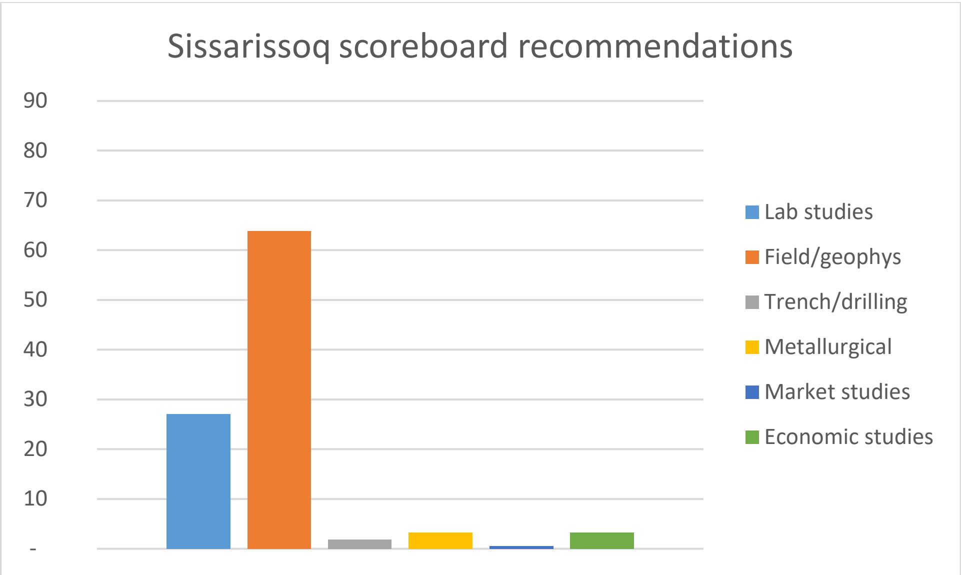

Figure 11. *The scoreboard of prioritised recommendations (average of total 10 points in %) for the Sissarissoq occurrence.*

The scoreboard of prioritised recommendations for Sissarissoq highlights the need to initiate investigations aimed at gaining more information about the quality and the geological setting of the graphite (Figure 11).

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.

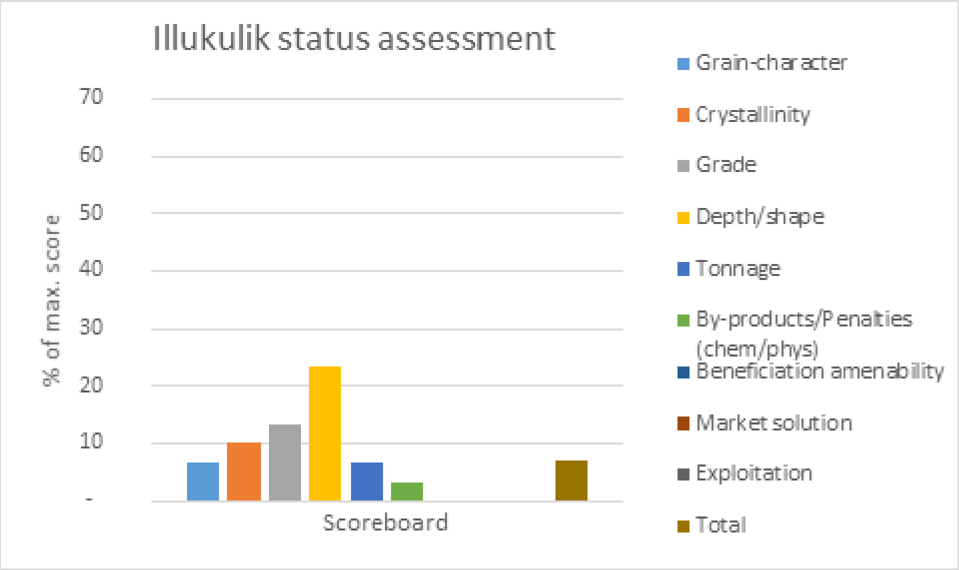

Figure 12. *Scoreboard results indicating the current progress for the Illukulik occurrence. Average scores shown as % of total for each parameter.*

Very little information was available for the assessing the current progress status of the Illukulik, which is also reflected in the low total score (Figure 12).

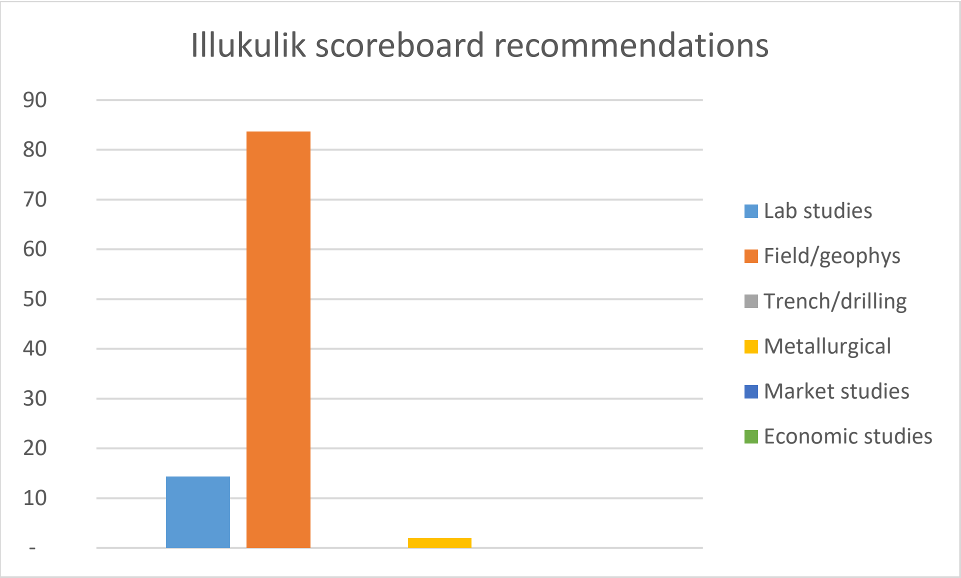

Figure 13. *The scoreboard of prioritised recommendations (average (%) of the scores) for the Illukulik occurrence.*

The scoreboard of prioritised recommendations for Illukulik strongly highlights the need for additional fieldwork/ geophysical surveys to be undertaken; additionally, it is recommended to undertake more laboratory work on existing material (Figure 13).

