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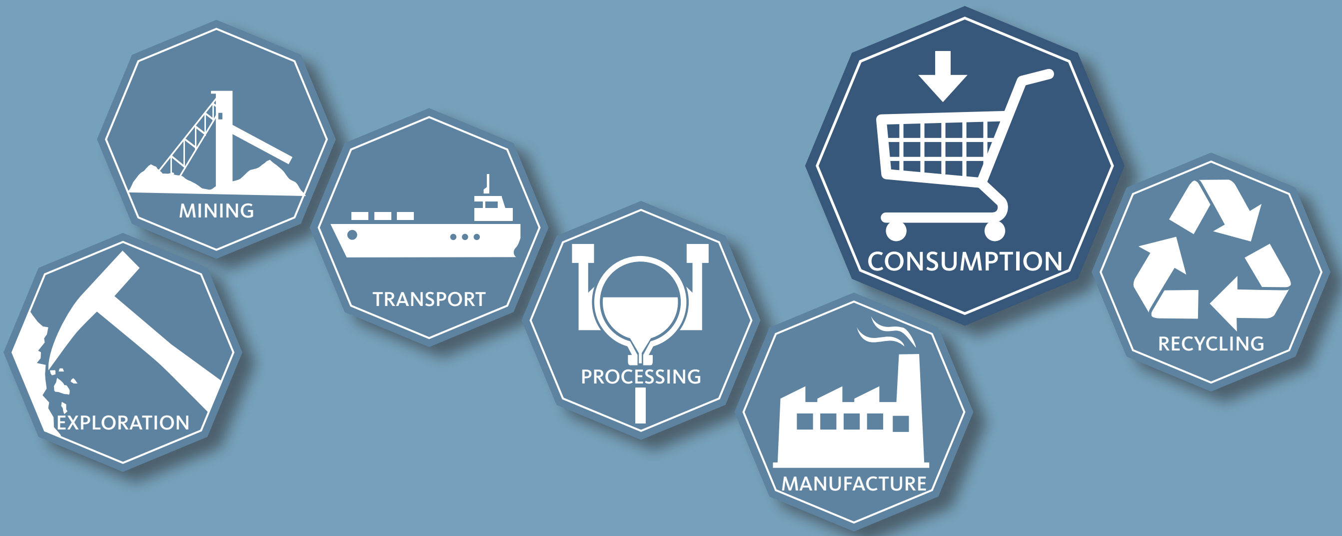
MiMa rapport 2023/1



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Abstract

Critical Raw Materials (CRMs), which are materials that both have a large economic importance to the industry and whose supply has a high risk of disruption, are essential to the society as they are the building blocks for our green and digital economy. Many factors influence the supply risk but, in many cases, it is related to monopolism in the up-stream part of the supply chain. Improving know-how related to mineral resource potential is thus one of the keys to overcome criticality.

This review presents the Greenlandic mineral resource potential of CRM, focusing on the raw materials labelled as critical by the European Commission in 2023 (European Commission 2023a), as well as some considered as potentially critical.

The Greenland ice-free zone covers approximately 0.4 million km^2, hosting complex geological terranes, that represent almost four billion years of geological history, extending the spectrum from Archaean to recent processes. This makes Greenland favourable for finding and exploiting a range of mineral resources, including some of the critical and potentially critical minerals.

This review confirms that Greenlandic occurrences host critical minerals, provides known resources of these, and presents brief descriptions of the geology, exploration history/reports as well as the tracts with favourable permissive geological settings that potentially could host mineral occurrences.

The review specifically reveals that the Gardar province in South Greenland constitutes an exceptional accumulation of CRM. This is documented by the known rare earth element (REE) deposits, some also hosting very significant lithium, fluorite, tantalum, niobium, hafnium and/or zirconium resources, namely the very large deposits of the Ilímaussaq (Kvanefjeld/Kuannersuit, Kringlerne/Killavaat Alannguat, Sørensen, Zone 3) and Motzfeldt. East Greenland stands out by hosting the very large Malmbjerg molybdenum deposit, the very large Karstryggen strontium deposit, and the large platinum group metals (PGMs), titanium and vanadium Skaergaard deposit. Additionally, and due to its relatively underexplored status, East Greenland can be considered to still hold a significant potential for yet undiscovered deposits of these commodities. Furthermore, this area also holds a significant, but relatively underexplored, potential for intrusion related tungsten, tin, and antimony, and for sedimentary copper. Carbonatites and anorthosites in southern West Greenland hold a potential for phosphorus and REE or feldspar, documented by the large Sarfartoq deposit and the large Qaqortorsuaq/White Mountain and the Majoqqap Qaava deposits, respectively. The Palaeoproterozoic terranes in West, South and East Greenland, have a potential for hosting undiscovered deposits of graphite, exemplified by the large Amitsoq deposit in South Greenland. The Thule black sands province, in North-West Greenland, holds a significant titanium endowment. Finally, the Palaeozoic Franklinian Basin of North Greenland has a very significant potential for zinc and lead deposits, from which germanium and gallium can be possible by-products.

1. Introduction

Mineral resources are essential raw materials for the development and progress of modern society and, particularly, the transition to a low carbon society will require significant quantities of metals and other materials (e.g. Bobba *et al.* 2020, Hund *et al.* 2020, Watari *et al.* 2020, Jonsson *et al.* 2023). Although recycling will increase and cover part of the future raw material needs, presently there is only a limited stock of secondary sources to draw from, which means that the expanding demand for new green technologies is expected to be met predominately through access to primary resources.

Many factors affect the criticality of mineral resources such as geological, technological, geopolitical, and economic factors (Graedel & Nasser 2015), and various definitions of mineral criticality have been suggested (e.g. Gradel & Reck 2015; Jin *et al.* 2016; Schrijvers *et al.* 2020). Although there is no standard method to assess mineral criticality there is general consensus that raw materials are considered critical if they simultaneous are (i) important to societies' needs, (ii) subject to a significant supply risk, and (iii) there is a lack of (viable) substitutes. This means that what is considered critical is both dynamic, and varies from country to country, depending on their resource endowment and the structure of their 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 (CRMs) has been undertaken on global, national, and regional levels (e.g. Miyamoto *et al.* 2019; Schulz *et al.* 2017; Nassar & Fortier 2021, The White House 2021; Eilu *et al.* 2021; Lusty *et al.* 2021; European Commission 2020a).

In 2010, the European Commission (EC) carried out a first criticality analysis for raw materials (non-energy, non-agricultural materials), also addressing opportunities for their substitution and recycling (European Commission 2010). In this study, 14 raw materials were defined as critical to the European industry. Subsequently, the EC has published revised lists of CRMs in 2014, 2017, 2020 and 2023 (European Commission 2014, 2017, 2020a, 2023). The methodology for the EU criticality assessment is based on the main criteria of supply risk (SR) and economic importance (EI), with thresholds of SR > 1.0 and EI > 2.8 (Figure 1).

In the latest assessment, 67 individual raw materials and three materials groups were assessed, of which 32 surpassed the CRMs thresholds and are therefore considered as critical (Figure 1). In addition, even though copper and nickel do not meet the threshold for CRMs, these were designated by the European Commission (2023) as strategic raw materials, and were therefore included in the CRM list, adding up to 34.

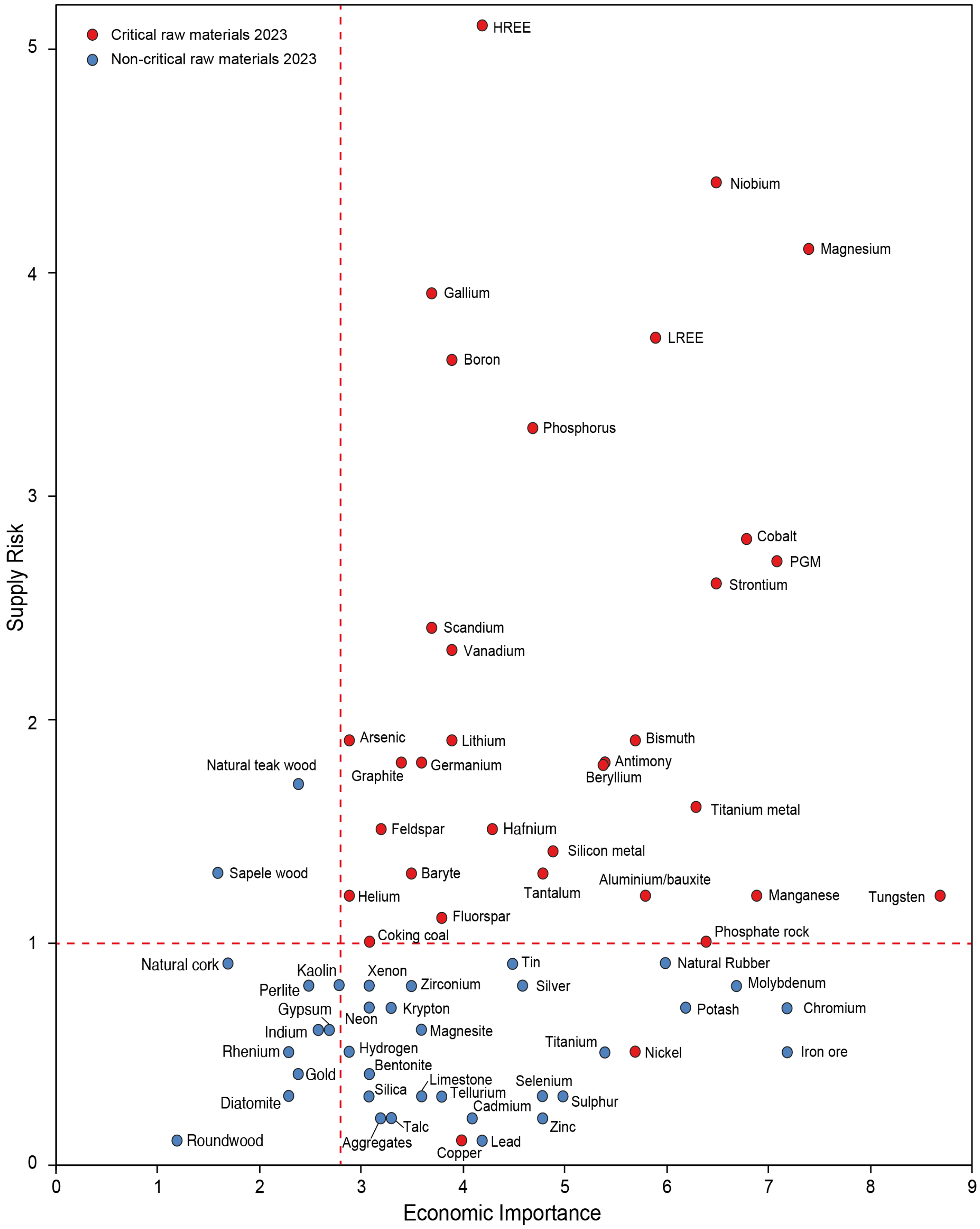

Figure 1 *Assessment of mineral criticality based on economic importance and supply risk (after European Commission 2023). Raw materials shown in red are considered critical by the EU. Please note that copper and nickel do not meet the CRM thresholds but were included in the CRM list due to their status as strategic raw materials (European Commission 2023).*

2. Approach

Geological knowledge is key when evaluating possible scarcity issues because geology places the most essential and unavoidable constraints on mineral resource availability. Therefore, geology should be considered prior to other constraining parameters. Thus, assessments of mineral resources potential and the identification of areas and geological terranes endowed with mineralisation is fundamental for ensuring future access and supply to critical raw materials.

It was within this framework that Centre for Minerals and Materials (MiMa) assessed the Greenlandic potential resources of critical minerals, focusing on the raw materials labelled as critical by the European Commission in 2023, and some potentially critical. The present report constitutes a second edition of a previous assessment (Stensgaard *et al.* 2016), updated according to the most recent list of critical raw materials for the EU (European Commission 2023).

Detailed geological maps as well as comprehensive geophysical and geochemical data exist for most of the ice-free area. Furthermore, decades of mineral exploration campaigns undertaken by the private sector have provided a wealth of detailed data. Most of the data can be accessed in publicly available reports from the Geological Survey of Denmark and Greenland (GEUS) and the Greenland Mineral Resource Portal found on the webpage www.greenmin.gl. Finally, 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 (European Commission 2023).

A total of 38 raw materials were evaluated (see Table 1). This evaluation included raw materials not strictly considered as critical according to the European Commission (2023). As mentioned above, nickel and copper are included in the CRM list despite having a SR below the threshold of 1 (see Figure 1) because the European Commission (2023) proposed them as strategic raw materials. Furthermore, chromium (Cr), molybdenum (Mo), tin (Sn) and zirconium (Zr) all are economically important and have a relative high supply risk and were therefore considered potentially critical and are also assessed here.

As a result of the evaluation, the resource potential in Greenland for arsenic, bauxite, borate, coking coal, scandium (from bauxite), manganese and magnesium was generally considered low, and is therefore not further discussed, despite the inclusion of these raw materials in the EU critical list (European Commission 2023). For the remaining 31 commodities assessed, for which Greenland is estimated to hold either an unknown or moderate to high resource potential, a detailed overview is presented. This overview includes a list of known important occurrences in Greenland, together with a description of the tracts that are thought to contain favourable permissive geological settings that potentially could host undiscovered mineral occurrences.

Due to chemical affinities, some metals tend to occur in the same deposit type and in similar geological settings and are therefore discussed together (e.g. the platinum group metals (PGM), the rare earth elements (REE), hafnium-zirconium, niobium-tantalum, tin-tungsten and titanium-vanadium). Phosphate rock and phosphorus are sourced from the same deposit types and the latter results from the processing of former, so these two CRM are also discussed together.

Table 1 *Greenland critical raw material resource potential (European Commission (2023) CRM list, plus chromium, tin, molybdenum, and zirconium).*

	Critical material list (2023)	Commodities assessed in this report	Estimated resource potential in Greenland	Likely product type in Greenland	
				Primary	By-/co-product
Antimony (Sb)	X	X	Moderate	✓	✓
Arsenic (As)	X		Low		
Baryte ($BaSO_4$)	X	X	Moderate	✓	
Bauxite	X		Low		
Beryllium (Be)	X	X	Moderate		✓ of REE
Bismuth (Bi)	X	X	Unknown		✓ of Pb, W-Sn
Borates (BO_3)	X		Low		
Chromium (Cr)		X	Moderate	✓	✓
Cobalt (Co)	X	X	Moderate		✓
Coking coal	X		Low		
Copper (Cu)	X	X	Moderate	✓	✓
Feldspar	X	X	Moderate	✓	✓
Fluorspar (CaF_2)	X	X	Moderate	✓	✓ of REE
Gallium (Ga)	X	X	Unknown		✓ of PGM, Zn
Germanium (Ge)	X	X	Unknown		✓ of Zn, Pb
Graphite (C)	X	X	High	✓	
Hafnium (Hf)	X	X	High		✓ of Zr
Helium (He)	X	X	Unknown	✓	
HREE	X	X	High	✓	✓
Lithium (Li)	X	X	Moderate	✓	✓
LREE	X	X	High	✓	✓
Magnesium (Mg)	X		Low		
Manganese (Mn)	X		Low		
Molybdenum (Mo)		X	High	✓	
Nickel (Ni)	X	X	Moderate	✓	✓
Niobium (Nb)	X	X	High	✓	✓
PGMs	X	X	High	✓	✓
Phosphate rock (PO_4)	X	X	Moderate	✓	✓
Phosphorus (P)	X	X	Moderate	✓	✓
Scandium (Sc)	X		Low (from bauxite)		
Silicon metal (Si)	X	X	Moderate	✓	
Strontium (Sr)	X	X	High	✓	
Tantalum (Ta)	X	X	High	✓	✓
Tin (Sn)		X	Moderate	✓	✓
Titanium metal (Ti)	X	X	High	✓	
Tungsten (W)	X	X	Moderate	✓	✓
Vanadium (V)	X	X	Moderate		✓
Zirconium (Zr)		X	High	✓	

LREE (light rare earth elements): lanthanum (La), cerium (Ce), praseodymium (Pr), neodymium (Nd), samarium (Sm), and HREE (heavy rare earth elements): europium (Eu), gadolinium (Gd), terbium (Tb), dysprosium (Dy), holmium (Ho), erbium (Er), thulium (Tm), ytterbium (Yb), lutetium (Lu) and yttrium (Y). The PGMs (platinum group metals) include Pt, Pd, Rh, Ru, Ir, and Os.

Furthermore, some CRMs can be of economic interest by themselves, while others constitute by-products obtained during mineral beneficiation or further downstream supply chain steps (Table

2). By-products may provide important economic contributes to a mining project, and thus their presence should also be evaluated during exploration activities. However, the concentrations of these by-products of the production of main metals (e.g., gallium, indium, and germanium) have not been typically evaluated in the past, so often there is no detailed data available on their abundance and distribution. Thus, the assessment of the resource potential of these by-products, also called companion metals, is merely based on the identification of favourable geological contexts.

Table 2 *Overview of some of the main metals 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 (European Commission 2023).*

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

An extensive classification scheme is traditionally employed to describe mineral resources according to geological knowledge and the degree of confidence in their existence. Public attention usually is focused on current mineral reserves, which refers to the economically mineable part of a Measured or Indicated Mineral Resource, demonstrated by at least a preliminary feasibility study. As a result, a mineral deposit is defined as an enriched body of rock with a measured or indicated tonnage of a metal or minerals of economic interest that could be considered for mining. Greenlandic CRM deposits are listed in Appendix 1 CRM deposits in Greenland, with their geographical locations, estimated resource ore and tonnages, and EU Inspire size categories. The wider concept of mineral occurrence covers any locality where a useful mineral or material is found. Considering that many of such occurrences have been identified in Greenland, only occurrences that were considered significant are included in this study, but descriptions of additional occurrences can be found via the Greenland Mineral Resource Portal.

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

In Chapter 3 the individual critical raw materials are reviewed. The assessment includes commodity fact sheets, geological maps showing deposits, significant occurrences, and mineral potential domains (mineral tracts) of all the assessed commodities. The list structure of the CRMs reviewed one after the other in this report implies that there are certain repetitions and cross-referencing, however, as many readers will be only interested in some parts or particular raw materials, a format where individual CRMs can be read independently has been chosen.

3. Resource potential for critical raw materials in Greenland

3.1 Antimony [Sb]

Table 3 *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 2022 amounts to about 110,000 t with the dominating countries being China (55 %), Russia (18 %), Tajikistan (16 %), Australia (3.6 %), and Burma (3.6 %) (USGS 2023).
Main mineral	The main commercial source of antimony is stibnite (Sb_2S_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) main product; b) by-product to Au and Ag; and c) by-product from the smelting process of Zn and Pb. Global reserves are about 1.8 Mt antimony, concentrated in China (19 %), Russia (19 %), Bolivia (17 %) and Kyrgyzstan (14 %) (USGS 2023).
Known resources in Greenland	3,780 t
Market constraints	Due to its dissipative applications, very limited amounts of antimony are presently recycled, and its supply is strongly dependent on primary sources. However, China, holding a fourth of the global reserves, has been shutting down antimony mines and smelters 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 deposits and important antimony occurrences (Figure 2)

North Margeries Dal, central East Greenland

At North Margeries 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 t grading 3.5 % Sb. The mineralisation is 'open' and other antimony occurrences 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 Ordovician 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).

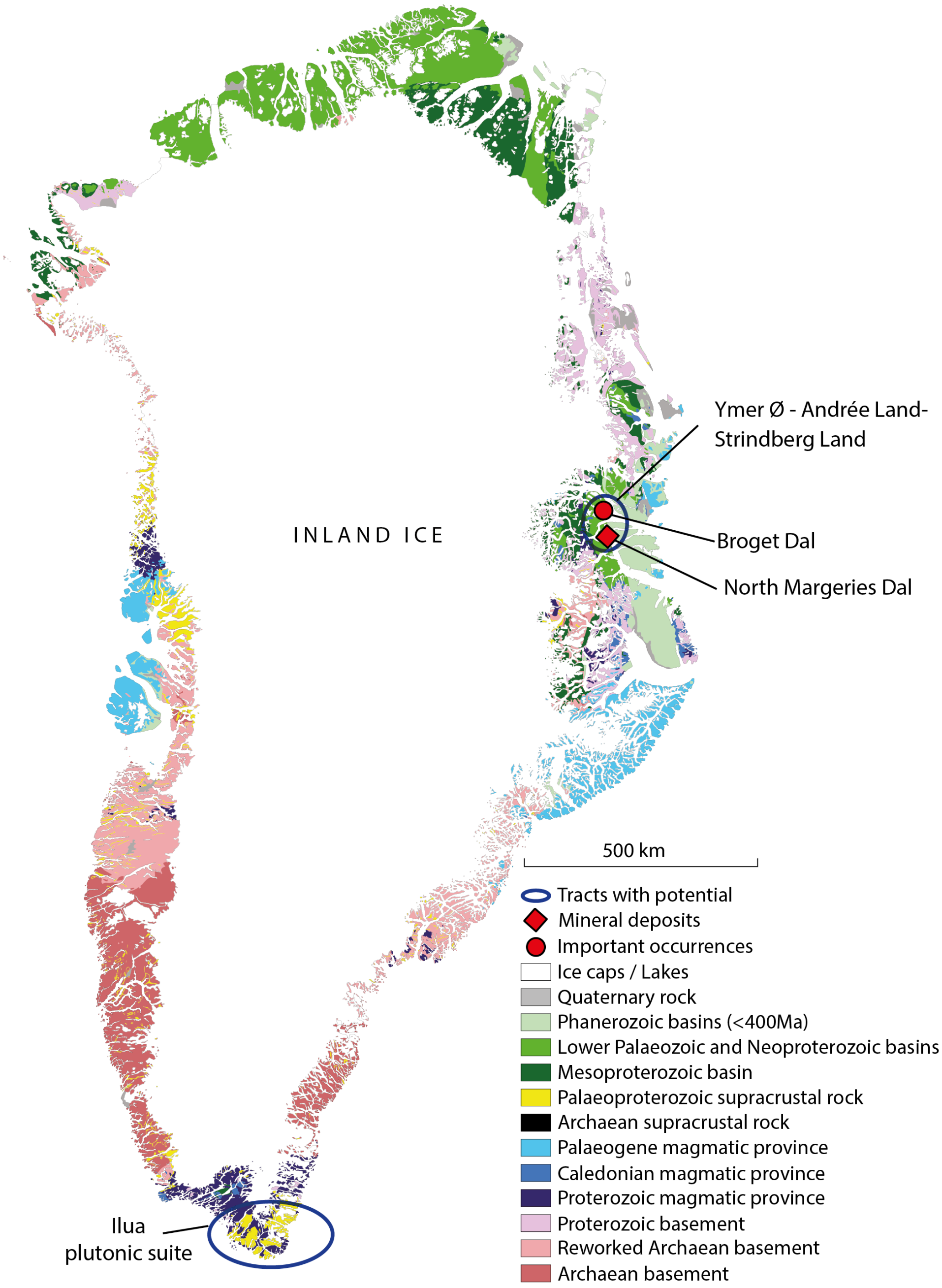

Figure 2 *Map of known antimony deposits, significant occurrences, and favourable tracts. Simplified geological map is based on 1:2 500 000 geological map by Henriksen et al. (2009).*

Broget Dal, central East Greenland

Sedimentary copper-antinomy mineralisation occurs in a 500 by 1000 m area, within 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. A bulk sample (35 kg) yielded 1.33 % Cu and 1.07 % Sb (Harpøth *et al.* 1986). No resource estimates have been attempted at this locality.

Tracts with resource potential for antimony (Figure 2)

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

In a similar setting to the one found at the North Margeries Dal antimony occurrence, faults in the region around Ymer Ø, Andrée Land, and Strindberg Land cut dolomitic shales of the Precambrian Ymer Ø Group of 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 tungsten mineralisation.

Ilua plutonic suite, South Greenland

Previously known as the rapakivi suite (Becker & Brown 1985; Garde *et al.* 1997), the 1755-1720 Ma Ilua plutonic suite (Steenfelt *et al.* 2016) was emplaced within the Psammite and Pelite zones of South Greenland and is related to the final stages of transpression during the Palaeoproterozoic Ketilidian orogeny. Only limited exploration activities have been carried out targeting these granites, which are believed to hold a potential for hydrothermal antimony mineralisation, as well as commonly associated metals (tungsten, tin, bismuth, indium, copper, zinc).

3.2 Baryte [$BaSO_4$]

Table 4 *Overview of the commodity baryte.*

Main application	Most baryte is directly employed as an additive in drilling muds, used in oil and natural gas exploration and production, to increase fluid density. Baryte is also used as a filler, extender, or weighting agent in products such as paints, plastics, and rubber, or as a radiation shielding agent in concrete. Small amounts of elemental barium are used as an additive in the manufacturing of optical glass, ceramic glazes, and other products.
Annual production and leading producing countries	Total production in 2022 amounts to about 8 Mt (USGS 2023) with the main producing countries being India (38.6 %), China (28%), Morocco (19 %), Kazakhstan (7 %), and Mexico (5%). However, note that the US production is not known for 2022.
Main mineral	Baryte (or barite) is naturally occurring barium sulphate ($BaSO_4$).
Resource/reserve	The total amount of identified baryte resources are about 740 Mt and 320 Mt of reserves (USGS 2023), with Iran and Kazakhstan holding the largest reserves. No systematic assessment of global baryte resources has been conducted since the 1980s.
Known resources in Greenland	480,000 t
Market constraints	Global reserves and resources are relatively abundant, and production is reasonably distributed. However, European reserves, resources and production are quite small. For the use as drilling mud, several alternatives exist (celestite, ilmenite, iron ore and synthetic hematite), but baryte has retained its dominance.

