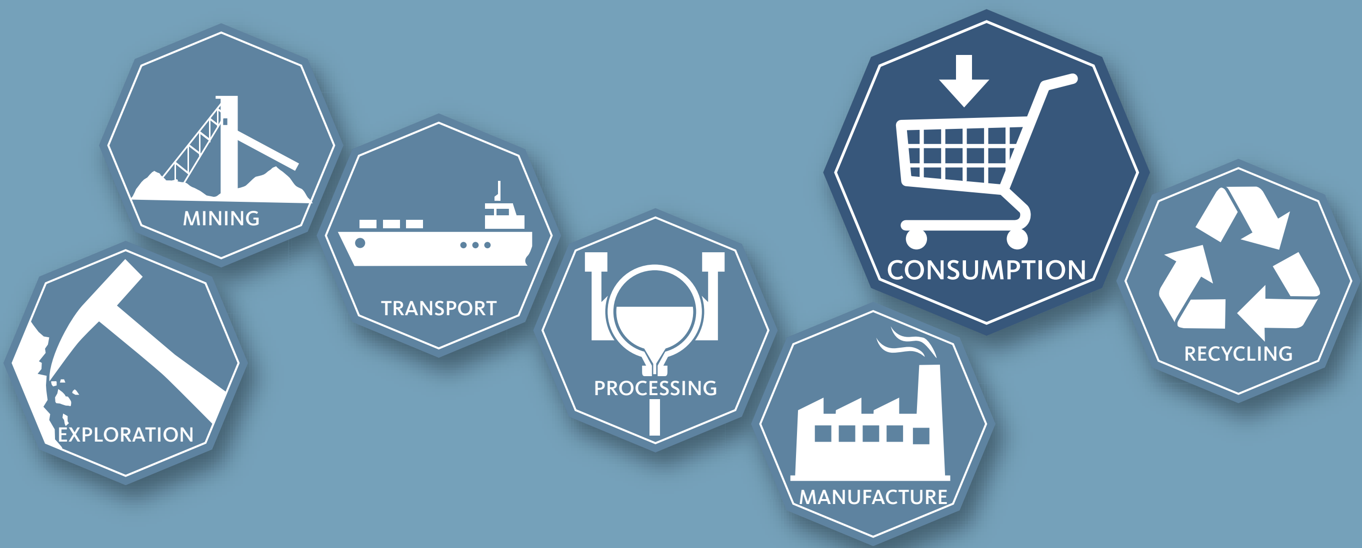
Review of potential resources for critical minerals in Greenland

Bo M. Stensgaard, Henrik Stendal, Per Kalvig and Karen Hanghøj

MiMa rapport 2016/3



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G E U S

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Authors: Bo Møller Stensgaard, Henrik Stendal, Per Kalvig & Karen Hanghøj

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Advisory center under The Geological Survey of Denmark an Greenland (GEUS)
Ministry of Energy, Utilities and Climate
Øster Voldgade 10
DK-1350 Copenhagen K

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1. Introduction

Minerals are essential raw materials for the development and progress of modern society. The availability of raw materials varies from commodity to commodity, and from country to country. Some raw materials, however, are of crucial importance to the society and at the same time the supply-chain is threatened; such raw materials are defined as critical raw materials. Supply risk is in many cases related to monopolism in the up-stream part of the supply chain.

It is on this background that this review of the Greenland potential resources for critical minerals is undertaken, focusing the raw materials labelled as critical by the European Commission in 2014 (EC 2014). In addition, a few less critical raw materials are included in this work.

For each of the commodities chosen, their known occurrences in Greenland are listed together with a description of the regional to semi-regional tracts that are thought to contain favourable permissive geological settings that potentially could host undiscovered mineral occurrences of the primary deposit type for the specific commodity. In some instances, and due to chemical affinities, some metals and minerals tend to occur in the same deposit type and similar geological settings and are therefore discussed as a whole (e.g. tin and tungsten, the platinum group metals and the rare earth elements).

In some cases, commodities can be of economic interest by themselves, in other cases, these can be valuable co- or by-products of the mining of other metals. In any case, knowledge about their distribution is a valuable input for the assessment of exploration and mining opportunities in Greenland.

2. Critical raw materials

Raw materials are considered critical if they at the same time are (i) important to society's needs, (ii) subject to a significant supply risk, and (iii) there is a lack of (viable) substitutes. This means that the conclusion of what is considered critical is both scale dependent, dynamic, and varies from country to country, depending on the resource endowment and the structure of the raw material consuming industries. Consequently there are considerable differences between what is critical for China, Japan, USA or Europe. A large number of assessments of critical raw materials are currently undertaken on global, national, and regional levels, e.g. UNEP 2009; EC 2010 and 2014; U.S Research Council 2008; British Geological Survey 2012. Additionally, the importance of industry specific commodities have been assessed e.g. for the automotive industry in Germany (Thun & Hoenig 2011) and for the electricity supply in USA (US DOP 2011).

The European Commission carried out their first criticality analysis for raw materials (non-energy, non-agricultural materials) in 2010, also addressing opportunities for substitution and recycling of raw materials (EC 2010). In this study, fourteen raw materials were defined as critical to the European industry. In 2014 the European Commission published a revised analysis in which 20 out of 54 raw materials were identified as critical (EC 2014) (Figure 1), including all the raw materials defined in the 2010 report (EC 2010), except for tantalum. Six new raw materials were defined as critical: borates, chromium, coking coal, magnesite, phosphate rock and silicon metal. Furthermore, it was decided to split the Rare Earth Elements (REE) in light rare earth elements (LREE: lanthan (La), cerium (Ce), praseodym (Pr), neodym (Nd), samarium (Sm) metals), including Scandium (Sc), and heavy rare earth elements (HREE: europium (Eu), gadolinium (Gd), terbium (Tb), dysprosium (Dy), holmium (Ho), erbium (Er), thulium (Tm), ytterbium (Yb), lutetium (Lu) and yttrium (Y) metals).

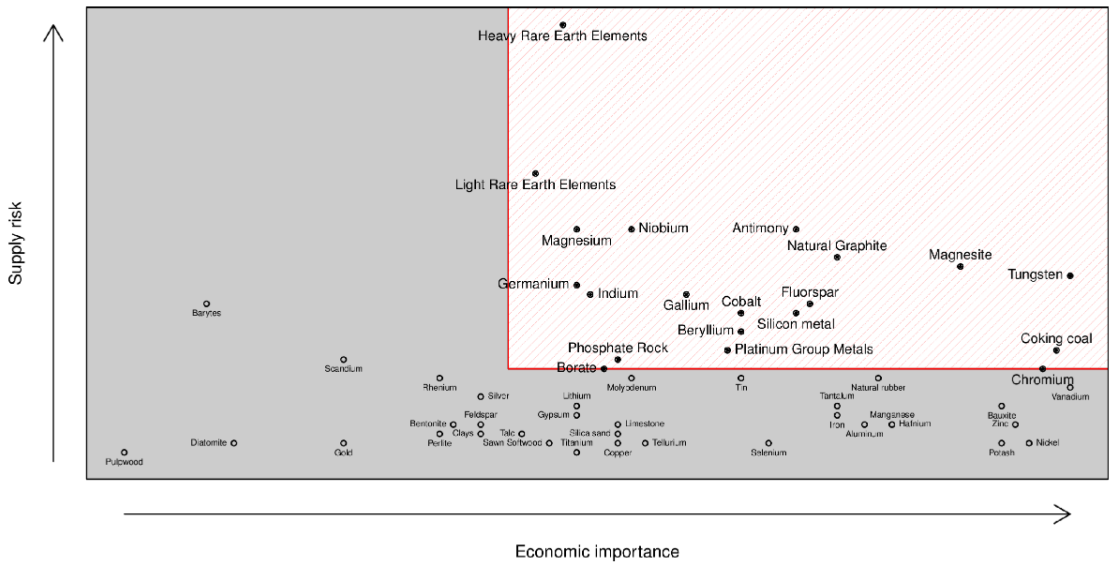

Figure 1. *Assessment of mineral criticality based on economic importance and supply risk (after EC 2014). Minerals lying in the pink area are considered critical.*

The present review of the potential critical mineral resources in Greenland is considering eleven of the critical raw material as defined by EC in 2014 (antimony, beryllium, chromium, cobalt, fluorspar, molybdenum, natural graphite, niobium, PGMs, REEs, and tungsten), of which Greenland is endowed with a high or moderate resource potential (Table 1). Total rare earth elements (TREE) are here defined as the 15 lanthanides, excluding Pr, plus Y.

Given that the resource potential in Greenland for magnesium, magnesite, phosphate rock, borate, and coal is in general considered low and these commodities are not considered further, despite they are included in the EU critical list of raw materials (EC, 2014). However, in addition to the raw materials ranged as critical the following three commodities, tin (Sn), molybdenum (Mo), and vanadium (V), are included in this review, which all are considered to be economically important but currently not characterized as being in the high supply risk zone (EC 2014) (Table 1).

Table 1. *Greenland resource potential for critical raw materials (in bold). Critical raw materials are defined according to the European Commission 2014 list; additionally, tin, molybdenum, and vanadium are included in the present review.*

	Current critical raw material (EC 2014)	Estimated resource potential in Greenland	As primary product ● or by-/co-product ○
Antimony	X	Moderate	●/○
Beryllium	X	High	○ of REE(?)
Borates	X	Unknown	●
Chromium	X	Moderate	●/○
Cobalt	X	Moderate	○
Coking coal	X	Unknown	●
Fluorspar	X	High	○ of REE
Gallium	X	Unknown	○ of PGM
Germanium	X	Unknown	○ of Zn
Indium	X	Unknown	○
Magnesite	X	Low	●
Magnesium	X	Low	●
Molybdenum		Medium	●
Graphite	X	High	●
Niobium	X	High	●/○
PGMs	X	Moderate	●
Phosphate rock	X	Unknown	●
REE (heavy)	X	High	●
REE (light)	X	High	●
Silicon metal	X	Unknown	
Tin		Low	●/○
Tungsten	X	Moderate	●/○
Vanadium		Low	○

3. Resource potential for critical raw materials in Greenland

The review presented is a geological assessment of the potential for finding – outcropping or undiscovered – deposits that are large enough to justify assessment towards an identification of the resource. The assessment is not considering any costs associated with infrastructure, mining, metallurgy processing, transport of ore, or the like.

Historical exploration data has been a large part of this evaluation. For further information on the historical reports made by various exploration companies on mineral deposits in Greenland please refer to the DODEX database, www.geus.dk/dodex.

Some of the critical raw materials are strictly companion metals derived from the production of selected major industrial metals (e.g. gallium (Ga), indium (In), and germanium (Ge)), and is described separately in Chapter 4.

3.1 Antimony [Sb]

Table 2. *Overview of the commodity antimony*

Main application	Antimony is as an ingredient in flame retardants. Minor amounts are used in alloys with lead for use in lead-acid batteries.
Annual production and leading producing countries	Total production in 2015 amounts to about 150 000 ton; the five dominating countries are: China (77%), Russia (6%), Australia (4%), Tajikistan (3%), Bolivia (3%) and Turkey (3%) (Source: U.S. GEOLOGICAL SURVEY (2016)).
Main mineral	The main commercial source of antimony is from the mineral stibnite (Sb_2O_3) which occurs predominantly in low-temperature hydrothermally formed veins, far from any igneous intrusions. The antimony deposits appear in rocks of a variety of geological ages.
Resource/reserve	Antimony is sourced by several routes: a) principal product; b) by-product to Au, Ag; and c) by-product from the smelting process of Zn and Pb. Global reserves are about 2 Mt antimony of which the most important countries are China (48%), Russia (18%) and Bolivia (16%) (U.S. Geological Survey 2016).
Market constraints	Due to its scattered applications, very limited amounts of antimony are presently recycled and its supply is strongly dependent on primary sources. However, China, holding half of the global resources, has been shutting down antimony mines and smelters in an effort to control environmental issues and address safety concerns. This has limited the global supply, and new antimony mine projects are being developed in Australia, Canada, and Laos. Nevertheless, accepted substitutes are known.

Known antimony occurrences

Known antimony occurrences and tracts with potential for antimony in Greenland are shown in Figure 2.

North Margerie Dal antimony occurrence, central East Greenland

At North Margerie Dal on Ymer Ø, central East Greenland, Nordisk Mineselskab A/S discovered a stibnite mineralisation in 1979. Drilling results included a 2.5 m intersection grading 20.9% Sb, 13 m grading 4.0% Sb and 7 m grading 4.7% Sb. The antimony resource (non-compliant to any current international reporting standards) was estimated by Nordisk Mineselskab A/S to be 108 000 ton grading 3.5% Sb. The mineralisation is 'open' and other antimony mineralisations are known in the area. The mineralisation occurs within shales and dolomites of the Precambrian Ymer Ø Groups of the upper Eleonore Bay Supergroup, where intense fracturing, jointing and thin quartz veining are frequent (Harpøth *et al.* 1986; Pedersen & Stendal 1987). Stibnite, associated with quartz, is found as massive to semi-massive veins with a thickness of 1–50 cm. The largest known zone of stibnite mineralisation is > 150 m by 50 m by 13 m. The veins are found in and around fault planes near specific beds of alternating red shales and yellow dolomite. The faults are related to Ordocivian to Devonian deformation, when large open folds with N-S fold axes developed, and 1–2 km wide graben structures formed 10–15 km apart, perpendicular to the fold axes (Harpøth *et al.* 1986). Tungsten mineralisation is also present in the area, sometimes associated with the structurally controlled antinomy-gold and gold-only bearing quartz veins. It is suggested, that the tungsten-antimony mineralisation is formed by precipitation from circulating hydrothermal solutions, where the faults acted as pathways for the fluids, and that the close association between stibnite and dolomitic shale, reflects a chemical induced precipitation of the antimony (Harpøth *et al.* 1986; Pedersen & Stendal 1987; Stendal & Frei 2008).

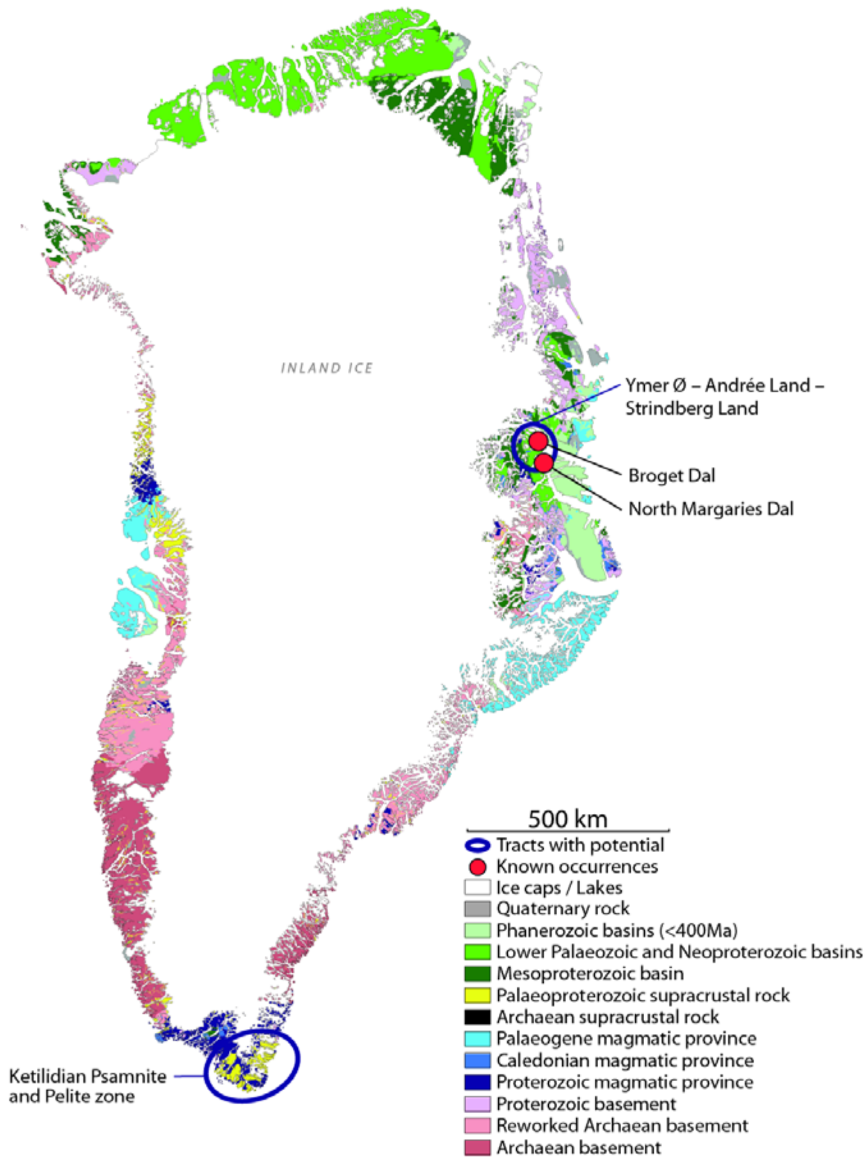

Figure 2. *Map of known antimony occurrences and tracts with potential for antimony. Simplified geological map is based on 1:2 500 000 geological map by Henriksen* et al. *(2009).*

Broget Dal copper-antimony occurrence, central East Greenland

Copper-antinomy mineralisation occurs in a 500 by 1000 m area with Upper Devonian faults cutting the Eleonore Bay Supergroup at Holmesø in Broget Dal (Appel 1974; Gruner & Probst 1976). A single borehole yielded a 1.4 m intersection with 1.3% Cu and 0.7% Sb. No resource estimates have been attempted at this locality.

Tracts with resource potential for antimony

Ymer Ø – Andrée Land – Strindberg Land, central East Greenland

In a similar setting to the one found at the North Margerie Dal antimony occurrence, faults in the region around Ymer Ø, Andrée Land, and Strindberg Land cut dolomitic shales of the Pre-cambrian Ymer Ø Groups in the upper Eleonore Bay Supergroup. These faults could potentially host antimony mineralisation. Caledonian granite and granodiorite intrusions in the area (Higgins *et al.* 2004) may also be potential targets for antimony deposits associated with tung-sten mineralisation.

Rapakivi granites in the Ketilidian Psammite and Pelite Zone, South Greenland

Rapakivi suite intrusions (Becker & Brown 1985; Garde *et al.* 1997) and their possible associat-ed hydrothermal systems within the Psammite and Pelite Zone in South Greenland are related to the final stages of transpression during the Palaeoproterozoic Ketilidian orogeny. Only lim-ited exploration activities have been carried out on the Rapakivi granites which are believed to hold a potential for hydrothermal mineralisation of antimony as well as commonly associated metals (tungsten, tin, bismuth, copper, gold).

3.2 Beryllium [Be]

Table 3. *Overview of the commodity beryllium*

Main application	Structural components and special alloys for the defence/military and aerospace industries, tools and precision instrumentation. Also used in radiation windows for x-ray tubes and in the nuclear industry.
Annual mine production and leading producing countries	The global production was about 300 ton in 2015, of which the following countries were the major producers: USA (92%), China (7%), and Mozambique (1%) (U.S. Geological Survey 2016).
Main mineral	The two most economically important beryllium minerals are: bertrandite ($Be_4\,Si_2\,O_7\,(OH)_2$), which is the main mineral mined in USA; and beryl ($Be_3\,Al_2\,Si_6\,O_{18}$), which is the main mineral mined outside USA. Both minerals are most often found in veins or pegmatites associated with granitic rocks, and associated with greisen and skarn zone.
Resource/reserve	According to USGS (2012) global resources in known deposits amounts to 80 000 ton plus, of which about 65% is located in the USA.
Market constraints	Resources are concentrated in the USA. The high price and toxic nature of beryllium has led to strongly regulated production and use, and this promotes beryllium´s relatively high recycling rate.