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 (Berthelsen & Henriksen 1975).

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 1–10 m. In the beginning of the 1900, 80 tonnes of sample material, from two closely spaced graphite-bearing zones, were sampled at regular intervals and reported to yield 21 % Cg and 5.5 % S. Further to the east, at Maligiaq, graphite-bearing mica schists have been sampled over a distance of 800 m, with a carbon content in graphite ranging from 5 % to 25 % Cg (Kalvig 1994).

Akuliaruseq

In the Nordre Strømfjord region, West Greenland, graphite is abundant in Palaeoproterozoic sulphide-rich supracrustal rocks (Fig. 14). 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 ca. 1.85 Ga Nagssugtoqidian Orogeny (Bondam 1992). 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 (Figure 15). The graphite occurrence was investigated by Kryolitselskabet Øresund A/S between 1982 and 1986 (Morthost & Keto 1984). This company 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.

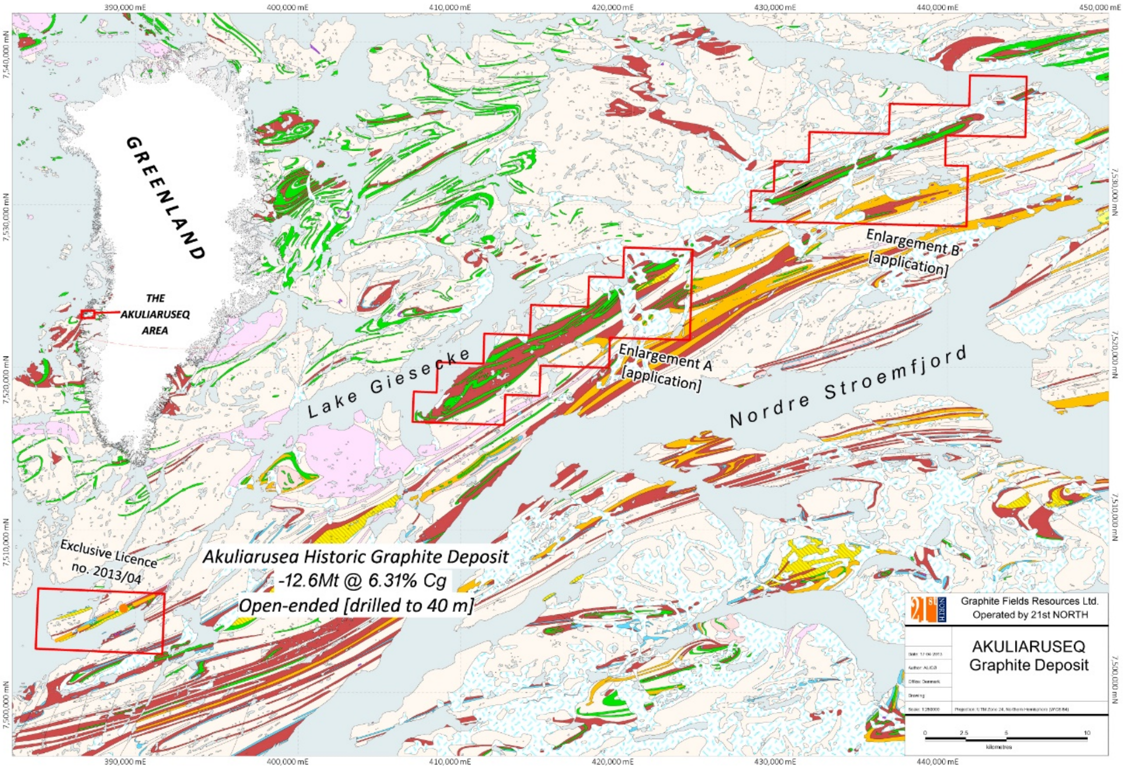

Figure 14. *Geological map of the Nordre Strømfjord region with Akuliaruseq occurrence to the left, and enlarges in Figure 13. The Giesecke occurrence in the middle red square, Ataneq in the red box to the right (Source: 21st North 2013).*

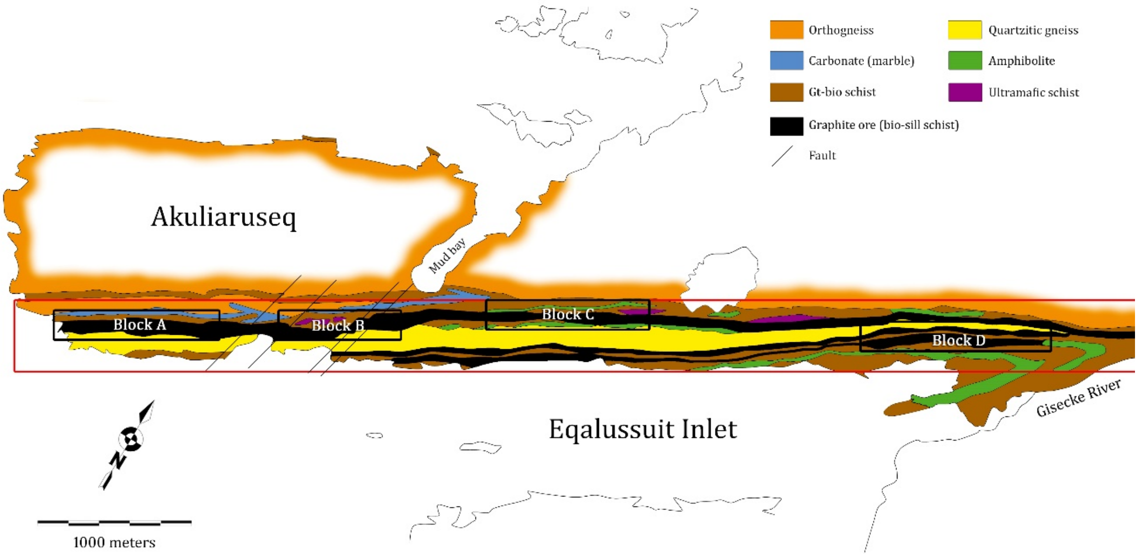

Figure 15. *Geological map of the Akuliaruseq area. (Source: 21st North, workshop presentation)*

Two different types of graphite occur: 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 35–60 m, but this encompasses 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. (2016), predicts a graphite resource of 12.6 million tonnes grading 6.3 % Cg including a high-grade zone encompassing 8.9 million tonnes grading 7.6 % Cg. Figure 16 shows geochemical sampling on the occurrence by current licence holder.