Known baryte deposits and important occurrences (Figure 3)

Bredehorn, central East Greenland

This deposit is hosted by Upper Permian limestones and occurs inside a *c.* 1 km² fault-bounded area also hosting several galena-sphalerite-bearing quartz-baryte veins of uncertain age. The area is covered by talus and the mineralisation is only well exposed in a steep cliff. The strata-bound mineralisation is *c.* 10 m thick and characterised by rhythmically bedded units consisting of alternating bands of white and grey baryte – zebra baryte – with minor disseminations and lenses of galena and sphalerite. It was probably formed by replacement of porous limestones with quartz-baryte veins acting as feeders.

A reserve of 300,000 t with 72 % baryte has been delineated by Nordisk Mineselskab A/S (Nordmine), but in total the area is believed to host several million t of baryte and a considerable lead-zinc tonnage (Harpøth 1983). In view of the potentially relatively large baryte resource and possible mining, Arctic Consultant Group – SWECO assisted Nordmine in a reconnaissance study to evaluate possible locations for a beneficiation plant and transportation routes to a shipping harbour.

Oksedal, central East Greenland

This deposit is hosted by Upper Permian limestones and situated adjacent to a Pb-Zn bearing quartz vein. The baryte occurs as alternating, mm-thick layers of white and grey baryte – zebra baryte – probably formed by replacement of porous limestone, the quartz vein presumed to have acted as feeder. Lead and zinc concentrations are negligible.

An estimate of 440,000 t with 60 % baryte, including 260,000 t with 90 % baryte (direct ship) has been delineated for a near-surface part of the occurrence through 5 shallow Winkie drill holes

(Swiatecki & Thomassen 1981; Harpøth 1983). This deposit is found near the coast and is therefore particularly accessible.

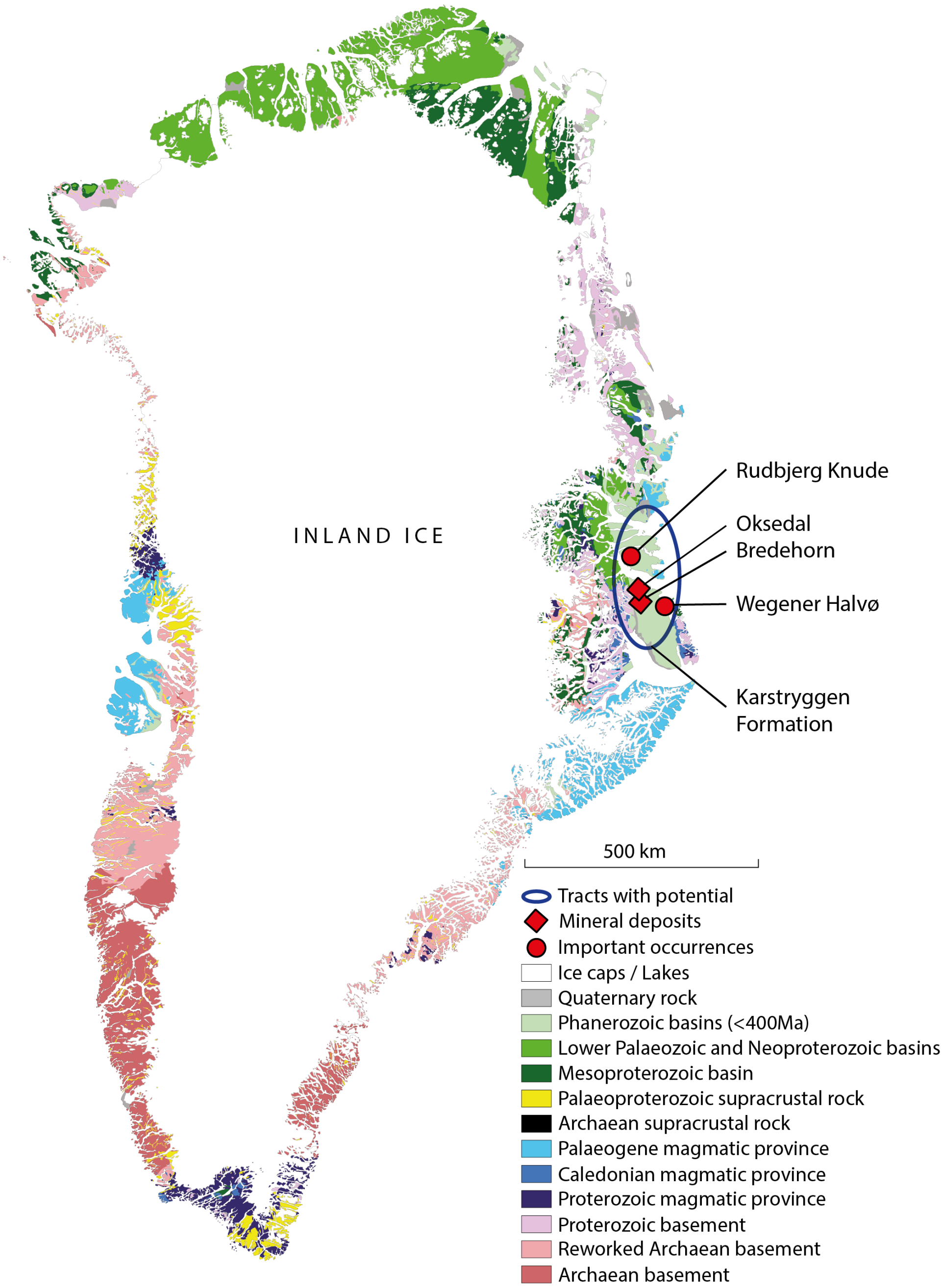

Figure 3 *Map of known baryte deposits, significant occurrences, and favourable tracts. Simplified geological map is based on 1:2 500 000 geological map by Henriksen et al. (2009).*

Rubjerg Knude, Traill Ø, central East Greenland

A fault, which cuts across Upper Carboniferous sediments, has baryte veining on a 50–100 m wide zone, along a length of 4 km. The veins range from mm to dm in thickness, averaging in the cm-range, and their spacing is variable. The overall grade is relatively low, estimated at 5–10 wt.% baryte, so that no resource estimate has been made (Harpøth *et al.* 1986).

Wegener Halvø, central East Greenland

Scattered baryte veins occur in the Upper Devonian of Wegener Halvø, namely on the northern side of Devondal, where a sub-concordant 4 m thick baryte-quartz-sulphide horizon occurs over c. 1 km^2, along the contact between reef limestone and bedded limestone/sandstone. The scattered and silica-rich nature of this occurrence limits the economic interest of this occurrence (Swiatecki & Thomassen 1981).

Tracts with resource potential for baryte (Figure 3)

Karstryggen Formation, central East Greenland

The tract displays the approximate extent of the Karstryggen Formation, a marine marginal carbonate and evaporite sequence, which is known to include stratabound baryte (Harpøth *et al.* 1986).

3.3 Beryllium [Be]

Table 5 *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 280 t in 2022, of which the following countries were the major producers: USA (64 %), China (25 %), and Mozambique (4.6 %) Uganda (2.5 %) and Brazil (1.1 %) (USGS 2023).
Main mineral	The two most used beryllium minerals are: bertrandite ($Be_4Si_2O_7(OH)_2$), which is the main mineral mined in the USA; and beryl ($Be_3Al_2Si_6O_{18}$), which is the main mineral mined outside the 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 (2023) global resources in known deposits amount to 100,000 t plus, of which about 60 % are found in the USA.
Known resources in Greenland	65 t
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 deposits and important occurrences (Figure 4)

Taseq deposit, South Greenland

In the Ilímaussaq intrusion in the Gardar Province, South Greenland, several localities with beryllium minerals have been identified (Steenfelt *et al.* 2016). 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.

The Taseq beryllium deposit 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 (Hansen & Løvborg 1966; Engell et al. 1971). An estimate based on the surface expression of the mineralisation gives an estimate of 180,000 t with an average of 0.1 % BeO (non-compliant to recent international reporting standards).

Nuuk region pegmatites, 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 their metal content.

Kobberminebugt, 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, North-East Greenland

A major Palaeogene felsic intrusive complex, with a caldera sequence and extensive hydrothermal alteration, is found at Kap Simpson, which has yielded whole rock analyses with up to 0.15 % Be.

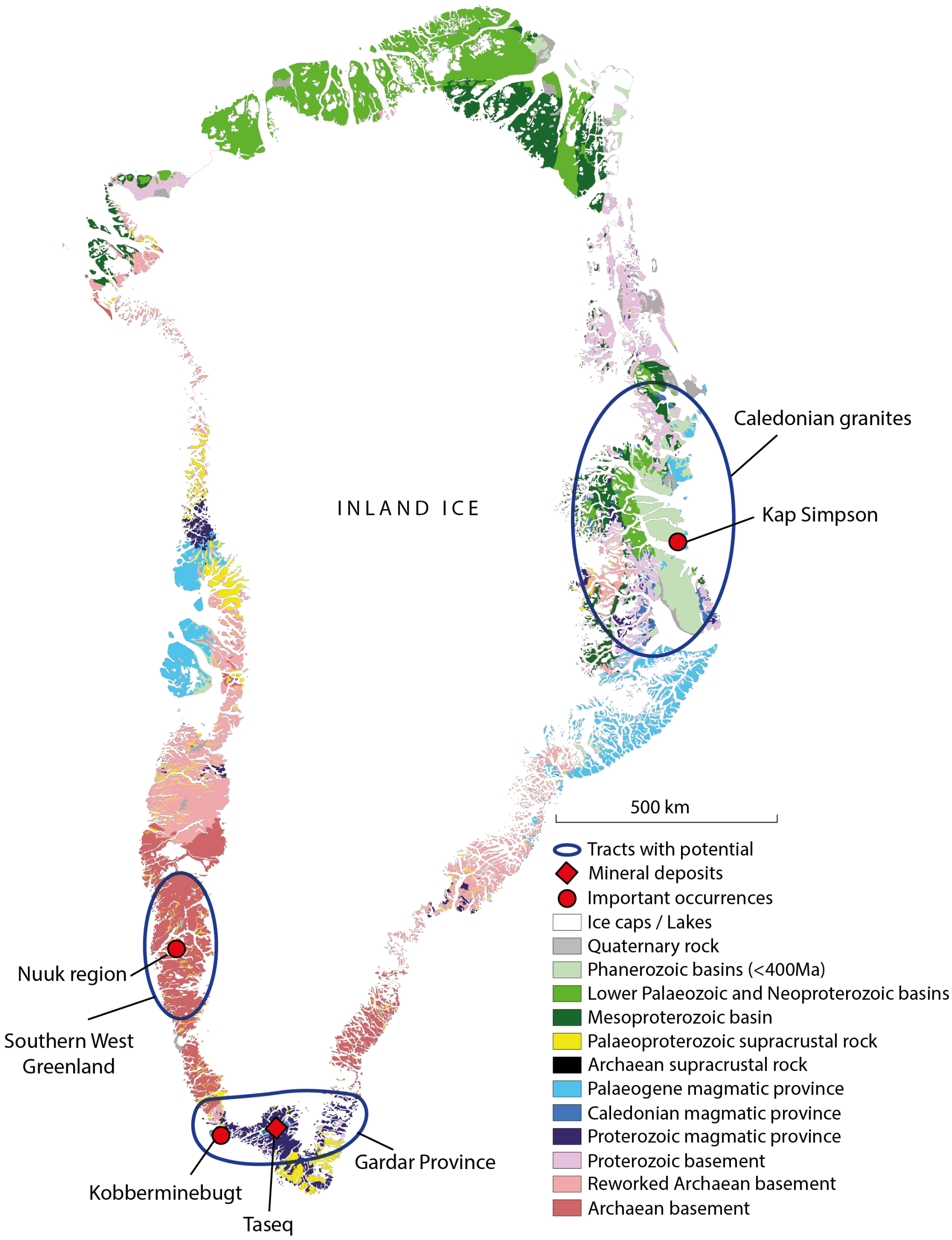

Figure 4 *Map of known beryllium deposits, significant occurrences, and favourable tracts. Simplified geological map is based on 1:2 500 000 geological map by Henriksen et al. (2009).*

Tracts with resource potential for beryllium (Figure 4)

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

Gardar Province, South Greenland

The 1300–1140 Ma Gardar period involved continental rifting, sedimentation, and alkaline magmatism. Numerous dykes and 10 ring-shaped intrusion complexes were formed across South Greenland. Residual magmas and fluids resulting from extreme magmatic differentiation, possibly combined with assimilation of older crust, created mineral deposits including cryolite that was mined at Ivittuut, large low-grade deposits of uranium-rare earth elements-zinc-fluorine-lithium at Kvanefjeld/Kuannersuit and tantalum-niobium-rare earth element-zirconium at Kringlerne/ Killavaat Alannguat, in the Ilímaussaq complex, as well as tantalum-niobium-rare earth elements at Motzfeldt in the Igaliko complex (Steenfelt *et al.* 2016).

Southern West Greenland

Pegmatites have been described in multiphase highly deformed and highly metamorphosed terranes in the Nuuk region, which 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, and North-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, tungsten, bismuth, and molybdenum).

3.4 Bismuth [Bi]

Table 6 *Overview of the commodity bismuth.*

Main application	Bismuth is mostly used in chemicals, mainly pharmaceutical and cosmetics products (62 %), low-melting alloys (28 %), metallurgical additives (10 %) (USGS 2022). Minor uses include coatings, pigments, and semiconductor. Bismuth is an environmentally friendly substitute for lead in plumbing and many other applications.
Annual mine production and leading producing countries	20,000 t Bi (smelter production in 2022; mine production is not known) (USGS 2023). Refinery Bi production in 2022: China 80 %, Laos 10 %, Republic of Korea 4.8 %, Japan 2.4 %. (USGS 2023). Regarding mine production, China has the only mine in the World with Bi as a main product. Most Bi is by-product from tungsten and lead ores.
Main mineral	The most common bismuth minerals are bismuthinite and bismite, but most Bi is recovered as a companion metal of tungsten and other metals, during downstream processing (USGS 2022).
Resource/reserve	Quantitative estimates of resources and reserves are not available.
Known resources in Greenland	No known resources in Greenland.
Market constraints	Bismuth is not traded on any metals exchange, and there are no terminal or futures markets where buyers and sellers can fix an official price. Because Bi it is mainly used in dissipative applications, such as pigments and pharmaceuticals, it is difficult to impossible to recycle.

Known important bismuth occurrences (Figure 5)

Occurrences in the East Greenland Caledonides, North-East Greenland

The most relevant bismuth occurrences are found in central East Greenland and are associated to W-Sn skarns and veins, or Au-rich veins, presumably related to Caledonian intrusions (Harpøth *et al*. 1986). These include Gemmedal (Andrée Land), a scheelite skarn with up to 200 ppm Bi; Milne Land, a scheelite skarn with native bismuth; Kalkdal (Liverpool Land), quartz-scheelite veins with bismuthinite, with up to 0.5% Bi; Kap Allen (Canning Land), with As-Cu-Bi greisen veinlets with native bismuth, bismuthinite, with up to 0.1% Bi; Bersærkerbræ (Scoresby Land), quartz-cassiterite veins with minor native Bi and galena containing 9.46% Bi; Forsblad Fjord (Lyell Land), quartz veins with arsenopyrite, gold, native bismuth, bismuthinite and chalcopyrite; and Luciagletscher (Andrée Land), with quartz-sulphide veins in boulders with gold, Bi-rich galena and native bismuth, with up to 200 ppm Bi.

Other relevant bismuth occurrences are related to veins and breccias formed during Palaeogene magmatism, also in central East Greenland. These are Malmbjerg (Werner Bjerge), with greisen veins with wolframite, molybdenite and, locally, native Bi and bismuthinite; Kap Simpson (Traill Ø), with calcite veins with galena, chalcopyrite, and sphalerite; with up to 200 ppm Bi; and Kap Broer Ruys (Hold with Hope), with tourmaline breccias with up to 5–10% bismuthinite.

Finally, anomalous bismuth concentrations are also found in polymetallic veins, of central East Greenland, such as Galenadal (Alpefjord), with quartz veins with iron sulphides, arsenopyrite, chalcopyrite, bismuthinite, sphalerite and scheelite; Gastisdal (Gauss Halvø), with quartz-fluorite-calcite veins with chalcopyrite, chalcocite, bornite, with up to 150 ppm Bi; and Sernander Bjerg (Hudson Land), with quartz veins with galena and sphalerite, with up to 150 ppm Bi.

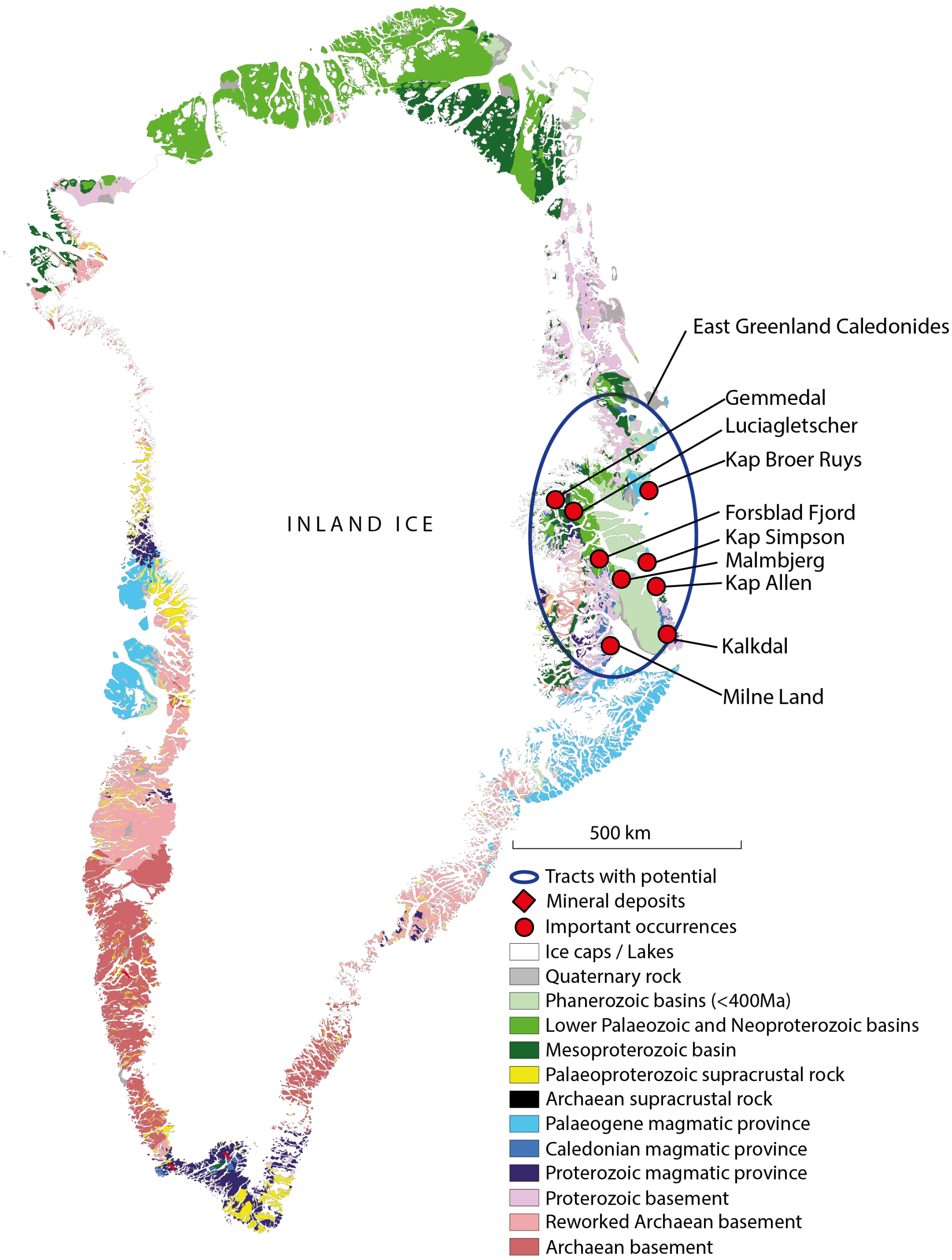

Figure 5 *Map of known significant bismuth occurrences and favourable tracts. Simplified geological map is based on 1:2 500 000 geological map by Henriksen et al. (2009).*

Tracts with resource potential for bismuth (Figure 5)

East Greenland Caledonides, central East, and North-East Greenland

Caledonian intrusions (granites) and faults in central East and North-East Greenland are considered to hold a potential for tin and tungsten, with bismuth possibly produced as a by-product. Bi-bearing veins and breccias formed during Palaeogene magmatism also occur in this area. Even though only limited exploration has been carried out, the many known bismuth occurrences described above suggests that this setting may hold potential for additional mineralisation.

3.5 Chromium [Cr]

Table 7 *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. Chromium compounds are used as industrial catalysts and pigments, as well as for tanning leather. However, the waste effluent is toxic, so alternatives are being investigated.
Annual mine production and leading producing countries	Total production 2022: 41 Mt of which the main producers are South Africa (44 %), Turkey (17 %), Kazakhstan (16 %), and India (7 %) (USGS 2023).
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 560 Mt, of which Kazakhstan holds 41 %, South Africa 36 %, and India 10 % (USGS 2023).
Known resources in Greenland	560,000 t
Market constraints	Chromium has no substitute in stainless steel, the leading end-use, or in superalloys, 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 deposits and important occurrences (Figure 6)

Economic chromite deposits are generally found in three different geological environments: 1) stratiform deposits, related to igneous rock such as norite or peridotite; this type is hosting two of the largest chromite deposits (Bushveld and Great Dyke); 2) podiform deposits, which 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.

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, leucogabbro, 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).

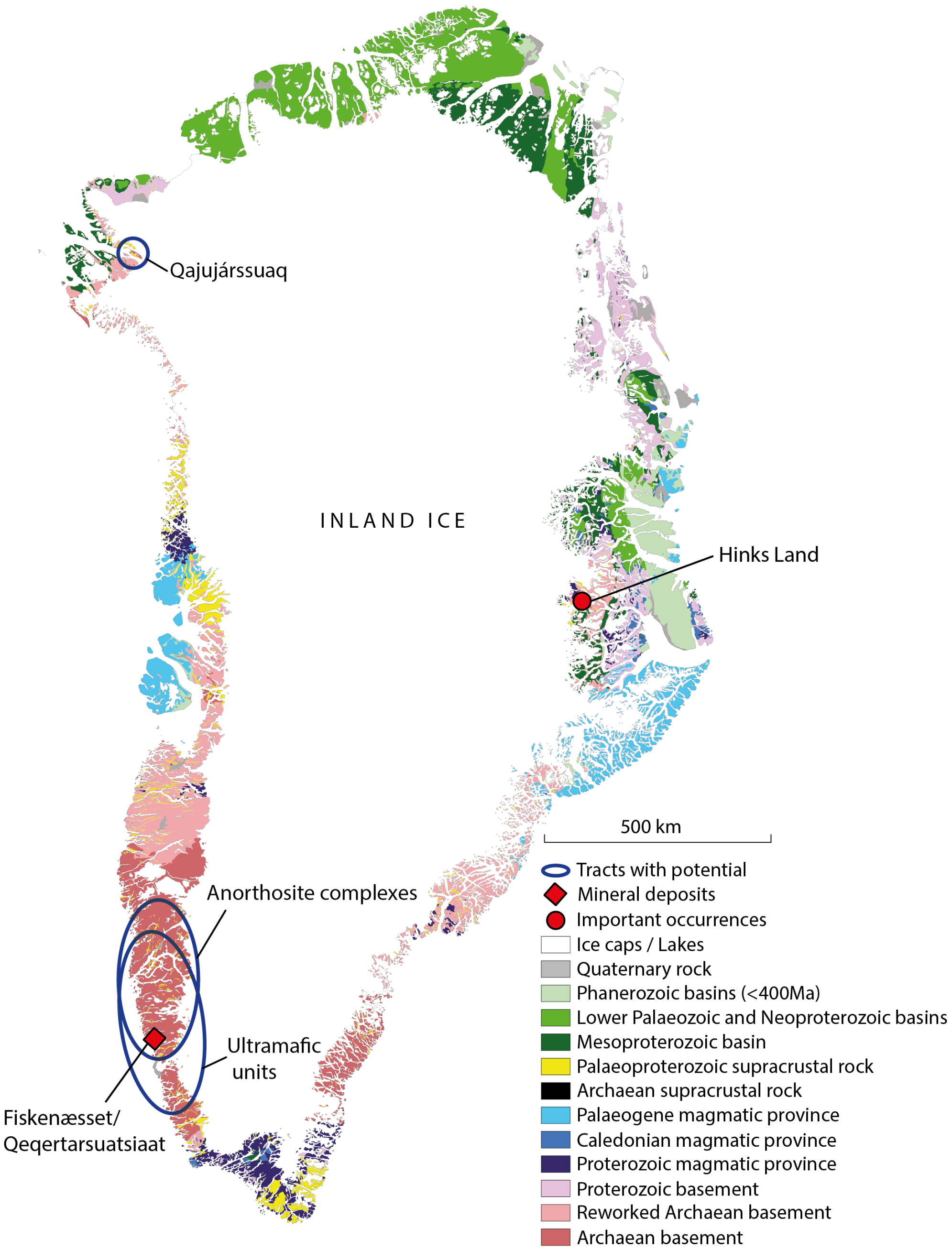

Figure 6 *Map of known chromium deposits, significant occurrences, and favourable tracts. Simplified geological map is based on 1:2 500 000 geological map by Henriksen et al. (2009).*

Hinks Land, central East Greenland

Hornblendite, dunite or peridotite plugs hosting chromite mineralisation intrude the Flyverfjord Archean gneisses, southeast of the Daugaard-Jensen glacier. Mineralisation was recognised in 1969 but has not seen any subsequent follow-up work. It consists of pods of chromite up to 0.8 m in diameter and cm-thick massive layers. Massive chromite and magnetite samples yielded 10–15 % Cr (Harpøth *et al.* 1986).