Known beryllium occurrences

In Figure 3 known beryllium occurrences and the tracts that constitute the geological settings which could host undiscovered occurrences in Greenland can be seen.

Taseq beryllium occurrence, South Greenland

In the Ilímaussaq intrusion in the Gardar Province, South Greenland, several localities with beryllium minerals have been identified. The most considerable concentration is found on the northern shore of the lake Taseq. The occurrence is described by Engell *et al.* (1971) as beryllium minerals, predominately chkalovite, in hydrothermal veins and metasomatic zones in naujaiite near lujavrite rocks.

The Taseq beryllium occurrence occupies an area with a length of approx. 500 m and a width of up to 200 m, in which mineralised veins with a width of 1 mm to 2 m, but typically only a few centimetres, and lengths of a few tens of metres are present. Berylometer measurements indicate an average concentration of less than 0.1% BeO in most of the mineralised area. An estimate based on the surface expression of the mineralisation gives an estimate of 180 000 ton with an average of 0.1% BeO (non-compliant to recent international reporting standards).

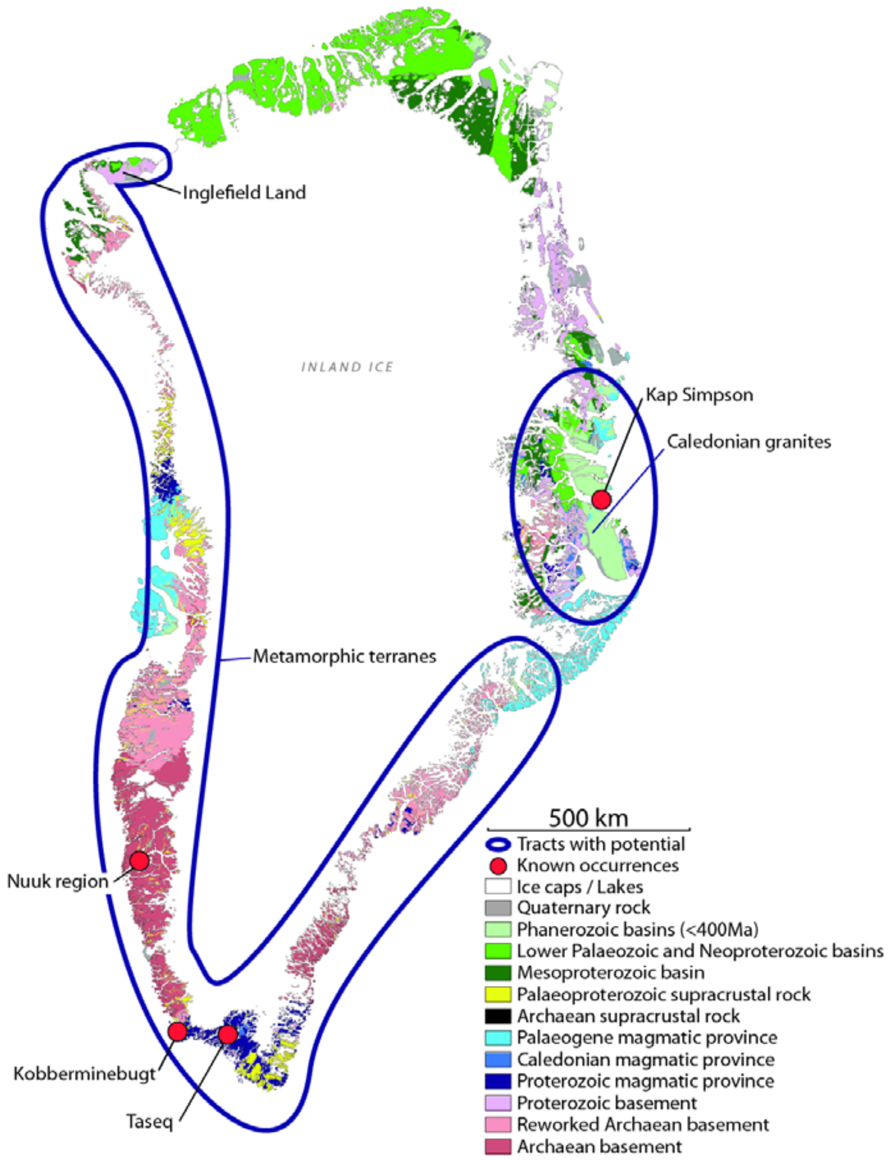

Figure 3. *Map of known beryllium occurrences and the tracts that constitute the geological settings which could host undiscovered occurrences. Simplified geological map is based on 1:2 500 000 geological map by Henriksen* et al. *(2009).*

Nuuk region pegmatite beryllium occurrences, southern West Greenland

Beryl-bearing pegmatites are known from several localities in the Nuuk region (Stendal *et al.* 2011). However, in all cases they have been investigated for their gemstone quality of beryl crystals, especially for the blue-green variety aquamarine, and not for the metal content.

Kobberminebugt beryl occurrence, southern West Greenland

At Alángorssuaq in Kobberminebugt a beryl-bearing pegmatite lens, 10 × 3 m in size, has been described by Steenfelt *et al.* (2007a).

Kap Simpson beryllium occurrence, central East Greenland
In the Kap Simpson Palaeogene felsic intrusive complex a caldera sequence and extensive hydrothermal alteration has yielded whole rock analyses with up to 0.15% Be.

Tracts with resource potential for beryllium

Geologically the tracts described below are defined as the geological environments characterized by pegmatites and granites.

Pegmatites, South, West, North-West, North-East and East Greenland
Pegmatites, especially those located in multiphase highly deformed and highly metamorphosed terranes and those in areas with Palaeoproterozoic and younger granitic and granodiorite intrusives, might be a target for beryllium in the mineral beryl. Steenfelt *et al*. (2007a) provide an overview of pegmatite occurrences in Greenland and their mineral potential.

Caledonian granites, central East Greenland
Caledonian S-type granites and granodiorites and associated pegmatites and hydrothermal veins hold a potential for beryllium (and commonly associated metals such as tin (Sn), wolfram (W), bismuth (Bi) and molybdenum (Mo)).

3.3 Chromium [Cr]

Table 4. *Overview of the commodity chromium*

Main application	Chromium is used to harden steel, to manufacture stainless steel (to prevent rust) and to produce several alloys. About 90% of all leather is tanned using chrome. However, the waste effluent is toxic so alternatives are being investigated. Chromium compounds are used as industrial catalysts and pigments.
Annual mine production and leading producing countries	Total production 2015: 30.5 Mt of which the main producers are: South Africa (49%), Kazakhstan (12%), Turkey (12%), and India (11%) (Source: U.S. Geological Survey 2016).
Main mineral	Chromite ($FeCr_2O_4$) is the only economic ore mineral for chromium.
Resource/reserve	The global reserves of chromium are estimated to about 480 Mt, of which Kazakhstan holds 48%, South Africa 42%, and India 11% (U.S. Geological Survey 2016).
Market constraints	Chromium has no substitute in stainless steel, the leading end-use, or in super-alloys, another important end-use. Global chromium resources are relatively plentiful, but resources are concentrated in South Africa and Kazakhstan, and the fact that production is dominated by South Africa, has led this metal to be considered critical.

Known chromite occurrences

Economic chromite deposits are generally found in three different geological environments: 1) stratiform deposits, related to igneous rock such as norite or periodotite; this type is hosting two of the largest chromite depostits (Bushveld and Great Dyke); 2) podiform deposits are large slabs of oceanic lithosphere that have been thrust up onto a continental plate – commonly known ophiolites; and, 3) beach sands derived from the weathering of chromite-bearing rocks.

Figure 4 outlines the known chromium occurrences and tracts with potential for chromium in Greenland.

Fiskenæsset (Qeqertarsuatsiaat), southern West Greenland

At Fiskenæsset/Qeqertarsuatsiaat metamorphosed layered anorthosite and gabbroic rocks of the Fiskenæsset anorthosite complex are well-known for occurrences of chromium, vanadium, nickel and PGM. The complex is intruded into amphibolite units and covers ~ 4000 km^2. It is a layered complex comprising gabbro, dunite, peridotites, hornblendites, leuccogabbro, anorthosite and chromitite. The complex has been repeatedly deformed and metamorphosed under amphibolite facies and, locally, granulite facies conditions. The layered anorthosite complex has an average thickness of 380 m and an exposed strike length of more than 200 km. The chromite occurrences are typically chromitite bands in anorthosite at certain stratigraphic levels. The bands are usually between 0.5 m and 3 m thick, locally reaching thicknesses of 20 m (Ghisler 1970, 1976; Myers 1976, 1985). Plagioclase augen-chromitite, a spotted rock of white plagioclase associated with chromite and hornblende, is the most common chromite-bearing rock type. Massive hornblende-chromitite is also encountered, often as numerous thin layers intercalated with plagioclase. Chromite is associated with rutile, ilmenite and sulphides, and may contain exsolutions of magnetite. Based on surface expression and surface sampling/chip profiles the estimate of the resources includes 2.5 Mt of chromitite with 32.7% Cr_2O_3 in one location, and more widespread 100 Mt of low-grade ore (Ghisler 1970, 1976) (non-compliant with current international standards for reporting).

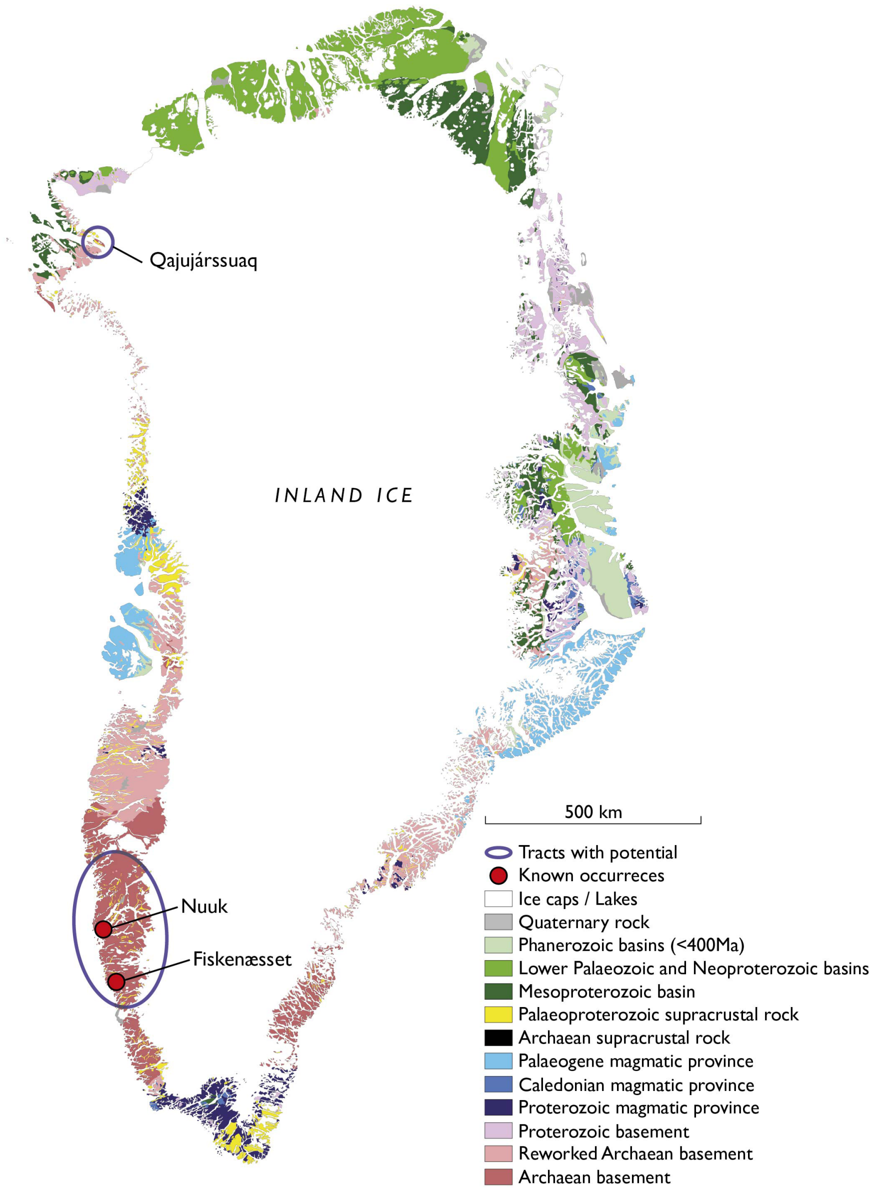

Figure 4. *Map of known chromium occurrences and tracts with potential for chromium. Simplified geological map is based on 1:2 500 000 geological map by Henriksen* et al. *(2009).*

Tracts with resource potential for chromite

Geologically the tracts described below are defined as the geological environments characterized by ultramafic rocks and anorthosites.

Ultramafic rock units, Nuuk to Søndre Strømfjord, southern West Greenland

Chromite seams have been reported from several ultramafic rock units within the Archaean craton in southern West Greenland, e.g. from the Fiskefjord area north of Nuuk, and from the Bjørnesund area north of Frederikshåbs Isblink. The ultramafic units are most often either layers within larger mafic units that constitute a major part of supracrustal belts or isolated lens-formed bodies embedded in Archaean gneisses.

Anorthosite units, southern West Greenland

Anorthosite units are frequent in the Archaean basement. However, mafic and ultramafic units (like those found in the Fiskenæsset Anorthosite Complex) are usually absent (or present in smaller volumes) in other areas with anorthosite units. The potential for additional chromite occurrences in other areas with anorthosites in the Archaean basement is present if the anorthosites also have mafic components.

Qaqujârssuaq anorthosite complex, Thule region, North-West Greenland

Similar to the anorthosite units in southern West Greenland the little known, but very large (> 1000 km^2) Qaqujârssuaq anorthosite complex (Dawes 1972, 2006; Nutman 1984) has a potential for chromium mineralisation. The complex is described mainly as an anorthositic body with some gabbro and leucogabbro units.

3.4 Cobalt [Co]

Table 5. *Overview of the commodity cobalt*

Main application	Cobalt is refined into both metal and chemicals. Chemical compounds (including those in batteries) accounts for about 30%, followed by super-alloys (for steel) (18%), carbides and diamond tools (13%), catalysts (9%), pigments (9%), and magnets (7%) (EC 2014). Super-alloys accounts for about one fifth and is a fast growing market for e.g. wind mills, cars, and mobile phones. Cobalt is ferromagnetic and keeps its magnetic properties at high temperatures (1100 C° plus).
Annual production and leading producing countries	Global production is 124 000 ton of which the following countries are the main producers: DRC (51%), China (6%), Canada (5%), Australia (4%), and South Africa (4%) (U.S. Geological Survey 2016).
Main mineral	More than 100 cobalt-containing minerals are known to exist, of which thirty are cobaltiferous, but only four are commercial: the sulphide cobaltite ((Co,Fe)AsS), and the arsenides skutterudite ($(Co,Ni)As_3$), smaltitechloanthite ($(Co,Ni,Fe)As_{3-2}$), and safflorite ($(Co,Fe)As_2$). A characteristic feature of cobalt is its ability to form commercial concentrations in deposits of other metals (nickel, copper, and iron), where it occurs mainly in cobalt-containing ore minerals (pyrite, pentlandite, and asbolites), rather than only in the form of strictly cobaltiferous minerals. Cobalt is a by-product of nickel mining (50%) and copper mining (35%), and is associated to Ni- and Cu sulphides/arsenides.
Resource/reserve	The most important cobalt resources are located in the Copper Belt in DRC and Zambia. Additional resources are associated to Ni-bearing laterite deposits and Ni-Cu sulphide deposits in Australia, Canada and Russia. Potentially, also huge resources may exist in manganese nodules. The global reserve is estimated to 7.1 Mt, of which 48% is located in DRC, 15% in Australia, and 7% in Cuba; China holds only about 1% of the reserves (U.S. Geological Survey 2016).
Market constraints	65% of all cobalt is mined in Africa, but only 5% is refined there; China refines about 40% and no cobalt reserves are reported from China. Due to the extensive cobalt production in DRC, cobalt is sometimes classified as a ‘conflict mineral’. Volatile market with fluctuating prices.

Known cobalt occurrences

The most prominent cobalt ore is related to magmatic copper-nickel ores in which pentlandite is the main cobalt-containing mineral; as well as copper-pyrite and skarn-magnetite ores, in which; pyrite is the most important cobalt source. Secondly, cobalt is associated with the sedimentary-hosted copper deposits of central Africa (DRC and Zambia).

The known cobalt occurrences and tracts with potential for cobalt in Greenland are shown in Figure 5.

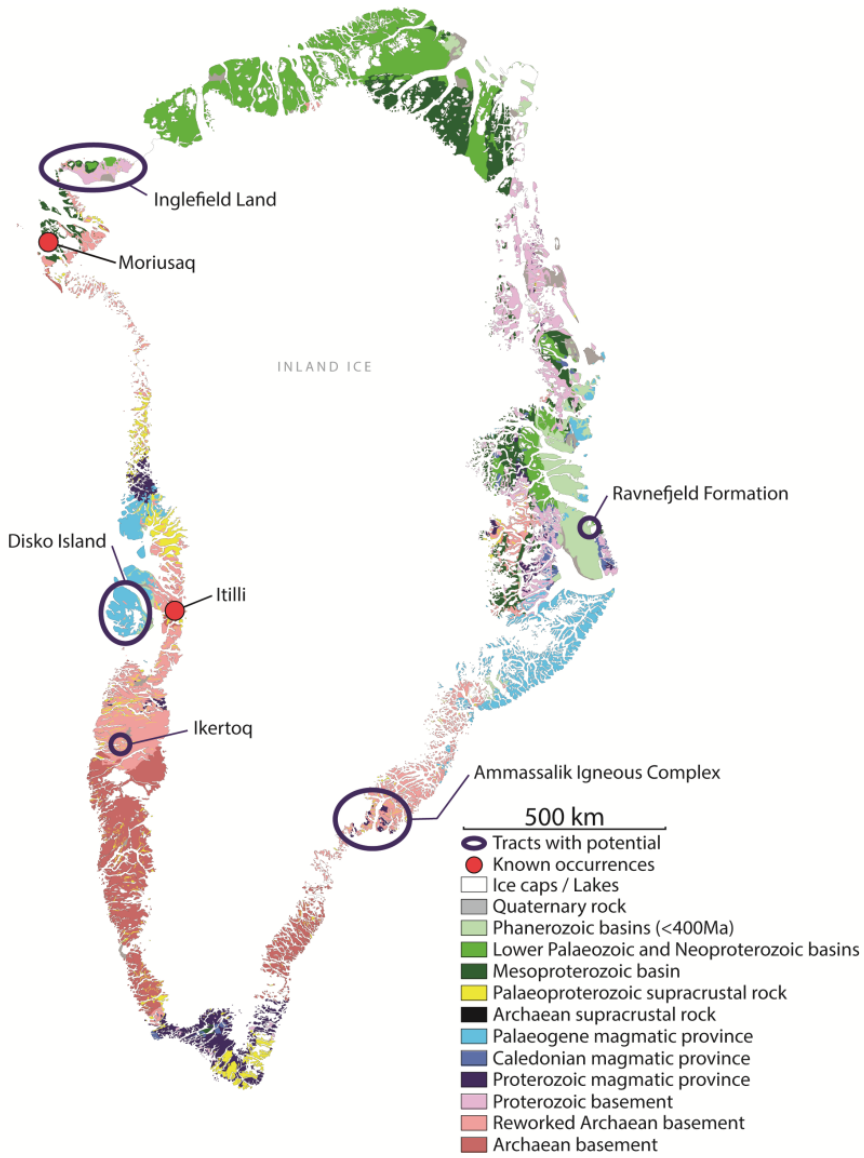

Figure 5. *Map of known cobalt occurrences and tracts with potential for cobalt. Simplified geological map is based on 1:2 500 000 geological map by Henriksen* et al. *(2009).*

Itilli, central West Greenland

Syn- and epigenetic sulphide mineralisation and low-grade copper-gold-cobalt mineralisation is widespread in an amphibolite unit in the supracrustal belt at Itilli, in the north-eastern Disko Bugt, (Gothenborg & Morthorst 1981; Gothenborg & Morthorst 1982; Gothenborg & Keto 1986; Stendal & Schønwandt 2003). Syngenetic mineralisation is mainly found as semi-massive to massive lenses up to 2 m wide and 10 m long. The sulphide lenses are hosted in amphibolites, schists and paragneisses. Epigenetic disseminated sulphide hosted in amphibolite occurs in close relation to minor shear zones about one metre wide. Locally, these shear zones host quartz lenses/veins (5–10 cm wide and 1 m long) parallel to the fabric of the shear zone and is often accompanied by a halo of hydrothermal alteration. The epigenetic vein mineralisation is widespread in the area and comprises locally As-, Ni-, Co- and Au-bearing sulphides.