Figure 16. *Sampling at the Akuliaruseq occurrence, carried out by Graphite Field Resources. (Photo: 21st North.)*

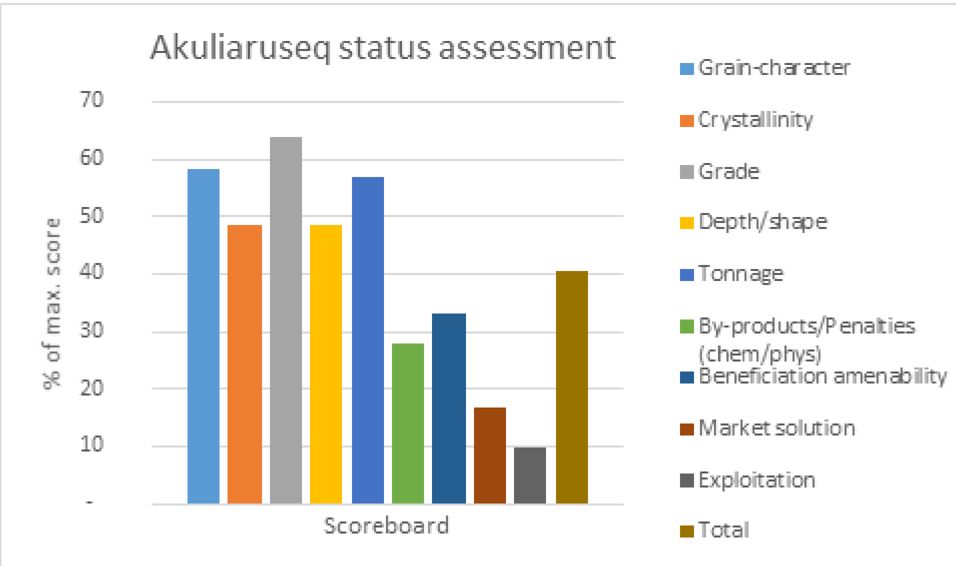

Figure 17. *Scoreboard results indicating the current progress for the Akuliaruseq occurrence. Average scores shown as % of total for each parameter.*

Akuliaruseq is one of the occurrences, which has been studied in more detail. This is reflected in scoreboard (Figure 17), which shows a relatively high score related to the ore quality and the volume of the occurrence as well as the beneficiation,

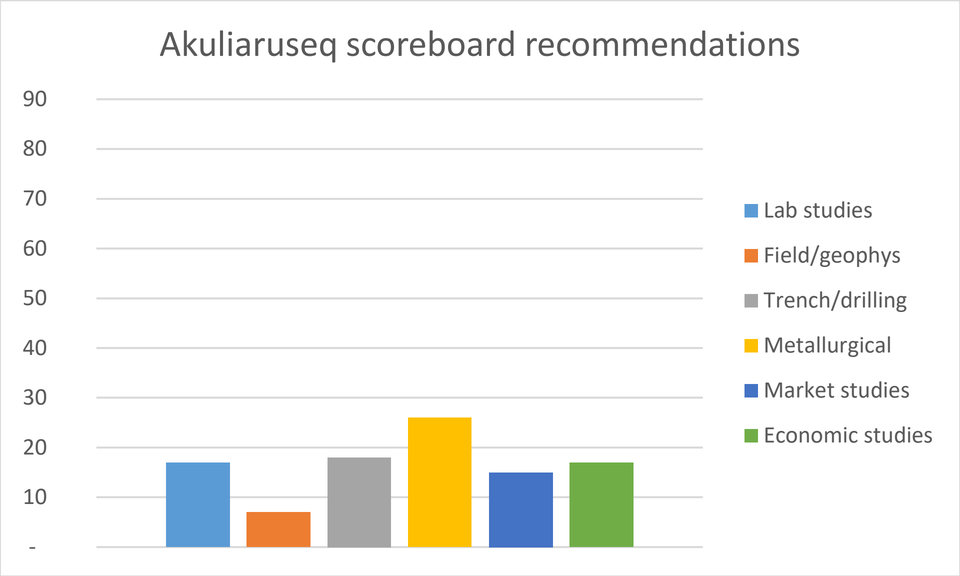

Figure 18. *The scoreboard of prioritised recommendation (average (%) of 10 total points allocated) for the Akuliaruseq occurrence.*

The scoreboard of prioritised recommendations for Akuliaruseq, reflects that this is an advanced graphite project (Figure 18). The recommendation is to carry out more work on all parameters, except for fieldwork and geophysics; in particular it is recommended to undertake more metallurgical work and various kinds of viability analysis in order to advance the project.

Giesecke

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

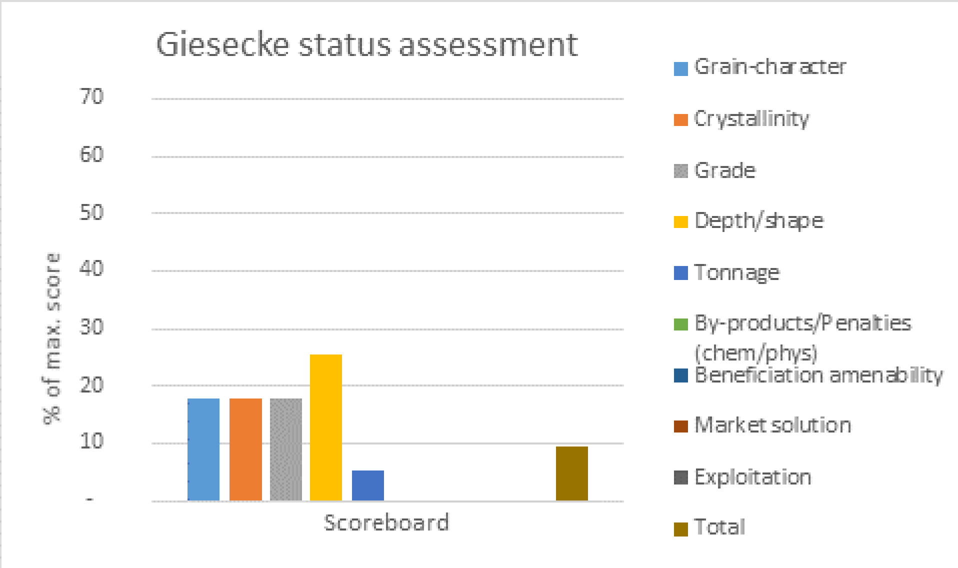

Figure 19. *Scoreboard results indicating the current progress for the Giesecke occurrence. Average scores shown as % of total for each parameter.*

Very little information was available for the assessing the current progress status of the Giesecke, which is also reflected in the low total score (Figure 19).