Tracts with resource potential for chromite (Figure 6)

Geologically the tracts described below are defined as the geological environments characterised by ultramafic rocks and anorthosites, these two tracts are to some extend geographically overlapping.

Ultramafic rock units, 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.

The Fiskefjord area in the central Akia terrane is dominated by amphibolites, dioritic to tonalitic orthogneisses, and peridotites. The peridotites occur as large discontinuous lensoid bodies within tonalitic orthogneiss. Exposures of these peridotites can be found in the Miaggoq, Seqi, Ulamertoq, and Amikoq ultramafic bodies, which are also associated with noritic rocks (Szilas *et al.* 2015, 2018). Several of the peridotite bodies have chromite seams (Guotana *et al.* 2018).

Anorthosite complexes, 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 (> 1,000 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.

3.6 Cobalt [Co]

Table 8 *Overview of the commodity cobalt.*

Main application	Cobalt is refined into both metal and chemicals. The largest use of cobalt is for Li-ion batteries (portable electronics, automotives), accounting for 57 % of world consumption, followed by superalloys for steel (13 %), hard metals for carbides (8 %), pigments (6 %), catalysts (5 %), and magnets (4 %) (Cobalt institute 2021).
Annual production and leading producing countries	Global mine production in 2022 was 190,000 t, of which the following countries are the main producers: DRC (69 %), Indonesia (5.3 %), Russia (4.7 %), Australia (3.1 %), Canada (2.1 %), Philippines (2 %) (USGS 2023).
Main mineral	More than 100 cobalt-containing minerals are known, of which thirty are cobaltiferous, but only four are commercial: the sulphide cobaltite ((Co,Fe)AsS), the arsenides skutterudite ($(Co,Ni)As_3$), the smaltitechloanthite ($(Co,Ni,Fe)As_{3-2}$), and the 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 (56 %) and copper mining (28 %) and is associated to Ni- and Cu sulphides/arsenides.
Resource/reserve	The most important cobalt resources are found 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 be 8.3 Mt, of which 48 % is found in DRC, 18 % in Australia, 7.2 % in Indonesia, and 6.0 % in Cuba; China holds only about 1.7 % of the reserves (USGS 2023).
Known resources in Greenland	No known resources in Greenland.
Market constraints	70 % of all cobalt is mined in Africa, but only 5 % is refined there; China refines about 65 %; 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 important cobalt occurrences (Figure 7)

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 weather to gossans. The mineralised semi-massive to massive sulphide samples typically grade 3-7 wt% Ni, 0.1-6.3 wt% Cu, 0.1-0.2 wt% Co and up to 0.3 ppm Pt+Pd+Au (North American Nickel Inc. 2017, 2022). 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. North American Nickel Inc. conducted an exploration program between 2011 and 2019 including a comprehensive drilling campaign and helicopter borne TEM and magnetic surveys were carried out. This expanded the footprint of the historic mineral occurrence at the Imiak Hill Complex and Fossilik and in addition resulted in the discovery of several new occurrences of mineralised norite and identified new conductive bodies at depth. Assays highlights include 24.75 m @ 3.19 % Ni and 1.14 % Cu (North American Nickel Inc. 2022), no resource estimates have been attempted for the targets at the Maniitsoq prospect.

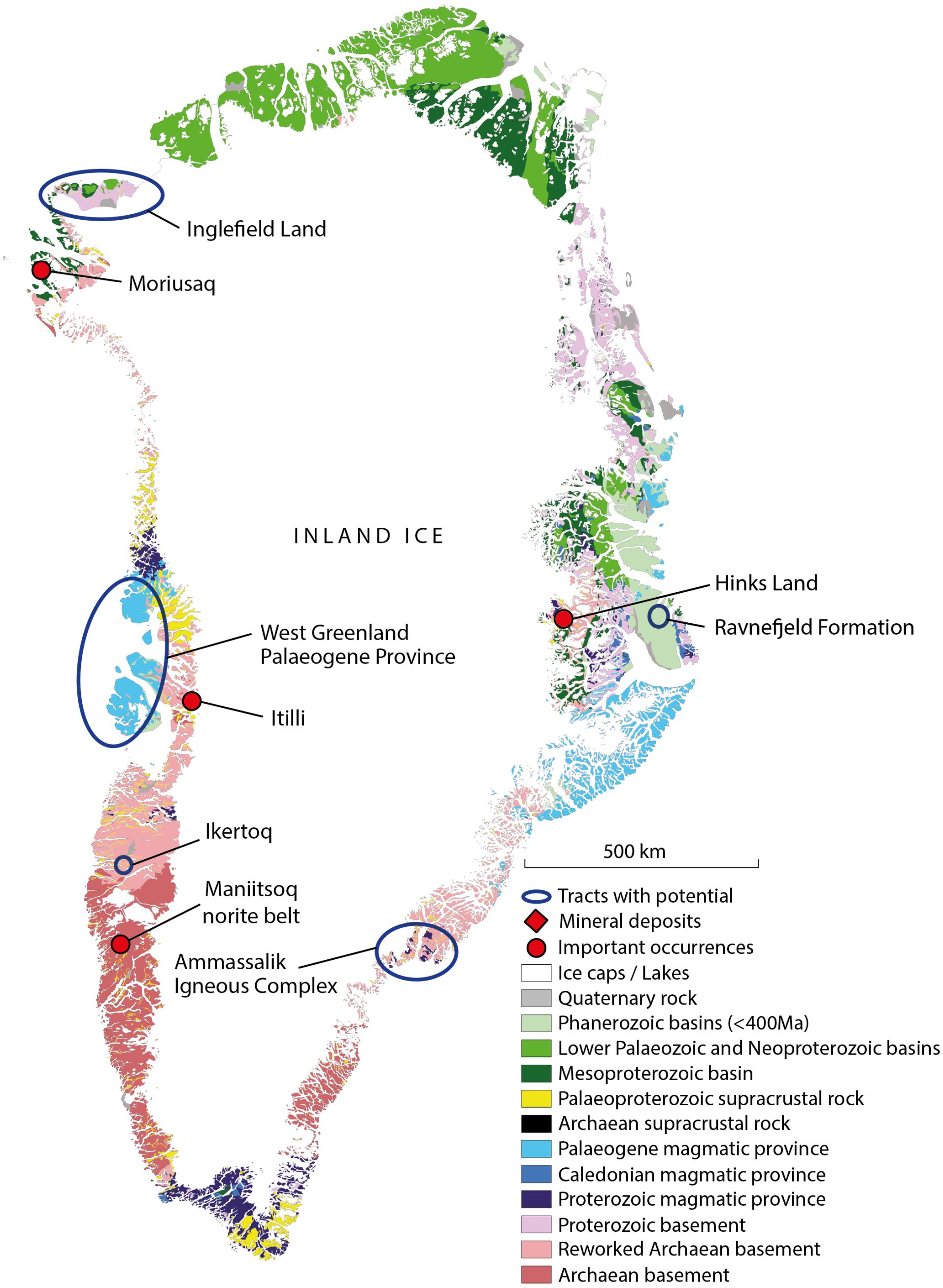

Figure 7 *Map of known significant cobalt occurrences, and favourable tracts. Simplified geological map is based on 1:2 500 000 geological map by Henriksen et al. (2009).*

Hinks Land, central East Greenland

Hornblendite, dunite or peridotite plugs hosting chromite mineralisation intrude the Flyvefjord Archean gneisses, southeast of the Daugaard-Jensen glacier. Mineralisation consists of pods of chromite up to 0.8 m in diameter and cm-thick massive layers. Massive chromite and magnetite samples yielded up to 700 ppm Co (Harpøth *et al.* 1986).

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 1 m 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 (Stendal *et al.* 2004).

Moriussaq, North-West Greenland

Ilmenite-rich black-sand placers occur at Moriussaq in the Thule (Pituffik) region (Dawes 1989; Ghisler & Thomsen 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). Dundas Titanium reports a JORC compliant mineral resource of 117.3 Mt, grading 1.7 % Ti (Bluejay Mining plc 2020).

Tracts with resource potential for cobalt (Figure 7)

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

Ikertoq, southern West Greenland

Co-bearing Fe-Ni-Cu-sulphides have been described from the Ikertoq Ni-Cu-(Co) komatiite-hosted type occurrence, north of Søndre Strømfjord, southern West Greenland (Rosa *et al.* 2013).

West Greenland Palaeogene Province, central West Greenland; Ammassalik, South-East Greenland

Cobalt may be produced as a by-product from conduit-type nickel occurrences, further described in section 3.17 Nickel [Ni],potentially existingon Disko Island in the West Greenland Palaeogene Province, and at the Ammassalik igneous complex, South-East Greenland. Other tracts identified with a potential for conduit-type nickel mineralisation may also hold a potential for cobalt. Please see section 3.17 Nickel [Ni] for more information on the potential for conduit type nickel occurrences.

Inglefield Land, North-West Greenland

A rock float from Anoritooq in the Palaeoproterozoic Inglefield Land Mobile Belt, yielded 8.8 wt% cobalt, 7.6 wt% 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 characterised 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.

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, see sub-section 3.7 Copper [Cu]. 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)).

3.7 Copper [Cu]

Table 9 *Overview of the commodity copper.*

Main application	Copper is a versatile and highly useful metal that has a wide range of applications in various industries and applications. The main usages of copper include power cables and wiring, buildings (pipes, taps, valves, fittings, roof plates), electronics (microchips, circuit boards) transportation (automobiles, airplanes), industrial applications (heat exchangers, chemical processing equipment, etc.) and medical applications such as surgical and medical equipment.
Annual production and leading producing countries	Global mine production in 2022 was 22.0 Mt, with Chile producing 24%, Congo and Peru producing each 10 %, China 8.6 %, USA 5.9 % and Russia 4.5 % (USGS 2023).
Main mineral	The principal copper ore mineral is chalcopyrite ($CuFeS_2$) that accounts for about 50 % of the global production (BGS 2007). Other important ore minerals include covellite (CuS), bornite (Cu_5FeS_4), chalcocite (Cu_2S), and the oxide cuprite (Cu_2O).
Resource/reserve	Total global Co reserves amount to 890 Mt of which 21 % are in Chile, 11 % in Australia, 9.1 % in Peru, 7.0 % in Russia, 6.0 % in Mexico, 4.9 % in the USA, 3.5 % in DRC, and 3.0 % in China (USGS 2023). Total known resources are 2,100 Mt and undiscovered resources contained an estimated 3,500 Mt (USGS 2023).
Known resources in Greenland	108,000 t. 'Undiscovered resources' of sedimentary-hosted copper has been estimated by Stensgaard *et al.* (2011) to 3.68 Mt.
Market constraints	On the supply side in 2022, Chile and Peru, the largest copper producing countries, experienced a number of incidents and production shutdowns, while the production in the rest of the world remained flat due to weak demand for blister copper in China.

Known copper deposits and important occurrences (Figure 8)

Only limited copper exploration has been undertaken in Greenland. Nevertheless, the activity that has been carried out has successfully identified numerous, predominantly smaller, deposits and occurrences in several areas of Greenland. Most exploration has been based on traditional surface-exploration on exposed rocks, and only a limited number of occurrences have been investigated in detail to a level which allow for geological estimate of overall tonnage and grade.

Bersærkerbræ, East Greenland

This deposit is found in a vertical N-S striking baryte-fluorite vein hosted in contact metamorphosed sediments close to a late Caledonian granite (Harpøth *et al.* 1986). The vein has a central part of fluorite which is rimed by baryte with chalcocite and bornite and galena found in up to 5 mm thick veinlets. Analyses of the vein has up to 35.5 % Cu, 540 ppm Ag, 150 ppm Mo, 400 ppm Pb and 0.1 ppm Au. A preliminary tonnage of 100,000 t with 2-3 wt.% Cu and 50 ppm Ag was estimated by Harpøth *et al.* (1986).

Sortebjerg, East Greenland

The Sortebjerg deposit is found as an extension of the fault structure which also hosts the Pb-Zn Blyklippen deposit that was mined from 1956-1962. The Sortebjerg quartz vein system, located approximately 5 km south of the Blyklippen mine, is 10-30 m wide and is estimated to contain 220,000 t of ore at grades of 9.3% Zn, 2.1% Pb and 0.7% Cu (Swiatecki, 1981). Main ore minerals consist of galena, sphalerite, and chalcopyrite and the Sortebjerg-Blyklippen vein zone is an epithermal mineralization that is structurally controlled by a graben fault (Harpøth *et al.* 1986). In 2011, Ironbark Zinc Ltd conducted exploration and identified the extension of Zn-Pb veins with high-grade Zn-Pb-Ag mineralization in drill intercepts at both Blyklippen and Sortebjerg (Kolb *et al.* 2016).

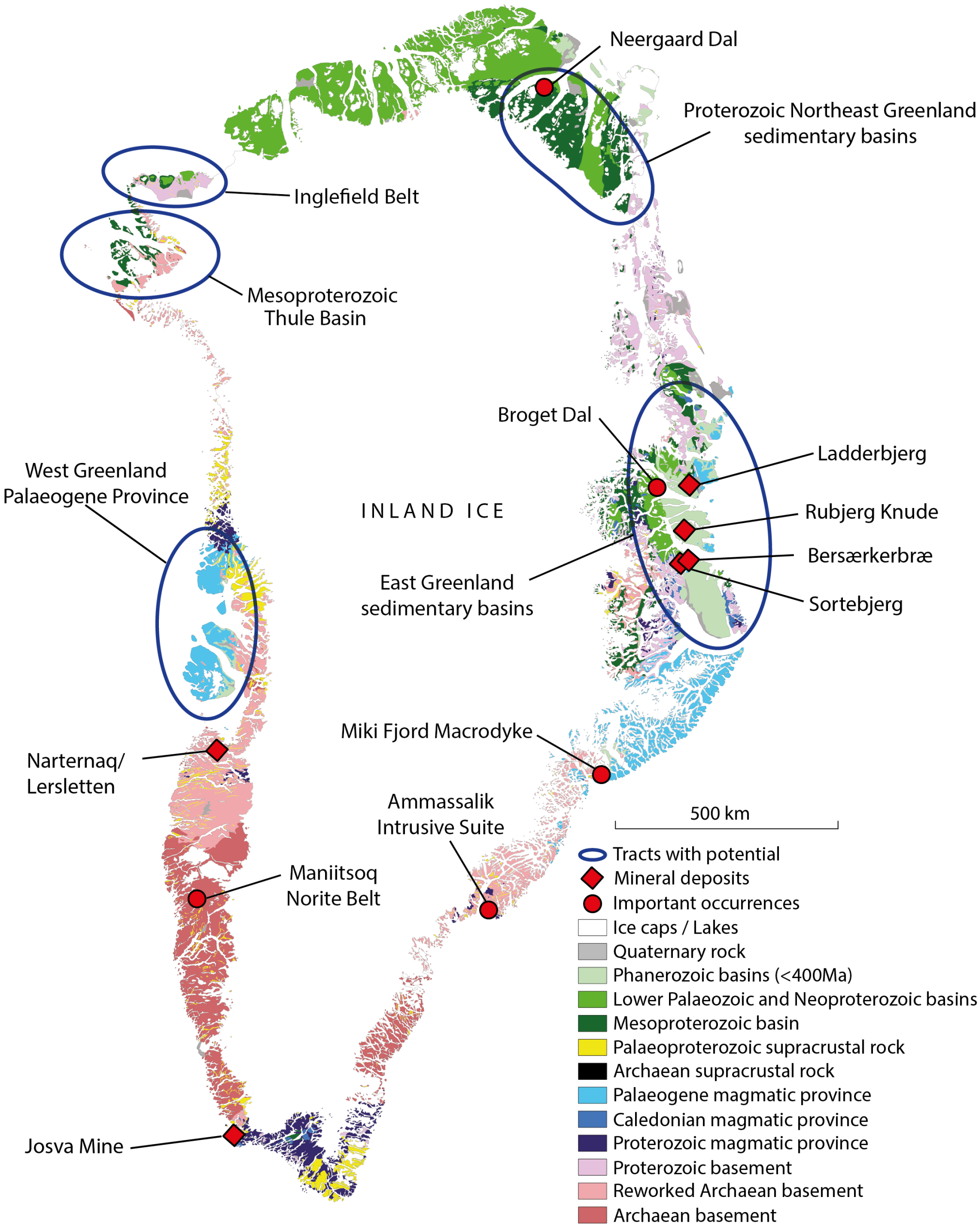

Figure 8 *Map of known copper deposits, significant occurrences, and favourable tracts. Simplified geological map is based on 1:2 500 000 geological map by Henriksen et al. (2009).*

Josva Mine, South Greenland

The Josva Mine, located in the Qeqertarsuatsiaat area, South Greenland, was in production from 1853-1855 and again in 1905 to 1914. About 2200 t of ore were mined and it has been estimated that about 90 t of Cu and 50 kg Ag, and 0.5 kg Au were extracted (Steenfelt *et al.* 2016). According to Ball (1923) The ore had a grade of 4.1 % Cu, 0.8 ppm ppm Au and 11 ppm Ag. The size of the remaining ore body at Josva Mine is estimated to be 2000–3000 tons of ore containing 30–40 t of Cu (Nielsen, 1976). The copper mineralization occurs in veins, breccias, foliation-parallel stringers, and vugs, with an ore assemblage consisting predominately of bornite, chalcocite, ilmenite, magnetite and hematite-chalcopyrite (Harry & Oen, 1964). The mineralisation zone of the Josva Mine is being explored by the company Amaroq Minerals Ltd. that reports samples with up to 4.2 % Cu over 2.5 m including 11.6 % Cu over 50 cm (Amaroq Minerals Lt.d 2023). The exploration company interprets the mineralisation as skarn related, probably associated with Ketilidian magmatism, and hypothesizes that the Kobberminebugt shear zone could contain other Cu mineralised bodies along strike (Amaroq Minerals Ltd. 2023).

Neergaard Dal, North-east Greenland

This Redbed-type Cu occurrence is exposed in the northern part of the Neergaard Valley in I.C Christensen Land. The extent of the mineralisation has not been defined, but the exposed vertical thickness can be estimated to a minimum 2 m. The mineralisation is hosted by bleached, relatively homogeneous grey sandstone of the Jyske Ås Formation and consist predominately of bornite, but also include chalcocite, covellite and native copper. Historical results by GGU yielded peak assay of up to 3.8 % Cu and a composite chip sample returned 3.1% Cu and 106 ppm Ag. Exploration is ongoing and is currently undertaken by Greenfields Exploration as part of their ARC Project that extends over a very large area containing sediment-hosted copper/silver within the Proterozoic Northeast Greenland sedimentary basin (Greenfields Exploration 2023).

Ladderbjerg, central East Greenland

The Ladderbjerg deposit, which is located in Giesecke Bjerge on the Gauss Halvø peninsula, is hosted by conglomerate of the Upper Permian Hulebjerg Formation. This is a red bed-type Cu-Pb occurrence which occurs over 700 m along strike with strong zonation from chalcopyrite at the base to galena at the top with some replacement of sulphides by secondary malachite, acurite and goethite. A resource, non-compliant to recent international reporting standards, of 2.5 Mt at 0.15 wt.% Cu,0.1 wt. % Pb, and 8 ppm Ag has been estimated (Harpøth *et al.* 1986).

Rubjerg Knude, Traill Ø, central East Greenland

This Revett-type deposit extends laterally for 200-300 m in paleochannel units and has a thickness of 5-20 m, with a lateral zonation of chalcopyrite and chalcocite. Recent exploration by Avannaa Exploration Ltd returned chip samples with 2500 ppm Cu, 900 ppm Zn, 150 ppm Pb and 5 ppm Ag, with the highest values of 0.54 wt% Cu and 8 ppm Ag over 3 m in the fine-grained rocks. The ore minerals, which are disseminated in the cement and form encrustations on pebbles and cobbles, include chalcocite, bornite, chalcopyrite, galena, and secondary minerals such as malachite, azurite, covellite, native copper, and cerussite. The estimated resources of the deposit are 5-12 Mt ore at 0.3 wt.% Cu and 5 ppm Ag (Thomassen, 2012).

Narternaq/Lersletten, West Greenland

The Naternaq belt, situated to the south of Disko Bugt, is host to a sulphide-quartz mineralization, which may have resulted from hydrothermal processes in VHMS or SEDEX systems (Østergaard *et al.* 2002; Garde and Hollis, 2010). Small-scale fold structures in the fold hinges exhibit semi-massive to massive sulphide lenses that measure up to 2 m x 10 m. The ore is made up of pyrrhotite, chalcopyrite, sphalerite, and minor pyrite, arsenopyrite, magnetite, and graphite. Geological and geophysical exploration, trenching, and drilling resulted in a resource estimation of 2.4–4.8 Mt, with a concentration of 2.7 wt% Cu, 3.75 wt% Zn, and an additional 0.6 ppm Au over 0.35 m (Østergaard *et al.* 2002).

Broget Dal, central East Greenland

Sedimentary copper-antinomy mineralisation occurs in a 500 by 1000 m area, within 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. A bulk sample (35 kg) yielded 1.33 % Cu and 1.07 % Sb (Harpøth *et al.* 1986). No resource estimates have been attempted at this locality.

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 1.39 % Ni, 0.46 % Cu, and 0.3 ppm PGM (21st North 2012). Extensive iron sulphide mineralisation and Ni-Cu-Au mineralised grab-samples from more restricted mineralisation has also recently been found by GEUS within the intrusive rock suite itself.

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 mineralised semi-massive to massive sulphide samples typically grade 3-7 wt% Ni, 0.1-6.3 wt% Cu, 0.1-0.2 wt% Co and up to 0.3 ppm Pt+Pd+Au (North American Nickel Inc. 2017; 2022). 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. North American Nickel conducted an exploration program between 2011 and 2019 including a comprehensive drilling campaign and helicopter borne TEM and magnetic surveys were carried out. This expanded the footprint of the historic mineral occurrence at the Imiak Hill Complex and Fossilik and in addition resulted in the discovery of several new occurrences of mineralised norite and identified new conductive bodies at depth. Assays highlights include 24.75 m @ 3.19 % Ni and 1.14 % Cu (North American Nickel Inc. 2022), no resource estimates have been attempted for the targets at the Maniitsoq prospect.

Miki Fjord Macrodyke, East Greenland

This occurrence, located approximately 2 km northeast of the Skaergaard intrusion, has Cu-Ni-PGE-Au mineralisation at its margins (Holwell *et al.* 2012) with grades up to 3.3 ppm Pd, 0.16 ppm Au, 2.2 % Cu, and 0.8 % Ni in hand specimen (Platina Resources Ltd. 2016). Diamond drilling did not test the mineralization, but geophysical investigations indicate possible mineralization targets at depth (Andersen 1997).

Tracts with resource potential for copper (Figure 8)

Copper mineralisation in Greenland is widespread and of several metallogenetic types with sedimentary-hosted copper being prevalent but orthomagmatic, hydrothermal and skarn/contact type mineralisation also being present.

The potential for sedimentary-hosted Cu mineralisation in Greenland was assessed during a mineral resource assessment workshop in 2009 (Stensgaard *et al.* 2011). The main sedimentary-hosted Cu mineralisation types found in Greenland are *reduced facies Cu* (Kupferschifer), *redbed Cu*, and *Revett Cu*, see explanation and examples of deposits/occurrences of these Cu types in Steensgaard (2011) and Stensgaard *et al.* (2011). As part of the workshop the undiscovered sedimentary-hosted resources were quantified derived by statistical simulation, which used globally tonnage/grade models for known deposits worldwide and bids on number of undiscovered sediment-hosted copper deposits within different sedimentary basins in Greenland. The undiscovered Cu resources were estimated to approximately 3.5 Mt with largest resources belonging to the reduced facies Cu-type in central East Greenland.

Central East to North-East Greenland sedimentary basins

Two major sedimentary basins dominate large parts of Central East to North-East Greenland and are important for copper mineralisation: the Neoprotozoic Eleonore Bay Basin and the Permian and Triassic successions of the Jameson Land Basin. The Eleonore Bay Supergroup comprises a more than 14 km thick succession of shallow-water sedimentary rocks. Stratabound Cu occurrences stretch for more than 300 km which can be found in eight stratigraphic levels (Ghisler *et al.* 1980, Stendal and Frei 2008) with the most Cu-rich parts found in the upper part of the Eleonore Bay Supergroup and showing similarities with part of the Zambian copper belt (Stensgaard 2011). The Jameson Land Basin, related to continental break-up, consists of conglomerates, sandstones, shales, carbonates, and evaporites. Reduced-facies Cu deposits occur in both Upper Permian and Upper Triassic strata. Copper occurrences in the Ravnefjeld Formation's black shales are widespread and like the European Kupferschiefer type. Copper occurrences in the Jameson Land Basin's Triassic strata are found at several levels, with the most promising found in the Upper Triassic Pingel Dal Formation and the Fleming Fjord Formation and belonging to reduced facies-type Cu mineralisation types (Stensgaard *et al.* 2011).