Moriussaq, North-West Greenland

Ilmenite-rich black-sand placers occur at Moriussaq in the Thule (Pituffik) region (Dawes 1989; Ghisler 1971). The placer sand also contains magnetite and titanomagnetite and minor zircon, sphene, garnet and sillimanite. Magnetite from the black-sand beaches yields 0.1% CoO. The placers occur along the entire coast in the region. The most conspicuous exposures are on the beaches, but raised beaches with black sand deposits are also present. The flat uplifted plain is up to 3 km wide, dominated by alluvial and littoral deposits and forms the outer coast morphology for more than 80 km. The darkest sands are concentrated in diffuse layers (up to 50 cm thick). The black sands on the uplifted beaches are comprised of much coarser material and in general, these deposits have smaller concentrations of heavy minerals. The raised beach deposits have an average content of 12% TiO_2 and active beaches an average content of 20-40% TiO_2 (Weatherley & Johannessen, 2016; Weatherley, 2015).

Tracts with resource potential for cobalt

Geologically the tracts described below are defined as the geological environments characterized by the following features: (i) Sulphide phase concentrated in magmas (e.g. Disko Island, and Ammassalik Igneous Complex); (ii) Hydrothermal volcanogenic environments (e.g. Inglefield Land); and (iii) Sediment hosted mineralisation (e.g. Central East Greenland)

Inglefield Land, North-West Greenland

A rock float from Anoritooq in the Palaeoproterozoic Inglefield Land Mobile Belt, yielded 8.8% cobalt, 7.6% nickel, 16 ppm gold and 15 ppm silver. The rock, collected by a Greenlander under the annual Ujarassiorit program (public-hunt-for-minerals) was awarded the 3rd price in 2009. The Ni-Co-Au-Ag mineralisation is believed to represent vein mineralisation related to hydrothermal events within the Mobile Belt. The E–W trending belt is dominated by a complex mixture of meta-sediments and meta-igneous rocks. The orogeny is characterized by polyphase magmatism, deformation and high-grade metamorphism (Dawes 2004). The Inglefield Land Mobile Belt is relatively underexplored and no follow-up on the rock float has been carried out.

Ikertoq, Ammassalik and Disko Island, central West, and South-East Greenland

A mineral resource assessment workshop in 2012 (Rosa *et al.* 2013) assessed the potential for undiscovered conduit-type nickel mineralisation related to picrite and/or tholeiitic basalt dyke-sill complexes in Greenland. Cobalt may be produced as a by-product from this type of mineralisation. Co-bearing Fe-Ni-Cu-sulphides have been described from the Ikertoq Ni-Cu-(Co)-occurrence, north of Søndre Strømfjord, central West Greenland, in the Ammassalik Igneous Complex, South-East Greenland, and at Disko Island in the western Greenland Flood Basalt Province. Other tracts identified with a potential for conduit-type nickel mineralisation may also hold a potential for cobalt. Refer to Rosa *et al.* (2013) for more information on the potential for conduit-type nickel.

Sedimentary-hosted copper mineralisations, Ravnefjeld Formation, central East Greenland

Cobalt occurs as a by-product in sedimentary-hosted reduced-facies copper mineralisation (also known as Kupferschifer type or Copper Belt type). The potential for this type of mineralisation in Greenland was assessed during a mineral resource assessment workshop in 2009 (Stensgaard *et al.* 2011). Only the black shales of the Permian Ravnefjeld have been investigated in detail. The shales have been correlated and compared to the Polish Kupferschifer type copper mineralisation, which contains considerable amounts of cobalt as a by-product. However, no anomalous amounts of cobalt have been identified from Ravnefjeld (two chip sample profiles returned only 30 and 50 ppm Co (Harpøth *et al.* 1986)).

3.5 Fluorite [CaF_2]

Table 6. *Overview of the commodity fluorite*

Main application	Fluorite is an important industrial mineral used in many chemical, ceramic, and metallurgical processes. The chemical sector is consuming more than half of the fluorite produced hydrofluoric acid which is used in the pharmaceutical and agrochemical industries; fluorspar is used by the steel industry as a flux. The aluminium industry produces synthetic cryolite on the basis of fluorite; other important fluorspar consuming industries are in the aluminium, steel and ceramic production where it is used as a flux.
Annual production and leading producing countries	Annual production for fluorite was 6.2 Mt in 2015 (U.S. Geological Survey 2016). China is the dominant producer (about 61%) followed by Mexico (18%), Mongolia (6%), and South Africa (3%) (U.S. Geological Survey 2016).
Main mineral	Fluorite (CaF_2) is categorized in four commercial classes: acid grade ('acidspar') (high CaF_2 %), metallurgical grade ('metspar') (60-85% CaF_2), ceramic grade (96% CaF_2), and Optical grade (special high grad quality).
Resource/reserve	The global fluorite reserve figure for selected countries is estimated to be about 250 Mt of which 16% is located in South Africa, 13% in Mexico, 10% in China, and 9% in Mongolia (U.S. Geological Survey 2016).
Market constraints	China is a dominating market player (*c.* 60%) followed by Mexico, Mongolia and South Africa. China has lifted the export quota for fluorspar, but a 15% export tax is currently applied. Further, China has increased freight costs and reduced the annual production.

Known fluorite occurrences

Economic deposits of fluorite are mainly hosted in veins by hydrothermal processes, where it often occurs as a gangue mineral associated with metallic ores. Fluorite is also found in the fractures and cavities of some limestones and dolomites.

In Figure 6 known fluorite occurrences and tracts with potential for fluorspar in Greenland are shown.

Ilímaussaq complex, South Greenland

The Ilímaussaq syenite complex hosts two separate peralkaline REE-deposits, Kvanefjeld and Kringlerne, situated in South Greenland, both of them world-class REE-deposits, containing also fluor.

The Kvanefjeld REE-U-Zn deposit, located north of the township Narsaq, contains the fluorine mineral, villiaumite (NaF). The villiaumite content varies from accessory to 20% by volume (Kalvig 1994). More info under the REE description. The Kvanefjeld deposit has been explored for decades by various groups focusing on REE, with Zn and F as by-products. The recent license holder, Greenland Minerals & Energy has estimated a JORC-compliant resource for

Kvanefjeld, Sørensen Zone and Zone 3 of 1.01 Bt REE-U-Zn ore has (GMEL 2015). More details in sub-chapter 3.9.

At the Kringlerne Zr-Nb-Ta-REE deposit, fluorine contents of 2% and 1% in samples of black and white karkortokite respectively are reported (Bailey *et al.* 2001). Presently, there are no available resource estimations for fluorite. More details in sub-chapter 3.9

The remaining parts of the Ilímaussaq intrusive complex is known to host other occurrences of fluorine minerals, both in hydrothermal veins and as highly elevated fluorine content in the alkaline igneous rock themselves.

Ivittuut, South-West Greenland
The Ivittuut cryolite deposit in southern West Greenland also contains a fluorite resource. The fluorite is widely distributed in parts of the cryolite deposit and in the intermediate western part of the deposit, fluorite is the dominant mineral component (Kalvig 1994). Resource estimates on the fluorite zone report an in situ tonnage of approx. 500 000 ton grading 50% fluorite (Bondam 1991).

Various localities, central East Greenland
Harpøth *et al.* (1986) describes fluorite veins from Moskusokse Land and Hudson Land, especially in North-South trending sub vertical hydrothermal veins, hosted in Devonian sediments with intercalated rhyolitic volcanic rocks and shallow granites. The veins appear as massive veins or as fillings of fault breccia and are typically of cm to dm thickness. Fluorite is mostly white to faint purple, but it also has green, yellow and black colours. At Kap Franklin, Gauss Halvø the largest known occurrence is an up to 1.8 m wide, 25 m long lens of massive fluorite occurring in a 2 m wide fluorite cemented breccia zone. Fluorite veins are also known from Hudson Land and Canning Land. Here veins are Upper Devonian or Carboniferous of age, and they normally intersect Middle-to Upper Devonian rocks but not Upper Permian and younger units.

Fluorit Dal at Kap Simpson, central East Greenland
Hydrothermal fluorite veining associated with Palaeogene igneous and hydrothermal activity is reported at Kap Simpson, where a 0.3 m wide and 250 m long massive fluorite vein occurs in Fluorit Dal.

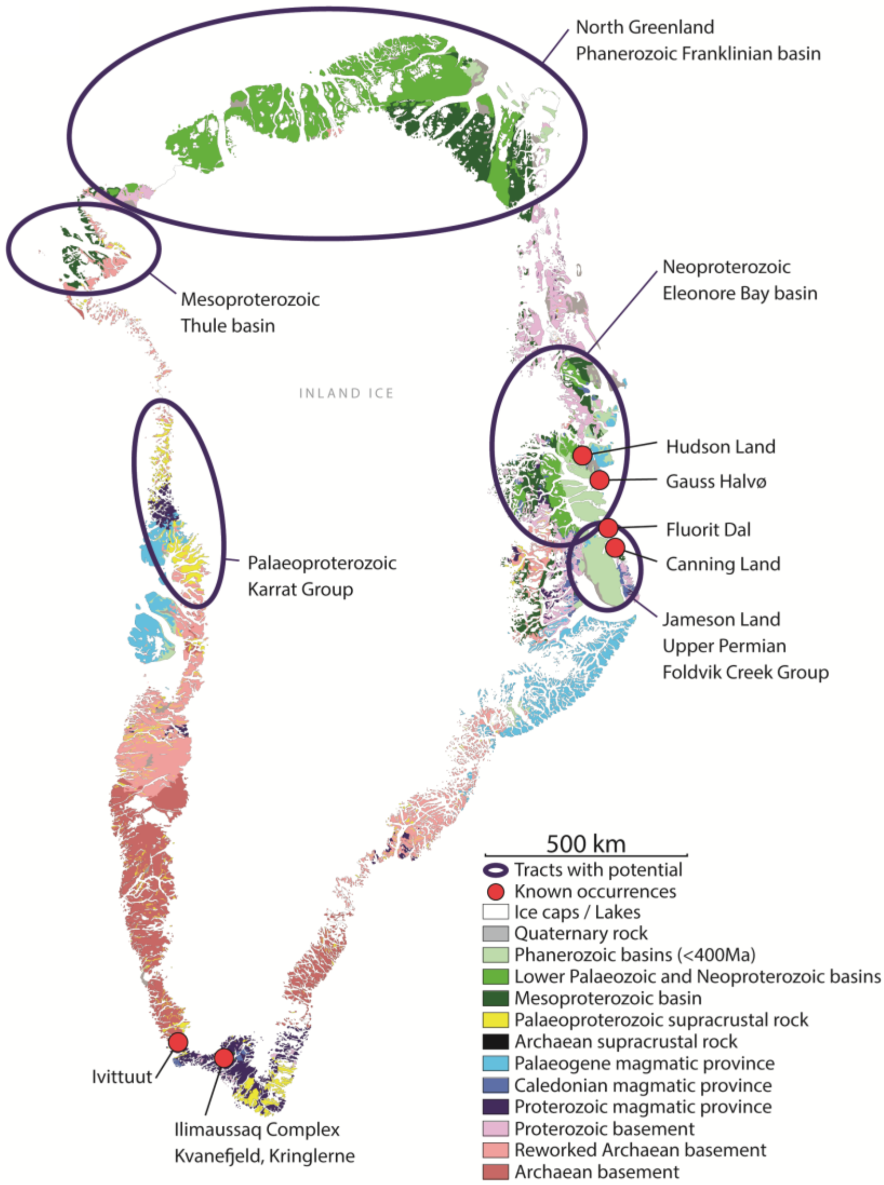

Figure 6. *Map of known fluorite occurrences and tracts with potential for fluorspar. Simplified geological map is based on 1:2 500 000 geological map by Henriksen* et al. *(2009).*

Tracts with resource potential for fluorspar

Mississippi Valley Type, North-West, northern West, North, central East Greenland

Fluorite is a common by-product of zinc production from Mississippi Valley Type (MVT) zinc-lead deposits. As part of a sedimentary-hosted zinc resource assessment workshop carried out in 2011, the potential for undiscovered MVT type mineralisation was assessed and the Phanerozoic Franklinian basin in North Greenland and the Palaeoproterozoic Karrat Group in North-West Greenland, in particular, were regarded as holding potential for undiscovered MVT deposits (Sørensen *et al.* 2013). While most showings have no or only small amounts of fluorite, significant amounts of fluorite were reported in one Zn-Pb showing in Peary Land by Rosa *et al.* (2014).

Other areas that were found to host a potential for Mississippi Valley Type mineralisation, although smaller potential than the areas mentioned above, are the Mesoproterozoic Thule Basin in northern West Greenland and the Neoproterozoic Eleonore Bay Supergroup and the Phanerozoic Jameson Land basin in East Greenland.

3.6 Graphite [C]

Table 7. *Overview of the commodity graphite*

Main application	The main application of graphite are: steel/foundries and refractories; the automotive industry for construction materials and for brake linings and clutch materials; as an industrial lubricant, in several types of batteries; and for carbon brushes in electronic motors, as well as some specialized high-tech applications (including large-scale fuel-cell applications and graphene construction materials might become fast growing areas). Each sector requires specific graphite resource (amorphous natural, flake natural, vein natural). About 50% of the graphite is used for refractories, and this ratio is expected to remain (EC 2014). However, the demand for manufacture of Lithium-Ion batteries is expected to grow (Investing News, 2017)
Annual production and leading producing countries	Graphite is produced in many countries. USGS (2016) reports the global production to amount to 1.2 Mt (excluding the USA production) of which China produced 66% followed by North Korea (14%), and Brazil (7%). Other groups report higher global figures.
Main mineral	The main mineral is graphite, composed of the element graphite only. Three types of natural graphite are commercial products: Flake, lump and chip, and amorphous graphite. Additionally, synthetic graphite is being marketed. Cg is the unit for total carbon in graphite form; also referred to as graphitic carbon.
Resource/reserve	USGS (2016) reports the reserves as follows: Turkey (90 Mt), China (55 Mt, amorphous, flake), India (8 Mt; flake), Mexico (3 Mt, amorphous, flake), and Madagascar (0.9 Mt, flake).
Market constraints	China has introduced export quota for natural graphite. Recycling of graphite has been rather low. For some applications synthetic graphite can substitute natural graphite (e.g. brake linings, lubricants and carbon brushes, but not in refractory applications).

Known graphite occurrences

In Figure 7 known graphite occurrences and tracts with potential for graphite in Greenland can be seen.

Amîtsoq, South Greenland

Graphite hosted by graphitic schists embedded in strongly sheared cordierite-sillimanite-biotite gneisses occur at Amîtsoq (Bondam 1992; Mosher 1995). The ore consists of finely disseminated graphite flakes in a quartz-rich groundmass, accompanied by pyrite and biotite. The graphite is flaky and up to 15 mm in size and the graphite content is 20–24 vol.%. 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 original ore body is estimated to contain 250 000 t of graphite. The Amîtsoq graphite mine produced a total of 6000 t graphite ore averaging 21% Cg (graphitic carbon) during its operation from 1915–24.

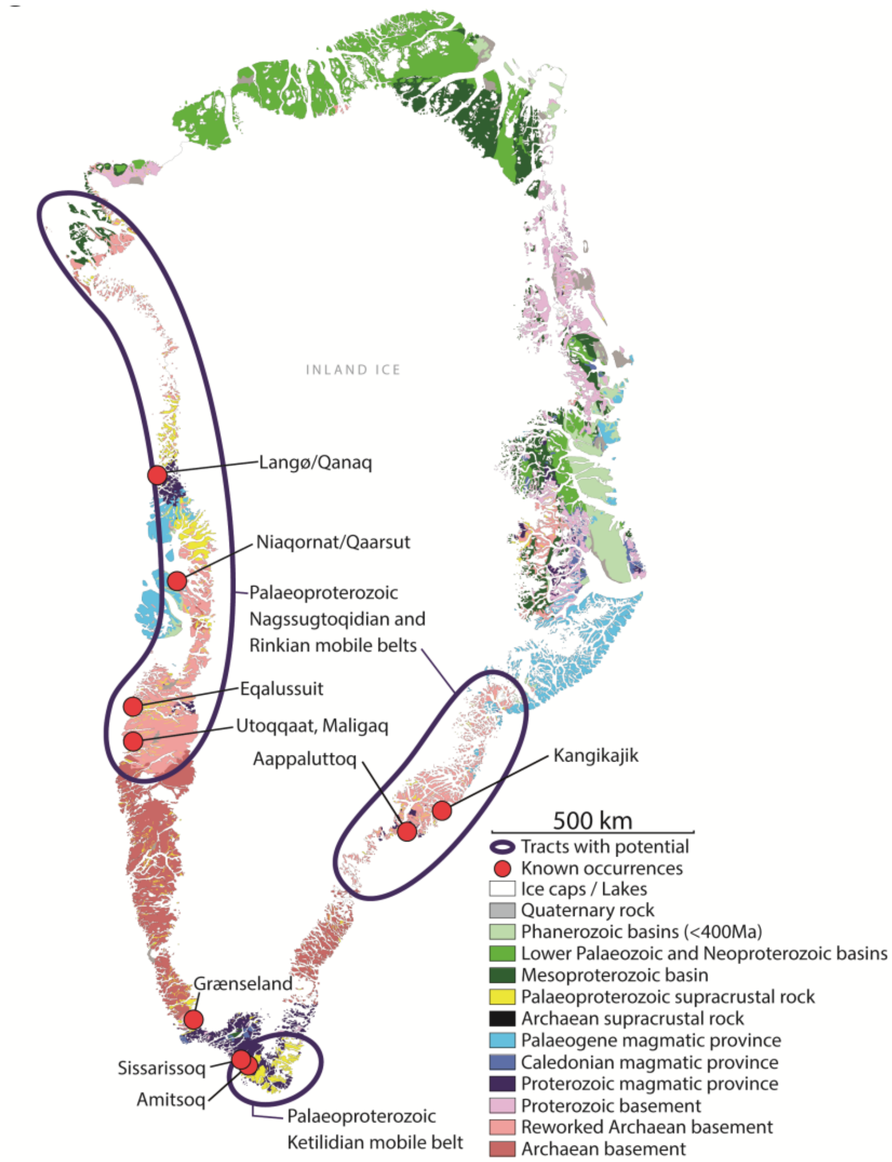

Figure 7. *Map of known graphite occurrences and tracts with potential for graphite. Simplified geological map is based on 1:2 500 000 geological map by Henriksen* et al. *(2009).*

Eqalussuit (Akuliaruseq), central West Greenland

Graphite is abundant in Palaeoproterozoic sulphide-rich supracrustal rocks in West Greenland. 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 the Nagssugtoqidian subduction (Bondam 1992).