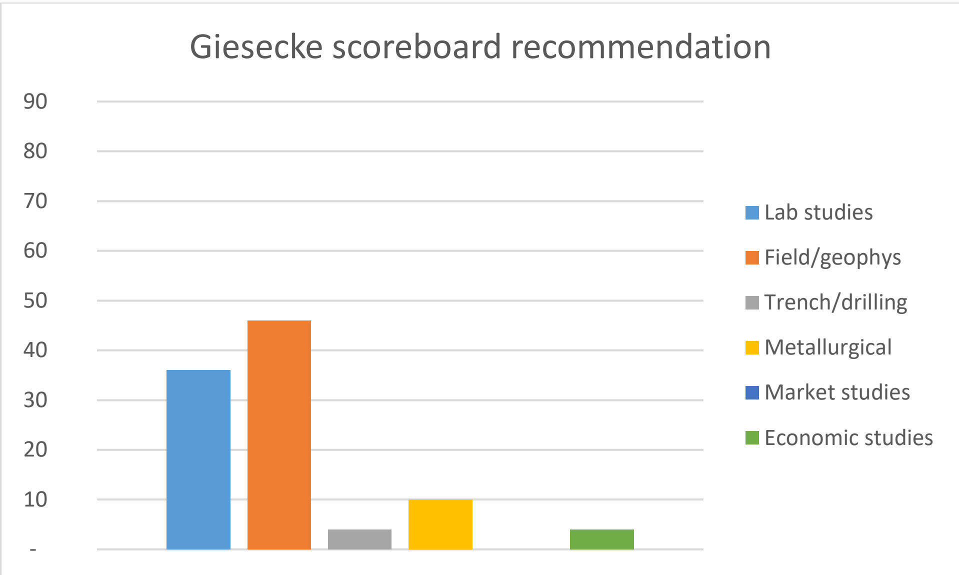

Figure 20. *The scoreboard of prioritised recommendation (average (%) of total points allocated) for Giesecke.*

The scoreboard of prioritised recommendations for Giesecke recommends to gain more information about the quality and the geological setting of the graphite (Figure 20).

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 (Bondam 1992).

Langø, Upernavik

South of Upernavik, graphite occurs as lenses and veins in pelitic and garnet-bearing schist at the island Langø and adjacent areas (Figure 5) (Lindås 1915; Ball 1923). The host rock is a pegmatite intruding the Palaeoproterozoic Karrat Group at the end of the ca. 1.85 Ga Nagssugtoqidian-Rinkian Orogeny. The area experienced high-grade metamorphism during the Nagssugtoqidian-Rinkian Orogeny.

Figure 21. *Old graphite pit at Langø. (Photo: Thomassen, GEUS).*

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 (Høeg 1915). 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. To-day, five abandoned pits are still visible (Fig 21). They are 1-3 m wide and 5-15 m long and a couple of meters deep (Thomassen et al. 1999).

North Greenland

Gable Gletscher, Thule District

The Palaeoproterozoic Prudhoe Land supracrustal complex (Figure 5 and 22) hosts hydro-thermally overprinted, pyrite- and graphite-rich schists with large rust zones estimated to contain 10-20 % of graphite (Thomassen et al. 2002). However, the area is underexplored and needs closer investigation to study the potential for graphite. A section at Gable Gletscher (Figure 23) was studied for graphite and returned values of 8.5 and 3.9 % Cg, which are considered as minimum values.

Figure 22. *Typical colour anomaly in the Prudhoe Land supracrustal complex. View east-wards with Gable Gletscher in the background. (Photo: Thomassen et al. 2002).*

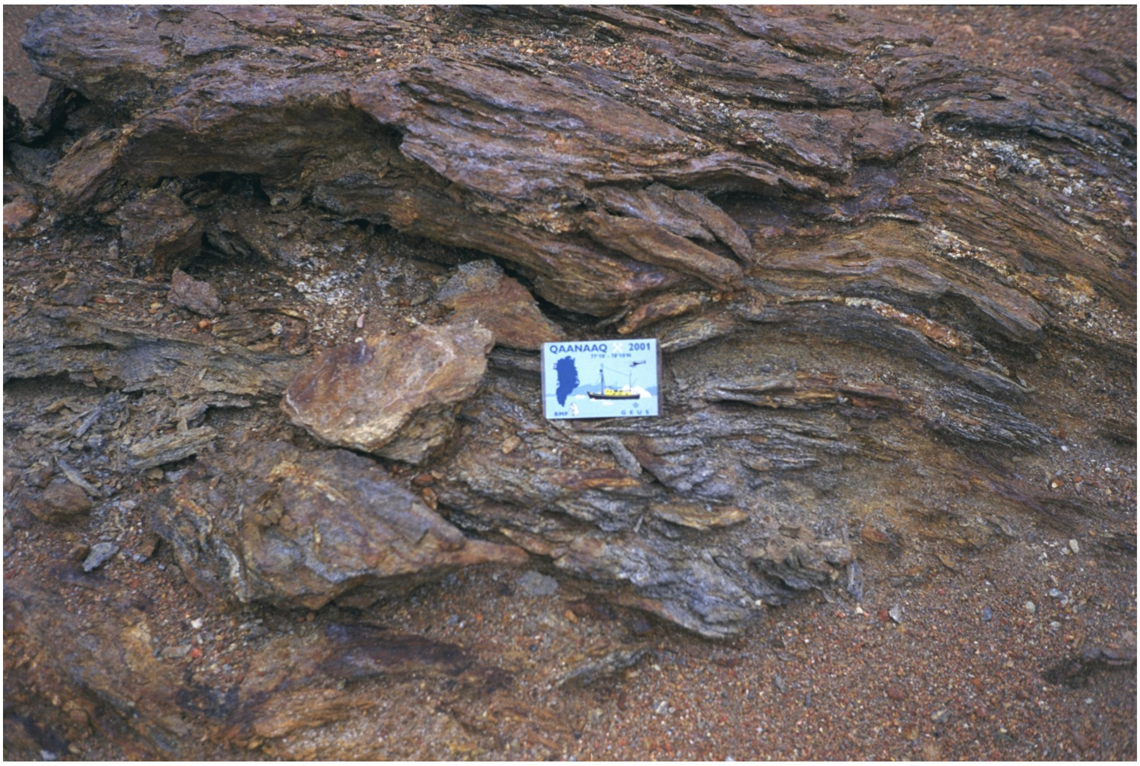

Figure 23. *Typical graphite-pyrite schist, west of Gable Gletscher. Logo is 8.5 cm. (Photo: Thomassen et al. 2002).*