Proterozoic basins, North-East Greenland sedimentary basins

In North Greenland, native copper and copper sulphides are found in the Hagen Fjord Group of the Meso-Neoproterozoic Hekla Sund Basin and in the Palaeoproterozoic Independence Fjord Group, namely within fluvial sandstones of the Jyske Ås Formation in the lower part of the Hagen Fjord Group (Stensgaard *et al.* 2011). It is speculated that these indications could represent volcanic red bed-type volcanic copper mineralization (Stensgaard 2011; see also Neergaard Dal occurrence above).

Mesoproterozoic Thule Basin, North-West Greenland sedimentary basins

Red bed-type Cu occurrences are found in volcanic rocks of the Nares Strait Group and from the Baffin Bay Group. Compelling evidence suggests that the basin has undergone substantial and persistent fluid/brine activity necessary to facilitate the mixing of fluids and ultimately lead to the formation of red bed-type mineralisation. Whithin the Thule region there are also contact/skarn hosted Cu (and Pb, Zn) occurrences, associated with sills and dykes of the Dundas Group, but these probably have a limited potential.

Inglefield Belt, North-West Greenland

The Paleoproterozoic Inglefield Belt covering Inglefield Land and Prudhoe Land in northern West Greenland, is a E-W trending mobile belt dominated by complex intercalation of metasediments and meta-igneous rocks forming and E-W trending belt (Dawes 2004). Copper-Au mineralisation, hosted in gneisses and mafic-ultramafic, occurs in a roughly 70 km x 4 km area with grades up to 0.4 wt% Cu and 8.6 ppm Au (Pirajno *et al.* 2003) and could presumably be of IOCG type.

West Greenland Palaeogene Province, central West Greenland

A mineral resource assessment workshop in 2012 (Rosa *et al.* 2013) assessed the potential for undiscovered conduit-type nickel mineralisation, which can also host copper, related to picrite and/or tholeiitic basalt dyke-sill complexes in Greenland. The Disko Island, part of The Palaeogene West Greenland Province was considered to hold a significant potential for this deposit type, which can yield PGM as a by-product. The volcanic succession in the northern part of the West Greenland Palaeogene Province on The Svartenhuk Halvø and the areas north and northeast of this, are generally correlatable with the southern part of the province (Larsen & Larsen 2022) and low contents of V, Cu and Ni in some crustally contaminated lavas could indicate that these elements and accompanying PGM could be present at depth (Larsen & Larsen 2022). Please see section 3.17 Nickel [Ni] for more information on the West Greenland Palaeogene Province.

3.8 Feldspar

Table 10 *Overview of the commodity feldspar.*

Main application	Feldspar is essentially used in the ceramics and glass industry, and less so as paper, paint, and polymer filler.
Annual production and leading producing countries	Total production in 2022 amounted to approximately 28 Mt, with India (22 %) and Turkey (28 %) as key players (USGS 2023).
Main mineral	Feldspar is more accurately defined a group of rock-forming minerals, of which anorthite ($Ca_2Al_2Si_3O_8$), albite ($NaAlSi_3O_8$) and potassium feldspar ($KAlSi_3O_8$) are the main endmembers.
Resource/reserve	Quantitative data on feldspar resources has not been compiled, but these resources are adequate to fulfil expected global demand (USGS 2023).
Known resources in Greenland	80.8 Mt anorthosite
Market constraints	Feldspar can be substituted in some of its applications by clay, slag, feldspar-silica mixtures, nepheline syenite, pyrophyllite, spodumene, or talc. Nepheline syenite was the major alternative material for feldspar. This mineral was considered critical in the most recent EC list due to the increase in supply risk induced by higher import dependency from Turkey which now supplies 51 % of the EU needs (Grohol & Veeh, 2023).

Known feldspar deposits (Figure 9)

Qaqortorsuaq/White Mountain, southern West Greenland

The anorthosite rock found at Qaqortorsuaq exhibits distinct characteristics of white color, fine to medium-grained texture, and low content of dark minerals like hornblende and biotite. The white colour of the 1,300 m high mountain has led to its' Greenland name Qaqortorsuaq (The Great White). The complex has not been radiometrically dated, but based on its structural relationships with surrounding rock suggests that it is probably Archean (Thaarup *et al.* 2020). The deposit was discovered by the Geological Survey of Greenland in the 1940s and was further explored by Kryolitselskabet Øresund in 1977. Later Hudson Resources drilled the western part of the mountain in search for diamonds, which was unsuccessful. However, this drilling campaign revealed a substantial anorthosite resource that in 2012 and subsequently was explored by Gold Resources and Hudson Resources Inc. (Druecker & Simpson 2013; Thaarup *et al.* 2020). Hudson Minerals (subsequently renamed Lumina Sustainable Materials) has a fully permitted mining project for anorthosite, with an initial 43-101 resource model outlining 27 Mt of indicated and 32 Mt of inferred resources at Na_2O cut-off of 2.5 wt.% (Hudson Resources, 2018). Mining was commenced in 2019 with a planned production of 200,000 tpa which is intended to be increased to 500,000 tpa in the future.

Majoqqap Qaava, southern West Greenland

The Majoqqap Qaava deposit is part of the Fiskenæsset complex, further described in section 3.5 Chromium [Cr].The anorthositic unit is c. 250 m thick (Myers 1985) that hosts the Majoqqap Qaava anorthosite deposit. Greenland Anorthosite Mining has submitted environmental and social impact assessments for its Majoqqap Qaava project with a 21.8 Mt inferred resource (Greenland Anorthosite Mining, 2022). The company plans to mine between 460-940 kt of raw anorthosite per year, and ship product materials to Europe and North America.

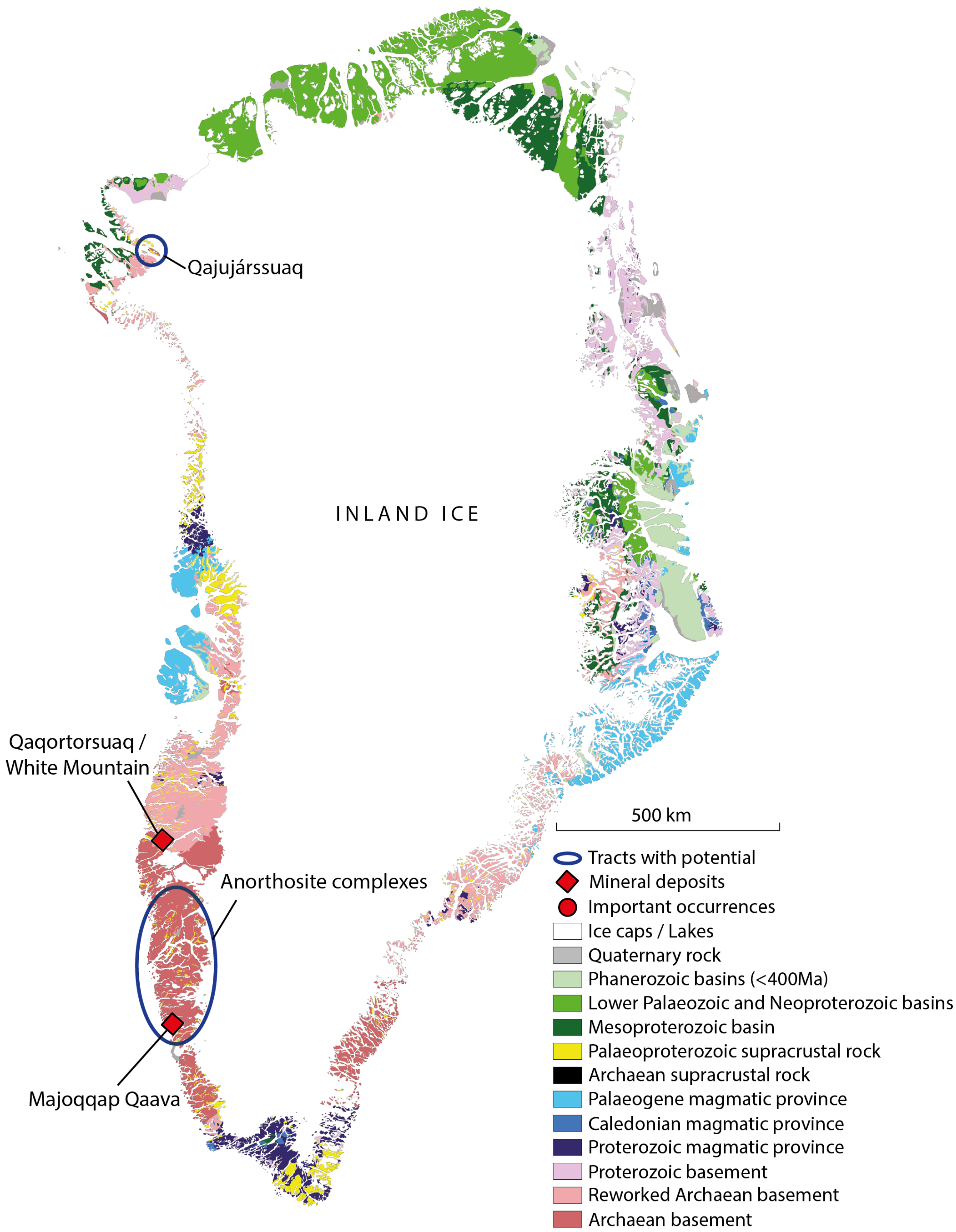

Figure 9 *Map of known feldspar deposits and favourable tracts. Simplified geological map is based on 1:2 500 000 geological map by Henriksen et al. (2009).*

Tracts with resource potential for feldspar (Figure 9)

Feldspar is a ubiquitous mineral, occurring in many geological settings. But its use in industry, especially in demanding but expanding industries such as fiberglass, requires homogenous and consistent material with low levels of impurities. Around 12 anorthosite complexes have been identified in Greenland (Knudsen *et al.* 2012), but other than the deposits described above, a clear picture of feldspar characteristics for demanding industrial usage in other parts of Greenland is not available. Anorthosite complexes in the tracts presented below should be considered of interest and is considered to hold potential.

Anorthosite complexes, southern West Greenland

The highest concentration of anorthosite complexes in Greenland is found in the core of the Archean block around and south of Nuuk and include in addition to the Majoqqap Qaava deposit, the anorthosites of Akia, Innajuattoq, Qarliit Nunaat, Buksefjorden (Knudsen *et al.* 2012).

Qaqujârssuaq anorthosite complex, Thule region, North-West Greenland

Similar to the anorthosite units in southern West Greenland the little known, but very large (> 1,000 km^2) Qaqujârssuaq anorthosite complex (Dawes 1972, 2006; Nutman 1984) has a potential for high quality feldspar (i.e. low levels of impurities). The complex is described mainly as an anorthositic body with some gabbro and leucogabbro units.

3.9 Fluorite [CaF_2]

Table 11 *Overview of the commodity fluorite.*

Main application	Fluorite (also referred to as fluorspar) is an important industrial mineral used in many chemical, ceramic, and metallurgical processes. The chemical sector is consuming more than half of the fluorite for the production of hydrofluoric acid which is used in the pharmaceutical and agrochemical industries; fluorspar is used by the steel industry as a flux. The aluminium industry uses synthetic cryolite manufactured from 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 8.3 Mt in 2022 (USGS 2023). China is the dominant producer (about 69 %), followed by Mexico (12 %), South Africa (4.2 %), Mongolia (4.2 %) and Vietnam (2.7 %) (USGS 2022).
Main mineral	Fluorite (CaF_2) is categorised 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 for selected countries is estimated to be about 260 Mt of which 27 % are in Mexico, 19 % in China, 16 % in South Africa, and 8.4 % in Mongolia (USGS 2023).
Known resources in Greenland	250,000 t
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. The global availability of fluorspar has increased in 2020 due in decreased consumption and ramp-up of new mines in Canada and South Africa.

Known fluorite deposits and important occurrences (Figure 10)

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 the Greenlandic context, namely the peralkaline deposits of the Gardar Province, fluorine can be sourced from fluorite in Ivittuut, or from villiaumite (NaF) in the Ilímaussaq complex, which is therefore here discussed as well.

Ivittuut, South-West Greenland

The Ivittuut deposit contains fluorite, widely distributed in parts of the cryolite deposit and in the intermediate western part of the deposit (Kalvig 1994). Resource estimates on the fluorite zone report an in situ tonnage of 0.5 Mt grading 50 % fluorite (Bondam 1991).

Ilímaussaq complex, South Greenland

The Kvanefjeld/Kuannersuit REE-U-Zn deposit, part of the Ilímaussaq syenite complex, located north of the township Narsaq, contains the F-mineral villiaumite (NaF). The villiaumite content varies from accessory to 20 % by volume (Kalvig 1994). The Kvanefjeld/Kuannersuit 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/Kuannersuit, Sørensen Zone and Zone 3 of 1.01 Bt REE-U-Zn ore (Energy Transition Minerals, 2023). More details can be found under the Rare Earth Elements section below.

At the Kringlerne/Killavaat Alannguat Zr-Nb-Ta-REE deposit, fluorine contents of 2 % and 1 % in samples of black and white karkortokite respectively are reported (Bailey *et al.* 1981). Presently, there are no available resource estimations for fluorine. More details can be found under the REE section.

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.

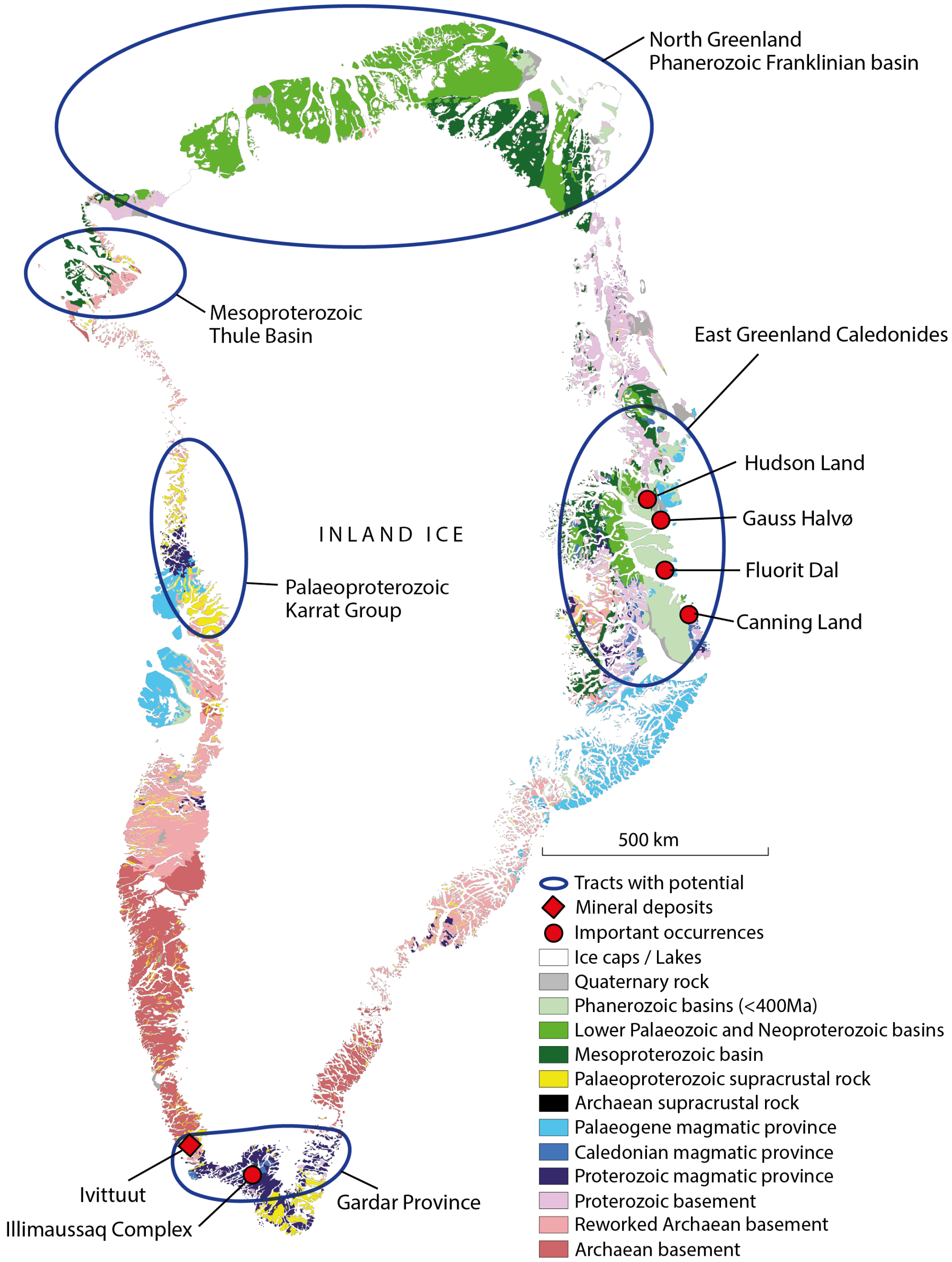

Figure 10 *Map of known fluorite deposits, significant occurrences, and favourable tracts. Simplified geological map is based on 1:2 500 000 geological map by Henriksen et al. (2009).*

Various localities, central East, and North-East Greenland

Harpøth *et al.* (1986) and Stendal (1999) describe fluorite veins from 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 Canning Land, where veins are Upper Devonian or Carboniferous of age, and normally intersect Middle-to Upper Devonian rocks but not Upper Permian and younger units. Finally, 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.

Tracts with resource potential for fluorite (Figure 10)

Gardar Province

The 1300–1140 Ma Gardar period involved continental rifting, sedimentation, and alkaline magmatism. Numerous dykes and 10 ring-shaped intrusion complexes were formed across South Greenland. Residual magmas and fluids resulting from extreme magmatic differentiation, possibly combined with assimilation of older crust, created mineral deposits including cryolite that was mined at Ivittuut, large low-grade deposits of uranium-rare earth elements-zinc-fluorine-lithium at Kvanefjeld/Kuannersuit and tantalum- niobium- rare earth element- zirconium at Kringlerne/ Killavaat Alannguat, in the Ilímaussaq complex, as well as tantalum-niobium-rare earth elements at Motzfeldt in the Igaliko complex (Steenfelt *et al.* 2016).

Mississippi Valley Type, central West, North-West and North 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 central 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). Another area that was found to host a potential for Mississippi Valley Type mineralisation, although smaller potential than the areas mentioned above, is the Mesoproterozoic Thule Basin in northern West Greenland.

East Greenland Caledonides, North-East and central East Greenland

There is a small potential for fluorite to be recovered as a by-product of the mining of W-Sn deposits related to the Caledonian granite magmatism. Fluorite veins and breccias formed during Palaeogene magmatism also occur in this area.

3.10 Gallium [Ga]

Table 12 *Overview of the commodity gallium.*

Main application	Gallium is 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 (European Commission 2020b; USGS 2022).
Annual production and leading producing countries	Total annual production in 2022 was estimated to be 550 t, compared to 218 t in 2011 (USGS 2022). China is the major producer (98 %), followed by Russia, Japan, and South Korea; each country producing approximately 1 % (USGS 2023).
Main mineral	Gallium occurs mainly as a trace element in minerals 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, so this metal is mostly produced as a by-product of aluminium production.
Resource/reserve	USGS (2023) estimates that worldwide resources of gallium contained within bauxite exceed 1 Mt, and considerable amounts are also thought to be present in zinc ores. Quantitative estimates of reserves are not available. However, much of the gallium is associated with 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 found in phosphate ores and coal, which might well be the largest reserves of gallium.
Known resources in Greenland	152,000 t
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 (European Commission 2014). Primary low-purity gallium (99.99 % Ga) prices in China increased by more than 30 % in 2020 owing mostly to reduced Chinese production.

Known gallium deposits (Figure 11)

Skaergaard Intrusion, southern 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 1,520 Mt (non-compliant to recent international reporting standard), containing 152,000 t Ga. For further description of the Skaergaard intrusion please see section 3.19 Platinum Group Metals [PGM: Pt, Pd, Rh, Ru, Ir, Os].

Tracts with resource potential for gallium (Figure 11)

Mississippi Valley Type, central West, North-West and North 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 central West

Greenland, in particular, were found to host a potential for MVT mineralisation (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. Another area that is considered to host a potential for MVT mineralisation, although smaller potential than the areas mentioned above, is the Mesoproterozoic Thule Basin in North-West Greenland.

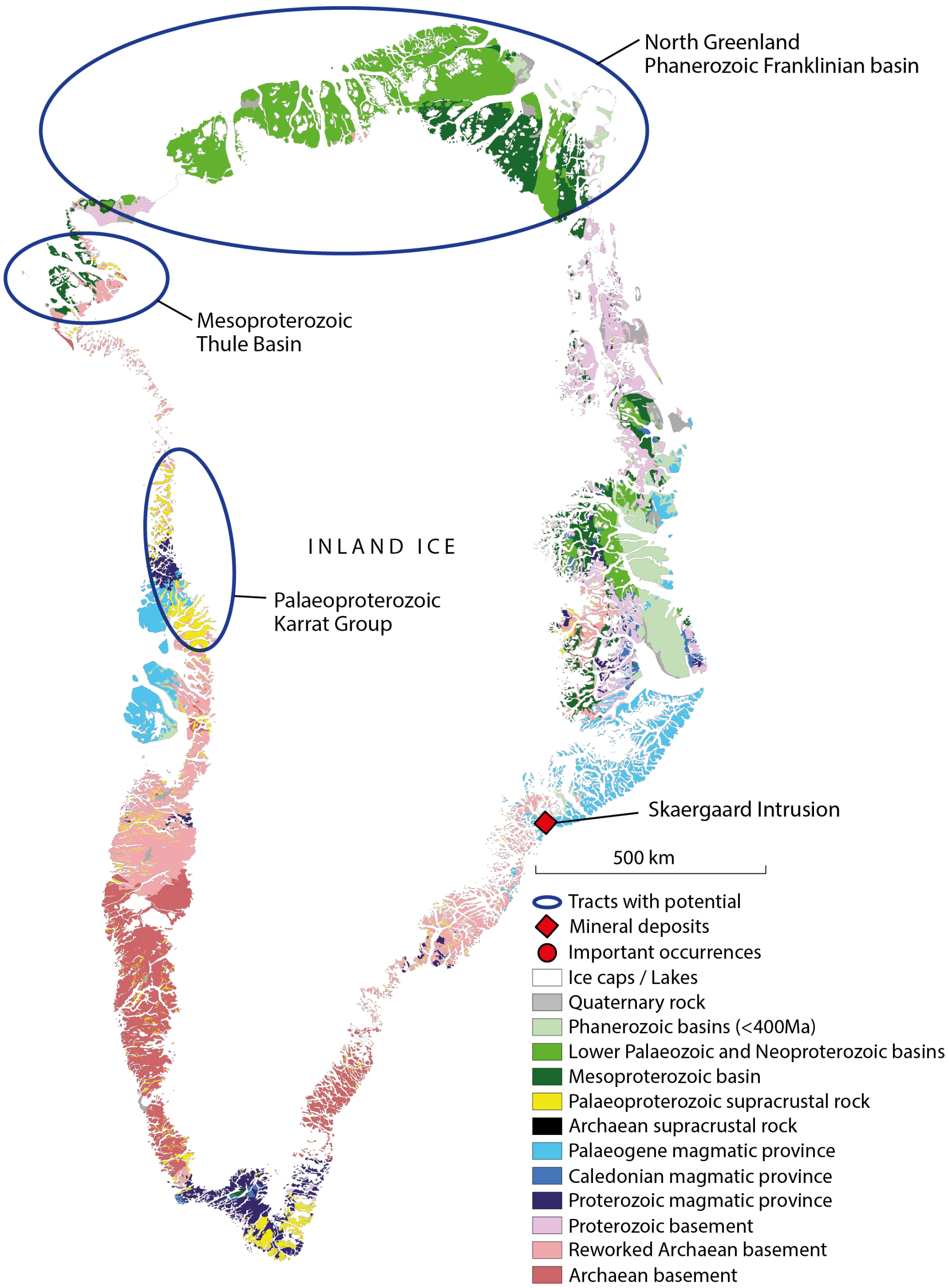

Figure 11 *Map of known gallium deposits and favourable tracts. Simplified geological map is based on 1:2 500 000 geological map by Henriksen et al. (2009).*

3.11 Germanium [Ge]

Table 13 *Overview of the commodity germanium.*

Main application	Germanium is used in fibre-optic systems ($GeCl_4$ (30 %), infra-red optics (GeMe) (25 %), polyethylene terephthalate (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 from 2009 to 2012, and only the electronic and photovoltaic sector experienced an increase in demand in the period, but at a slower pace than expected.
Annual production and leading producing countries	The annual production in 2021 was about 140 t of which China produced 68 %, Russia 4 % and other countries 28 % (USGS (2022); USGS did not publish production data for any country for year 2022).
Main mineral	Germanium is primarily extracted from sphalerite (ZnS) or from certain coal fly-ashes (mainly in China and Russia).
Resource/reserve	Melcher & Bucholz (2012) estimated the global germanium resources to be about 11,000 t from zinc ore and 2,000 t from coal mainly from Russia (49 %), China (30 %), DRC (11 %) and USA (7 %).
Known resources in Greenland	No known resources in Greenland.
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.