At Eqalussuit, just north of Nordre Strømfjord, graphite occurs as layers and lenses. Kalvig (1992) reviews the occurrences and concludes that the graphite is hosted in schists, amphibolites and ultramafic rocks, which form a narrow, steep dipping synform. The graphite occurrence was investigated by Kryolitselskabet Øresund A/S between 1982 and 1986. Kryolitselskabet Øresund A/S found that the graphite were 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 in two different types: I) disseminated graphite flakes, grading 6–8% graphite, as large lumpy flakes and small flakes, none of which contain impurities; and II) massive graphite in intensely deformed parts of the schist, grading up to 20–24% Cg. The thickness of the graphite-bearing rocks varies considerably between 35–60 m, but contains numerous 1–20 m wide low-grade zones. The resource has been calculated by Kryolitselskabet Øresund A/S to contain 5.3 million ton of flake graphite ore, having an average content of 9.5% Cg (Morthorst & Keto 1984; Kryolitselskabet Øresund A/S 1989). Other resource figures refer to mineable 1.37 million ton at a grade of 14.1% Cg (Bondam 1992) (none of the above stated resources are compliant with current international reporting standards).

Langø/Qanaq, Upernavik, northern West Greenland

Graphite occurs as lenses and veins in pelitic and garnet-bearing schist at Langø and adjacent areas. Bulk-sampling and bench testing were carried out in the start of the 19^{th} century yielding high grade (Bondam 1992; Kalvig 1994). However, samples are not documented to be representative, and the occurrence does not appear to have economic importance (Bondam 1992).

Utoqqat/Maligiaq, Sisimiut, central West Greenland

At Utoqqat, graphite occurs in Archaean gneisses and schists. Seven graphite-bearing horizons of graphite-bearing schists have been identified, and these extend for 1.2 km and have widths between 1–10 m. Sample material, 80 ton, from two closely spaced graphite-bearing zones were sampled at regular intervals and are 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, and range from 5% to 25 % Cg (Kalvig 1994).

Kangikajik, South-East Greenland

At the Kangikajik peninsula, 100 km north of Tasiilaq, five graphite-bearing supracrustal units in Archaean gneisses are identified (Kalvig 1992, 1994). Graphite occurs mainly as flake graphite (0.2–2 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. Reconnaissance prospecting programmes in the late 1980s and early 1990s, estimate that the potential graphite resource is 500 000 ton of graphite (non-compliant resource according to recent international reporting standards). 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).

Aappaluttoq, South-East Greenland
Graphite-bearing supracrustal rocks, including biotite and quartzitic schists, outcrop along the coast west of the Sermilik fjord, about 50 km north-west of Tasiilaq. At the most distinct mineralised area, the supracrustal schist is between 50 m and 100 m thick, and may contain several graphite layers. The layers vary in width from 5 m to 10 m and extend for more than 200 m. A preliminary analysis on one sample assayed yield *c.* 25% LOI and about 5% ash soluble in aqua regia (Bondam 1992).

Grænseland, South-West Greenland
Coal, anthracite and graphite are found in a thin sedimentary unit in the Foseelv Formation near the base of the Ketilidian Sortis Group in Grænseland, South-West Greenland. Where contact metamorphosed by mafic dykes carbonaceous material has been altered to almost pure graphite. The amount of graphite was reported to 10 000 ton (non-compliant resource according to recent international reporting standards). The southern part of the deposits is graphite schist and the northern part is an anthracite coal layer (Berthelsen & Henriksen 1975, and references herein).

Niaqornat and Qaarsut, West Greenland
At Nuussuaq, West Greenland, Early Cretaceous to Palaeocene bituminous shales contains graphite. Where these sediments are cut by Palaeogene mafic dykes the carbonaceous matter in the sediment are either partially cooked or metamorphosed to amorphous graphite. Two localities are mentioned; the Niaqornat and the Qaarsut, of which the latter is described as a quartzitic bituminous shales metamorphosed over a zone of 3–5 m on both sides of an ultramafic dyke. Three samples from the Qaarsut occurrence collected and analysed more than one hundred years ago is reported to yield 93 to 95% Cg, and 3.6–4.9 ash. Note; these numbers most likely represent ore concentrates or very-rich graphite-bearing samples or even massive graphite or graphite flakes; and they are probably not representative for the entire occurrences. 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).

Sissarissoq, South Greenland
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 (Bondam 1992; Kalvig 1994).

Tracts with resource potential for graphite

Geologically the tract described below is found in the geological environments of Palaeoproterozoic terranes.

Palaeoproterozoic terranes, South, central West, North-West, northern West and South-East Greenland

The reworked, deformed and metamorphosed Palaeoproterozoic orogeny and the Palaeoproterozoic Mobile Belts of Greenland have relatively high abundance of graphitic material hosted in supracrustal rocks.

3.7 Niobium [Nb] (and associated tantalum [Ta])

Table 8. *Overview of the commodity niobium*

Main application	Niobium is mainly used in steel in the construction industry, the automotive industry and the oil- and gas industry in order to provide strength to alloys and hence to reduce weight.
Annual production and leading producing countries	The world production of mineral concentrates of niobium in 2015 was about 56 000 ton. The production is mainly controlled by Brazil (90%) and Canada (9%) (U.S. Geological Survey 2016).
Main mineral	More than 60 Nb-minerals are known of which the majority are silicates. However, mainly the Nb-oxides are commercial products, of which columbite and pyrochlore are the main source of niobium, though e.g. lueshite and euxenite also contain high content of niobium.
Resource/reserve	Brazil and Canada holds the vast majority of the known niobium reserves, estimated to 4 Mt plus, of which about 95% is located in Brazil and related to secondary deposits.
Market constraints	Resource and production concentration in one country (Brazil). Recycling may be as much as 20% of apparent consumption. Substitution is possible at higher cost or lower performance. The demand follows the demand for steel, and therefore China is consuming about 25%.

Known niobium occurrences

The known niobium occurrences and the tracts with potential for niobium in Greenland are shown in Figure 8.

Motzfeldt Centre intrusion, South Greenland

The Motzfeldt Centre covers an area of approx. 300 km^2 and consists of several igneous intrusions within the Proterozoic Gardar Province (Emeleus & Harry 1970; Tukiainen 1985; Tukiainen *et al.* 1984). The Motzfeldt Centre of the Igaliko Nepheline Syenite Complex is the oldest intrusion in the complex and its formation can be resolved into three major and several minor intrusive phases. Nepheline syenites of the second phase and the Motzfeldt Sø formation are peralkaline and volatile-rich, and some are strongly enriched in Zr, Nb, Ta, REE, U and Th, locally forming pyrochlore deposits of economic interest (Tukiainen 1988) in an area of about 20 × 15 km. The mineralisation and the hydrothermal alteration are thought to have formed by an upwards migrating volatile phase, rich in alkalis, fluorine and incompatible elements. The pyrochlore enrichment at Motzfeldt Sø is a 'low grade – large tonnage' deposit. The pyrochlore content increases outwards and upwards towards the roof of the syenite unit of the intrusion. The pyrochlore at the deeper levels is enriched in Ta and Ca, whereas that of the higher levels of the intrusion is more enriched in Nb, U and REE. The Ta content in the pyrochlore varies from 1.3% to 8.3%, and the Nb/Ta ratio is typically around 11. A niobium-tantalum resource estimate indicates a mineralised rock volume of more than 500 Mt with average 0.14% Nb, 120 ppm Ta, 60 ppm U and 90 ppm Th (Tukiainen 1988). High grade zones carry up to 426 ppm Ta. With the cut-off grade at 250 ppm Ta, the estimated reserve is at least

30 Mt Additionally, a Nb resource of at least 130 Mt with 0.4–1.0% Nb_2O_5 has been reported (Tukiainen 1988).

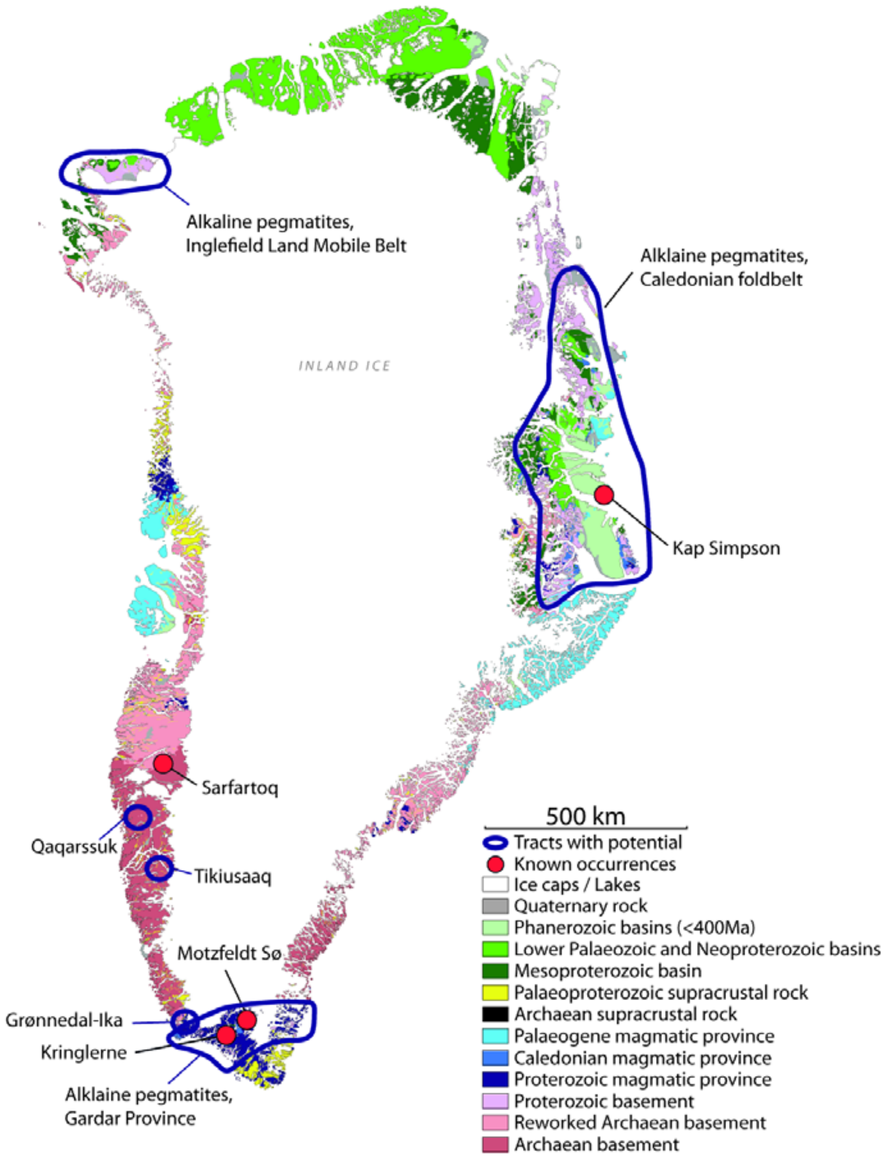

Figure 8. *Map of known niobium occurrences and tracts with potential for niobium. Simplified geological map is based on 1:2 500 000 geological map by Henriksen* et al. *(2009).*

Kringlerne / Killavaat Alunnguat, South Greenland

The Ilímaussaq intrusion (17 × 8 km) in South Greenland belongs to the Mesoproterozoic Gardar province. The province is a cratonic rift province, consisting of sandstones, and a variety of volcanic and plutonic igneous rocks many of which are alkaline. The alkaline rocks evolved towards Si-rich melts such as comendites and alkali granites, and towards Si-poor melts such as phonolites and neheline syenites (Bailey *et al.* 2001). The alkaline Ilímaussaq intrusion is one of the later intrusions (1160 Ma), largely emplaced by block subsidence, and formed by three pulses of which the third formed a layered series of nepheline syenites. The Ilímaussaq intrusion is unusual in terms of the enrichment of the elements U, Th, Nb, Be, Zr, Li, F, and REE, which is reflected in the great number of minerals recorded. The Ilímaussaq intrusion hosts two different types of REE deposits, i.e. Kvanefjeld (dominated by lujavrites) and Kringlerne (dominated by the kakortokite bottom cumulates).

The Kringlerne Zr- REE-Nb deposit, situated about eight kilometres south of Narsaq and 20 km north-east of Qaqortoq, is hosted in the lower cumulates of the layered agpaitic nephenline syenites, referred to as kakortokite (microcline, nepheline, arfvedsonite, aegirine, eudialyte). The kakortokite cumulates form a 200 m thick package composed by 29 cyclic layers; each layer is formed by three kakortokite units (arfvedsonite dominated ('black kakortokite'); eudialyte dominated ('red korkortokite'); and feldspar dominated ('white kakortokite'). Red kakortokite contains about 0.2% Nb_2O_5. The main Nb-mineral is eudialyte, which is also enriched in Ta, Zr and REE.

The current license holder, TANBREEZ Mining Greenland A/S, estimates the resource to be not less than 4,300 Mt grading 0.65% REO, 1.9% ZrO_2, 0.2% Nb_2O_5, and 0.025% Ta_2O_5 (Tanbreez 2013). The ratio of LREE: HREE is reported to be about 2:1. The company submitted application for exploitation license in 2013 and negotiations are ongoing.

Sarfartoq carbonatite complex, central West Greenland

The Sarfartoq carbonatite complex occurs within the foreland of the Nagssugtoqidian orogeny, south of the central part of Søndre Strømfjord (Secher & Larsen 1980). The 565 Ma old elliptical complex comprises a core zone of 15 km^2 and a marginal and aureole zone of 75 km^2, hosted by gneisses and amphibolites. The core zone is mostly dolomite rich carbonatite, and is surrounded by a marginal fenitised aureole zone which is cut by dykes of carbonatite, carbonatite breccias and agglomerates, and calcite veins. The hydrothermal fenitised aureole contains vein-type mineralisation of pyrochlore with REE, Nd, Ta, Th and U located in a tangential set of cataclastic fractures believed to be generated before the emplacement of the intrusion. Pyrochlore is identified in several places, two of these, named 'Sarfartoq 1' and 'Sarfartoq 2', have so far been regarded as the most promising, with the former being the main focus of most work. The 'Sarfartoq 1' deposit occurs as a steep to vertical dipping breccia lens measuring 10 × 100 m. The central part of the lens at 'Sarfartoq 1' consists of 95 vol.% pyrochlore. An expected minimum resource of 100 000 ton ore with 15% Nb_2O_5 and 0.18%, Ta_2O_5 has been calculated to a depth of 50 m, exclusively based on surface observations.

Maximum grades are as high as 58% Nb_2O_5 and 0.58% Ta_2O_5. In 1989, Hecla Mining Company drilled 568 m of core at 'Sarfartoq 1', and estimated a resource of 25 000 t to 30 000 t of ore with a cut off at 10% Nb_2O_5. The company concluded that the mineralisation pinched-out laterally as well as at depth and as a result ceased exploration at the license (Druecker 1990). In 1998, New Millennium carried out 800 m of diamond drilling and calculated a measured resource at 35 000 t at 11.3% Nb_2O_5 with additional 100 000 t at 4.6% Nb_2O_5 in the indicated category (Woodbury 2003).

Kap Simpson, central East Greenland

A major Palaeogene felsic intrusive complex with a caldera sequence and extensive hydrothermal alteration occurs at Kap Simpson in central East Greenland. Felsic dykes and veins in the marginal parts of the complex are reported to contain niobium mineralisation together with REE. Grab samples have yielded up to 3.2% Nb and 3% TREE, in addition to beryllium (max. 0.15%), yttrium (max. 0.3%), zinc (max. 0.35%) and barium (max. 0.3%). The overall content is not reported, but the niobium content of the veins is estimated to be above 0.2%. (Harpøth *et al.* 1986).

Tracts with resource potential for niobium

Geologically the tracts described below are related to alkaline pegmatites or carbonatites.

Qaqarssuk, Tikiusaaq and the Grønnedal-Ika carbonatite complexes, southern to northern West Greenland

West Greenland has several carbonatite complexes, in addition to the Sarfartoq complex, such as Qaqarssuk, Tikiusaaq and the Grønnedal-Ika complexes. The Qaqarssuk carbonatite complex is reported to contain 1.2 Mt @0.8% Nb_2O_5 (MeerConsulting 2000). Furthermore, yet undiscovered complexes in this region may hold a potential for niobium mineralisation together with tantalum, REE, uranium and thorium.

Alkaline pegmatites, South, North-West and northern East Greenland

The Mesoproterozoic Gardar Province and the Palaeogene alkaline province in central East Greenland are the two areas with the largest and most important group of alkaline rocks, and also host the Motzfeldt Centre and Kap Simpson igneous complexes respectively. These areas also hold a potential for pegmatites enriched in niobium and tantalum. Other areas that also could contain alkaline pegmatites are the Inglefield Land Mobile Belt in North-West Greenland, and the Caledonian Orogen in northern East Greenland (Steenfeldt *et al.* 2007).

3.8 Platinum Group Metals [PGM: Pt, Pd, Rh, Ru, Ir, Os]

Table 9. *Overview of the commodity platinum group metals (PGM)*

Main application	The PGMs commonly occur together, but are used for somewhat different applications, due to slightly different chemical and physical specifications. Platinum (Pt) is mainly (40%) used in the auto-catalysts industry specifically for diesel engines; about 35% are consumed in the jewellery sector. About two-third of the Palladium (Pd) is used in the auto-catalyst industry for non-diesel vehicle engines, followed by the electronic industry (12%) and jewellery (4–5%). Also Rhodium (Rh) is mainly used in for the auto-catalysts in combination with Pd as well the glass industry consumes some Rh. Also, PGMs are used in hard disks drives to increase storage capacity, in multilayer ceramic capacitors, and in hybridized integrated circuits. PGMs are used by the glass manufacturing sector in the production of fiberglass, liquid crystal displays, and flat-panel displays.
Annual production and leading producing countries	Platinum: global production (2015) was 178 000 t of which RSA produced (70%); Russia (13%), Zimbabwe (7%) and Canada (5%) (U.S. Geological Survey 2016). Palladium: global production (2015): Russia (38%), RSA (35%), Canada (12%), USA (6%), and Zimbabwe (5%) (U.S. Geological Survey 2016).
Main mineral	The most important PGM mineral is pentlandite ($(FeNi)_9S_8$), followed by cooperate/braggite (Bushveld, Norilsk, Stillwater and Great Dyke). The main platinum mineral is sperrylite $PtAs_2$.
Resource/reserve	The world PGM reserve is 66 Mt plus, of which about 95% is located in South Africa, and minor reserves are occur in Russia, and the USA (U.S. Geological Survey 2016).
Market constraints	Both the reserve and production of PGM is concentrated in a few countries (dominated by South Africa and Russia), which in combination with at rather volatile price structure may create supply problems. The main driver of the demand is the auto-catalyst sector.

Known PGM occurrences

In Figure 9 known platinum group metal occurrences and tracts with potential for platinum in Greenland can be seen.

PGM deposits are divided into deposits where 1) PGM is the primary commodity; and 2) PGM is a by-product to nickel-copper production. The primary PGM deposits include the a) Reef-type mineralisation (Bushveld, Stillwater and the Skaergaard intrusions), b) dunite related deposits, and c) contact related mineralisation, which for example constitutes part of the Platreef mineralisation in Bushveld and the Duluth complex in the USA.