Advance Bugt, Inglefield Land

The Palaeoproterozoic Etah Group of Inglefield Land (Figure 5) 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 ca. 5 vol. % Cg. Three samples were measured and contain 2.4 % Cg. The occurrence at Advance Bugt was found by Rio Tinto Mining and Exploration Ltd. in 1991 (Sharp 1991) and studied further by GEUS in 1995 (Thomassen & Appel, 1997; Pirajno et al. 2003).

East Greenland

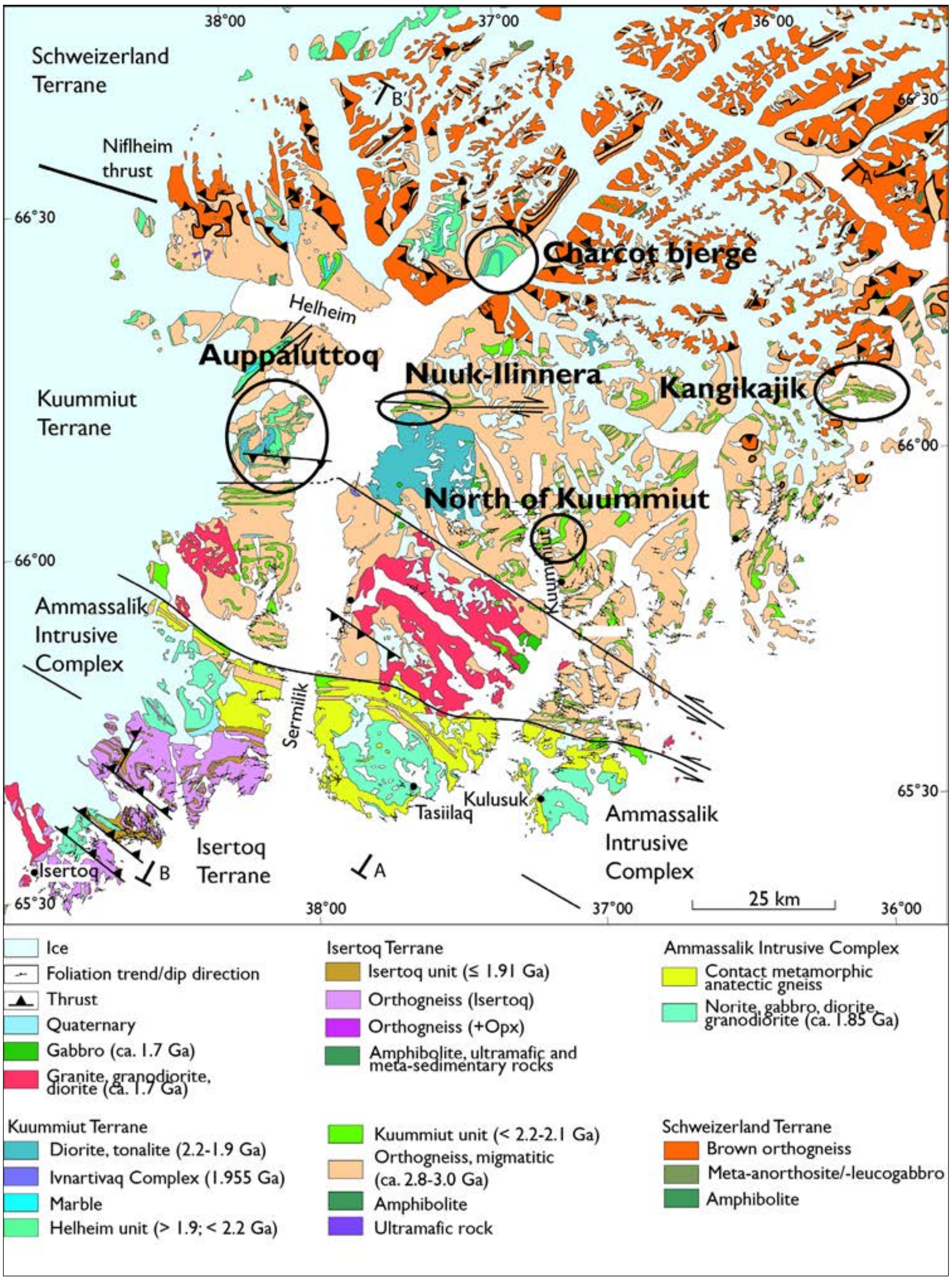

Figure 24. *Geological map of the Ammassalik mobile belt, with the Auppaluttoq and the Kangikajik occurrence. (Source: Rosing-Schow et al. 2017).*

Auppaluttoq

The Aappaluttoq area is located in the Palaeoproterozoic mobile belt of Ammassalik, about 60 km north-west of Tasiilaq (Figure 5). Graphite-bearing supracrustal rocks, including biotite and quartzitic schists, outcrop along the coast west of the Sermilik Fjord (Bondam 1992). The schists are brownish to greenish grey and fine to medium grained. The graphite occurs as mm thick layers and films alternating with biotite. The flakes range in length from 1-6 mm, with the most common size being 3-4 mm. At 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 thee separate ridges for approximately 750-1000, 1500 and 2000 meters (Figure 25). The last licence holder, Graphite Field Resources Ltd. (2015), made two new profiles 400 m apart. The analyses yielded a weighted average of 2.3 % Cg over 13.2 meters and 7.6 % Cg over 14.5 meters. High-grade grab samples of semi-massive graphite-schist yielded 10.4 to 30.4 % Cg.