Known important germanium occurrences (Figure 12)

There are no deposits occurrences in Greenland, but Ge 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 (North Greenland) 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). Furthermore, Ge-rich chalcopyrite and briartite ($Cu_2(Zn,Fe)GeS_4$) inclusions in sphalerite have been identified in ores of the Black Angel deposit in central West Greenland (Horn *et al.* 2019).

Tracts with a germanium resource potential (Figure 12)

Mississippi Valley Type, central West, North-West and North Greenland

Besides samples from known MVT showings in North Greenland and the Black Angel deposit in central West 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 mineralisation was assessed and the Phanerozoic Franklinian basin in North Greenland and the Palaeoproterozoic Karrat Group in central West Greenland were regarded as 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. Another area that was identified as to hosting a potential for MVT mineralisation, although smaller potential than the areas mentioned above, is the Mesoproterozoic Thule Basin in North-West Greenland.

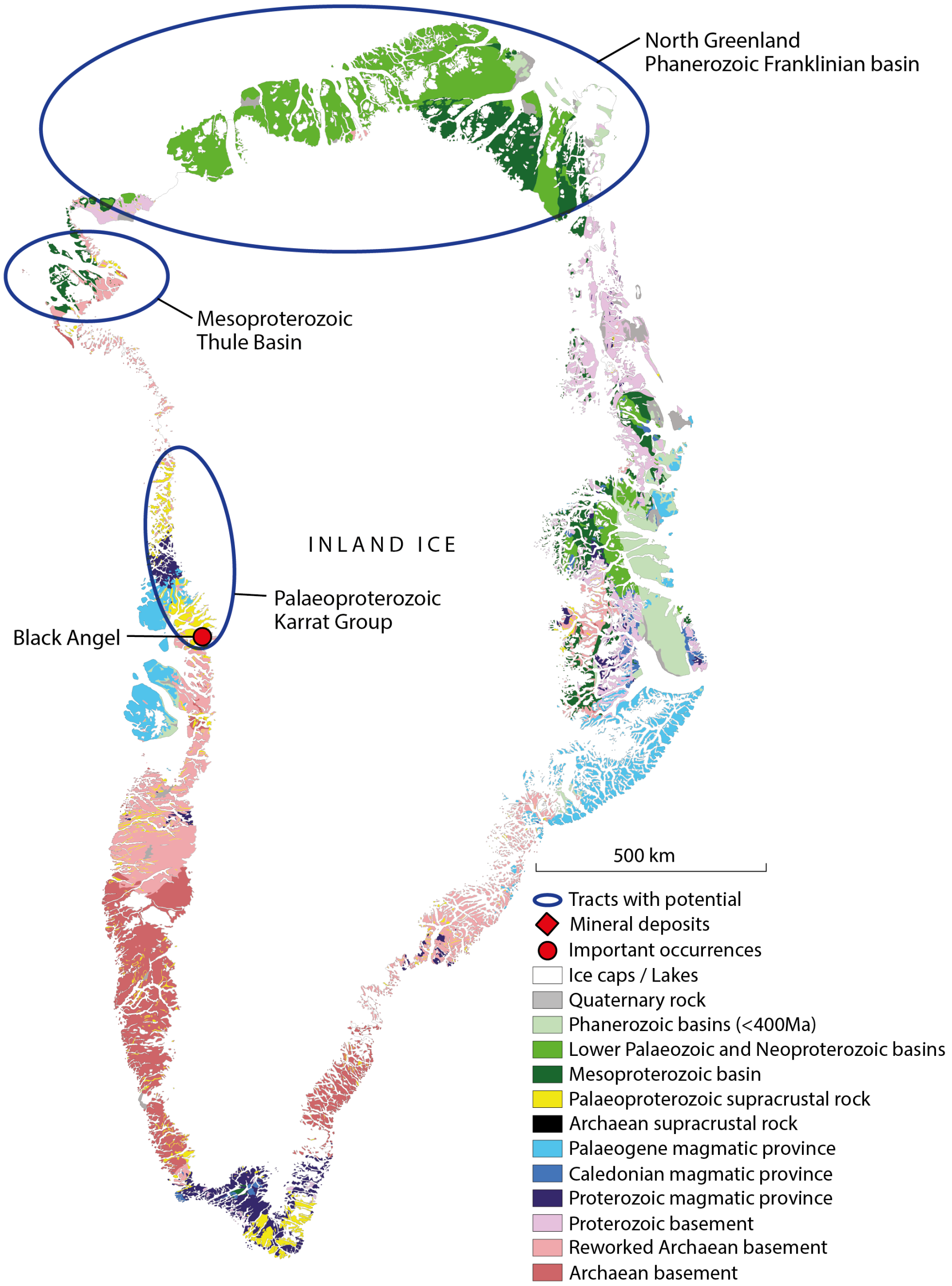

Figure 12 *Map of known significant germanium occurrences and favourable tracts. Simplified geological map is based on 1:2 500 000 geological map by Henriksen et al. (2009).*

3.12 Graphite [C]

Table 14 *Overview of the commodity graphite.*

Main application	The main applications 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 specialised 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). The deployment of electric vehicles and the development of energy storage systems is predicted to drive most of the growth of future natural graphite demand (European Commission 2020b).
Annual production and leading producing countries	Graphite is produced in many countries. USGS (2023) reports the 2022 global production as amounting to 1.3 Mt of which China produced 65 %, followed by Mozambique (13 %), Brazil (6.7 %), and South Korea (1.2 %).
Main mineral	The main mineral is graphite, composed of elemental carbon only. Three types of natural graphite are commercial products: flake, lump and chip, and amorphous graphite. It is the flake sized and carbon content that determine the price and end-use of the produced graphite concentrate. Cg is the unit for total carbon in graphite form; also referred to as graphitic carbon. Additionally, synthetic graphite is being marketed.
Resource/reserve	USGS (2023) reports resources of minimum 800 Mt, and 330 Mt of reserves of which 27 % are in Turkey, 22 % in Brazil, 16% in China, 7.9 % in Madagascar, and 7.6 % in Mozambique.
Known resources in Greenland	6 Mt.
Market constraints	The deployment of electric vehicles and the projected associated need for Li-ion batteries is forecasted to drive most of the future need for natural graphite, but graphite is expected to be also used in a broad spectrum of industries in the future. China is the dominant consumer and producer of battery grade graphite. The EU import reliance for natural graphite is 98 % (European Commission 2020b). 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 deposits and important occurrences (Figure 13)

Amîtsoq, South Greenland

Graphite hosted by graphitic schists embedded in strongly sheared cordierite-sillimanite-biotite gneisses occur at Amîtsoq (Bondam 1992a; Mosher 1995; Thrane & Kalvig 2018). 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 Amîtsoq graphite mine produced a total of 6,000 t graphite ore averaging 21 % Cg (graphitic carbon) during its operation from 1915–24. GreenRoc Mining Plc. published a significant maiden JORC resource of 23.05 Mt at an average grade of 20.41 %, giving a total contained graphite content of 4.7 Mt (GreenRoc Mining Plc. 2023).

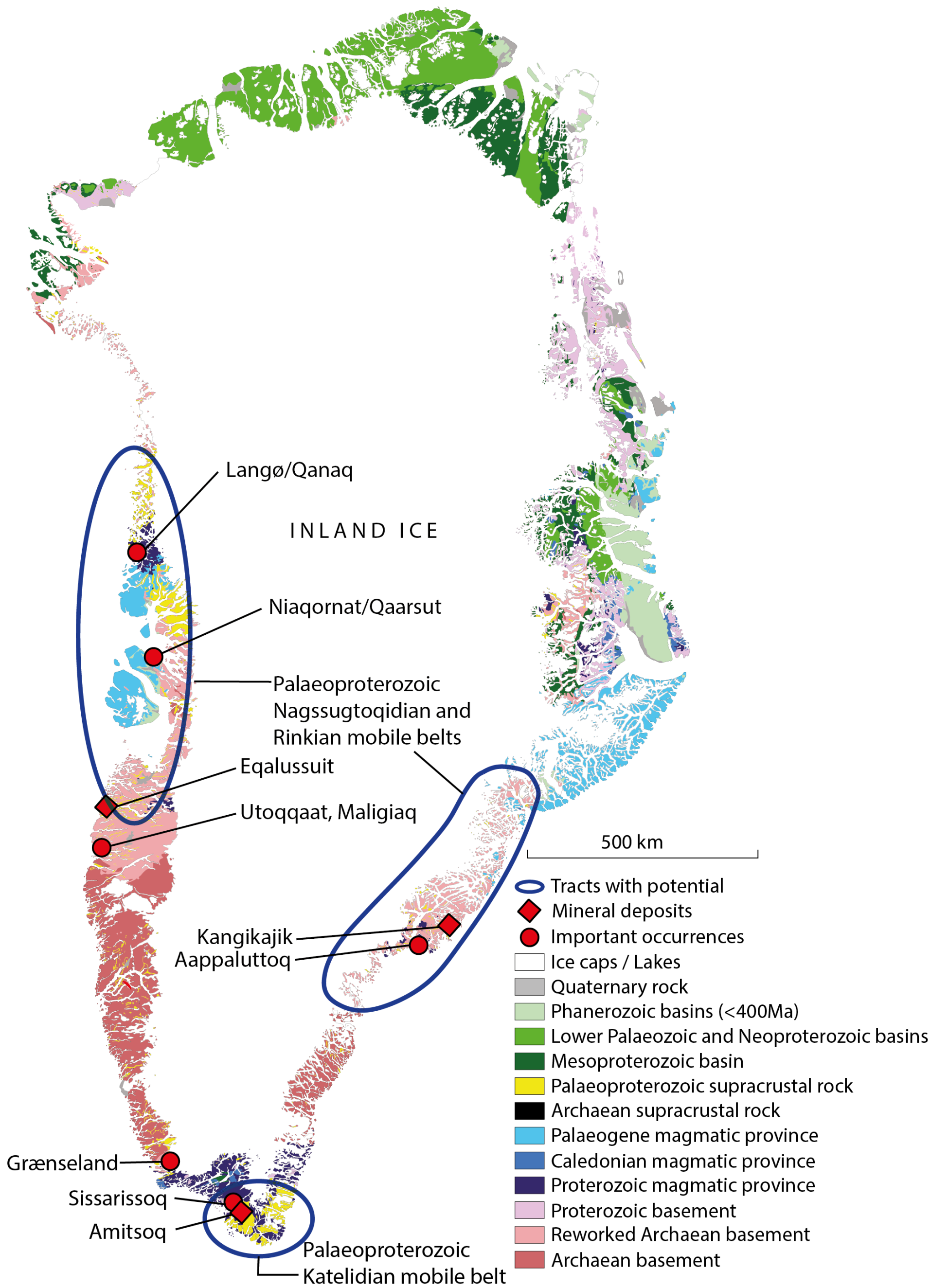

Figure 13 *Map of known graphite deposits, significant occurrences, and favourable tracts. Simplified geological map is based on 1:2 500 000 geological map by Henriksen et al. (2009).*

Eqalussuit/Akuliaruseq, southern 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 1992a; Thrane & Kalvig 2018).

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 Mt 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 Mt at a grade of 14.1 % Cg (Bondam 1992a), and finally Graphite Field Resources Ltd. estimated in 2016 a graphite resource of 12.6 Mt grading 6.3 wt% Cg including a high-grade zone encompassing 8.9 Mt grading 7.6 % Cg (Thrane & Kalvig 2018). None of the above stated resources are compliant with current international reporting standards.

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; Rosing-Schow *et al.* 2017). 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 t 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 (Rosing-Schow *et al.* 2017). 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 1992a).

Niaqornat and Qaarsut, central West Greenland

At Nuussuaq, central 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 100 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 mineralisation. 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 1992a).

Langø/Qanaq, Upernavik, North-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 19th century yielding high grade (Bondam 1992a; Kalvig 1994). However, samples are not documented to be representative, and the occurrence does not appear to have economic importance (Bondam 1992a).

Utoqqaat/Maligiaq, Sisimiut, southern West Greenland

At Utoqqaat, 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 t, 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).

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 t (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).

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 1992a; Kalvig 1994).

Tracts with resource potential for graphite (Figure 13)

Geologically the tracts described below are found in the geological environments of Palaeoproterozoic terranes.

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

The reworked, deformed, and metamorphosed Palaeoproterozoic Mobile Belts of Greenland can locally have relatively high abundance of carbonaceous material hosted in supracrustal rocks. This material, under appropriate metamorphic conditions, could have been transformed into graphite.

3.13 Hafnium [Hf] and Zirconium [Zr]

Table 14 *Overview of the commodity hafnium.*

Main application	Main uses of hafnium are in superalloys 60 %, plasma cutting 15 %, and nuclear rod manufacturing 10 %. Minor applications include catalysts, optical use, blue lasers, and semiconductors. Future uses: current main uses assumed to remain the most significant with nuclear and aerospace uses increasing. In addition, solar cells (CIGS), infra-red and fibre optics, thermoelectric materials, radiative cooling materials, and radiation oncology (European Commission 2020b).
Annual production and leading producing countries	There are no primary hafnium ores in the world, the metal being a by-product of zirconium production (European Commission 2020b). Refinery production of about 70 t; France 50 %, USA 44 %, China 3 %, Russia 3 %.
Main mineral	Production of Hf-free zirconium is the main source for Hf.
Resource/reserve	Estimates of global hafnium resources are not available (USGS 2023).
Known resources in Greenland	107,500 t
Market constraints	No data for supply, reserves or reserves; not traded publicly, and thus price trends and demands are not transparent.

Table 15 *Overview of the commodity zirconium.*

Main application	Main uses for zirconium are in ceramics, foundry sand, opacifiers, and refractories. Minor uses for zircon include abrasives, chemicals, metal alloys, and welding rod coatings. The leading consumers of zirconium metal are the chemical process and nuclear energy industries.
Annual production and leading producing countries	The annual production of zirconium ores and zircon concentrates in 2022 was about 1.4 Mt, of which Australia produced 36 % and South Africa 23% (USGS 2023).
Main mineral	Zircon, baddeleyite and eudialyte.
Resource/reserve	Global reserves are of 68 Mt ZrO_2 of which 71 % are in Australia, 8.7 % in South Africa, 3.8 % Senegal, and 2.6 % in Mozambique.
Known resources in Greenland	57.1 Mt
Market constraints	Zirconium sourced from eudialyte is not yet available in the market, which is therefore exclusively sourced from zircon.

Known hafnium/zirconium deposits (Figure 14)

Kringlerne/Killavaat Alunnguat, South Greenland

The Kringlerne/Killavaat Zr-REE-Nb deposit, situated about 8 km south of Narsaq and 20 km north-east of Qaqortoq, is hosted in the lower cumulates of the layered agpaitic nepheline 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 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, and 0.003 % HfO_2. The grade of HREE (including 16.6% Y) is reported to be 27.1 % (Schønwandt *et al.* 2016).

Motzfeldt, 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). A total inferred mineral resource of 340 Mt at 4,600 ppm ZrO_2, in addition to Nb, Ta and REO, has been defined by RAM Resources (2012).

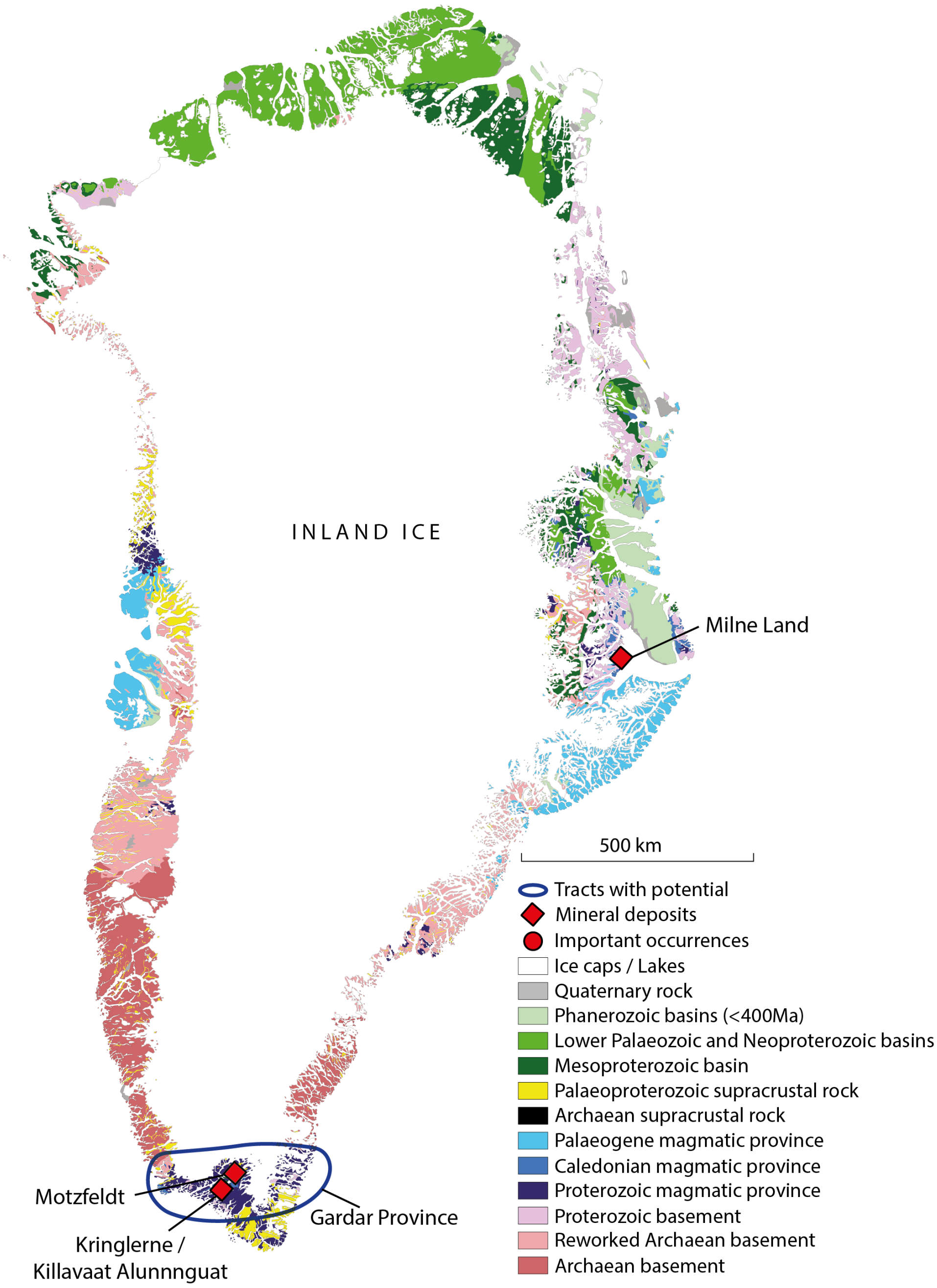

Figure 14 *Map of known hafnium and zirconium depositsand favourable tracts. Simplified geological map is based on 1:2 500 000 geological map by Henriksen et al. (2009)*

Milne Land, central East Greenland

The Mesozoic Milne Land palaeoplacer was discovered in 1968 by Nordisk Mineselskab A/S in connection with a heavy mineral concentrate sampling program, an airborne 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 (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. More recently, CGRG estimated a resource of 4 Mt grading 1–2 wt% of ZrO_2, in addition to REO and Ti (CGRG 2019).

Tracts with resource potential for hafnium/zirconium (Figure 14)

Gardar Province, South Greenland

The 1300–1140 Ma Gardar period involved continental rifting, sedimentation, and alkaline magmatism. Numerous dykes and 10 ring-shaped intrusion complexes were formed across South Greenland. Residual magmas and fluids resulting from extreme magmatic differentiation, possibly combined with assimilation of older crust, created mineral deposits including cryolite that was mined at Ivittuut, large low-grade deposits of uranium- rare earth elements- zinc at Kvanefjeld/Kuannersuit and tantalum-niobium-rare earth element-zirconium at Kringlerne/Killavaat Alanguat, in the Ilímaussaq complex, as well as tantalum-niobium-zirconium-rare earth elements at Motzfeldt in the Igaliko complex (Steenfelt *et al.* 2016).

Hafnium is a typical companion metal in zirconium minerals such as zircon and eudialyte. In the Gardar alkaline province, these minerals are common in the Kringlerne/Killavaat Alanguat and Motzfeldt deposits, and a considerable potential for these Hf bearing minerals is thought to exist in other evolved magmatic rocks of the Gardar Province.

3.14 Helium [He]

Table 16 *Overview of the commodity helium.*

Main application	Helium is best known for its use to fill decorative balloons, weather balloons and airships, applications in which its low density induces lift. However, this gas has many other important uses. It is used in cryogenics, ie as a cooling medium for the superconducting magnets in magnetic resonance imaging (MRI) scanners and in nuclear magnetic resonance (NMR) spectrometers, as well in aerospace. Because of its very unreactive nature, helium is also used to provide an inert protective atmosphere for fibre optics and semiconductor manufacturing, and for arc welding. Helium is also used to detect leaks in a variety of industrial settings.
Annual production and leading producing countries	Total production in 2022 amounted to about 160 million m^3, dominated by the USA (47%), Qatar (38%) and Algeria (5.6 %) (USGS 2023).
Main mineral	Helium is not sourced from a mineral. Instead, it has traditionally been produced as a by-product of natural gas processing. Significant stockpiles were built up during the cold war in the USA, which have in the meantime been significantly drawn down.
Resource/reserve	Global resources are of approximately 40,000 million m^3 (USGS 2022).
Known resources in Greenland	No known resources in Greenland.
Market constraints	Due to its unique properties, helium cannot be substituted in many applications, namely in cryogenics, but could potentially be replaced by argon in welding. Efforts are being made to promote its recycling. A major issue is the fact that helium is a by-product of natural gas, whose production is expected to decrease due to decarbonization targets set by many countries and industries. As a result, an opportunity emerges for the production of primary, rather than secondary, helium.

Known helium occurrences (Figure 15)

Tunu hot springs, central East Greenland
The company Skyfire Ltd (subsequently Pulsar Helium Inc.) was granted a mineral prospecting licence and a mineral exploration licence to explore helium and hydrogen in Liverpool Land. Two of the many hot springs in the area were sampled and helium concentrations in the gas fractions of up to 0.8 % were identified (Pulsar Helium, 2023).

Uunartoq hot springs, South Greenland
Total helium concentrations over 2 % are known in the gas fraction from the Uunartoq island hot springs in South Greenland (Persoz *et al.* 1972). These values of He concentration were confirmed by new analyses of samples collected by GEUS in June 2013 from the same hot springs. These concentrations are likely related to radioactive decay of Mesoproterozoic Gardar magmatic rocks, from which helium ascends, together with geothermal fluids, along faults.

Tracts with resource potential for helium (Figure 15)

Liverpool Land, central East Greenland
According to Pulsar Helium Inc., Liverpool Land has both favourable helium source rocks (old and radioactive basement) and a deep heat source (the Jan Mayen and Iceland mantle plumes) which can induce the liberation of helium from the source rocks and, potentially, lead to the formation of primary helium accumulations. Further sampling of gas seepages and the imaging of possible helium-trapping structures using airborne geophysical data acquisition is planned (Pulsar Helium, 2023).

Gardar Province, South Greenland

The 1300–1140 Ma Gardar period involved continental rifting, sedimentation, and alkaline magmatism. As a result of the extreme magmatic differentiation of the latter, radioactive elements have built up in residual magmas and fluids. Radioactive decay generates helium, which has only been identified in the Uunartoq hot springs so far. However, helium is rather inconspicuous and has not routinely been analysed for. Therefore, the possibility remains that helium occurs in other springs, throughout the province and has been overlooked to date. Helium could also have even been trapped in favourable structures resulting in primary accumulations.