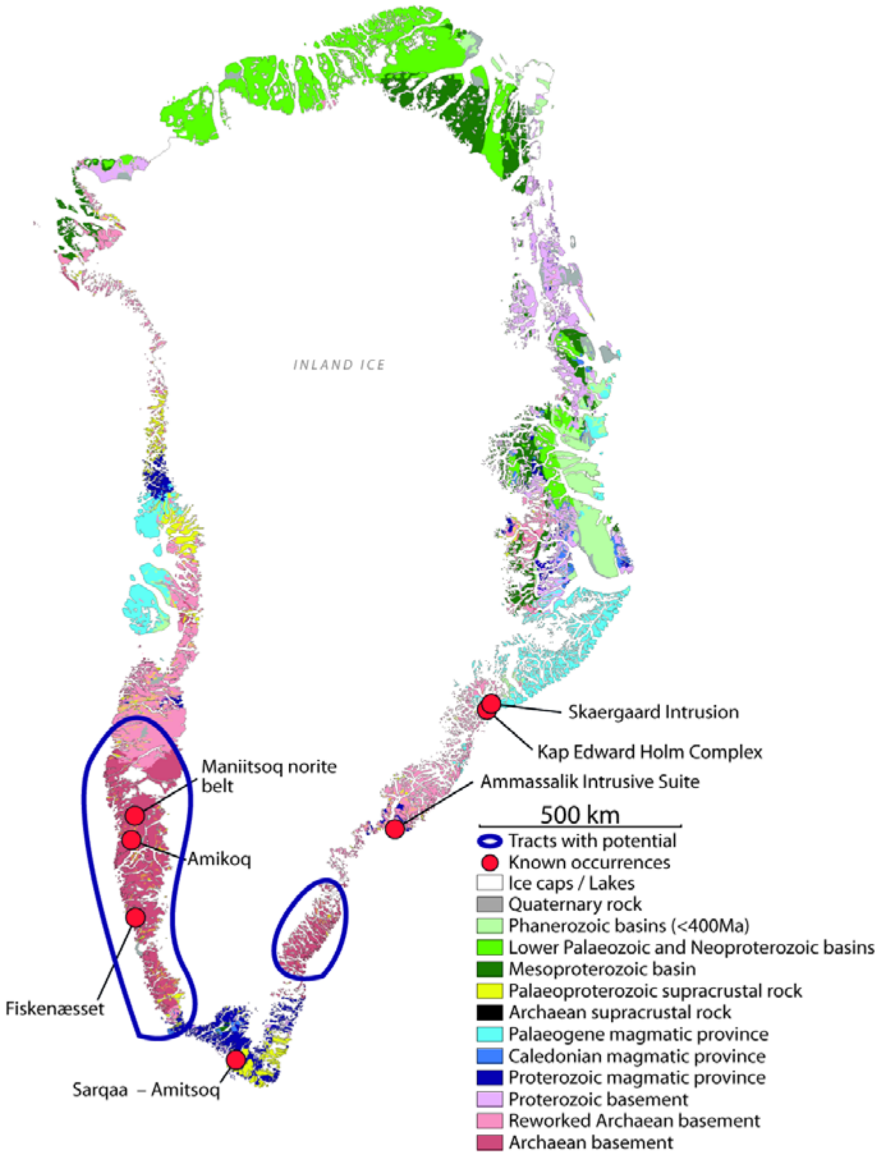

Figure 9. *Map of known platinum group metal occurrences (red dots) and tracts with potential for platinum group metals. Simplified geological map is based on 1:2 500 000 geological map by Henriksen* et al. *(2009).*

Skaergaard, East Greenland

The tholeiitic layered gabbroic Skaergaard intrusion (Nielsen *et al. 2015;* Irvine *et al.* 1998; Wager & Brown 1968) is one of several tholeiitic gabbro intrusions, emplaced during the rifting and opening of the North Atlantic at 60–54 Ma. The Skaergaard intrusion has a surface exposure of 70 km^2 and contains a stratiform PGM-Au mineralisation. The deposit is also enriched in titanium and vanadium. The following description is from Andersen *et al.* (1998); Nielsen (2004) and Nielsen *et al.* (2005, 2015). Palladium and gold is hosted in and below the Triple Group, a stratigraphic unit characterised by three distinct leuco-grabbro layers. The mineralisation is referred to as the 'Platinova Reef' and appears to have formed in response to silicate-sulphide liquid immiscibility in the basaltic magma and is enriched in palladium, platinum, gold and copper. The Platinova Reef includes at least five main levels of palladium-enrichment and the total stratigraphic section hosting all palladium-levels is 45 m thick. All levels are concordant with the magmatic layering of the host rocks and form a saucer shape, which is 7 km wide in an E–W cross section with a central depression of *c.* 700 m. The number of developed palladium-levels decreases systematically toward the margins of the intrusion, where only one palladium-level is developed. Gold is always concentrated in or just above the top of the palladium-levels. The stratigraphic separation between the Pd-levels and the Au-rich zones increases from 5 m at the margin of the intrusion to 60 m in the centre of the intrusion. Palladium and gold minerals are characteristically alloys (e.g. PdCu, AuPd, (Pd, Au) Cu) or intimately associated with Fe-poor, Cu sulphide minerals dominated by bornite and chalcosine group minerals.

Platina Resources Ltd., who currently holds the license, reported in accordance with the JORC Code (2012) the indicated reserve to amount to 203 Mt grading 0.88 g/t Au and 1.33 g/t Pd at a 1 g/t Au equivalent cut-off grade and minimum mining thickness of 1 m (www.platinaresources.com.au/projects/skaergaard/). Additional commodities are Ti and V (Andersen *et al.* 1998; Bird *et al.* 1991; Nielsen 2006; Nielsen *et al.* 2005) yielding up to 7.17% TiO_2 and 868 ppm V.

Kap Edward Holm, East Greenland

The Kap Edward Holm complex (~ 800 km^2) is a layered, tholeiitic gabbro complex approx. 50 Ma old (Nevle *et al.* 1994; Tegner *et al.* 1998). The lower part of the complex is interpreted as ocean-floor type tholeiitic layered gabbro (Bernstein *et al.* 1992). The cumulates contain a 1 to 20 m thick and more than 6 km long stratiform layer, mineralised with gold and PGMs. In this layer, average concentrations over 3 m thickness are 0.25 ppm Pt, 0.04 ppm Pd, and 0.05 ppm Au, with individual samples containing up to 5 ppm Pt, and 6 ppm Au (Arnason & Bird 2000).

Amikoq layered complex, southern West Greenland

Occurrences of PGM mineralisation are abundant in the Archaean shield of West Greenland. One of them is the Amikoq layered complex located 75 km northeast of Nuuk. Amikoq is the largest of several mafic-ultramafic intrusive complexes in the region and is older than 3000 Ma (Garde 1997). The complex extends for 25 km in N-S direction and consists of norites, pyroxenites, dunites and harzburgites intruded between a floor of tonalitic to granitic gneisses and a roof of amphibolites. NunaMinerals A/S (2009) reported the following PGM-values for the complex: I) 'Octopus Reef': 0.4–1.0 ppm Pt+Pd in a 2–4 m thick sheet, traced along 2.5 km, open ended; II) 'Rhodium Zone': Up to 1.0 ppm Pt+Pd+Rh with Rh-dominated PGM patterns, traced along 500 m. Channel sampling across several traverses over a strike distance of 2.5 km has revealed the 'Octopus Reef' as a well-defined stratigraphic level. Drilling intersected the reef at up to 100 m depth. The same channels and boreholes have revealed parallel PGM-mineralised zones above the 'Octopus Reef'. The same types of host rocks at Arnaquassaaq to the north of the Amikoq contain Pt+Pd grades up to 1.25 ppm (NunaMinerals A/S, Announcement no.: 2009/17, Amikoq PGM prospect returns to full NunaMinerals ownership, 2 pp.)

Maniitsoq Norite Belt, southern West Greenland

The Archaean craton of the Maniitsoq area, hosts a suite of noritic-gabbroic rocks (Secher 1983) which are suggested to surround a large Archaean impact structure (Garde *et al.* 2012; Garde *et al.* 2013). The mafic intrusions comprise a 15 × 75 km crescent shaped belt known as the Maniitsoq Norite Belt. The size of the individual norite bodies varies from just 2–5 metres across up to 2 × 4 km (Secher 2001). The norites are intruded in the Finnefjeld gneiss complex (3.03 Ga) within the Akia terrane (Garde 1997). Sulphides in the norites include pyrrhotite, chalcopyrite, pyrite and pentlandite, and gives rise to gossans. The Ni-content of the mineralised rocks is up to 2%. The norite and associated rocks have relatively high Pd and Pt contents, up to 0.6 and 2.2 ppm respectively and up to 2.1 ppm Au (Secher 2001). Exploration on numerous rust zones was initiated in the 1950s and 1960s and several nickel-sulphide showings were identified. The initial work was followed up by shallow drilling. Later, in 1995, fixed-wing airborne electromagnetic surveys were carried out with limited follow-up. In 2011 helicopter-borne TEM and magnetic surveys were carried out. During these surveys many new conductive bodies were identified and subsequent drilling has resulted in several new nickel occurrences. However, no new PGM values have been reported yet.

Sarqaa and Amîtsoq, South Greenland

In the Nanortalik area, several ultramafic plugs/dykes have been described (Berrangé 1970; Chadwick *et al.* 1994; Schønwandt 1971, 1972; Smith & Bow 1988) with ages of 1509 ± 64 Ma. Chadwick *et al.* (1994) suggested that all the plugs are related to an appinite suite found throughout the Ketilidian orogen. On Amîtsoq, one of these plugs/dykes occurs as a hornblendite-peridotite intrusion exposed from the shore and up to 335 m above sea level on central Amîtsoq. The intrusion has been mapped over a length of 1.5 km and it varies in width between 90 and 250 m. The intrusion can best be described as an E–W striking dyke-like body that pinches and swells in three dimensions (Berrangé 1970; Schønwandt 1971). The sulphide content is about 0.2% and can reach 15% in 10–20 cm wide zones. Pyrrhotite, pentlandite, chalcopyrite and cubanite dominate, accompanied by 5–10 vol.% magnetite (Schønwandt 1971). Berrangé (1970) recorded traces of gold, platinum and palladium. Five km east of the Amîtsoq plug, another ultramafic plug/dyke occurs on the Nanortalik peninsula named Sarqaa. An exploration programme was initiated here in 1987 after finding a mineralised float containing 10.8 ppm Pt+Pd. The follow-up study resulted in the location of the ultramafic Sarqaa dyke. The mineralisation occurs as disseminated to semi-massive net-textured sulphide in hornblende peridotite. Assays of the sulphide bearing samples yielded up to 6 ppm Pt+Pd+Au (combined platinum-paladium-gold; Smith & Bow 1988).

Ammassalik intrusive suite, South-East Greenland

Ni-Cu-PGM sulphide mineralisation is associated with ultramafic rocks hosted by sulphidic and graphite-rich supracrustals of the Siportoq sequence south of Tasiilaq, at the southern shore of the Ammassalik Island. The supracrustal sequence is altered and contact metamorphosed by the Palaeoproterozoic Ammassalik Intrusive Suite which is composed of norite-diorite-granodiorites. Sampling returned to have 1.39% Ni, 0.46% Cu, and 0.3 ppm PGM (21st North

2012). Extensive iron sulphide-mineralisations and Ni-Cu-Au mineralised grab-samples from more restricted mineralisation has also recently been found by GEUS within the intrusive rock suite itself. It is currently being investigated whether the Ni-Cu-PGM-bearing ultramafic rocks hosted by the Siportoq supracrustal sequence represents a komatiitic-affinity, as suggested in company reports, or whether it represents an orthomagmatic mineralisation.

Fiskenæsset anorthosite-gabbro complex, southern West Greenland
At Qeqertarsuatsiaat (Fiskenæsset), the metamorphosed layered anorthosite and gabbroic rocks of the Fiskenæsset anorthosite complex described in the section about Cr (sub-section 3.3), also has PGM mineralisation.

Initial exploration in 1969 and 1970 was carried out by Platinomino A/S. The targets were Ni-Cu- and Merensky Reef type platinum deposits. However, only a limited number of samples (approx. 45 out of 750) were assayed for PGMs. In 1991 and 2008-2009, GEUS investigated the Qeqertarssuatsiaat area and found the ~ 5 m wide Ghisler reef with up to 2.0 ppm Pt+Pd+Au, which can be traced over ~ 5 km (Appel 1993; Appel *et al.* 2011). Present knowledge indicates that PGEs are concentrated in hornblendite in the upper part of the middle gabbro unit overlying the upper leucogabbro unit (Appel 1993; Appel *et al.* 2011). In 2009, GEUS conducted additional channel sampling and mapping in the western part of the Fiskenæsset, which returned anomalous grades up to 1.9 ppm PGM over 1 m and 0.61 ppm PGM over 5 m (Dahl 2009; Appel *et al.* 2011).

Recent exploration by the exploration company 21st North yielded up to 6.7 ppm PGM total from grab sampling (Pd dominated). Nineteen channel sample profiles from 2010 outlined a continuous mineralised reef in the ultramafic sequence, which is traceable on kilometre-scale, with an average grade of 0.52 ppm Pt+Pd over 4.8 m width (21st North 2012).

Tracts with resource potential for PGM

Geologically the tract described below is defined to anorthosite-gabbro and other mafic-ultramafic complexes of the North Atlantic Craton (Archaean) in southern West and East Greenland.

Anorthosite-gabbro complexes and other mafic-ultramafic complexes, West and South-East Greenland

Archaean anorthosite-gabbro complexes, as well as mafic-ultramafic rock units in the Archaean and the Palaeoproterozoic reworked parts of Greenland host a potential for PGM, together with nickel or chromite. Only few of the mafic and/or ultramafic bodies/lenses that are found throughout the craton and the Palaeoproterozoic counterparts have been investigated for the PGM potential, e.g. the large ultramafic bodies located in the Fiskefjord region north of Nuuk, southern West Greenland.

3.9 Rare Earth Elements [REE]

The Rare Earth Elements (REE) comprises the lanthanides (lanthanum (La), cerium (Ce), praseodymium (Pr), neodymium (Nd), promethium (Pm), samarium (Sm), europium (Eu), gadolinium (Gd), terbium (Tb), dysprosium (Dy), holmium (Ho), erbium (Er), thulium (Tm), ytterbium (Yb) and lutetium (Lu)) and in addition the elements yttrium (Y) and scandium (Sc), of which Pm and Sc are not included in the commercial REE[1].

Table 10. *Overview of the commodity rare earth elements (REE)*

Main application	Metallurgy and battery alloys (La, Ce, Pr, Nd, Sm, Y) Permanent magnets (Nd, Pr, Sm, Gd, Tb, Dy) Catalysts and chemical process (La, Ce, Pr, Nd) Polishing powder (La, Ce) Ceramics (La, Ce, Pr, Nd, Y) Glass additives (La, Ce, Pr, Nd, Y) Phosphors (Eu, Y, Tb, Nd, Er, Gd (Ce, Pr))
Annual production and leading producing countries	The annual production for 2015 is estimated to about 124 000 ton of REE of which China accounts for 110 000 ton; the remaining 24 000 ton non-Chinese producers are Malaysia/Australia, India, Russia, Kazakhstan, and South Africa (U.S. Geological Survey 2016). A wide range of production statistics on REE has however been published.
Main mineral	REE is associated with more than 300 minerals. However, the following four groups comprise the main minerals: carbonates (bastnaesite), phosphates (monazite, xenotime, apatite), silicates (eudialyte, allanite) and niobates (loparite). Most of the global production has been extracted from bastnaesite ores and minor amounts from loparite, xenotime, monazite, and ion adsorption clays. Eudialyte is the main mineral in quite a few of the REE-projects being developed. Additionally, apatite is being considered as a potential by-product REE-source.
Resource/reserve	USGS (2016) report the global REO-reserves to amount to 130 Mt, of which 55 Mt is located in China, followed by Brazil (22 Mt), and about 41 Mt in other countries. Extensive development on new discoveries have added substantial amounts of resources which within the next few years will be added to the global reserve figures; of these Greenland has the potential to contribute with large reserve figures.
Market constraints	The REE-market is not balanced. For the REE, a balanced market is very difficult to obtain, because (i) any REE occurrence will have to find customers for all the REE, and each of the market segments consume only a few of the individual REE; (ii) the price and availability is inversely related, thus large volumes are low-price products and small products are highly priced; (iii) the REE-application is very dynamic and changes over time. The market drivers are the Nd and Dy for permanent magnets; however, in order to produce the adequate amount of Nd to satisfy the market this will lead to an overproduction of La, Ce, Pr, Pr, Eu, Gd, and Tb. The drivers on the small HREE market are mainly Eu, Tb, Dy, Y.

[1] Pm is radiogenic and Sc is sourced from other minerals and processes. For these reasons Pm and Sc are not included in the commercial REE-commodities.

Known REE occurrences

Figure 10 shows the known REE occurrences and tracts with potential for REE in Greenland.

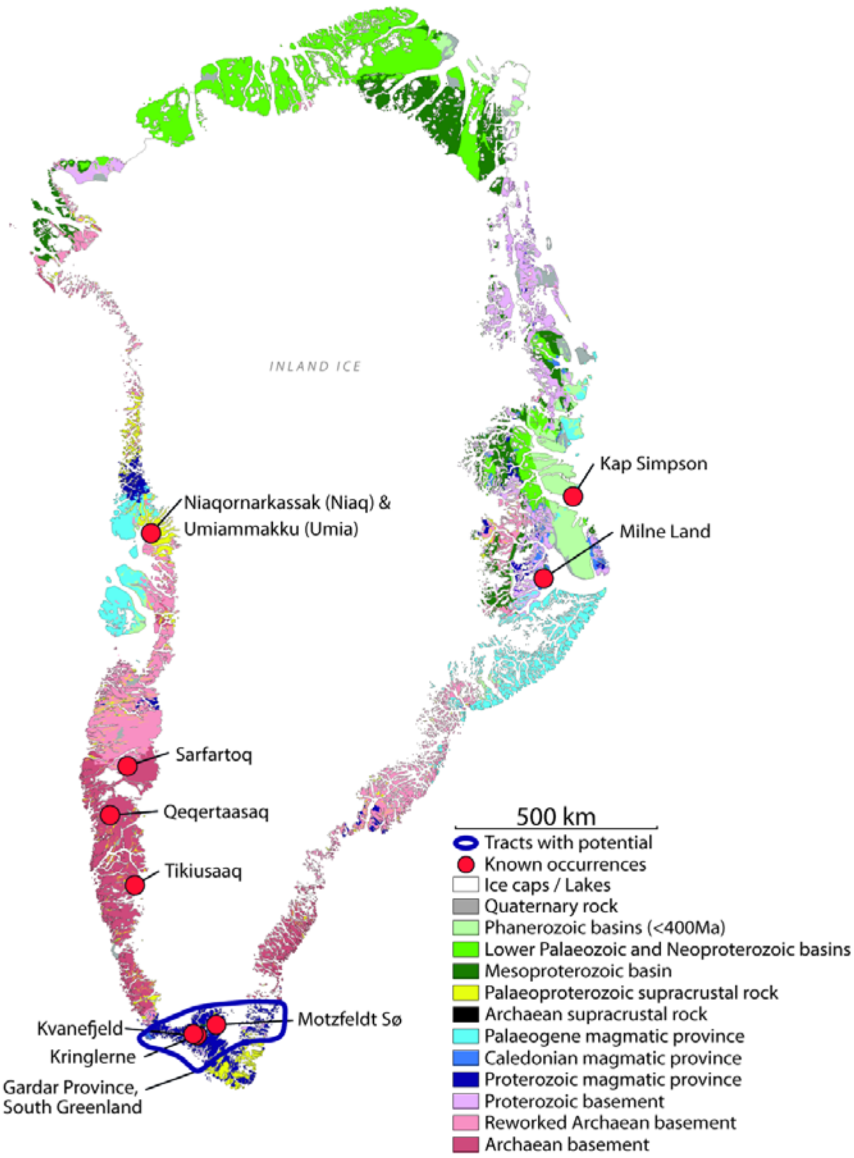

Figure 10. *Map of known rare earth elements occurrences and tracts with potential for rare earth elements. Simplified geological map is based on 1:2 500 000 geological map by Henriksen* et al. *(2009).*

Ilímaussaq Complex, South Greenland – Kvanefjeld and Kringlerne REE deposit

The Ilímaussaq intrusion (17 × 8 km) in South Greenland belongs to the Mesoproterozoic Gardar province. The province is a cratonic rift province, consisting of sandstones, and a variety of volcanic and plutonic igneous rocks, many of which are alkaline and per-alkaline. The alkaline rocks evolved towards Si-rich melts such as comendites and alkali granites, and towards Si-poor melts such as phonolites and neheline syenites (Bailey *et al.* 1981). The Ilímaussaq intrusion is one of the later intrusions (1160 Ma), largely emplaced by block subsidence, and formed by three pulses of which the third formed a layered series of nepheline syenites. The

Ilímaussaq intrusion is unusual in terms of the enrichment of the elements U, Th, Nb, Be, Zr, Li, F and REE, which are reflected in the great number of minerals recorded. The Ilímaussaq intrusion hosts two different types of REE deposits; Kvanefjeld (dominated by lujavrites) and Kringlerne (dominated by the kakortokite bottom cumulates).