Figure 25. *Outcropping semi-massive graphite-schist mostly rusty and coated by iron sulphate. (Photo: 21st North)*

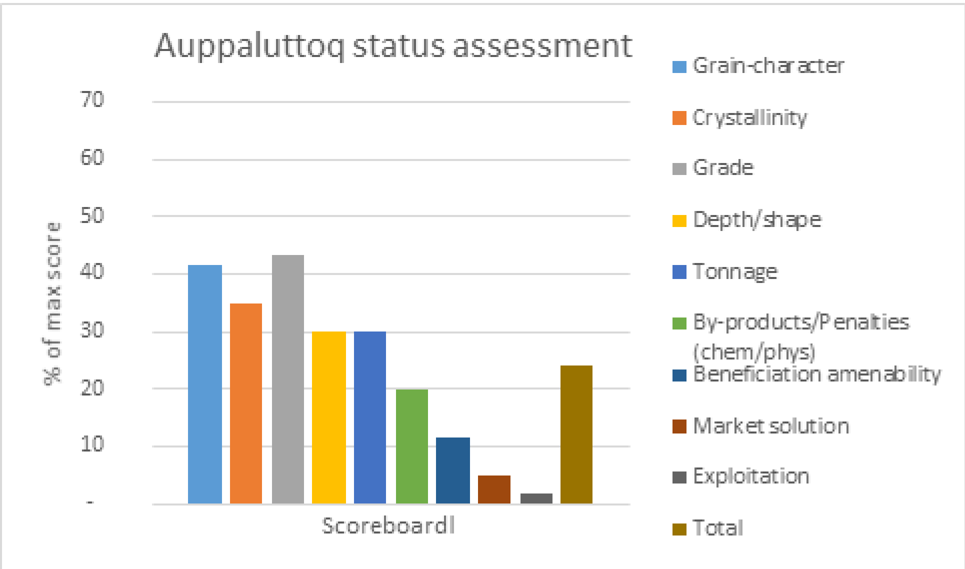

Figure 26. *Scoreboard results indicating the current progress for the Auppaluttoq occurrence. Average scores shown as % of total for each parameter.*

The current progress status of the Auppaluttoq, yields a rather low total score. However, providing a relatively high score related to the ore quality and the volume of the occurrence (Figure 26).

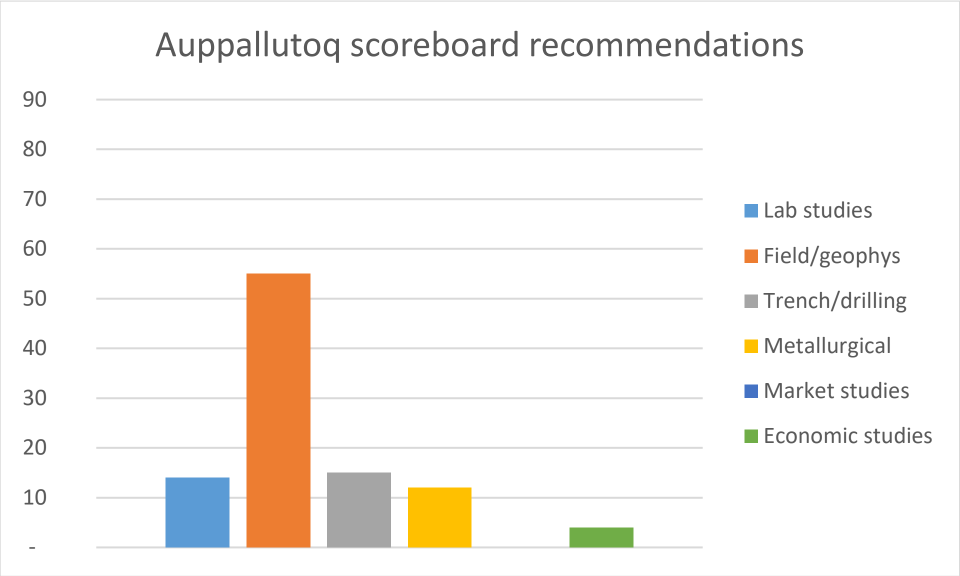

Figure 27. *The scoreboard of prioritised recommendations (average (%) of total points allocated) for Auppaluttoq.*

The scoreboard of prioritised recommendations for Auppaluttoq indicates that more information on the volume and quality of the occurrence is recommended in order to advance the project further (Figure 27).

Kangikajik

Kangikajik peninsula, 100 km north-east of Tasiilaq, is also part of the Palaeoproterozoic mobile belt of Ammassalik (Figure 5). 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 outward from the shear zones and the highest concentrations occur in the largest shear zones (Figure 28 and 29). 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). Metallurgical 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 (Kalvig 1992).