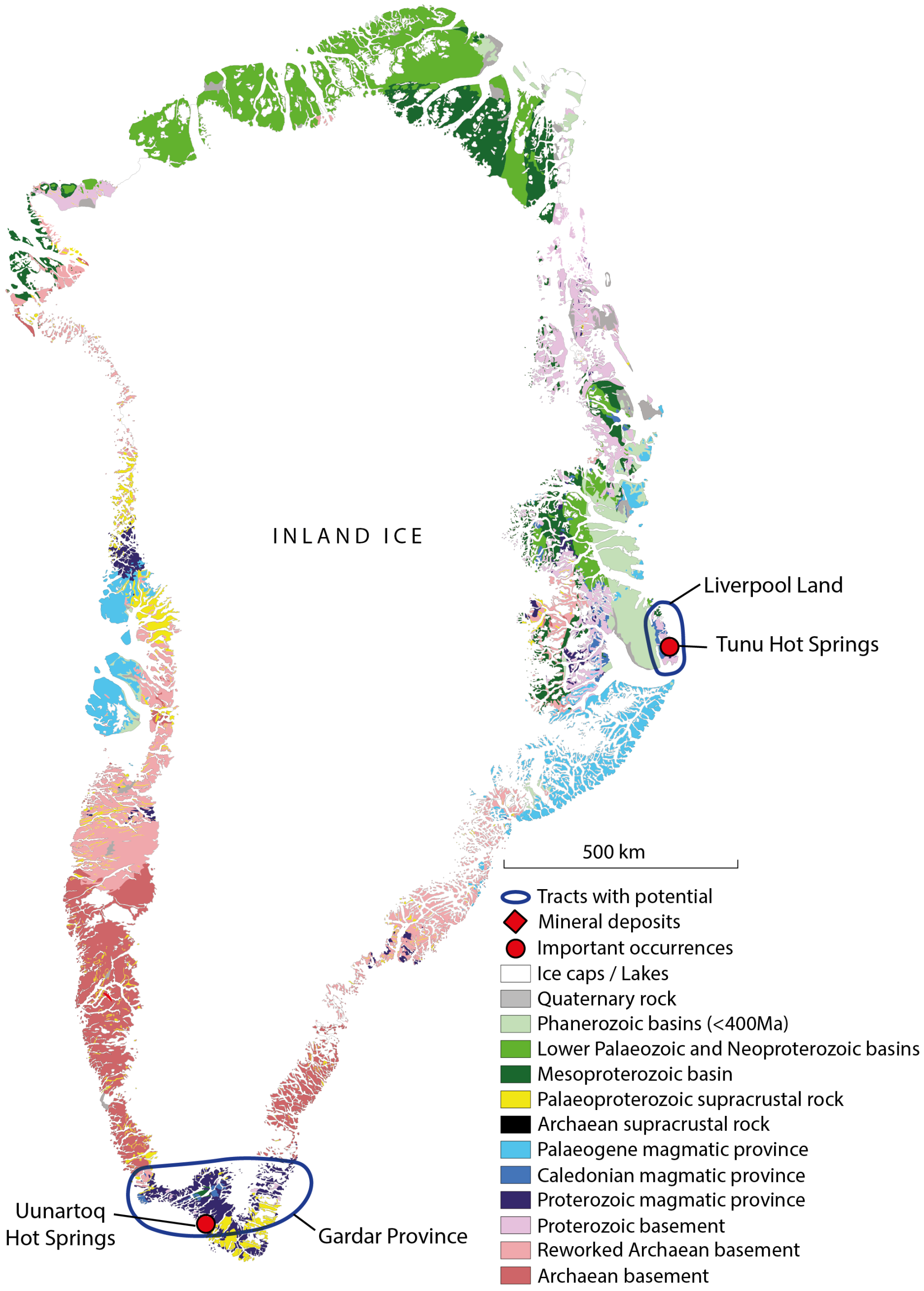

Figure 15 *Map of known helium occurrences and favourable tracts. Simplified geological map is based on 1:2 500 000 geological map by Henriksen et al. (2009).*

3.15 Lithium [Li]

Table 17 *Overview of the commodity lithium.*

Main application	Main use is in Li batteries, followed by application in the ceramics and glass industries.
Annual production and leading producing countries	According to the USGS (2023), global production, was about 130,000 t, dominated by Australia (47 %), Chile (30 %), China (15 %), and Argentina (4.8 %).
Main mineral	Lithium is extracted from petalite, amblygonite, lepidolite and spodumene recovered from hard rock mining operations in Australia, Brazil, China, and Portugal, and from brines in Argentina, Chile and China (USGS 2022, Tan & Keiding in press).
Resource/reserve	Global reserves are of 26 Mt, with Chile accounting for 36 %, Australia 24 %, Argentina 10 %, and China 7.7% (USGS 2023).
Known resources in Greenland	235,000 t
Market constraints	Substitution possible in most applications. The need to secure supply security for the expanding battery applications, namely for electric vehicles, has led manufacturers to establish partnership with exploration and mining companies, leading to many projects in various stages of development worldwide.

Known important lithium deposits (Figure 16)

Greenland is not considered to hold a significant potential for lithium in brines which account for about 45 % of the global lithium production (Tan & Keiding in press). Therefore, the occurrences and tracts discussed reflect only a potential for the recovery of lithium from hard-rock sources, related to igneous rocks and processes.

Kvanefjeld/Kuannersuit, South Greenland

Lithium is found dispersed but enriched (900–1900 ppm Li; Kunzendorf *et al.* 1982) in the fine-grained groundmass minerals (especially in arfvedsonite, but also in other ground-mass minerals) of the naujakasite and arfvedsonite lujavrite rocks (agpaitic nepheline syenites) which make up the most of the Kvanefjeld/Kuannersuit intrusion and the Kvanefjeld/Kuannersuit REE-U-Zn-F deposit. Kunzendorf *et al*. (1982) provide a geological resource estimate of lithium for the Kvanefjeld/Kuannersuit deposit based on 600 samples from 7 drill cores from drilling conducted in 1977. The estimated lithium resource based on the limited number of drill holes was 235,000 t Li (grade being 0.19 % Li) (non-compliant resource according to international reporting standards).

Tracts with resource potential for lithium (Figure 16)

Gardar Province, South Greenland

The 1300–1140 Ma Gardar period involved continental rifting, sedimentation, and alkaline magmatism. Numerous dykes and 10 ring-shaped intrusion complexes were formed across South Greenland. Residual magmas and fluids resulting from extreme magmatic differentiation, possibly combined with assimilation of older crust, created mineral deposits including cryolite that was

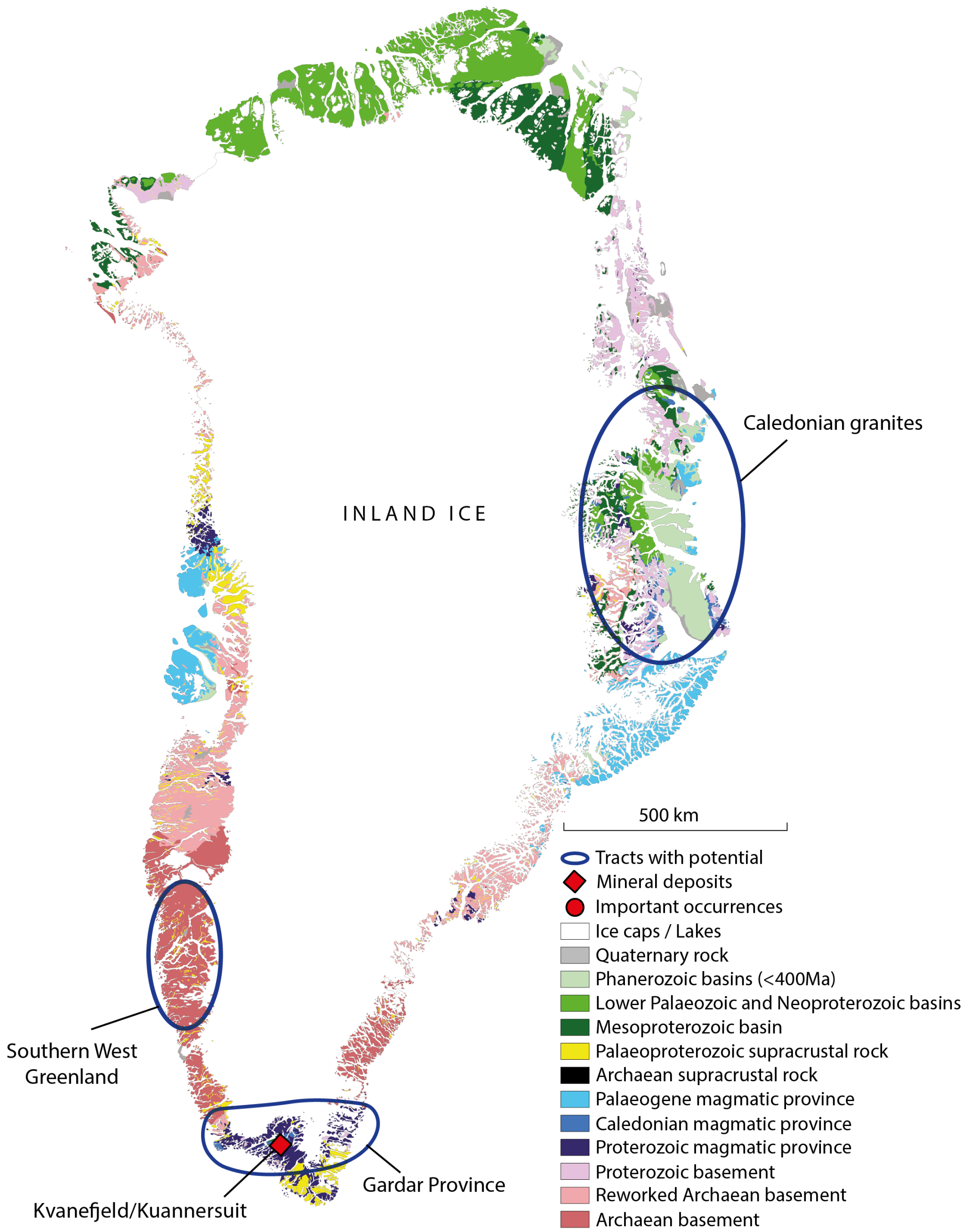

Figure 16 *Map of known lithium deposits and favourable tracts. Simplified geological map is based on 1:2 500 000 geological map by Henriksen et al. (2009).*

mined at Ivittuut, large low-grade deposits of uranium-rare earth elements-zinc-fluorine-lithium at Kvanefjeld/Kuannersuit and tantalum-niobium-rare earth element-zirconium at Kringlerne/Killavaat Alannguat, in the Ilímaussaq complex, as well as tantalum-niobium-rare earth elements at Motzfeldt in the Igaliko complex (Steenfelt *et al.* 2016).

Southern West Greenland

Pegmatites have been described in multiphase highly deformed and highly metamorphosed terranes in the Nuuk region, which might be a target for lithium in lepidolite or spodumene. Steenfelt *et al*. (2007a) provide an overview of pegmatite occurrences in Greenland and their mineral potential.

Caledonian granites, central East and North-East Greenland

Caledonian S-type granites and granodiorites and associated pegmatites and hydrothermal veins hold a potential for lithium (and commonly associated metals such as tin, tungsten, bismuth, and molybdenum).

3.16 Molybdenum [Mo]

Table 18 *Overview of the commodity molybdenum.*

Main application	Most molybdenum is used to make alloys. It is used in steel alloys to increase strength, hardness, electrical conductivity and resistance to corrosion and wear. These 'moly steel' alloys are used in parts of engines. Other alloys are used in heating elements, drills and saw blades.
Annual production and leading producing countries	Annual production in 2022 was 250,000 t and the main producing countries were China (40 %), Chile (18%), USA (17 %), Peru (13 %), and Mexico 6.4 %) (USGS 2023).
Main mineral	Molybdenite (MoS_2)
Resource/reserve	Global identified resources of molybdenum are about 20 Mt and 12 Mt reserves with China accounting for 31 %, United States for 23 %, Peru for 20 %, and Chile for 11.7 % (USGS 2023).
Known resources in Greenland	324,000 t
Market constraints	Molybdenum occurs as the principal metal sulphide in large low-grade porphyry molybdenum deposits and as an associated metal sulphide in low-grade porphyry copper deposits. Resources of molybdenum are considered adequate to supply foreseeable world needs (USGS 2022).

Known molybdenum deposits and important occurrences (Figure 17)

Malmbjerg, central East Greenland

Malmberg is a Climax-type molybdenum-porphyry related to a Palaeogene (Brooks *et al.* 2004) composite alkali granite intrusion (Schønwandt 1988). The deposit is dome shaped with an outside diameter of up to 600 m and a height of approximately 150 m, and extensive hydrothermal altered. The resource estimate prepared for the present licence holder is 315 Mt of measured and indicated resources at 0.18 % MoS_2, with a 0.08 % MoS_2 cut-off (Greenland Resources 2022). It is anticipated that the deposit will be mined through an open pit, and ore will be transported via a ropeway aerial conveyor to a 35,000 t/d mill located approx. 20 km to the NE, where ore will be ground and floated.

Kap Simpson, North-East Greenland

The Palaeogene Kap Simpson complex on Traill Ø hosts a caldera structure with related igneous rocks and widespread alteration. Traces of molybdenum occur in fluorite veins and as scattered grains of molybdenite in quartz veins and disseminated in granite. The ore minerals are molybdenite, pyrite and the gangue minerals quartz and fluorite.

The older investigations of the Kap Simpson intrusive were general exploration, mainly for vein-type deposits, whereas the later investigations evaluated the potential for large Mo-type deposits. An extensive summary is given in Harpøth *et al.* (1986). Apart from local high concentrations of molybdenum in fluorite veins (up to 645 ppm Mo), no significant molybdenum mineralisation has been identified in exposures.

Flammefjeld, southern East Greenland

Flammefjeld is situated in the Kangerdlugssuaq alkaline intrusion near its contact with Precambrian gneisses. This 39.6 Ma subvolcanic complex consists of breccias, quartz-feldspar porphyries, and aplites (Geyti & Thomassen 1984, Brooks *et al.* 2004). These units are collectively referred to as the Flammefjeld igneous complex. The complex, which is hosted in syenite, has an oval shape with the dimensions 500 × 800 m and molybdenite is found mainly in the intrusive breccias where it forms typical stockwork (Climax-type Mo mineralisation). Molybdenite mineralisation is restricted to fragments of granitic rocks, quartz-feldspar porphyry, and granophyre. Analyses of ten samples of molybdenite mineralised breccia fragments show ranges of 390 to 4,100 ppm Mo, 3 to 49 ppm W, <10 ppm Sn, and 250 to 1,200 ppm F (Geyti & Thomassen 1984).

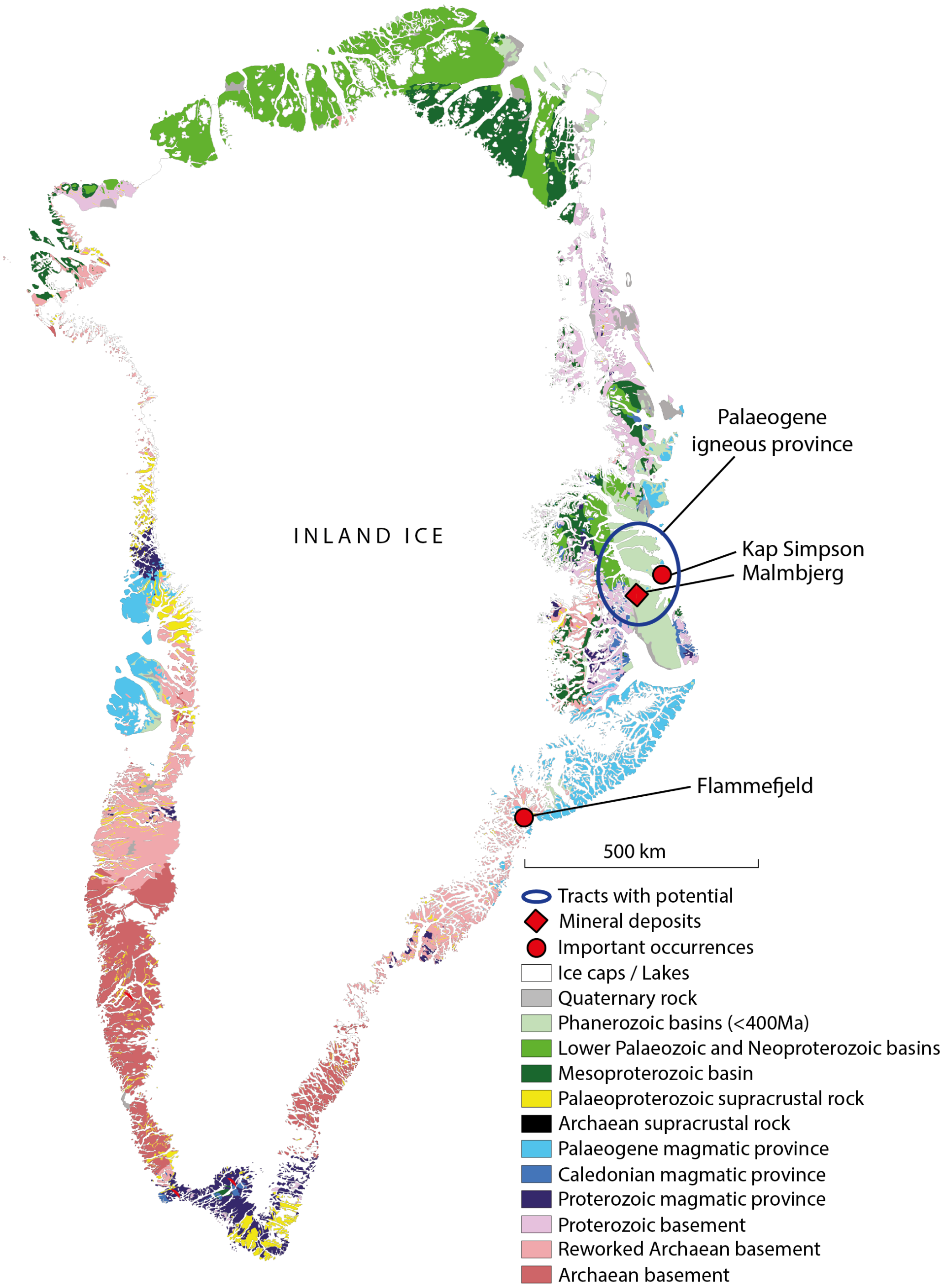

Figure 17 *Map of known molybdenum deposits, significant occurrences, and favourable tracts. Simplified geological map is based on 1:2 500 000 geological map by Henriksen et al. (2009).*

Tracts with resource potential for molybdenum (Figure 17)

Mestersvig Palaeogene Igneous Province

The best tract for molybdenum is the Palaeogene igneous province of the Mestersvig area in central East Greenland, which constitutes a prominent NE-SW trending line of plutonic-sub-volcanic centres traceable for approximately 125 km from the Werner Bjerge complex in the SW to Kap Parry in the NE (Rex *et al.* 1979; Schønwandt 1988).

3.17 Nickel [Ni]

Table 19 *Overview of the commodity nickel.*

Main application	Nickel is a crucial component of stainless steel which accounts for more than 65 % of the total Ni consumption. Other important applications include batteries, superalloys, non-ferrous alloys, coating, catalysts, and foundry products. Nickel is a key component for the production of batteries for electric vehicles (EVs) and renewable energy storage systems, both technologies that are key to the green transition.
Annual production and leading producing countries	Global mine production is 3.3 Mt, with leading countries being Indonesia 48.5 %, Philippines 10 %, Russia 6.7 %, New Caledonia 5.8 %, Australia 4.8 %, Canada 3.9 %, China 3.3 %, Brazil 2.5 % (USGS 2023).
Main mineral	Nickel is mainly extracted from two different types of ore deposits: (1) ortho-magmatic sulphide mineralizations and (2) laterites. The most important ore mineral in the magmatic deposit is pentlandite $(Ni,Fe)_9S_8$. The principal Ni ore minerals in laterites are garnierite $(Ni,Mg)_3Si_2O_5(OH)$ and nickeliferous limonite (Fe,Ni)O(OH).
Resource/reserve	Known resources are more than 100 Mt, with Australia accounting for 21%, Indonesia for 21 %, Brazil for 16 %, Russia for 7.5 %, and New Caledonia for 7.1 %, and Philippines for 4.8 % (USGS 2023).
Known resources in Greenland	No known resources in Greenland. 'Undiscovered resources' at a regional scale has been estimated by Rosa *et al.* (2013) to 3,800 Mt.
Market constraints	Nickel is mined, from sulphide or laterite ores, in more than 25 countries. But Indonesia has contributed significantly to recent production growth, achieved through Chinese investment in mines, processing plants and buyer agreements. As a result, even if is a relatively modest domestic production, China dominates the market.

Important nickel occurrences (Figure 18)

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.

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 mineralised semi-massive to massive sulphide samples typically grade 3-7 wt% Ni, 0.1-6.3 wt% Cu, 0.1-0.2 wt% Co and up to 0.3 ppm

Pt+Pd+Au (North American Nickel Inc. 2017; 2022). 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. North American Nickel Inc. conducted an exploration program between 2011 and 2019 including a comprehensive drilling campaign and helicopter borne TEM and magnetic surveys were carried out. This expanded the footprint of the historic mineral occurrence at the Imiak Hill Complex and Fossilik and in addition resulted in the discovery of several new occurrences of mineralised norite and identified new conductive bodies at depth. Assays highlights include 24.75 m @ 3.19 % Ni and 1.14 % Cu (North American Nickel Inc. 2022), no resource estimates have been attempted for the targets at the Maniitsoq prospect.

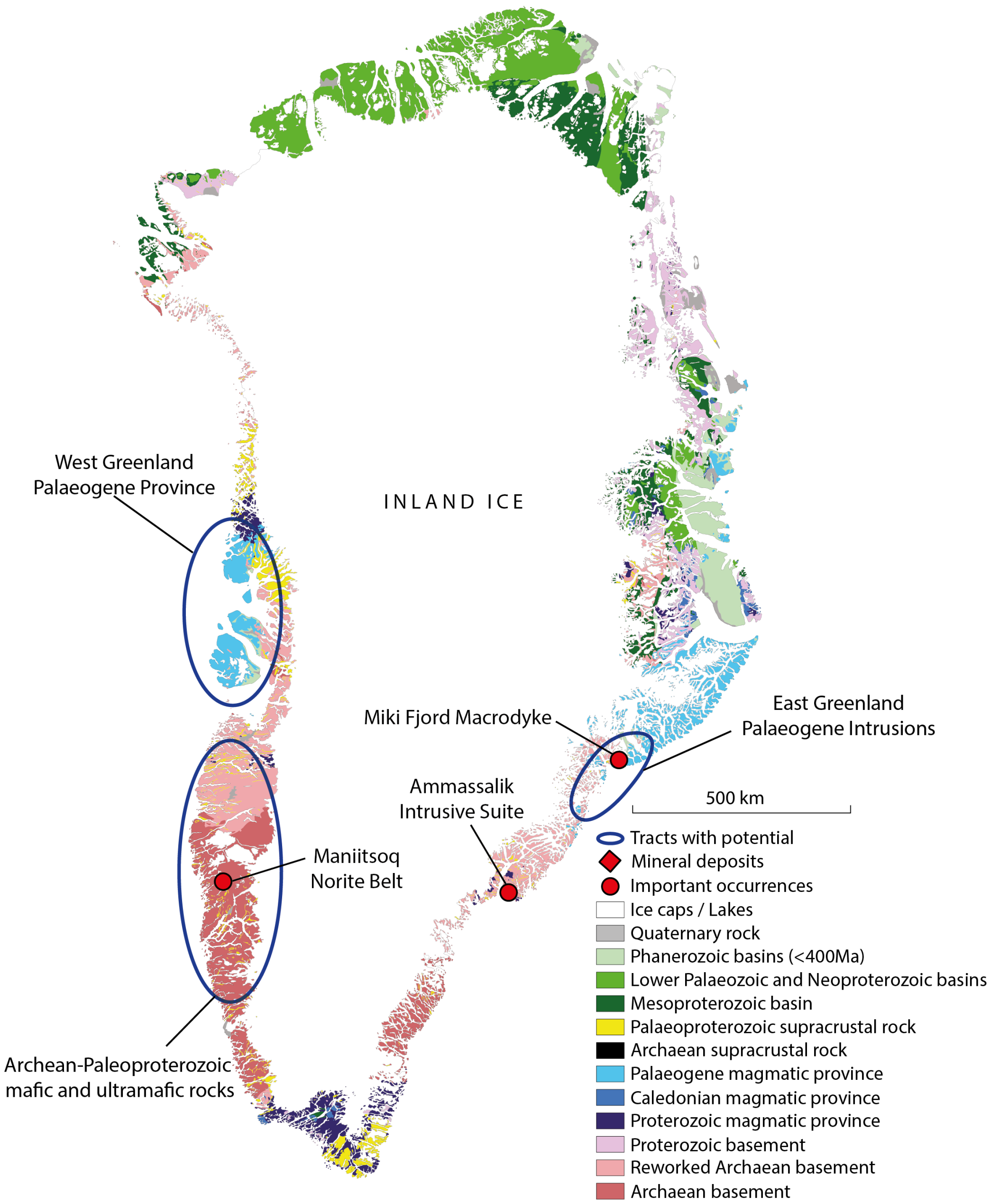

Figure 18 *Map of known significant nickel occurrences, and favourable tracts. Simplified geological map is based on 1:2 500 000 geological map by Henriksen et al. (2009).*

Miki Fjord Macrodyke, East Greenland

This occurrence, situated approximately 2 km northeast of the Skaergaard intrusion, has Cu-Ni-PGE-Au mineralization at its margins (Holwell *et al.* 2012) with grades up to 3.3 ppm Pd, 0.16 ppm Au, 2.2 % Cu, and 0.8 % Ni in hand specimen (Kolb *et al.* 2016). Diamond drilling did not test the mineralization, but geophysical investigations indicate possible mineralization targets at depth (Andersen 1997).

Tracts with resource potential for nickel (Figure 18)

The nickel potential in Greenland is related to mafic to ultramafic magmatism, which can be associated with komatiite-hosted occurrences, contact-type occurrences and conduit-type occurrences related to picritic and/or tholeiitic basalt dyke/sill complexes (Rosa et al. 2013).

Rosa et al. (2013) conducted an assessment to quantify the undiscovered Ni resources in Greenland using statistical simulation based on assumption about global tonnage/grade models worldwide for Ni mineralisation and their probability in Greenland. The findings indicated that undiscovered Ni resources are approximately 1.9 Mt with greatest potential for conduit-type deposits.

Tracts with potential for nickel extend from the Archean to the Palaeogene and in total 17 Nickel tracts were defined by Rosa et al. (2013). Below the most important tracts are described and for simplicity some tracts have been merged. The interested reader is referred to Rosa et al. (2013) for more detailed review of Greenlandic nickel tracts.