The Kvanefjeld REE-U-Zn deposit, is located eight kilometres north-east of the town Narsaq, South Greenland, and is a mega-breccia formed by various igneous rocks and supracrustals from the roof of the Ilímaussaq intrusion as well as rocks from the early phases of the alkaline intrusion, forming blocks and sheets within the later agpaitic magma. The bulk of the REE (and U and Th) in this part of the intrusion, is associated with the rock type lujavrite. The majority of the REE is hosted by the mineral steenstrupine making up 5% of the lujavrite, Zr silicates (lovozerite) which makes up 3% of the lujavrite and an unclassified REE mineral that makes up 1% of the lujavrite. The bulk of the lujavrite is composed by arfvedsonite (29%), alkali feldspar (35%), hydrated sodium silicates (11%), aegirine (7%), potassium silicates (4%), villaumite (3%, NaF), sphalerite (1%) and monazite/vitisite/xenotime (0.5%). The deposit also contains zinc, occurring as disseminated sphalerite in the lujavrite, and fluorine hosted in the water soluble mineral villiaumite (NaF). The Kvanefjeld deposit has been explored for decades by various groups, but the early focus was mainly for the potential of uranium. The current license holder of Kvanefjeld, Greenland Minerals and Energy A/S (GMEL), has identified an indicated and inferred grand total resource inventory: 1010 Mt containing 593 Mlbs U_3O_8, 11.14 Mt TREO, and 2.4 Mt Zn, based on a cut-off of 150 ppm U (GMEL 2015). This resource encompasses three individual deposits: (i) Kvanefjeld deposit (measured) 143 Mt containing 1.72 Mt TREO, 95 M lbs U and 0.34 Mt Zn; (ii) the Sørensen deposit (inferred) 242 Mt containing 2.67 Mt TREO, 162 Mlbs U_3O_8 and 0.63 Mt Zn; and (iii) the Zone 3 deposit (inferred) 95 Mt containing 1.11 Mt TREO, 63 Mlbs U_3O_8, and 0.26 Mt Zn (GMEL 2015).

The Kringlerne Zr- REE-Nb deposit, situated about eight kilometres south of Narsaq and 20 km north-east of Qaqortoq, is hosted in the lower cumulates of the layered agpaitic nephenline syenites, referred to as kakortokite (microcline, nepheline, arfvedsonite, aegirine, eudialyte). The kakortokite cumulates form a 200 m thick package composed by 29 cyclic layers; each layer is formed by three kakortokite units (arfvedsonite dominated; eudialyte dominated; and feldspar dominated). The mineral eudialyte is enriched in Zr-REE-Nb and the red kakortokite layers are the main exploration targets for REE. The present license holder, TANBREEZ Mining Greenland A/S, estimates the resource to be not less than 4300 Mt grading 0.65% REO, 1.9% ZrO_2, 0.2% Nb_2O_5, and 0.025% Ta_2O_5. The ratio of HREE (including Y) is reported to be 30%. The company submitted application for exploitation license in 2013 and negotiations are ongoing.

Sarfartoq carbonatite complex, central West Greenland

The Sarfartoq carbonatite complex described under Nb above also has REE mineralisation. In 2009, Hudson Resources Inc. commenced its REE exploration program in the Sarfartoq carbonatite complex. The REE targets were identified from datasets from previous exploration companies (e.g. the company New Millennium) fieldwork and results in the area. The REE minerals identified by Hudson Resources Inc. include bastnaesite, synchysite, and monazite, and the LREO/HREO average ratios are between 19 and 52 for different localities. The so-called 'ST-1' prospect is one of the most promising and has been investigated intensively. It is located along the western margin of the K-fenite-Precambrian gneiss contact in the outer ring structure of the complex. Rare earth element mineralisation in the ST-1 prospect is associated with ferrodolomite carbonatite dikes/veins emplaced along NNE-trending dilational fractures and shears in the outer ring structure. In 2010 Hudson Resources Inc. published a NI43-101 compliant resource estimate for the ST-1 site; 14 Mt inferred resource averaging 1.53% TREO at a cut-off grade of 0.8% TREO. The average thorium grade is *c.* 500 ppm Th, but U is very low. The results from the exploration indicate the occurrence of a high-grade shallow body with a large tonnage. Furthermore, results show that a large percentage (25–54%) of the REE is Nd and Pr (Pers.com. Hudson Resources Inc.).

Motzfeldt Sø, South Greenland

The Motzfeldt Sø intrusion centre of the Igaliko Nepheline Syenite complex described under Nb above also has REE mineralisation. Exploration for REE has been carried out by RAM Resources Ltd. (the license is taken over by Regency Mines Plc.) and their work indicates that the known Ta-Nb mineralisation is only weakly correlated with REE mineralisation. In the central part of the intrusion, where the richest Ta-Nb mineralisation is found, the lithology is predominantly altered syenite, with minor pegmatite and diorite dykes. However, high grade REE intersections are concentrated in the pegmatite intrusive at depth, but are also found scattered throughout the drill holes, gradually decreasing in grade towards the east. REE's were identified in zircon, monazite, bastnaesite. The main REE elements identified in the samples were La, Ce, Nd, Pr, Dy, Er, and Ho. The U and Th contents vary, but do not exceed 200 ppm.

The Niaqornakassak and Umiammakku Nunaa deposits, northern West Greenland

The Niaqornakassak (also referred to as Niaq) REE mineralisation is located on the island of Qeqertarsuaq, and was discovered in 2007 by Avannaa Resources Ltd. (Mott *et al.* 2013). An extension of the deposit was discovered in 2009 on the Umiammakku Nunaa (Umia) peninsula 7 km along strike from the Niaq site.

The REE mineralisation is a lithologically distinct horizon of banded carbonates hosted in an amphibolite unit of the Palaeoproterozoic Karrat Group. The REE-bearing carbonates are interpreted to be hydrothermal carbonatite-sourced (Mott *et al.* 2013). The strike length of Niaq is 1.5 km but open at both ends where it is limited by the coastline. The tabular Niaq ore body has been found to a maximum elevation of 56 m above sea level and down to 168 m below sea level; the thickness varies between 10 m and 33 m. The Niaq bulk samples indicate an average of TREO of 1.36%, of which the average HREO content is *c.* 13%. Preliminary resource estimates of the Niaq body are 26 Mt. The REE are mainly hosted by the minerals bastnaesite, monazite, allanite and other REE silicates. Only limited work has been undertaken on the Umia body. Based on the three drill holes the TREO of the Umia deposit is in the range of 0.08–0.12%. The deposit has an average of 500 ppm thorium.

Tikiussaq carbonatite complex, southern West Greenland

The Tikiusaaq carbonatite, discovered by GEUS in 2005, by interpretation of regional stream sediment data, regional airborne magnetic data and radiometric data, consists of massive dolomite-calcite carbonatite sheets intruded along a ductile shear zone at approx. 158–155 Ma (Steenfelt *et al.* 2007b; Tappe *et al.* 2009). The carbonatite is later intruded by carbonate-rich ultramafic silicate dykes. The deep volatile rich magmatism at Tikiusaaq forms part of a larger Jurassic alkaline province in southern West Greenland and represents the earliest manifestation of rifting processes related to the opening of the Mesozoic–Cenozoic Labrador Sea Basin. NunaMinerals A/S initiated exploration of the Tikiusaaq carbonatite in 2010, and focused on the carbonatite core defined from aeromagnetic data. Sampling was restricted to a series of widely spaced, sub-parallel gullies where 2–10 m thick, vertical carbonatite dykes and fenitised country rocks are well exposed. Most of the carbonatite sheets within the core represent early intrusive phases. However, REEs are typically enriched in the latest intrusive phases of carbonatite magmatism which is dominated by iron-rich dolomite and hematite. The main REE mineral is ancylite (Sr-REE carbonate). The REE composition of Tikiusaaq is 47% Ce, 33% La, 12% Nd, 4% Pr and 4% other REEs. Drill core samples have yielded up to 9.6% TREO (predominantly LREE). High phosphate grades (up to 8.5% P_2O_5) were returned from samples within the magnetic core of the carbonatite.

Interpretation of radiometric and magnetic data indicates a body about 750 m long and 100 m wide and extending to a depth of at least 500 m.

Qeqertaasaq / Qaqarssuk carbonatite complex, southern West Greenland

The Qaqarssuk carbonatite complex, situated 60 km east of Maniitsoq, West Greenland, is intruded into Archaean gneisses about 170 Ma ago, along with kimberlite and alkaline intrusions; the intrusion of the carbonatite is accompanied by extensive fenitisation (Knudsen 1991). The complex consists of an outer suite of steeply outward dipping concentric carbonatite sheets and an inner suite of less steeply dipping circular sheets. The composition of the carbonatite is soevite to rauhaugite - i.e. mainly calcite to dolomite dominated.

NunaMinerals A/S explored the carbonatite in 2010 with focus on locating potentially REE enriched carbonatite dykes in the core of the carbonatite complex. NunaMinerals A/S reports the average grade for a 1.5 km^2 area to 2.4% TREO. The carbonatite is LREE dominated with 50% Ce, 27% La, 16% Nd, 5% Pr and 2% other REEs. The REE mineralised dykes are generally less than 1 m thick, although thicker dykes (> 3 m) have been observed. Some of the thick dykes had promising grades up to 13.2% TREO. The main REE mineral at Qaqarssuk is coarse grained ancylite (Sr-REE-carbonate). The average grade of all 157 surface samples taken from a 1.5 km^2 area of initial interest is 2.4% TREO with very low uranium contents. Concentric thorium anomalies just outside the complex boundary, identified from historic radiometric data, were also investigated, but little REE prospective carbonatite was discovered here.

Kap Simpson, central East Greenland
The felsic intrusive complex at Kap Simpson described under Nb above, also has REE mineralisation. Felsic dykes and veins in the marginal parts of the complex are reported to contain niobium mineralisation together with REE. Grab samples have yielded up to 3.2% Nb and 3% REE in addition to beryllium (max. 0.15%), yttrium (max. 0.3%), zinc (max. 0.35%) and barium (max. 0.3%) (Harpøth *et al.* 1986).

Milne Land palaeoplacer, central East Greenland
The Mesozoic Milne Land palaeoplacer was discovered in 1968 by Nordisk Mineselskab A/S in connection with a heavy minerals concentrate sampling program, an air-borne radiometric survey and ground follow-up in 1971 and 1972. The placer is in the basal part of the Jurassic Charcot Bugt Formation (sandstone), and the most anomalous locality, 'Hill 800' in Bays Fjelde, is about 500 m in diameter and 40–50 m thick. It consists of three units of arkosic sandstones and breccias. The heavy minerals are hosted by the basal approx. 20 m thick unit. The sands are rich in garnet, ilmenite, rutile, zircon, and monazite. REE, U and Th are mainly hosted in monazite, and the Th/U ratio is around 10 and Ce is about 50% of the REE (Harpøth *et al.* 1986). Schatzlmaier *et al.* (1973) estimated the 20 m thick basal unit to contain 5 Mt with 1.0–3.8% Zr and 0.5–1.9% REO.

Tracts with resource potential for REE

Geologically the tract comprising the Gardar Province in South Greenland is far the most promising area for potential new REE deposits.

Gardar Province, South Greenland
South Greenland is believed to have a large potential for hosting undiscovered REE deposits in addition to the known deposits at Kvanefjeld, Kringlerne and Motzfeldt Centre. Some of the other geological sites that hold REE potential are: the Grønnedal-Ika carbonatite complex, the Qassiarsuk/Green Dyke and the Ivigtut alkaline intrusion. Also, trachytic lavas in the Gardar Province may have a REE potential (see also Sørensen *et al.* 2011).

3.10 Tin [Sn] and tungsten [W]

As tin and tungsten are found within the same deposit types they are here described together. There might be situations where one of the two geochemical elements is the major constituent in the ore, but the other element will almost always be present in smaller or larger quantities and may very well in many cases be another primary or by-product from such deposits. However, although tungsten mineralisation is known from a couple of occurrences in Greenland tin mineralisation is not.

Table 11. *Overview of the commodities tin*

Main application tin	Tin is used in many alloys, most notably tin/lead soft solders and for corrosion-resistant tin plating of steel. Tin is non-toxic and has therefore been used for tin cans.
Leading tin producing countries	The total primary production in 2015 was *c.* 294 000 ton, of which China was the dominant producer (29%) followed by Indonesia (17%), Burma (10%), Peru (7%), Bolivia (7%), and Brazil (6%) (U.S. Geological Survey 2016).
Tin resource/reserve Annual production	The global reserves are 4.8 Mt of which China holds about 31% and the remaining are almost equally located in eight countries.
Constraints for tin	For most of its applications, substitution is limited or at the expense of cost and performance.

Table 12. *Overview of the commodity tungsten*

Main application tungsten	Most tungsten (60–70%) is used for cemented carbides (hard metals) used in special tools. Additionally, tungsten is used for stellites alloys and creep-resistant steels and alloys, for electrodes, wires and chemicals.
Leading producing countries of tungsten	The global mine production in 2015 was 87 000 ton, of which China was the dominant producer (*c.* 82%) followed by Vietnam (6%), and Russia (3%), and minor productions in a number of other countries (USGS 2016).
Tungsten resource/reserve Annual production	The world mine reserves is *c.* 3.3 Mt. of which about 57% is located in China, followed by Canada (9%), Russia (8%) and Vietnam (3%) (U.S. Geological Survey 2016).
Constraints for tungsten	For most of its applications, substitution is limited or at the expense of cost and performance.

Known tin and tungsten occurrences

Tin and tungsten deposits in Greenland are not well known but are reported to be associated with the Caledonian and/or Tertiary magmatic activity in central East Greenland. Cassiterite is found in greisen veins in the Staunings Alper and at Malmbjerg (Harpøth *et al.* 1986).

In Figure 11 known tin and tungsten occurrences and tracts with potential for tin and tungsten in Greenland can be seen.

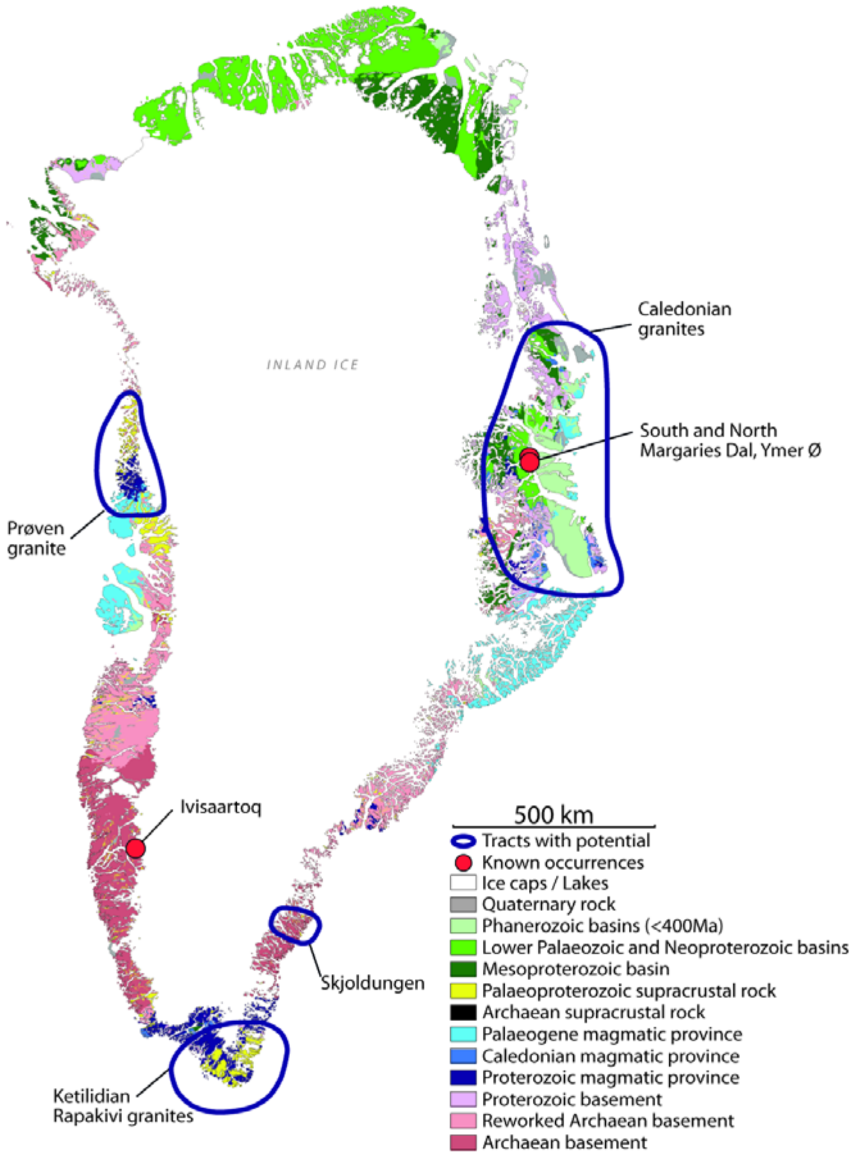

Figure 11. *Map of known tin and tungsten occurrences and tracts with potential for tin and tungsten. Simplified geological map is based on 1:2 500 000 geological map by Henriksen* et al. *(2009).*

Ymer Ø and Margerie Dal, northern East Greenland

Central and northern East Greenland comprises the Caledonian fold belt and is regarded as being the area with most potential for tungsten and tin deposits, although no larger occurrences of the latter is known. The area comprises several known tungsten deposits and occurrences, where the tungsten is found in the mineral scheelite. The high potential is largely attributed to the presence of favourable granitic intrusions and host rocks for the formation of tin-tungsten deposits, the known tungsten mineralisation in the area and the numerous tungsten geochemical anomalies seen in the area. At the same time, large parts of the area have only seen limited exploration activities of which most only have been carried out on surface exposures and the potential for deposits without surface expression has not been investigated. Stendal & Frei (2008) found a heterogeneous, probably local, source of tungsten, and support a genetic link to Caledonian magmatic activity. Their study also indicates mixing of late waningstage fluids from the granites and from interaction with wall rocks. In addition, the study indicates that fluids interacted with both Archaean-Palaeoproterozoic crystalline basement and Mesoproterozoic-Neoproterozoic sedimentary rocks. Mineral occurrences associated with fault zones and late Caledonian-age veins all show a genetic relationship with Caledonian granite emplacement. Thus, tungsten may have been deposited from fluids associated with Caledonian granites, which provided heat sources for local hydro-thermal circulation cells. Forced into faults, thrusts and fractures, the fluids were trapped by dominantly Ca-rich sediments.