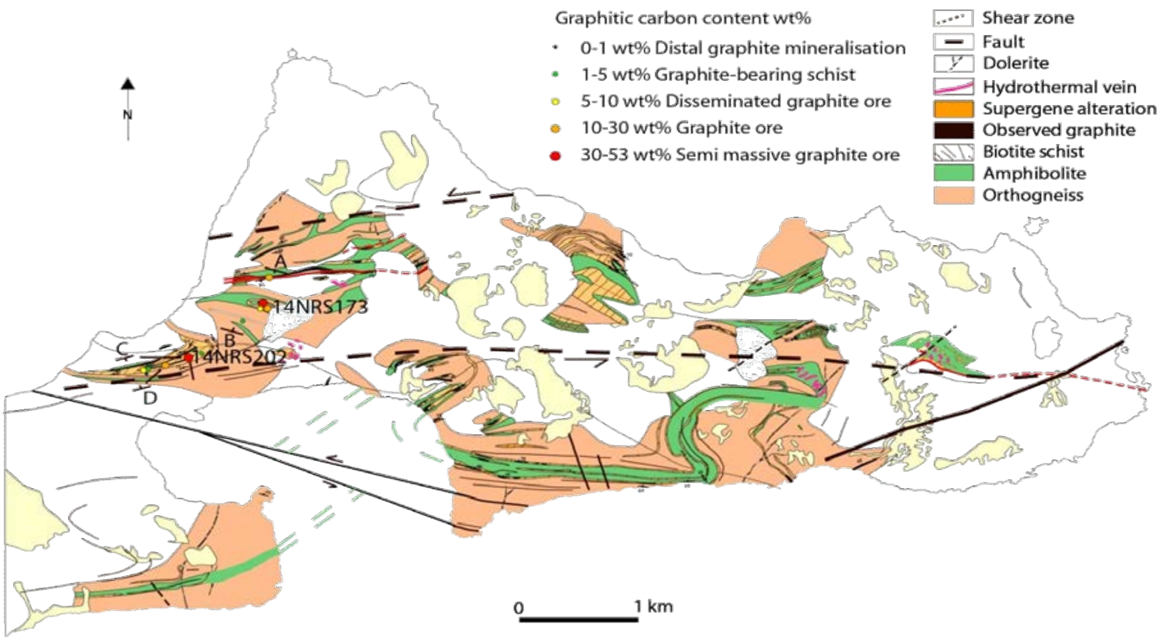

Figure 28. *Geological map of Kangikajik. (Source: Rosing-Schow et al. 2017).*

Figure 29. *Graphite mineralisation at Kangikajik. (Photo: Rosing-Schow et al. 2017).*

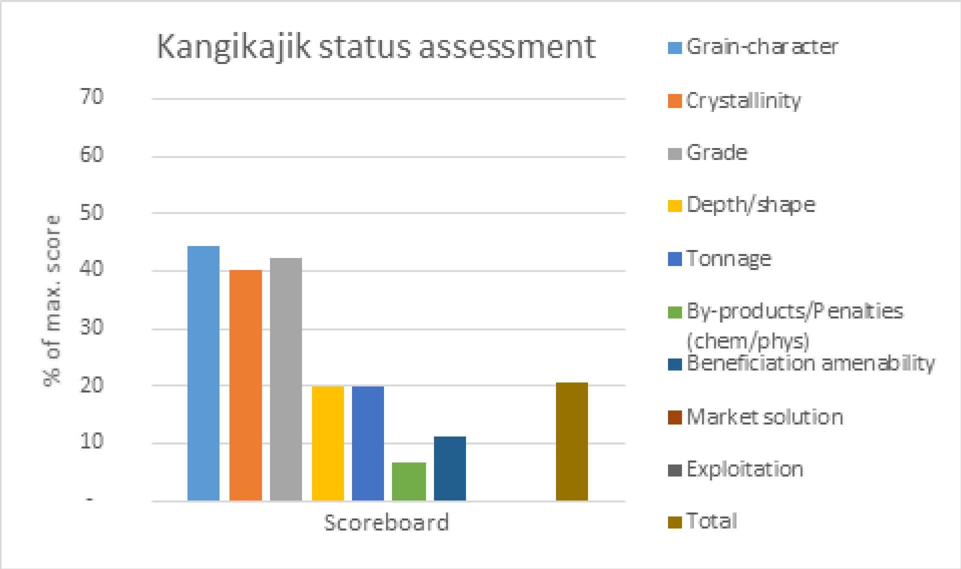

Figure 30. *Scoreboard results indicating the current progress for the Kangikajik occurrence. Average scores shown as % of total for each parameter.*

Very little information was available for the assessing the current progress status of the Kangikajik, which is also reflected in the low total score (Figure 30).

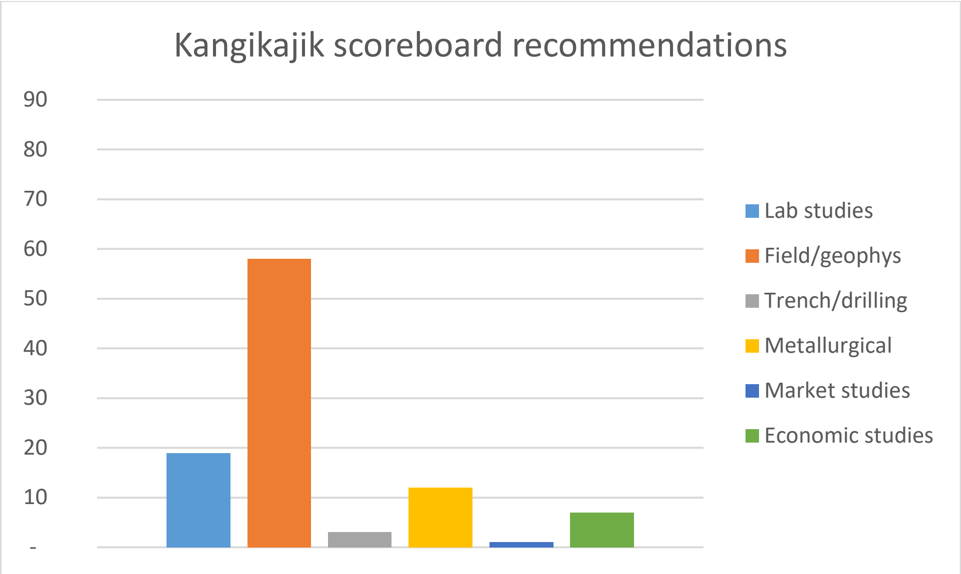

Figure 31. *The scoreboard of prioritised recommendations (average (%) of total points allocated) for Kangikajik.*

The scoreboard of prioritised recommendations for Kangikajik recommends in particular more fieldwork and sampling, and additional investigations of the quality of the graphite. Additionally, it is recommended to gain more metallurgical data (Figure 31).

Conclusions

Graphite exploration and exploitation has taken place in Greenland for decades, but only recently, the graphite potential has attracted renewed interest by the exploration groups.
A total of 12 graphite occurrences in Greenland were selected for scoreboard assessments, of which five are licensed for exploration. However, due to time constraints, only seven occurrences were assessed; very little information is available for this remaining group.

The workshop reached the conclusion that the five licensed occurrences are at a fairly early stage of exploration, and the data regarding the quality of the graphite and the volume of these occurrences, are inadequate to assess their viability. For the non-licensed group even less data are available, and the prospectivity remain unknown.

From the discussions and the scoreboard results it appears obvious that previous investigation has taken a classical metal exploration approach – focusing on grade and extension of the ore. As a result the quality of the graphite – which is a key parameter in the assessment - is not adequately described; for the same reason, the scoreboard point to the importance of metallurgical tests and laboratory studies. Only if the quality of the graphite is confirmed, should activities leading to the establishment of the volume and 3D extension of the occurrence take place.