Archean-Paleoproterozoic mafic and ultramafic rocks, South-West Greenland

Traces of nickel accumulations are numerous in in the Archaean and the Palaeoproterozoic reworked parts of West Greenland, particularly mafic-ultramafic rock units host a potential for nickel mineralisation as well as PGE and Cr. Areas of interest include the Maniitsoq Norite belt, the Archean Fiskefjord intrusion, Sillisissanguit Nunaat, Kakilisatooq and finally the Nassutooq-Arfersiorfik area, which could be a continuation of the ‘nickel belt’ in Canada.

West Greenland Palaeogene Province, central West Greenland

The Disko Island, part of the Palaeogene West Greenland Province holds a significant potential for conduit-type nickel mineralisation related to picrite and/or tholeiitic basalt dyke-sill complexes. The volcanic succession in the northern part of the West Greenland Palaeogene Province on the Svartenhuk Halvø and the areas north and northeast of this, are generally correlatable with the southern part of the province (Larsen & Larsen 2022) and low contents of V, Cu and Ni in some crustally contaminated lavas could indicate that these elements and accompanying PGM could be present at depth (Larsen & Larsen 2022). The Disko-Nuussuaq region favours a Norilsk style deposits (Lightfoot & Hawkesworth, 1997).

Sulphide-enriched basalt (together with metallic iron as cumulate) carry at least 1 % Ni and shows elevated PGM contents of up to 0.5 ppm. At Illukunnguaq, a sediment-contaminated, sulphide-rich dyke has a 28 t lump of sulphide ore, which was dug out in 1931 and several times since then the occurrence has been explored. Massive sulfide ore from this dyke contains 6.86 wt% Ni, 0.55 wt% Co, 3.71 wt% Cu and 2 ppm PGE (Olshefsky, 1992) and values of up to 10.3 wt% Ni are reported from hand specimen (Pauly, 1958). Magmatic pyrrhotite, pentlandite, chalcopyrite and native iron are also found in the Hammer Dal Complex on northwest Disko.

The West Greenland Paleogene Province has been explored almost continuously from the 1960s for Ni, Cu, Co and PGM, for further details see Kolb *et al.* (2016). Ongoing exploration is carried out by Nikkeli A/S, a joint venture company of Bluejay Mining plc and KoBold Metals, which is holding about 3000 km^2 of licenses at Disko and Nuussuaq, and by American Exploration Overseas Holdings Ltd. (Anglo American) which was granted five-year exploration licenses in 2019 at Disko, Nuussuaq, and at the Svartenhuk peninsular.

Palaeogene intrusions, East Greenland

More than 60 intrusions are recorded in the Palaeogene East Greenland volcanic rifted margin which is part of the North Atlantic Igneous Province (NAIP) that was formed during prolonged magmatism from 63 Ma to 13 Ma (Tegner *et al.* 1998; Larsen *et al.* 2014). Although felsic intrusions constitute an important component, mafic to ultramafic intrusions are most dominant. However, these intrusions have not been thoroughly explored for their mineral potential due to the remote and often inaccessible locations. The Kangerlussuaq area, where nearly half of the intrusions are located, has been interpreted as the track of the proto-Icelandic mantle plume (Brooks 1973; White & McKenzie 1989), and is endowed with orthomagmatic PGE Au mineralisation including the Skaergaard and Kap Edvard Holm intrusions. Nickel accumulations have so far only been reported only from the Miki Fjord macrodyke but the potential for other of the intrusive rocks being mineralised with Ni is considered significant.

3.18 Niobium [Nb] and Tantalum [Ta]

Table 20 *Overview of the commodity niobium.*

Main application	Niobium is mainly used as a steel alloy for the construction industry, the automotive industry, and the oil and gas industry.
Annual production and leading producing countries	The world production of niobium in 2022 was about 79,000 t. The production is mainly controlled by Brazil (90 %) and Canada (8.2 %) (USGS 2023).
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 ($(Fe,Mn)(Nb,Ta)_2O_6$) and pyrochlore ((Na,Ca)2Nb2O6(OH,F)) are the main source of niobium, though e.g. lueshite ($NaNbO_3$) and euxenite ($Y(Ti,Nb)_2(O,OH)_6$) also have high contents of niobium.
Resource/reserve	Brazil and Canada hold the vast majority of the known niobium reserves, estimated to >17 Mt, of which about 94 % are located in Brazil (USGS 2023).
Known resources in Greenland	5.9 Mt
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 %.

Table 21 *Overview of the commodity tantalum.*

Main application	Capacitors, sputtering targets, superalloys are major uses, while carbides, medical products, and chemicals are minor uses.
Annual production and leading producing countries	Global mine production, dominated by artisanal mining: 2,000 t Ta, with DRC 43 %, Brazil 19 %, Rwanda 18 %, Nigeria 5.5 %, and China 2.2 % (USGS 2023).
Main mineral	Columbite-tantalite, also known as columbotantalite or coltan is a mixture mixture of two minerals: columbite ($(Fe,Mn)(Nb,Ta)_2O_6$)and tantalite ($(Fe,Mn)Ta_2O_6$).
Resource/reserve	Identified world resources of tantalum, most of which are in Australia, Brazil, and Canada, are considered adequate to supply projected needs (USGS 2022).
Known resources in Greenland	916,000 t
Market constraints	Since the late 1990s the market has shown much instability and volatility and for the supply risk, much uncertainty is related to the confidence of trade in Central Africa (European Commission 2020b). Tantalum is considered a 'conflict mineral' together with tin, tungsten, and gold (often collectively referred to as 3TG). In 2021, EU implemented legislation that dictates a system of supply chain due diligence self-certification for European importers in order to curtail opportunities for armed groups and unlawful security forces to trade 3TG.

Known niobium and tantalum deposits and important occurrences (Figure 19)

Motzfeldt, 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 of the Motzfeldt 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 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 indicated a mineralised rock volume of more than 500 Mt averaging 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, this estimated resource 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). More recently, a total inferred mineral resource of 340 Mt at 120 ppm Ta_2O_5 and 1850 ppm Nb_2O_5, in addition to REO and Zr, has been defined by RAM Resources (2012).

The metals occur mainly in pyrochlore (Nb, Ta, U, REE), thorite (Th), zircon (Zr) bastnaesite (REE, Th) and monazite (REE) (Thomassen 1988, 1989; Lewis *et al.* 2012). Minor sulphide mineralisation is associated with fault zones and Thomassen (1988) mentions additional potential for Be (up to 797 ppm), Li (up to 1810 ppm) and Mo (up to 202 ppm) (Steenfelt *et al.* 2016; Stensgaard *et al.* 2016).

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 and peralkaline. The alkaline rocks evolved towards Si-rich melts such as comendites and alkali granites, and towards Si-poor melts such as phonolites and nepheline syenites (Bailey *et al.* 2001). The alkaline Ilímaussaq intrusion is one of the later intrusions (1.160 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; Kvanefjeld/Kuannersuit (dominated by lujavrites) and Kringlerne/Killavaat Alannguat (dominated by the kakortokite bottom cumulates).

The Kringlerne/Killavaat Alannguat Zr-REE-Nb deposit, situated about 8 km south of Narsaq and 20 km north-east of Qaqortoq, is hosted in the lower cumulates of the layered agpaitic nepheline 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 kakortokite'); 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 0.03 % Ta_2O_5 and HfO_2 (Tanbreez 2022). The ratio of LREE: HREE is reported to be about 2:1. The company was granted preliminary exploitation license in 2012 and a 30-year exploitation license is pending government approval of IBA and mining plan.

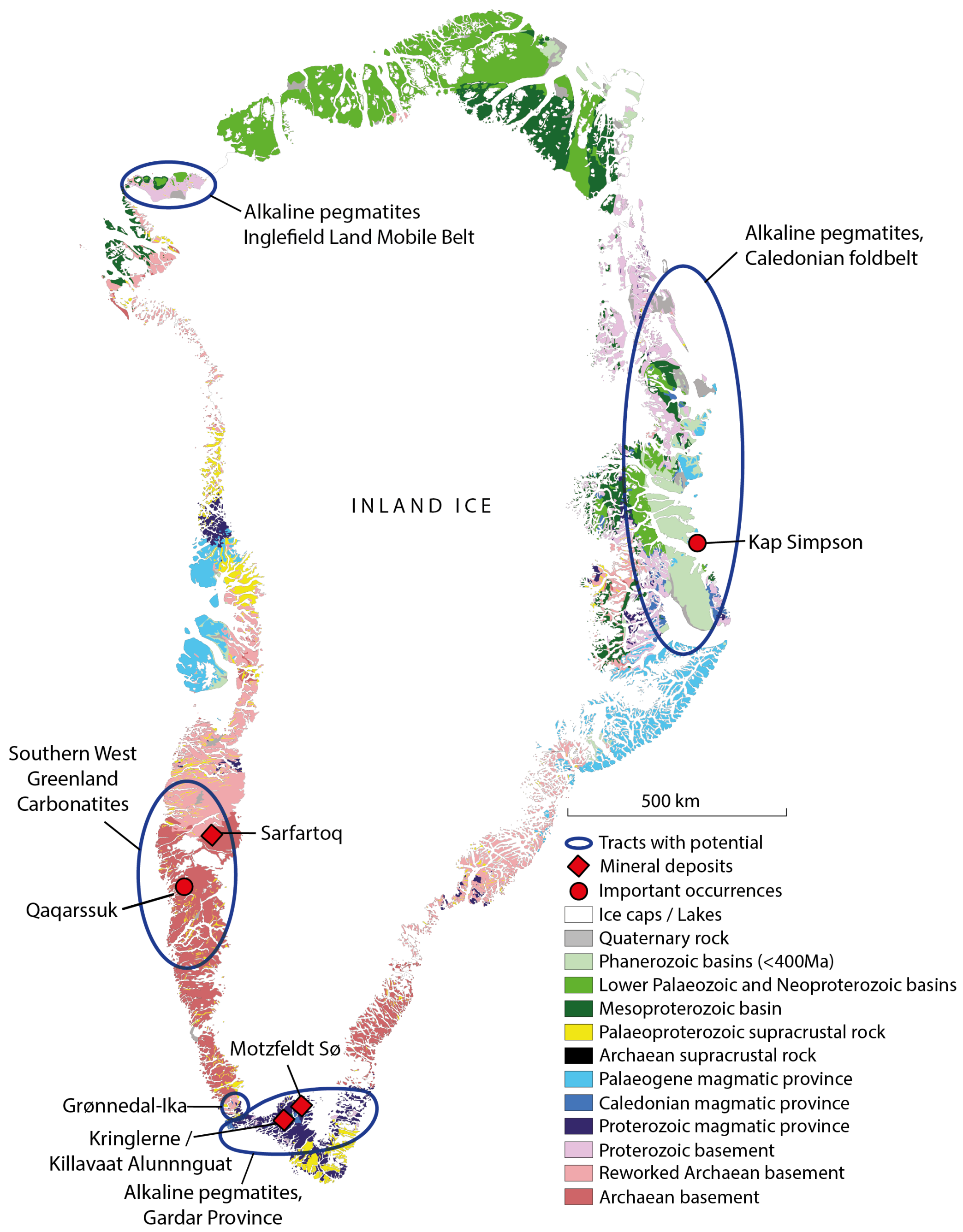

Figure 19 *Map of known niobium and tantalum deposits, significant occurrences, and favourable tracts. Simplified geological map is based on 1:2 500 000 geological map by Henriksen et al. (2009).*

Sarfartoq carbonatite complex, southern 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, 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 t 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 (Secher 1987).

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 reported a measured resource at 35,000 t at 10.6 % Nb_2O_5, within 186,000 t at 4.6 % Nb_2O_5 in the indicated category (Van der Meer 2000). The inferred resources to a depth of 90 m were subsequently estimated at 64,301 t at 3.89 wt% Nb (5.56 wt% Nb_2O_5) at a cut-off grade of 1.0 wt% Nb (Woodbury 2003; Stendal *et al.* 2004; Kolb *et al.* 2016).

Qeqertaasaq/Qaqarssuk carbonatite complex, southern West Greenland

This 166 Ma old carbonatite complex was emplaced into Archaean basement in at least two stages, concomitantly with extensive alteration of the wall rock. The main stage carbonatites consist of olivine søvite, søvite and dolomite carbonatite ring-dykes, whereas the late-stage carbonatites consist of fine-grained dolomite carbonatite, ferro-carbonatite, late-stage søvite, silico-søvite and REE carbonatite. Apatite is associated with pyrochlore-rich cumulates in the late- stage søvite and with pyrochlore precipitated during metasomatic alteration of basement adjacent to REE carbonatite veins.

This occurrence has been investigated, with a focus on its Nb potential, by Kryolitselskabet Øresund A/S (Gothenborg *et al.* 1976), leading to a pre-feasibility study which concluded that profitability of mining would be small (Outokumpu 1977).

Kap Simpson, North-East Greenland

A major Palaeogene felsic intrusive complex.,with a caldera sequence and extensive hydrothermal alteration, is found at Kap Simpson. 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).

Lhotský (2012) documented the occurrence of Zr-Nb-Ta-REE mineralisation within the Kap Simpson intrusive complex, on the southeast side of Bjørnedal. The Zr-Nb-Ta-REE mineralisation appears there in quartz veins that are a maximum of decimetres thick and are present in the mantle of the intrusive complex, at a few hundreds of metres from the intrusive body. Though the samples taken show up to 3.2 wt% of Nb and 3.0 wt% of REE, the average estimated content of Nb and REE in the quartz veins is significantly lower. On the other hand, the likelihood of the presence of the Zr-Hf-Y-Nb type of mineralisation has been documented in the northwest of Knebel Vig. The sample from the bedrock of the syenite porphyry vein there showed 5 to 7 wt% of Zr, 0.1 to 0.2 wt% of Hf, 0.15 wt% of Y_2O_3 and 0.15 to 0.2 wt% of Nb. In addition to these prospects, however, the Zr-Nb-Ta-REE mineralisation was also identified in boulders of pegmatites, alkaline syenites, and silicified quartzites from the moraine material of the Bredgletscher and Langgletscher glaciers and in the valley of Forchammers Dal. The potential of the occurrence of the Zr-Nb-Ta-REE type of mineralisation is therefore manifested throughout the entire near-contact zone of the intrusive complex.

Tracts with resource potential for niobium and tantalum (Figure 19)

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

Southern West Greenland carbonatites

West Greenland has several carbonatite complexes, in addition to the Sarfartoq and Qaqarssuk complexes, such as the Tikiusaaq and the Grønnedal-Ika complexes, further discussed under the Rare Earth Element section below. Furthermore, yet undiscovered complexes in this region may hold a potential for niobium and tantalum mineralisation together with REE and phosphorus.

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

The Mesoproterozoic Gardar Province and the Palaeogene alkaline province in central East and North-East Greenland are the two areas with the largest and most important group of alkaline rocks, and host the Motzfeldt 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 (Steenfelt *et al.* 2007a).

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

Table 22 *Overview of the commodity platinum group metals.*

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 3 5% are consumed in the jewellery sector. About ⅔ 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 hybridised 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 (2022) was 190 t, of which South Africa produced 74 %, Russia 11 %, Zimbabwe 7.8 %, and Canada 3.2 % (USGS 2023). Palladium: global production (2022) was 210 t, of which Russia produced 42 %, South Africa 38 %, Canada 7.1 %, Zimbabwe 5.7 %, and USA (5.2 %) (USGS 2023).
Main mineral	Platinum can occur as a native metal, but it can also occur in different minerals and alloys. Sperrylite (platinum arsenide, $PtAs_2$) ore is by far the most significant source of this metal. A naturally occurring platinum-iridium alloy, platiniridium, is found in the mineral cooperite (platinum sulphide, PtS). Platinum in a native state, often accompanied by small amounts of other platinum metals, and braggite ((Pt, Pd, Ni)S) is common in Bushveld, Norilsk, Stillwater and Great Dyke.
Resource/reserve	The world PGM reserve is 70,000 t, of which about 90 % is in South Africa, and minor reserves are found in Russia (7.8 %), Zimbabwe (1.8 %) and USA (1.3 %) (USGS 2022).
Known resources in Greenland	576 t
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 deposits and important occurrences (Figure 20)

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 (i) Reef-type mineralisation (Bushveld, Stillwater and the Skaergaard intrusions), (ii) dunite related deposits, and (iii) contact related mineralisation, which for example constitutes part of the Platreef mineralisation in Bushveld and the Duluth complex in USA.

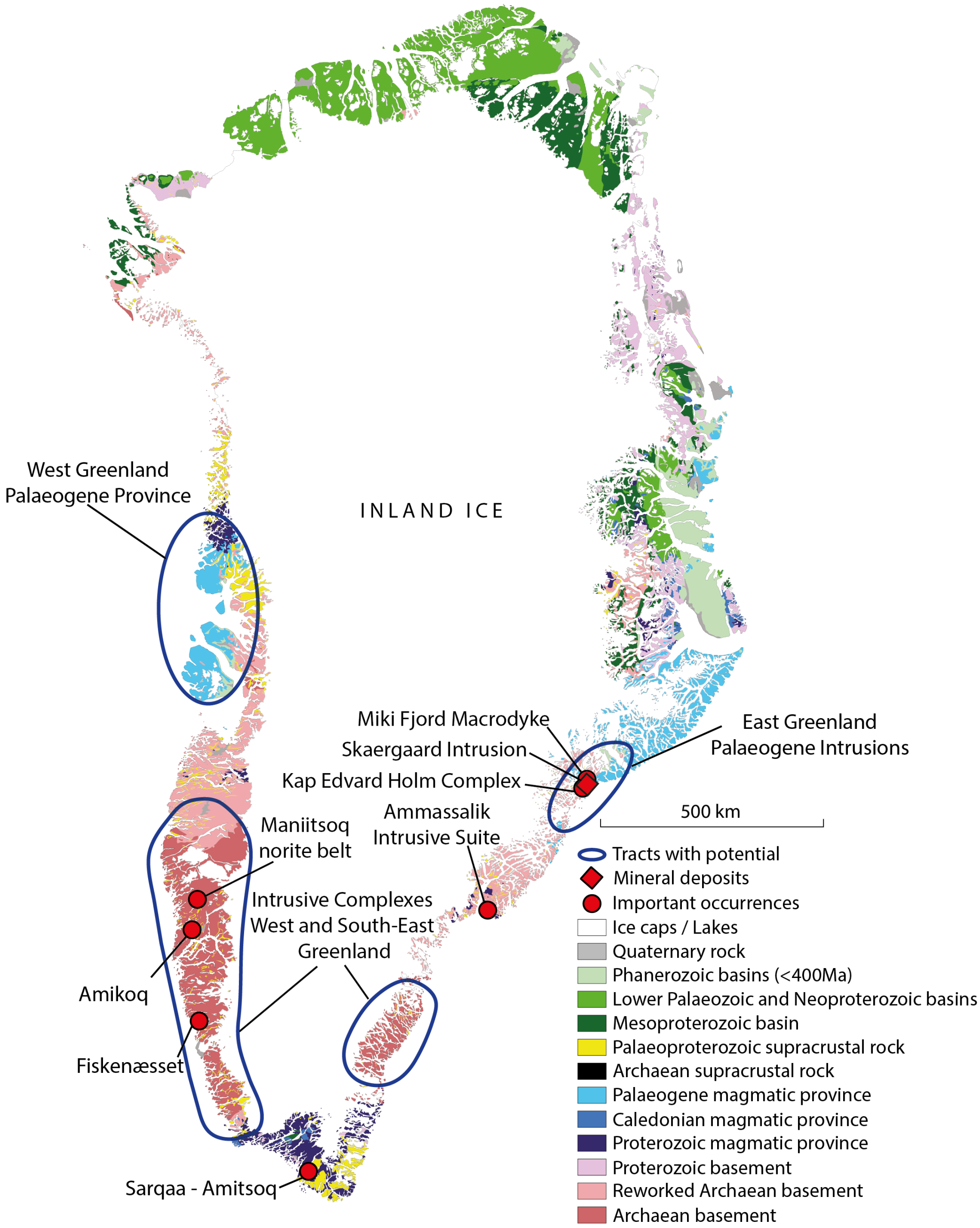

Figure 20 *Map of known platinum group metals (PGMs) deposits, significant occurrences, and favourable tracts. Simplified geological map is based on 1:2 500 000 geological map by Henriksen et al. (2009).*

Skaergaard Intrusion, 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 are 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 or intimately associated with Fe-poor, Cu-sulphide minerals dominated by bornite and chalcosine group minerals.

Major Precious Metals, who currently holds the license, reported a NI 43-101 compliant resource (indicated + inferred) amounting to 364.37 Mt grading 0.59 g/t Au, 1.46 g/t Pd and 0.11 g/t Pt at a 1.43 g/t Pd equivalent cut-off grade (Major Precious Metals 2022). Additional commodities are Ga, Ti and V (Andersen *et al.* 1998; Bird *et al.* 1991; Nielsen 2006; Nielsen *et al.* 2005) grading up to 7.17 wt % TiO_2 and 868 ppm V (also see section 3.10 Gallium [Ga] and 3.25 Titanium [Ti] and Vanadium [V]).

Kap Edvard Holm Complex, East Greenland

The Kap Edvard 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).

Miki Fjord Macrodyke, East Greenland

This occurrence, situated approximately 2 km northeast of the Skaergaard intrusion, has Cu-Ni-PGE-Au mineralization at its margins (Holwell *et al.* 2012) with grades up to 3.3 ppm Pd, 0.16 ppm Au, 2.2 % Cu, and 0.8 % Ni in hand specimen (Platina Resources Ltd. 2016). Diamond drilling did not test the mineralization, but geophysical investigations indicate possible mineralization targets at depth (Andersen 1997).

Amikoq layered complex, southern West Greenland

Occurrences of PGM mineralisation are abundant in the Archaean shield of West Greenland. The Amikoq 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. At the Amikoq locality, the peridotites crop out together with intercalated norites and orthopyroxenites, which based on their close association, appear to be co-genetic (Szilas *et al.* 2015). An U-Pb age of 2990 ± 13 Ma was obtained on zircon from the Amikoq complex by Nilsson *et al.* (2010), but this age likely reflects mineral growth associated with regional metamorphism. The peridotites found along Fiskefjord and in the Amikoq complex commonly have thin extensive layers of chromitite and are generally orthopyroxene (opx) rich (Szilas *et al.* 2015). New data yields an intrusion minimum age of 3004 ± 9 Ma (Aarestrup *et al.* 2020).

NunaMinerals A/S (Armitage 2009, 2010) 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; and

(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 (Armitage 2010).

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 mineralised semi-massive to massive sulphide samples typically grade 3-7 wt% Ni, 0.1-6.3 wt% Cu, 0.1-0,2 wt% Co and up to 0.3 ppm Pt+Pd+Au (North American Nickel Inc. 2017, 2022). 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. North American Nickel Plc. conducted an exploration program between 2011 and 2019 including a comprehensive drilling campaign and helicopter borne TEM and magnetic surveys were carried out. This expanded the footprint of the historic mineral occurrence at the Imiak Hill Complex and Fossilik and in addition resulted in the discovery of several new occurrences of mineralised norite and identified new conductive bodies at depth. Assays highlights include 24.75 m @ 3.19 % Ni and 1.14 % Cu (North American Nickel Plc. 2022), no resource estimates have been attempted for the targets at the Maniitsoq prospect.

Sarqaa and Amîtsoq, South Greenland

In the Nanortalik area, four 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 peridotite bodies are up to 1.5 km long and 90–250 m wide. The content of sulphides in the ultramafic rocks is about 0.2 vol.% and can rise to 10–15 vol.% in 10–20 cm wide zones (Turner *et al.* 1989). The minerals are chalcopyrite, cubanite (dominate), pentlandite, valleriite, pyrrhotite, bravoite, sphalerite accompanied by 5–10 vol.% magnetite (Schønwandt 1971). Gold, platinum, and palladium are found in trace amounts. The Waldorf occurrence (west of Ippatit) was drilled, and geophysical surveys (magnetometry, VLF and EM) were carried out (Turner *et al.* 1989).

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

The Ammassalik intrusive suite, sometimes also referred to as Tasilaq 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 Fiskenæsset anorthosite complex described in the section about Cr (sub-section 3.5), 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 Qeqertarsuatsiaat 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 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 in the Fiskenæsset region 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 (Figure 20)

West Greenland Palaeogene Province, central West 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. The Disko Island, part of The Palaeogene West Greenland Province was considered to hold a significant potential for this deposit type, which can yield PGM as a by-product. The volcanic succession in the northern part of the West Greenland Palaeogene Province on The Svartenhuk Halvø and the areas north and northeast of this, are generally correlatable with the southern part of the province (Larsen & Larsen 2022) and low contents of V, Cu and Ni in some crustally contaminated lavas could indicate that these elements and accompanying PGM could be present at depth (Larsen & Larsen 2022). For other tracts identified with a potential for conduit-type nickel mineralisation, and potentially PGM, please refer to Rosa *et al.* (2013). The Disko-Nuussuaq region favours a Norilsk style deposit (Lightfoot & Hawkesworth, 1997). Please see section 3.17 Nickel [Ni] for more information on the West Greenland Palaeogene Province.

Palaeogene intrusions, East Greenland

More than 60 intrusions are recorded in the Palaeogene East Greenland volcanic rifted margin which is part of the North Atlantic Igneous Province (NAIP) that was formed during prolonged magmatism from 63 Ma to 13 Ma (Tegner *et al.* 1998; Larsen *et al.* 2014). Although felsic intrusions constitute an important component, mafic to ultramafic intrusions are most dominant. However, these intrusions have not been thoroughly explored for their mineral potential due to the remote and often inaccessible locations. The Kangerlussuaq area, where nearly half of the intrusions are located, has been interpreted as the track of the proto-Icelandic mantle plume (Brooks 1973; White & McKenzie 1989), and is endowed with orthomagmatic PGE Au mineralisation including the Skaergaard and Kap Edvard Holm intrusions. This central part of the NAIP is considered to have significant potential for additional PGM mineralisations.