A number of scheelite-mineralised areas are found in a 350 km long belt in central and northern East Greenland. Outcropping scheelite occurrences are thus known from 12 areas with footprints varying from 1 to 20 km^2 in size, and scheelite-bearing boulders have been located in two other areas (see also Sørensen *et al.* 2014). It is possible to divide the scheelite-mineralised areas into three groups on account of their geological setting. The groups and their respective areas, with the North and South Margerie Dal on Ymer Ø being the most studied and most prospective target, are as follows:

- Scheelite mineralisation in Upper Proterozoic metasediments, often spatially associated with Caledonian or older granitic intrusions. The areas assigned to this group are Kalkdal, East Milne Land, Knivbjergdal, Gemmedal and Eremitdal.
- Scheelite mineralisation in the Lower Eleonore Bay Supergroup sediments, up to 7 km from outcropping Caledonian granites. The areas of this group comprise Bersærkerbræ, Skjoldungebræ, Trekantgletscher, Galenadal, Scheelitdal and Randenæs.
- Scheelite mineralisation in fault zones in Upper Eleonore Bay Supergroup sediments without spatial relation to granitic rocks. The areas of this group comprise North and South Margerie Dal on Ymer Ø, Panoramafjeld, Eleonores Bugt and Noa Dal.

The last group of deposits and occurrences are hosted in brecciated carbonates in minor fault zones with tungsten found in scheelite and antimony found in stibnite and tetrahedrite (Hallenstein 1981; Hallenstein & Pedersen 1982; Pedersen & Stendal 1987). The two most important occurrences are the North and South Margerie Dal on Ymer Ø. The occurrences on Ymer Ø reflect a crude zonation with scheelite and stibnite at higher stratigraphic level and pyrite, galena, sphalerite, chalcopyrite and locally arsenopyrite with gold at lower stratigraphic levels of the Upper Eleonore Bay Supergroup (Pedersen & Stendal 1987). The tungsten and antimony in the brecciated carbonates in the fault zones are without a direct magmatic association. The emplacement age of the bulk of the scheelite has been determined to be at 382 ± 39 Ma (Stendal & Frei 2008), which places the mineralising event during the latest stages or after the emplacement of the majority of Caledonian granites around 425 Ma. Genetically, it is proposed that the mineralisation is the result of the precipitation from circulating hydrothermal solutions where the fault zones acted as channels for solutions. Limestone and dolomite acted as chemical traps (Pedersen & Stendal 1987). The mineralising event is thought to be contemporaneous with the formation of the fault system through the limestone sequence. Results from drilling at one of the scheelite-stibnite breccia zone in North Margerie Dal indicates 42 000 Mt grading 0.7% W and 108 000 Mt with 3.5% Sb (Harpøth *et al.* 1986); high-grade scheelite is restricted to the thicker part of the breccia zone in which individual half m sections contain up to 24% W in drill cores.

In South Margerie Dal a vein carries 82 000 t grading 2.3% W (Harpøth *et al.* 1986). Locally the fault related mineralisation has quartz veins with some arsenic and gold contents. The gold yields a few ppm gold (Pedersen 1993).

Ivisaartoq, southern West Greenland

The Nuuk region hosts a major tungsten province with scheelite occurring in virtually every greenstone enclave. The Mesoarchaean greenstone is thus a prospective unit for tungsten, especially in the altered komatiites at Ivisaartoq (Appel 1994). The scheelite occurrences are mostly stratabound, and occur in banded amphibolites, tourmalinites and in carbonate altered komatiitic rocks (Appel 1986, 1994; Appel & Garde 1987; Chadwick 1986). Metre-wide veins of diopside, feldspar, garnet and vesuvianite, sometimes with abundant scheelite, were formed after at least one phase of deformation. Polat *et al.* (2007) concludes that the Mesoarchaean Ivisaartoq greenstone belt is a supra-subduction zone of oceanic crust.

The scheelite occurs as disseminated grains, porphyroblasts, stringers, and veinlets and as up to 25 cm wide veins with massive scheelite. Mostly, the scheelite has very low molybdenum contents as revealed by its blue-white fluorescence colours. Locally white to yellowish fluorescent scheelite is seen in cross cutting stringers due to a higher molybdenum content of the scheelite. The scheelite occurrences are interpreted as the result of submarine exhalative events (~ 3.08Ga), later modified and partly mobilised during subsequent deformation and metamorphism (Appel 1986, 1988, 1994; Appel & Garde 1987). The scheelite-bearing rocks are exceptionally rich in bromine, but with comparatively low chlorine contents yielding highly unusual Cl/Br ratios (Appel 1997). Analysis of channel samples revealed grades of 0.44% WO_3 over 2.5 m and 0.48% WO_3 over 1.5 m. With intervals, the scheelite-rich zones can be traced for more than 10 km along strike (Appel 1990, 1994).

Tracts with resource potential for tungsten

Geologically the tracts described comprise central East Greenland including geological units of pre-Devonian age. The other tracts shown in Figure 11 are based on geochemical data and not known tungsten occurrences in these areas.

Rapakivi granites, South Greenland and Caledonian granites, central and northern East Greenland, Prøven granite, northern West Greenland

Tungsten-rich porphyry-type deposits are related to reduced ilmenite-bearing, S-type granites that crystallize at a relatively deep crustal level. The S-type granites are derived by partial melting of continental crust, which includes a significant proportion of metasedimentary material. The rapakivi granites in the psammite and pelite zone of the Palaeoproterozoic Ketilidian orogeny in South Greenland represent the above described setting and may pose a potential for porphyry-type tungsten-(molybdenum) deposits. Only limited exploration has been devoted towards the rapakivi granites. Tungsten is known in heavy mineral concentrates deriving from the Ketilidian batholith in South Greenland.

Caledonian intrusions (granites) and faults in central and northern East Greenland are considered to be potential for tungsten. But only limited exploration has been carried out, but as exemplified by the Ymer Ø tungsten deposits; these settings may be potential for additional mineralisation of tungsten.

The large 1860 ± 25 Ma Prøven granite, northern West Greenland (charnockites and leucogranitic rocks; Kalsbeek 1981) within the Rinkian orogen in the Upernavik area, northern West Greenland, may have a potential for tungsten. The Prøven granite is emplaced into Archaean gneisses and Palaeoproterozoic metasediments of the very thick Karrat Group succession. The emplacement of the Prøven granite may be connected to the high-grade metamorphism. However, it is uncertain to which extent granite formation is related to partial melting of the crust, including the Karrat Group metasediments.

Skjoldungen, South-East Greenland

During fieldwork by GEUS in 2012, a quartz vein with wolframite and molydenite, with 1.6% tungsten, 0.26% molybdenum and 54 ppm rhenium, was identified (Sørensen *et al.* 2013). Furthermore, stratabound scheelite mineralisation (up to 0.5% W) also occurs in amphibolite horizons in the area. The extension of this mineralisation is poorly constrained but its presence suggests a potential for this style of mineralisation in the greater Skjoldungen region.

4. Potential companion-metal commodities

Some of the critical raw materials are strictly companion metals derived from the production of selected major industrial metals (e.g. gallium, indium, and germanium), and no detailed data are available for these metals. Thus the assessment of the resource potential of the companion-metals is derived from generalized knowledge.

As indicated in Table 13, gallium is typically derived from the production of aluminium. Indium and germanium is both potential by-product from zinc mining; indium may as well be derived from the production of tin and platinum. Vanadium is mainly a by-product derived from iron (titanium) ore.

Table 13. *Overview of some of the main minerals and their potential by-products (modified from Graedel* et al. *2014). Black: main commodity; Blue: main and/or by-product; Red: by-product. Italic: Defined as critical (EC 2014)*

Aluminium	Copper	Iron	Lead	Nickel	Platinum	Tin	Zinc
Gallium	*Cobalt*	*REE*	*Antimony*	*Cobalt*	*Palladium*	*Niobium*	*Indium*
	Molybdenum	*Niobium*	Bismuth	*PGM*	*Rhodium*	Tantalum	*Germanium*
	PGM	Vanadium	Silver	*Scandium*	*Ruthenium*	*Indium*	Cadmium
	Rhenium		Thallium		*Osmium*		
	Tellurium		*Indium*		*Iridium*		
	Selenium						
	Arsenic						
	Indium						

4.1 Gallium [Ga]

Table 14. *Overview of the commodity gallium*

Main application	Used in electronic components in integrated circuits, optoelectronic devices, which include laser diodes, light-emitting diodes (LEDs), photo detectors, and solar cells. Optoelectronic devices are used in areas such as aerospace, consumer goods, industrial equipment, medical equipment, and telecommunications. Uses of integrated circuits included military applications, high-performance computers, and telecommunications (USGS 2013).
Annual production and leading producing countries	Total annual production in 2012 was estimated to 273 ton, compared to 218 ton in 2011 (USGS 2013). China is the major producer, followed by Germany, Kazakhstan and South Korea, but no exact figures are reported.
Main mineral	Gallium occurs mainly as a trace element in minerals with other metals and economically recoverable concentrations are quite rare. Given the low concentration of gallium in metal ores, it is not economically viable to extract these minerals solely to recover the contained gallium.
Resource/reserve	The USGS (2016) estimates that worldwide resources of gallium contained within bauxite exceed 1 million ton, and considerable amounts are also thought to be present in zinc ores. However, much of the gallium is associated bauxite reserves which are not likely to be mined in the short term and thus gallium will not be available from these resources. Gallium is also contained in phosphate ores and coal, and might well be the largest reserves of gallium.
Market constraints	Gallium is principally (*c.* 90%) recovered as a by-product from bauxite, grading 30–80 ppm Ga, and only 10% of the annual production stems from zinc ore (Jackson 2010). The major constraint is due to the fact that only 10% of alumina producers extract gallium as well as the fact that only very few gallium high-purity refiners exist (EC 2014).

Known gallium related occurrences

In Figure 12 known gallium occurrences and tracts with potential for gallium in Greenland can be seen.

Skaergaard Intrusion, East Greenland

Titanomagnetite from the Au-Pd mineralised zone of the layered Skaergaard Intrusion is enriched in Ga with concentrations of 81 to 117 ppm (Platina Resources Ltd. 2007). Assuming that the entire width of the mineralised zone is mined, it would correspond to a total tonnage of 1520 Mt (non-compliant to recent international reporting standard). Titanomagnetite constitutes 18% of the ore and contains 21 300 ton Ga.

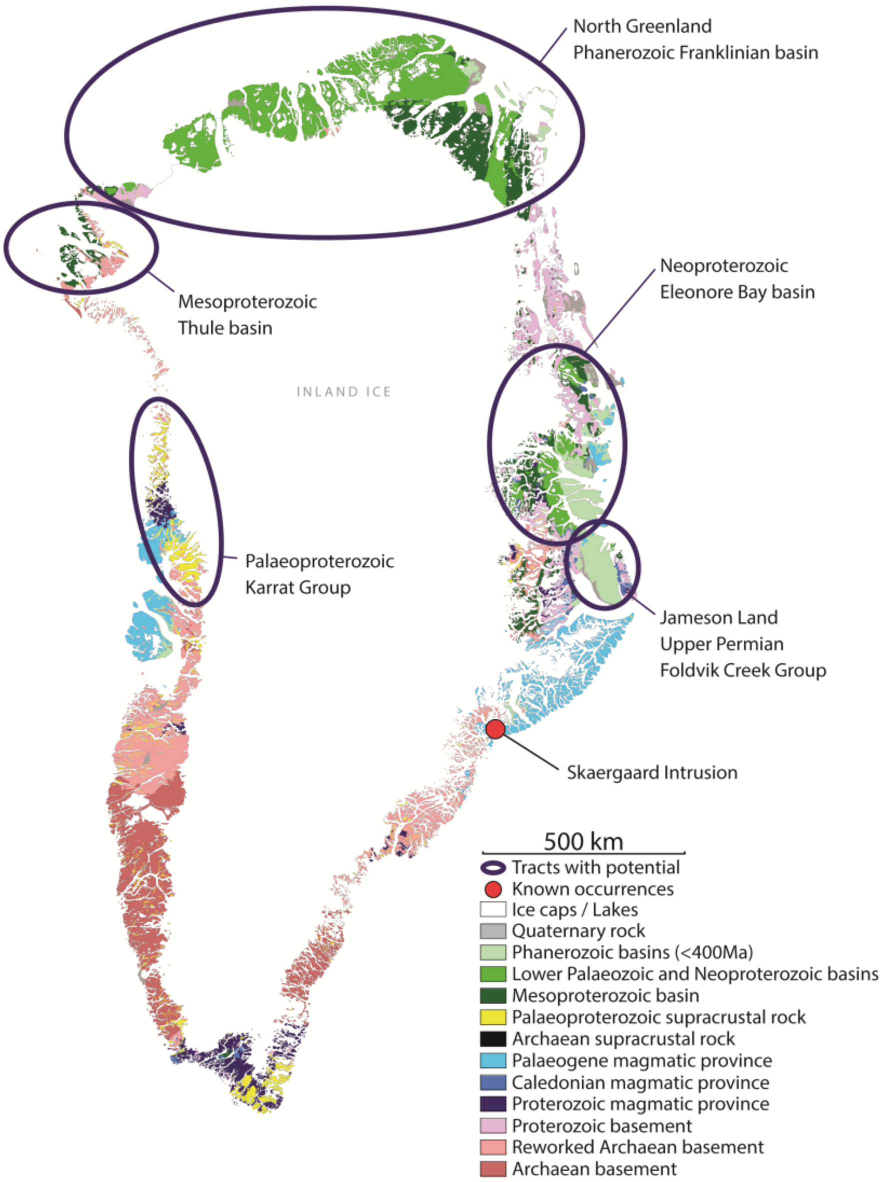

Figure 12. *Map of known gallium occurrences and tracts with potential for gallium. Simplified geological map is based on 1:2 500 000 geological map by Henriksen* et al. *(2009).*

Tracts with resource potential for gallium

Mississippi Valley Type, North, northern West Greenland and central East Greenland

Gallium is also a potential by-product of zinc production from Mississippi Valley Type (MVT) zinc-lead deposits. As part of a sedimentary-hosted zinc resource assessment workshop carried out in 2011, the potential for undiscovered MVT mineralisation was assessed and the Phanerozoic Franklinian basin in North Greenland and the Palaeoproterozoic Karrat Group in northern West Greenland, in particular, were found to host a potential for MVT mineralisations (Sørensen *et al.* 2013). However, since Ga does not tend to form identifiable mineral phases, and was not routinely assayed for, its concentrations in known MVT occurrences are not widely known. However, unpublished GEUS data shows that Ga concentrations in mineralised samples from North Greenland are irregular and modest, with a maximum value of 66 ppm.

Other areas that are considered to host a potential for MVT mineralisation, although smaller potential than the areas mentioned above, are the Mesoproterozoic Thule Basin in northern West Greenland and the Neoproterozoic Eleonore Bay Supergroup and the Phanerozoic Jameson Land basin in East Greenland.

4.2 Germanium [Ge]

Table 15. *Overview of the commodity germanium*

Main application	Germanium is a semiconductor which is used in fiber-optic systems ($GeCl_4$ (30%), Infra-Red optics (GeMe) (25%), polyethylene tereph-thalate (PET) (GeO_2) (25%), and electronics and photovoltaics (GeO_2) (15%) (Melcher & Bucholz 2012). Germanium is by many countries considered as a strategic raw material. The consumption in the first three sectors however shrank in the period 2009 to 2012, and only the electronics experienced a demand increase in the period, but at a slower pace than expected.
Annual production and leading producing countries	The annual production in 2011 was about 120 ton of which China produced 59%, Canada 17%, and USA 15% (EC 2014). Current and future germanium availability from primary sources: Melcher & Bucholz (2012) estimates global germanium resources to be about 11 000 ton from zinc ore and 25 000 ton from coal mainly located in Russia (49%), China (30%), DRC (11%) and USA (7%).
Main mineral	Germanium is primarily extracted from sphalerite or from certain coal ores by collecting the coal fly-ash (mainly in China and Russia).
Market constraints	Production of Ge is depending on zinc production, and the market is volatile due to low prices. Silicon can substitute as a less-expensive substitute for germanium in certain electronic applications. Some metallic compounds can be substituted in high-frequency electronics applications and in some light-emitting-diode applications. Expanding demand in emerging uses and limited sources of additional supply makes germanium critical. Recycled materials account for about one third of all germanium produced.

Tracts with a germanium resource potential

In Figure 13 known germanium occurrences and tracts with potential for germanium in Greenland can be seen.

Mississippi Valley Type showings, North Greenland

Germanium is a potential by-product of zinc production from Mississippi Valley Type (MVT) zinc-lead deposits. Samples from Mississippi Valley Type mineralised showings in Peary Land and Kronprins Christian Land have germanium contents of up several tens of ppm (GEUS unpublished data), which, assuming it is hosted in sphalerite, would probably yield a zinc concentrate with around 500 ppm germanium. This is comparable to values in zinc concentrates constituting the main source of germanium globally, which grade several hundreds of ppm germanium (Pohl 2011).

Mississippi Valley Type, North, northern West Greenland and central East Greenland

Besides samples from known MVT showings in North Greenland, other areas with potential for MVT zinc also hold the potential for germanium by-production. As part of a sedimentary-hosted zinc resource assessment workshop carried out in 2011 the potential for undiscovered

MVT mineralisations was assessed and the Phanerozoic Franklinian basin in North Greenland and the Palaeoproterozoic Karrat Group in northern West Greenland were regarded as holding potential regions for undiscovered MVT deposits (Sørensen *et al.* 2013). However, since Ge does not tend to form identifiable mineral phases, and was not routinely assayed for, its concentrations in known MVT occurrences are not widely known.

Other areas that were found to host a potential for MVT mineralisation, although smaller potential than the areas mentioned above, are the Mesoproterozoic Thule Basin in northern West Greenland and the Neoproterozoic Eleonore Bay Supergroup and the Phanerozoic Jameson Land basin in East Greenland.