The workshop supported the view, that Greenland carries the potential to host numerous high quality graphite occurrences, but turning this potential into active mining operation will require substantial dedicated graphite exploration campaigns.

Acknowledgments

The authors would like to thank all the individuals from the industry, academia, MMR and GEUS that have been involved in the assessment workshop for graphite occurrences and deposits in Greenland, and participated in the discussions. A special thanks to all the presenters, without their valuable input the assessment workshop would not have been possible.

References

21st NORTH 2013: Akuliaruseq, West Greenland. Field report.

Ball, S.H. 1923: The mineral resources of Greenland. Meddelelser om Grønland 63, 1, 1-60.

Berthelsen, A. & Henriksen, N. 1975: Geological map of Greenland 1:100,000 Ivigtut 61 V.1 Syd. The orogenic and cratongenic geology of a Precambrian Shield area. Grønlands Geologiske Undersøgelse.

Bernard, C. 1915: Report on Prospecting, South Greenland.

Bondam, J. 1992: Graphite occurrences in Greenland – a review. Open file series 92/6. Geological survey of Greenland.

Bøggild, O.B. 1953: The mineralogy of Greenland. Meddr. Grønland 149, 3, 422 pp.

Graphite Field Resources/21st NORTH 2016: The Akuliaruseq Graphite deposit, Nordre Strømfjord West Greenland.

Graphite Fields Resources/21st NORTH, 2015: The Auppaluttoq flake graphite prospect, Southeast Greenland.

Høeg, E. 1915: Extrakt af Grafitrapporter, Grønlands Minedrift (A/S (in archives of Geological Survey of Denmark and Greenland, GEUS Report File 21148), 11 pp.

Kalvig, P. 1992: Geologiske undersøgelser af grafitforekomsten Kangikajik, Tasiilaq Kommune. Internal report, Tasiilaq Kommune, 41.

Kalvig, P. 1994: Industrial mineral occurrences in Greenland – a review. GGU Open file Series 94/4, 94.

Lindaas, G. 1915: Rapport over expeditionen til Upernavikdistriktet. sommeren 1915. Internal report, Grønlands Minedrifts A/S, 25 pp. (GRF no. 21150).

Morthost, J. & Keto, L. 1984: Report on the graphite exploration in Aluliaruseq area. 1983. Internal report, Kyoliteselskabet Øresund A/S. Vol. 1, 29 pp. 22 plates. Vol. 2 (drilling statistics and core-logs).

Nielsen, B.L. 1973: A survey of the economic geology of Greenland (exclusive fossil fuels). Rapp. Grønl. Geol. Unders. 56, 45 pp.

Pirajno, F., Thomassen, B. & Dawes, P.R. 2003: Copper-gold occurrences in the Palaeoproterozoic Inglefield mobile belt, northwest Greenland: a new mineralisation style? Ore Geology Reviews 22, 225-249.

Rosing-Schow, N., Bagas, L., Kolb, J., Balic-Zunic, T., Korte, C. & Fiorentini, M.L. 2017: Hydrothermal flake graphite mineralization in Paleoproterozoic rocks of south-east Greenland. Miner. Deposita 52, 769-789.

Sharp, G. 1991: Gossan search on Inglefield Land, North West Greenland, 22 p. Unpublished report, RTZ Mining and Exploration Ltd., Bristol, UK, GRF. No. 21084.

Simandl, G.J. 2015: Graphite deposit types, their origin, and economic significance. British Columbia geological survey paper 2015-3.

Steensgaard, B.M., Stendal, H., Kalvig, P. & Hanghøj, K. 2016: Review of potential resources for critical minerals in Greenland. Center for minerals and materials report, 2016/3.

Taylor Jr., H.A. 2006: Graphite. In: Kogel, J.E., Trivedi, N.C., Barker, J.M. & Krukowski, S.T. (eds): Industrial minerals and rocks. 7th edition, 507-518.

Thomassen., B. & Appel, P.W.U. 1997: Ground check of airborne geophysical anomalies and regional rust zones in Inglefield Land, North-West Greenland. Danmarks og Grønlands Geologiske Undersøgelse Rapport 1997/141, 43 pp.

Thomassen, B., Krebs, J.D. & Dawes, P.R. 2002: Qaanaaq 2001: mineral exploration in the Olrik Fjord – Kap Alexander region, North-West Greenland. Danmarks og Grønlands Geologiske Undersøgelse Rapport **2002/86**, 72 pp.

Thomassen, B., Kyed, J. & Tukiainen, T. 1999: Upernavik 98: Mineral exploration in the Upernavik – Kap Seddon region, North-West Greenland. GEUS report 1999/35, 72 pp.

Appendix A: CD-ROM - Presentations from the workshop

Presenter	Title	Presentation number (on CD)
Per Kalvig (GEUS)	Intro to the Graphite workshop	1
Christoph Frey (ProGrapite)	Market sectors –demand and specifications	2
Christoph Frey (ProGrapite)	Supply Chain	3
Wolfgang Lämmerer (University of Leoben)	Graphite beneficiation, recycling, substitutions	4
Fiona Reiser (ProGraphite)	Geological settings of graphite deposits	5
Jan Steinar Rønning (NGU)	Graphite in Norway: exploration techniques	6
Håvard Gautneb (NGU)	Graphite in Fennoscandia	7
Trond Abelsen (Skaland)	Skaland graphite, Norway	8
Elin Ryösä (Leading Edge Materials Corp)	Woxna graphite deposite, Sweden	9
Edward Lynch (SGU)	Overview of the Nunasvaara graphite deposit, Sweden	10
Claus Østergaard (21stNorth)	The Akuliaruseq graphite project, southern West Greenland	11
Katrine Baden (GEUS)	Geology og the Ketilidian Orogen, South Greenland	12
Jeroen van Gool (Consultant)	Graphite occurrences in the Nanortalik region, South Greenland	13
Anders Lie (21st North)	The Auppaluttoq flake graphite prospect, SE Greenland	14
Nanna Rosing Schow (UiO)	Kangikajik, SE Greenland	15
Bjørn Thomassen (GEUS)	Langø graphite occurrence, NW Greenland	16
Ole Christiansen (Consultant)	Graphite observations South Greenland	17
Bjørn Thomassen (GEUS)	Graphite potential in NW Greenland	18

Lotte Melchior Larsen (GEUS)	Graphite in the Nuussuaq Basin, W Greenland	19