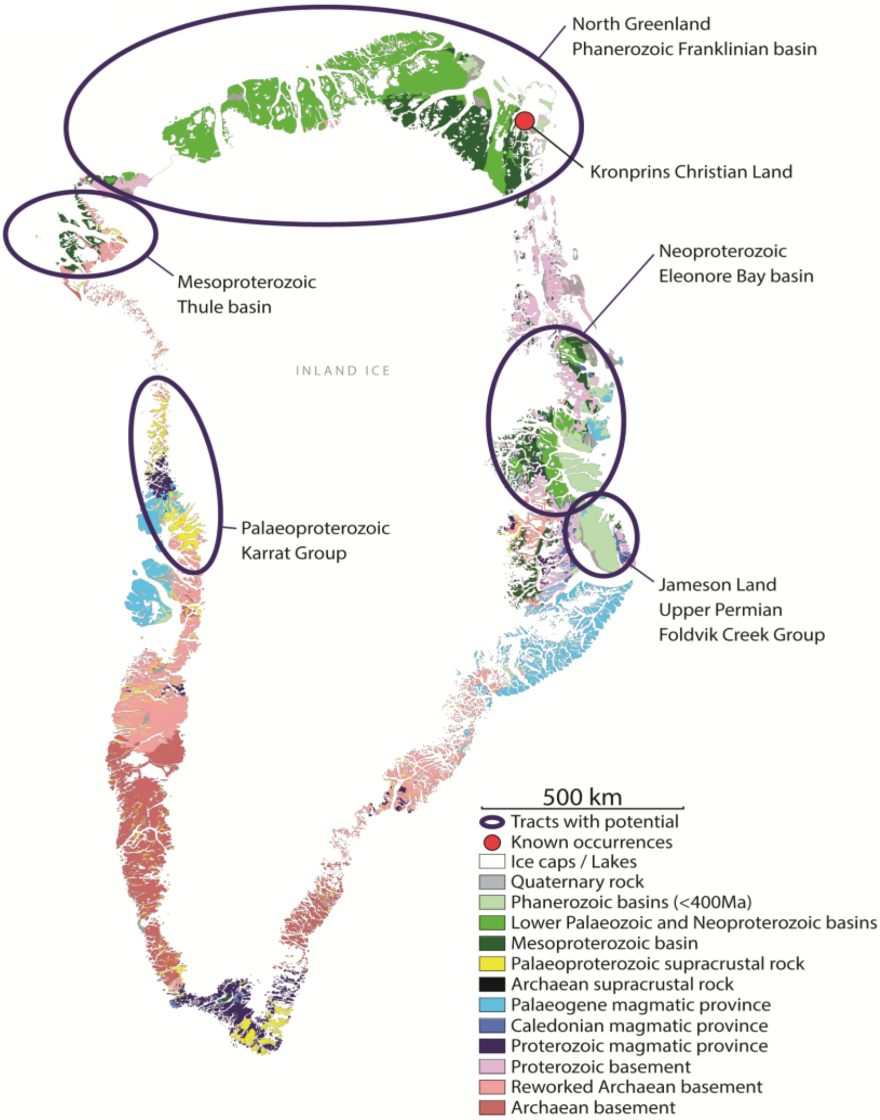

Figure 13. *Map of known germanium occurrences and tracts with potential for germanium. Simplified geological map is based on 1:2 500 000 geological map by Henriksen* et al. *(2009).*

4.3 Indium [In]

Table 16. *Overview of the commodity indium*

Main application	Indium-tin-oxide (ITO) for thin-film coatings is primarily used for electrically conductive purposes in a variety of flat-panel devices (LCDs), and used in solders and alloys, solar panels, LED-lamps and laser diodes. Use of antimony-tin-oxide coatings as ITO substitutes is expanding due to the increase of indium prices.
Annual production and leading producing countries	The annual production of indium in 2012 was about 700 ton, of which China produced 56%, North Korea (14%), Canada (9%), Belgium (4%), and Peru (2%); minor production was carried out in Brazil, Germany, Italy, Netherlands, Russia and England (Gunn 2014).
Main mineral	Because of its relatively low average level of occurrence indium can only be economically extracted as a by-product under appropriate conditions from indium bearing zinc or tin ores. Indium tends to occur with zinc in sulphide minerals because the two elements have similar atomic radii and other chemical properties. In a zinc concentrate the proportion of indium is 70–200 ppm. Native indium and indium minerals, such as indit ($FeIn_2S_4$) and roquesit ($CuInS_2$), are rare.
Resource/reserve	No quantitative estimates of reserves are available.
Market constraints	Only about 25% of indium is recovered due to the fact that not all zinc ore is processed at indium-capable refineries; this is regarded as a major constraint in coping with the indium demand (EC 2014). China has an export quota for indium.

Known indium related occurrences

There are no known indium occurrences in Greenland.

Tracts with resource potential for indium related mineralisation

Geologically the tracts described below are defined as the geological environments characterized by the potential developments of indium-bearing granite-hydrothermal mineralising system. However, it should be noted that most indium is extracted as a by-product from the processing of zinc- and lead-ore (see section on zinc potential in Greenland).

In Figure 14 map with tracts with potential for indium in Greenland can be seen.

Stauning Alper and Hudson Land, central East Greenland and Pelite Zone, South Greenland
High concentration of indium is known to occur in some W-Bi-Sn mineralised granites (greisen type mineralisation); e.g. the granite-hydrothermal Mount Pleasant Sn-In deposit in New Brunswick, Canada (Sinclair *et al.* 2006). In Greenland, one setting with potential for this type of mineralisation is related to Caledonian granites and pegmatites in the Stauning Alper and Hudson Land, central East Greenland. In this area, greisen-type W-Bi-Sn mineralised granites are known to occur.

Another favourable setting for greisen-type mineralisation is within the Psammite and Pelite zone of the Ketilidian Mobile Belt in which late, S-type, Rapakivi-granites occur. However, these granites and pegmaties have seen very little exploration.

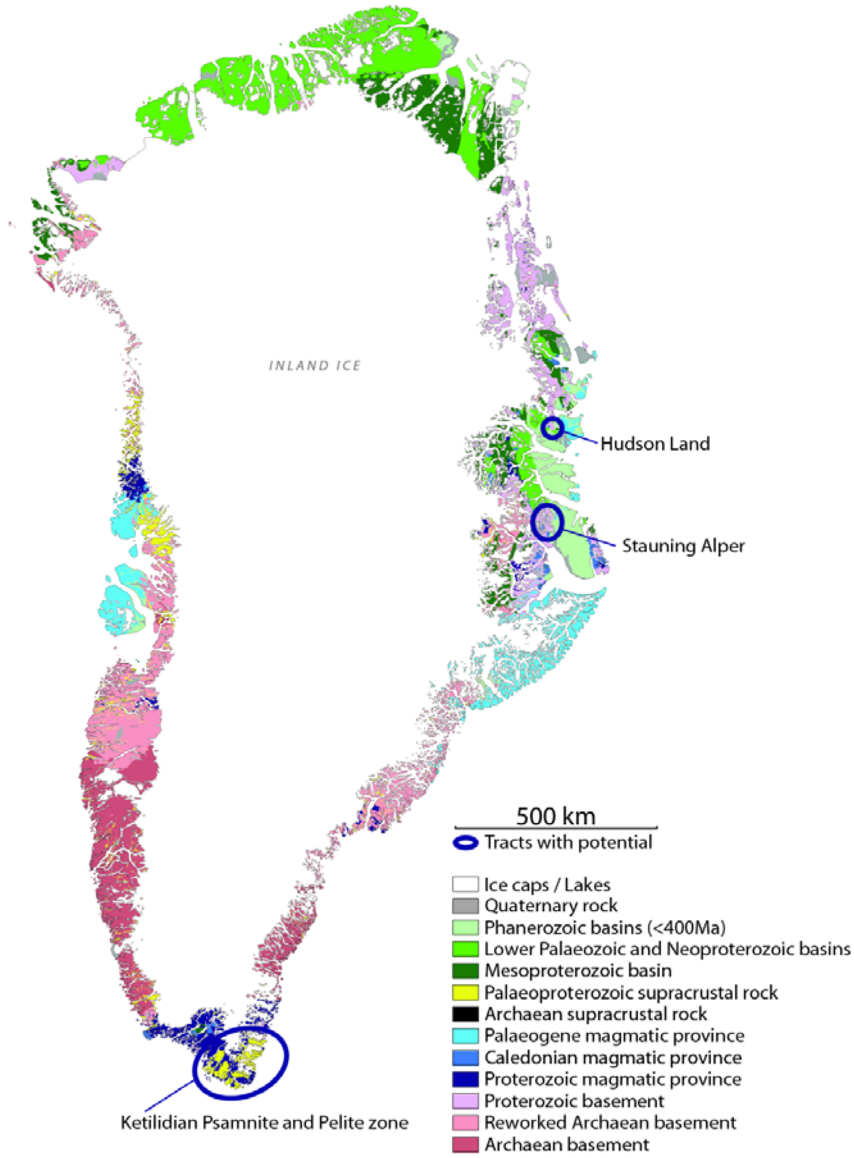

Figure 14. *Map of tracts with potential for indium. Simplified geological map is based on 1:2 500 000 geological map by Henriksen* et al. *(2009).*

4.4 Vanadium [V]

Table 17. *Overview of the commodity vanadium*

Main application	About 90% of the vanadium production is used for alloying element in steel and titanium alloys, and some is used as a catalyst for chemicals.
Annual production and leading producing countries	Production of vanadium in 2010 amounted to 61 500 ton, of which the major producers were South Africa (37%), China (36%), Russia (24%), Kazakhstan (2%), and USA (1%) (EC 2014).
Main mineral	Vanadium is primarily produced as a by-product from titanomagnetites, but also from uranium-vanadium ores, bauxites, and phosphates.
Resource/reserve	The total worldwide reserve of vanadium is 14 Mt, of which China holds 36%, Russia holds (36%), and South Africa 25%.
Market constraints	China, Russia and South Africa are dominating with regard to the reserves of vanadium as well as the annual production.

Known vanadium related occurrences

In Figure 15 known vanadium occurrences and tracts with potential for vanadium in Greenland can be seen.

Sinarsuk, southern West Greenland

The Sinarsuk titanium-vanadium occurrence is located within the easternmost part of the metamorphosed layered anorthosite and associated gabbroic rocks of the Fiskenæsset anorthosite complex (Myers 1985; Polat *et al.* 2011). The Fiskenæsset complex is described in more detail under Cr (page 17).

The titanium-vanadium-oxide mineralisation at Sinarsuk was discovered in 1997 by NunaOil A/S. Aeromagnetic surveys, carried out in 1998, outlined a magnetic anomaly that can be followed for approx. 15 km along NW-SE strike. Additional exploration, ground magnetic profile lines and metallurgical test work was completed in 1998. However, NunaOil A/S did not continue to work in the area. Now the license is held by 21st North.

The Sinarsuk mineralisation can be traced on the surface for more than 13 km and follows the aeromagnetic anomaly. The mineralisation occurs in a distinct stratiform package of gabbroic and subordinate pyroxenitic and dunitic rocks occurring at the base of the so-called Upper Gabbro Unit. The mineralised package is up to 250 m wide and intruded by late pegmatite veining causing the mineralised lithology to be fragmented into several larger blocks. Mineralisation is dominantly disseminated oxides and semi-massive to massive oxide layers at the base of the sequence. Individual massive oxide layers are up to 1 m thick and occur in a well-developed magmatic layering in leucocratic gabbro.

The average grade of 70 channel profiles (no cut-off) across the mineralised package is 0.25% V_2O_5 and 2.79% TiO_2 with higher grade sections returning more than 1 wt.% V_2O_5 and 10 wt.% TiO_2 (21st North 2012).

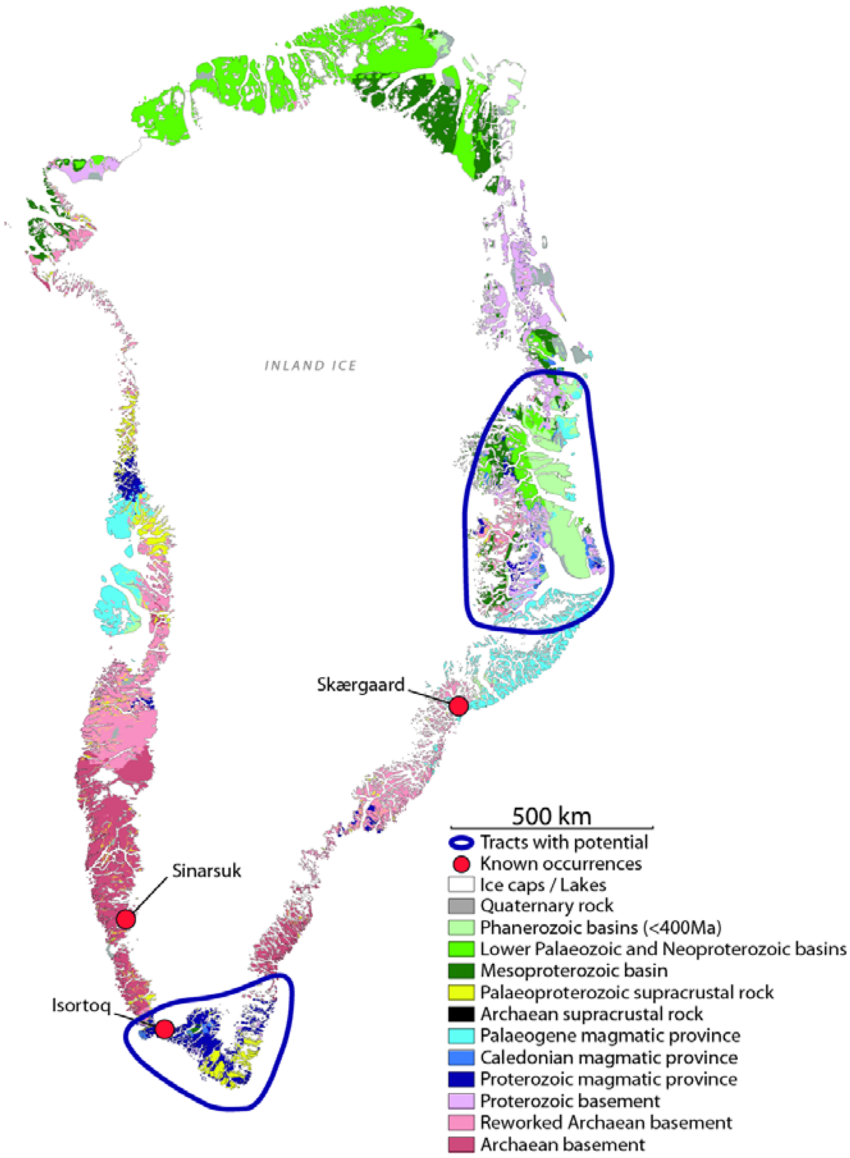

Figure 15. *Map of known vanadium occurrences and tracts with potential for vanadium. Simplified geological map is based on 1:2 500 000 geological map by Henriksen* et al. *(2009).*

Isortoq, South Greenland

In the Gardar Rift in the Palaeoproterozoic collisional Ketilidian Mobile Belt, we find widespread alkaline plutonic rocks, extrusives, and several generations of mafic dykes of varying composition crosscutting earlier rocks of the Ketilidian mobile belt. The Gardar related mafic dykes include troctolite, and a troctolige dyke at Isortoq has Ti-V-Fe mineralisation. The dyke at Isortoq has been divided into Isortoq South and Isortoq North. The Isortoq South extends over a total strike length of 7.0 km. The Isortoq North extends over a strike length of 8.5 km to the edge of an inland ice. An inferred global resource of 70.3 million ton grading 29.6% Fe, 10.9% TiO_2 and 0.144% V_2O_5 using a cut-off of 15% Fe has been defined by the current license holder, West Melville Metals Inc. (Turner & Nicholls 2013). The Isortoq resource is classified as an inferred mineral resource (according to NI43-101 standard) due to limited drilling and metallurgical test work.

Skaergaard Intrusion, East Greenland

Titanomagnetite from the layered Skaergaard Intrusion in East Greenland is found to be enriched in vanadium with values of 1.11 to 1.22 wt.% (Platina Resources Ltd 2007). The entire width of the Au-PGM mineralised horizons in the Skaergaard Intrusion contains a potential vanadium resource of 1.84 Mt.

Tracts with resource potential for vanadium related mineralisation

Geologically the tracts described below are defined as the geological environments that potential could host orthomagmatic vanadium mineralisations within mafic dykes and intrusions.

Mafic dykes and intrusions, South, South-East and central East Greenland

Orthomagmatic mineralisations could potentially host vanadium. Especially South Greenland and South-East to central East Greenland could be regions with potential for mafic dykes and intrusions that could host orthomagmatic mineralisations of Ti-V-Fe.

5. Summary

Greenland has a land area exceeding 2 million km^2, of which the ice-free marginal zone makes up about 0.4 million km^2 of ice-scoured outcrops forming a mountainous arctic landscape, exposed along steep fjords. In combination with complex geological terranes, representing almost four billion years of geological history, covering the spectrum from Archaean to recent processes, this makes Greenland favourable for finding and exploiting a wide range of mineral resources including some of the critical minerals.

Detailed geological maps as well as comprehensive geophysical and geochemical data exist for the majority of the ice-free area. Furthermore, decades of mineral exploration campaigns undertaken by the private sector has provided a wealth of detailed data. Most of the data can be accesses in publicly available reports from GEUS and found on the web page www.greenmin.gl.

GEUS and the Greenland Ministry of Mineral Resources (MMR) have since 2009 held annual regional mineral resource assessments workshops on selected commodities. The approach applied in these assessments constitutes the background for this review of the Greenlandic potential for hosting minerals critical to the European industry (EC 2014). The assessments take into consideration detailed information about known mineral deposits and occurrences.

This review points to some areas carrying a high potential to host undiscovered mineral deposits. For example, aside from the known deposits at Kvanefjeld and Kringlerne, South Greenland has a high potential for hosting undiscovered REE deposits, for example in the Grønnedal-Ika carbonatite, the Qassiarssuk/Green Dyke and the Ivittuut alkaline intrusion. South Greenland also has the potential for niobium occurrences and deposits in the same geological environment. Central East Greenland stands out with a high potential for tungsten and antimony. The North Atlantic Craton (Archaean) and the Palaeoproterozoic terranes have a good potential for hosting undiscovered deposits of chromium, platinum group metals, graphite and, as a by-product of cobalt.

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MiMa Rapport 2016/3

Review of potential resources for critical minerals in Greenland

Minerals are essential resources for the development and progress of modern society. The availability of the mineral resources varies from country to country and from commodity to commodity. In some instances the supply-chain of minerals that are of crucial importance to society, is threatened. Such mineral resources are defined as critical raw materials. Supply risk is in many cases related to monopolism in the up-stream part of the supply chain. Improving knowhow related to mineral resource potential is one of the keys to overcome criticality.

This report presents a review of the Greenlandic potential mineral resources for undiscovered deposits of critical minerals, focusing on the raw materials labelled as critical by the European Commission in 2014 (EC 2014).

The Greenland marginal ice-free zone makes up about 0.4 million km^2, hosting complex geological terranes, that represent almost four billion years of geological history, covering the spectrum from Archaean to recent processes. This makes Greenland favourable for finding and exploiting a wide range of mineral resources including some of the critical minerals. GEUS and the Greenland Ministry of Mineral Resources (MMR) have since 2009 held annual regional mineral resource assessment workshops on selected commodities. The approach applied in these assessments constitutes the background for this review.

For each of the commodities chosen, their known occurrences in Greenland are reported together with a description of the regional to semi-regional tracts with favourable permissive geological settings, settings that potentially could host mineral occurrences of the primary deposit type.

The review points out that some areas are likely to host high potential undiscovered mineral deposits. Aside from the known deposits at Kvanefjeld and Kringlerne, South Greenland has a high potential for hosting undiscovered REE deposits, for example in the Grønnedal-Ika carbonatite, the Qassiarssuk/Green Dyke, and the Ivittuut alkaline intrusion. South Greenland also has the potential for niobium occurrences and deposits in the same geological environment. Central East Greenland stands out with a high potential for tungsten and antimony. The North Atlantic Craton (Archaean) and the Palaeoproterozoic terranes have a good potential for hosting undiscovered deposits of chromium, platinum group metals, graphite and, as a by-product of cobalt.

Center for Minerals and Materials (MiMa)
is an advisory center under The Geological Survey
of Denmark and Greenland (GEUS).
MiMa imparts knowledge on mineral resources,
mineral occurrences, their circuit and influence on society.

De Nationale Geologiske Undersøgelser
for Danmark og Grønland (GEUS)
Geological Survey of Denmark and Greenland

Øster Voldgade 10
DK-1350 Copenhagen K
Denmark

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