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 (Szilas *et al.* 2015).

3.20 Phosphorus [P] and Phosphate rock [PO_4]

Table 23 *Overview of the commodity phosphorus and phosphate rock.*

Main application	Phosphate rock is mainly used in the production of phosphoric acid, which is employed in the manufacture of fertilisers and animal feed supplements. Accessorily, a small fraction of the phosphate rock is used in the production of elemental phosphorus, which is employed to manufacture phosphorus compounds, namely for the use as herbicides.
Annual production and leading producing countries	According to the USGS (2023), global production in 2022 reached 220 Mt of phosphate rock (equals to 29–40.7 Mt P). Productions is distributed among many countries but dominated by China (39 %) and Western Sahara + Morocco (18 %).
Main mineral	Whether from sedimentary deposits (Western Sahara, Morocco, China, Middle East, USA) or from igneous occurrences (Brazil, Canada, Finland, Russia, and South Africa), phosphorus is hosted in apatite (calcium phosphate).
Resource/reserve	Global reserves of phosphate rock total approximately 72,000 Mt, with Western Sahara + Morocco accounting for more than ⅔, and global resources of more than 300,000 Mt (USGS 2023).
Known resources in Greenland	11.5 Mt of phosphorus
Market constraints	Global reserves and resources are abundant, but demand is growing quickly, and phosphate (whether primary or secondary) is irreplaceable in its key application as fertiliser. Furthermore, the EU has very little production (Finland) and strongly relies on supplies from Western Sahara, a disputed non-self-governing territory. It is this elemental phosphorus, which is more critical, rather than the phosphate rock employed in its production.

Known phosphorus/phosphate rock deposits and important occurrences (Figure 21)

Greenland is not known to hold any sedimentary phosphate rock occurrences. However, several significant phosphate rock occurrences of igneous origin are known. These are related to carbonatite bodies, in which apatite could potentially be a sub-product of REE, Nb, or Ta mining.

Sarfartoq carbonatite complex, southern West Greenland

This 565 Ma old carbonatite complex, belonging to the 'North Atlantic alkaline rock province' (Secher & Larsen 1980), was discovered by GEUS in 1978, as the result of the follow up of airborne gamma-ray spectrometry anomalies (Secher 1976).

The complex, emplaced in the transition zone between an Archaean granulite facies gneiss complex and the Palaeoproterozoic Nagssugtoqidian orogen (Secher 1986), is ellipsoidal at the surface and covers about 90 km², of which 10 km² are intrusive carbonatites (Secher & Larsen 1980). Carbonatite magma emplacement happened during two stages, with the formation of a steeply dipping conical body (the core) of concentric sheets of carbonatite, followed by a series of concentric and radial dykes and agglomerates emplaced in the surrounding marginal shock-zone. The accompanying fenitisation, surrounding the core, is of the Na-type. The complex is divided into three zones based on the proportion of carbonatite to fenite. The inner core (> 50 % carbonatite) is only approximately 1 km² in area, the outer core (< 50 % carbonatite) forms a 1–3 km broad ring, occupying around 9 km². A narrow rim of fenite (about 5 km²) surrounds this.

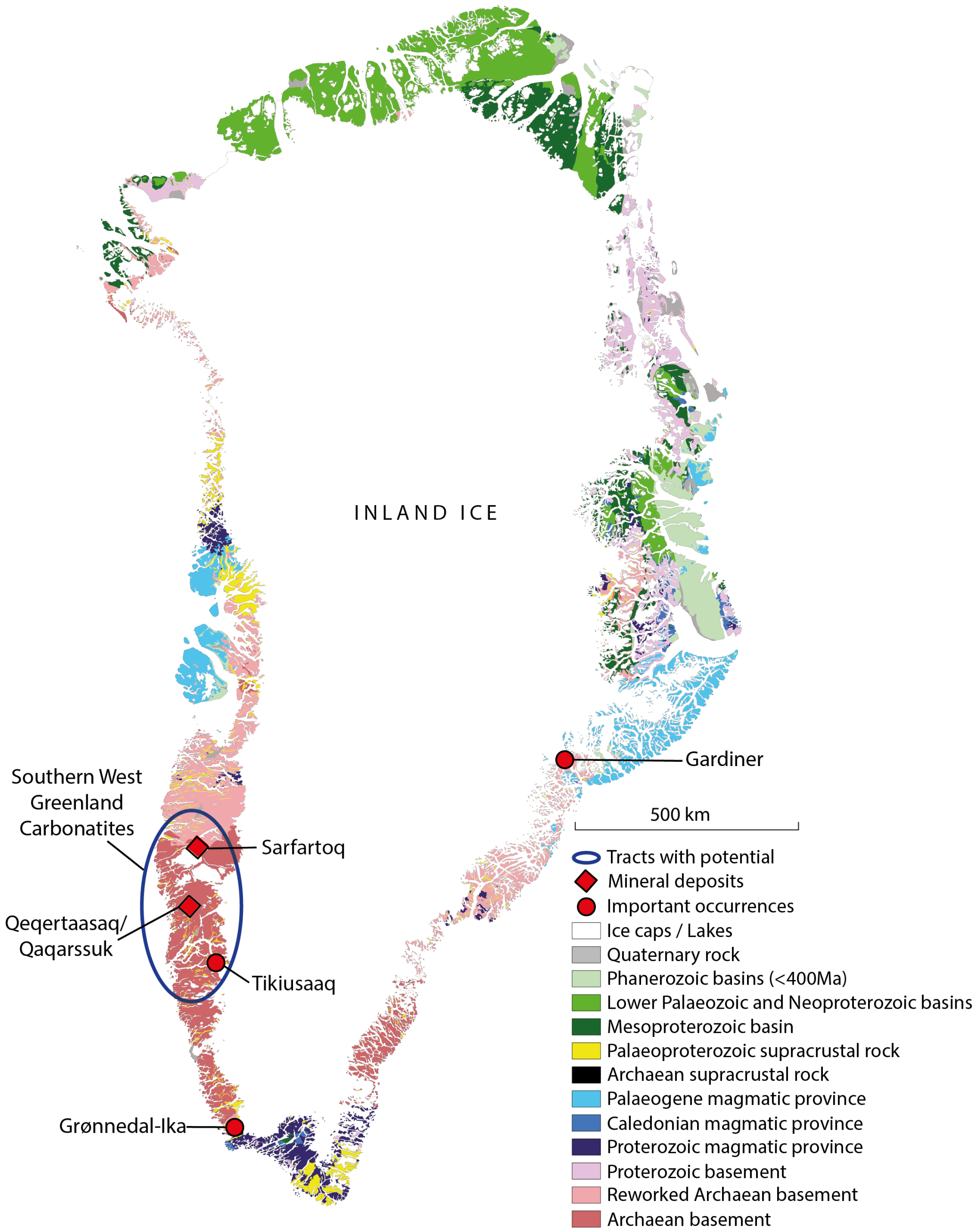

Figure 21 *Map of known phosphorus deposits, significant occurrences, and favourable tracts. Simplified geological map is based on 1:2 500 000 geological map by Henriksen et al. (2009).*

The predominant carbonatite type in the core is rauhaugite, with søvite occurring only sporadically in the outer core as schlieren, and as discrete layers in the inner core. The søvite of the inner core invariably has a low P_2O_5 content of 0.1–2.0 wt%. The rauhaugite of the outer core has a P_2O_5 content varying from 0.5 to 8.0 wt%, with a mean value of approximately 3.5 wt %. Values up to 12 wt% P_2O_5 are found in a few narrow layers of søvitic rauhaugite. While a given rauhaugite sheet has a relatively constant apatite content, there are large variations between sheets and adjacent sheets may show maximum differences. This heterogeneous distribution of fluorapatite and the size of individual deposits have, so far, not led to the identification of an exploitable resource (Secher 1986). However, resources of carbonatite may be roughly estimated to 500–1000 Mt averaging 3.5 wt% P_2O_5, to depths of 100 m and 200 m, respectively, with strontium and magnetite as possible by-products (Secher 1989). The Sarfartoq carbonatite complex has been explored relatively extensively by companies such as New Millennium (Van der Meer 2000) and Hudson Resources (Druecker & Simpson 2012), but their focus has been on REE and Nb-Ta, rather than phosphorus.

Qeqertaasaq/Qaqarssuk carbonatite complex, southern West Greenland

This 166 Ma old carbonatite complex was emplaced into Archaean basement in at least two stages, concomitantly with extensive alteration of the wall rock. The main stage carbonatites consist of olivine søvite, søvite and dolomite carbonatite ring-dykes, whereas the late-stage carbonatites consist of fine-grained dolomite carbonatite, ferro-carbonatite, late stage søvite, silico-søvite and REE carbonatite.

Apatite is associated with pyrochlore-rich cumulates in the late-stage søvite and with pyrochlore precipitated during metasomatic alteration of basement adjacent to REE carbonatite veins. Furthermore, apatite enrichment is also found in silico-søvite, where it is interpreted as diffusion differentiation, and in søvite, locally together with olivine and magnetite, where it is interpreted as resulting of crystal fractionation (Knudsen 1989, 1991). Apatite content in the silico-søvite is 3.5 to 6 wt% P_2O_5. At one locality a 12 m thick layer with an average of 3.9 wt% P_2O_5 can be followed 100 m along strike, indicating a probable reserve of about 0.8 Mt. Apatite-rich dolomite carbonatite dikes can in one case be followed over 200 m averaging 3.4 wt% P_2O_5 over 13 m of thickness indicating about 1.5 Mt (Knudsen 1991).

Tikiusaaq carbonatite complex, southern West Greenland

This complex, 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). 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. 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 evaluated the Tikiusaaq carbonatite, targeting the REE potential of its the carbonatite core defined from aeromagnetic data (NunaMinerals A/S 2011). High phosphate grades (up to 8.5 % P_2O_5) were returned from samples within the magnetic core of the carbonatite.

Grønnedal-Ika complex, South Greenland

This complex belongs to the Gardar intrusive suite and was emplaced into Archean gneisses. It comprises four, steeply dipping, ring structures of nepheline syenite, with late, central, plugs of xenolitic syenite, and carbonatite. The carbonatite is believed to have been formed by a single event as a Ca- and Fe-carbonatite plug surrounded by carbonate impregnated and brecciated nepheline syenite. The central carbonatite contains siderite, magnetite, and a trace sphalerite. Magnetite-bearing Ca-carbonatite merges into siderite-bearing Fe-carbonatite at the eastern extension of the prospected area (Emeleus 1964; Bondam 1992b). The magnetite mineralisation is suggested to have formed by contact metamorphism of siderite-bearing carbonatite during intrusion.

The siderite and magnetite-bearing carbonatite was investigated, through magnetic ground surveys, trenches and drill holes, by Kryolitselskabet Øresund A/S (Aho 1960; Bøgvad 1951). Subsequently, GEUS carried out a reconnaissance radiometric survey of the carbonatite. Finally, between 1983 and 1986, the Grønnedal-Ika complex was investigated as part of an European Economic Community funded project aimed at assessing its Nb and phosphorus potential (Morteani *et al.* 1986). Apatite is present in both Ca- and Fe-carbonatite and drill core samples have yielded 0.5–1.5 % P.

Gardiner, southern East Greenland

The emplacement of a melilitolite- and carbonatite-bearing alkaline ultramafic complex (Nielsen 1980) induced extensive metasomatic alteration with the formation of wide zones of glimmerite. Late irregular veins and dike-like bodies in the form of a major ring dike structure are composed of apatite-rich rocks (up to 90 %vol.), believed to be formed by immiscible separation of apatite liquid and related Fe-oxide liquid.

This complex was explored by Nordisk Mineselskab A/S (Frisch & Keusen 1977) and by Platinova Resources Ltd. (Waters 1987). No detailed estimate of possible resources of apatite and other commodities have been attempted due to the extremely difficult logistics and weather conditions, but the apatite resource is undoubtedly large.

Tracts with resource potential for Phosphorus (Figure 21)

Southern West Greenland Carbonatites

West Greenland has several carbonatite complexes, such as the Sarfartoq, Qaqarssuk, Tikiusaaq and the Grønnedal-Ika complexes described above. Furthermore, yet undiscovered complexes in this region may hold a potential for phosphate mineralisation together with tantalum, niobium, REE, and uranium.

3.21 Rare Earth Elements [REE]

The Rare Earth Elements (REE) comprise 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); however, in this context Pm and Sc are excluded, Pm because it is radioactive and Sc as it is mainly sourced from bauxite.

Table 24 *Overview of the commodity rare earth elements (based on Kalvig, 2022).*

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) Phosphorescence (Eu, Y, Tb, Nd, Er, Gd)
Annual production and leading producing countries	The annual production for 2021 is estimated to about 300,000 t of REO with China accounting for 70 %, USA 14%, Australia 6.0 %, and Burma 4.0 % of global production (USGS 2023). A wide range of production statistics on REE has however been published.
Main mineral	REE are present in 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 and monazite ores and minor amounts from loparite, xenotime, and ion adsorption clays. Eudialyte is the main mineral in quite a few of the REE-projects being explored. Additionally, apatite is being considered as a potential by-product for REE.
Resource/reserve	USGS (2023) report the global REO-reserves to amount to 130 Mt, of which 44 Mt are found in China, followed by Brazil and Russia (21 Mt each). 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 contributes with large reserve figures.
Known resources in Greenland	36.1 Mt REE (approximately corresponding to 42 Mt REO).
Market constraints	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. Additional constrains are related to the China value-chain dominance. 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, Sm, Eu, Gd, and Tb.

Known REE deposits and important occurrences (Figure 22)

Ilímaussaq complex, South Greenland – Kvanefjeld/Kuannersuit, and Kringlerne/Killavaat Alannguat and Appat

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 nepheline syenites (Bailey *et al.* 2001). 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 is reflected in the great number of minerals recorded. The Ilímaussaq intrusion hosts two different types of REE deposits; Kvanefjeld/Kuannersuit (dominated by lujavrites) and Kringlerne/Killavaat Alannguat (dominated by the kakortokite bottom cumulates).

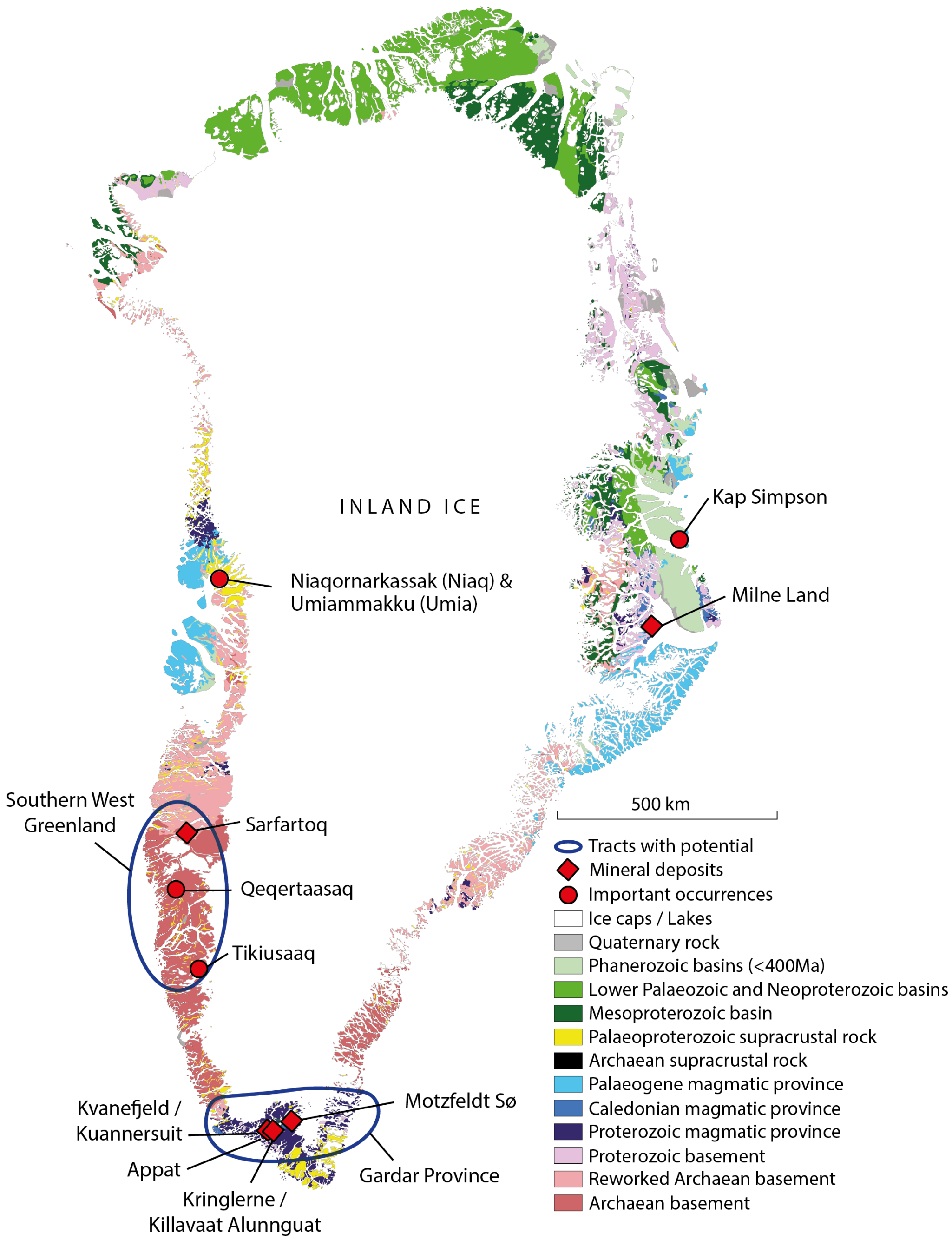

Figure 22 *Map of known rare earth elements deposits, significant occurrences, and favourable tracts. Simplified geological map is based on 1:2 500 000 geological map by Henriksen et al. (2009).*

The Kvanefjeld/Kuannersuit REE-U-Zn-F deposit, is located 8 km 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/Kuannersuit 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/Kuannersuit, Energy Transition Minerals (formerly Greenland Minerals Limited (GMEL)), has identified an indicated and inferred grand total resource inventory: 1010 Mt containing 0.269 Mt U_3O_8, 11.14 Mt TREO, and 2.42 Mt Zn, based on a cut-off of 150 ppm U (Energy Transition Minerals, 2023). This resource encompasses three individual deposits: (i) Kvanefjeld/Kuannersuit deposit (measured) 143 Mt containing 1.72 Mt TREO, 43,000 t U_3O_8 and 0.34 Mt Zn; (ii) the Sørensen deposit (inferred) 242 Mt containing 2.67 Mt TREO, 73,500 t U_3O_8 and 0.63 Mt Zn; and (iii) the Zone 3 deposit (inferred) 95 Mt containing 1.11 Mt TREO, 29,000 t U_3O_8, and 0.26 Mt Zn (Energy Transition Minerals, 2023). GMEL was in 2021 in the final approval phase for the Kvanefjeld deposit with and ongoing EIA process, but the project has been on hold since a new law has been introduced in Greenland that does not allow mineral exploration and mining of ore with an average concentration of more than 100 ppm uranium.

The Kringlerne/Killavaat Alannguat Zr-REE-Nb-Ta deposit, situated about 8 km south of Narsaq and 20 km north-east of Qaqortoq, is hosted in the lower cumulates of the layered agpaitic nepheline 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-Ta and the red kakortokite layers are the main exploration targets for 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 2022). The grade of HREE (including Y) is reported to be 27.1 % (Schønwandt et al. 2016). The company received a mining licence in 2020.

Lujavrite occurrences at Appat have been drilled to evaluate their Zr-Y-REE potential and a resource of 3.2 Mt ore at 1.2 % ZrO_2 and 0.1 % Y_2O_3 was indicated (LeCouteur, 1989; von Guttenberg and LeCouteur, 1992).

Motzfeldt, 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 of the Motzfeldt 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. 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 REEs identified in the samples were La, Ce, Nd, Pr, Dy, Er, and Ho. A total inferred mineral resource of 340 Mt at 2600 ppm TREO, in addition to Ta, Nb and Zr, has been identified by RAM Resources (2012).

Sarfartoq carbonatite complex, southern West Greenland

The Sarfartoq carbonatite complex described under Nb and phosphorus above also has a 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 2012, Hudson Resources Inc. published a NI43-101 compliant resource estimate for the ST-1 site; 5.9 Mt indicated averaging 1.8 % TREO, and 2.5 Mt inferred averaging 1.6 % TREO at a 1 % cut-off (Hudson Resources 2012). The average thorium grade is *c.* 500 ppm Th, and U is 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, 2012). Neo Performance Materials, a mid-downstream company, bought in August 2022, the mineral exploration rights from Hudson Resources Inc.

Milne Land, central East Greenland

The Mesozoic Milne Land palaeoplacer was discovered in 1968 by Nordisk Mineselskab A/S in connection with a heavy mineral concentrate sampling program, an airborne 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. More recently, CGRG estimated a resource of 4 Mt grading 0.6 to 1.2 wt% of REO, in addition to Zr and Ti (CGRG 2019).

Niaqornakassak and Umiammakku Nunaa, central West Greenland

The Niaqornakassak (also referred to as Niaq) REE mineralisation is located on the island 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 orebody 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 %. A preliminary resource target of the Niaq body was of 26 Mt. The REEs 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 occurence has an average of 500 ppm thorium.

Tikiussaq carbonatite complex, southern West Greenland

The Tikiusaaq carbonatite, discovered by GEUS in 2005 based on 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).

Interpretation of radiometric and magnetic data indicates a carbonatite 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 søvite 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 (Kolb et al. 2016). 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. Anomalies just outside the complex boundary, identified from historic radiometric data, were also investigated, but little REE prospective carbonatite was discovered here.

Kap Simpson, North-East Greenland

A major Palaeogene felsic intrusive complex, with a caldera sequence and extensive hydrothermal alteration, is found at Kap Simpson, Traill Ø. 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).

Lhotský (2012) describes that the Zr-Nb-Ta-REE mineralisation occurs in the marginal, heavily tectonised and altered central part of the intrusive body in the area of Forchammers Dal. Three samples taken at this site had REE + Y contents between 5,100 and 10,900 ppm. A second prospect in Prospektfjeld corresponds to veins intersecting an earlier phase of the central intrusive body, represented by heavily tectonised alkaline granites. Two samples taken in this area had REE+ Y contents between 4,400 and 13,700 ppm. Southeast side of Bjørnedal yields up to 3 % REE.

Tracts with resource potential for REE (Figure 22)

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/Kuannersuit, Kringlerne/ Killavaat Alannguat 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).

Southern West Greenland Carbonatites

West Greenland has several carbonatite complexes, such as the Sarfartoq, Qaqarssuk, Tikiusaaq and the Grønnedal-Ika complexes. Furthermore, yet undiscovered complexes in this region may hold a potential for phosphorus mineralisation together with tantalum, niobium, REE, and uranium.

3.22 Silicon Metal [Si]

Silicon metal is not a mineral commodity per se, but is produced from silicon dioxide (i.e., the mineral quartz). The production involves melting of SiO_2 using carbon as the reducing agent and requires 11–13 kWh per kg metal. The energy cost is therefore a significant proportion of the total production cost. Having said that, quartz for the production needs to fulfil strict criteria for purity to be considered metallurgical grade, and its Greenlandic potential is discussed here.

Table 25 *Overview of the commodity silicon metal.*

Main application silicon metal	Used in aluminium alloys, manufacturing of silicones, semiconductors, and photovoltaic cells.
Annual production and leading silicon producing countries	A total of 8.8 Mt silicon was produced worldwide in 2022 (USGS 2023), with China being the dominant producer (68 %).
Main mineral	Quartz
Resource/reserve	Quartz resources, namely as quartzite, are ample.
Known resources in Greenland	2.8 Mt
Market constraints	Main constraint is the availability of energy to produce silicon from quartz.

Known quartz deposits (Figure 23)

Ivittuut

The Ivittuut cryolite deposit is hosted in an intrusive complex, located within the roof zone of a 300 m wide pipe-like granite stock. The cryolite deposit is divided into a siderite-cryolite, a pure cryolite, a fluorite-cryolite and a fluorite-topaz unit, which is located above a large siderite and quartz rich unit (Pauly 1992; Pauly & Bailey 1999). Beneath the cryolite deposit, the intensity of greisenisation diminishes down to 550 m below sea level. At depths of 700–800 m, drill cores have indicated the presence of albitised granite and disseminated cryolite (Bondam 1991).

The upper (mined) part of the body consisted of siderite-cryolite with a few percent of sulphides (galena and sphalerite), fluorite and quartz. A siderite-quartz shell occurred beneath the eastern part of the siderite-cryolite, and an extensive unit consisting of quartz with minor amounts of siderite, muscovite and sulphides was found below the above-mentioned shells (Bailey 1980; Steenfelt *et al.* 2016).

Eclipse Metals is modelling the rich Ivittuut intrusion based on old drill core data returning wide quartz-rich intercepts at over 97 % silica. A resource of nearly 6 Mt grading 90 to 95 % silica oxide is expected (Eclipse Metals 2021).

Tracts with resource potential for quartz (Figure 23)

No tracts have been defined due to the lack of data on quartz quality.

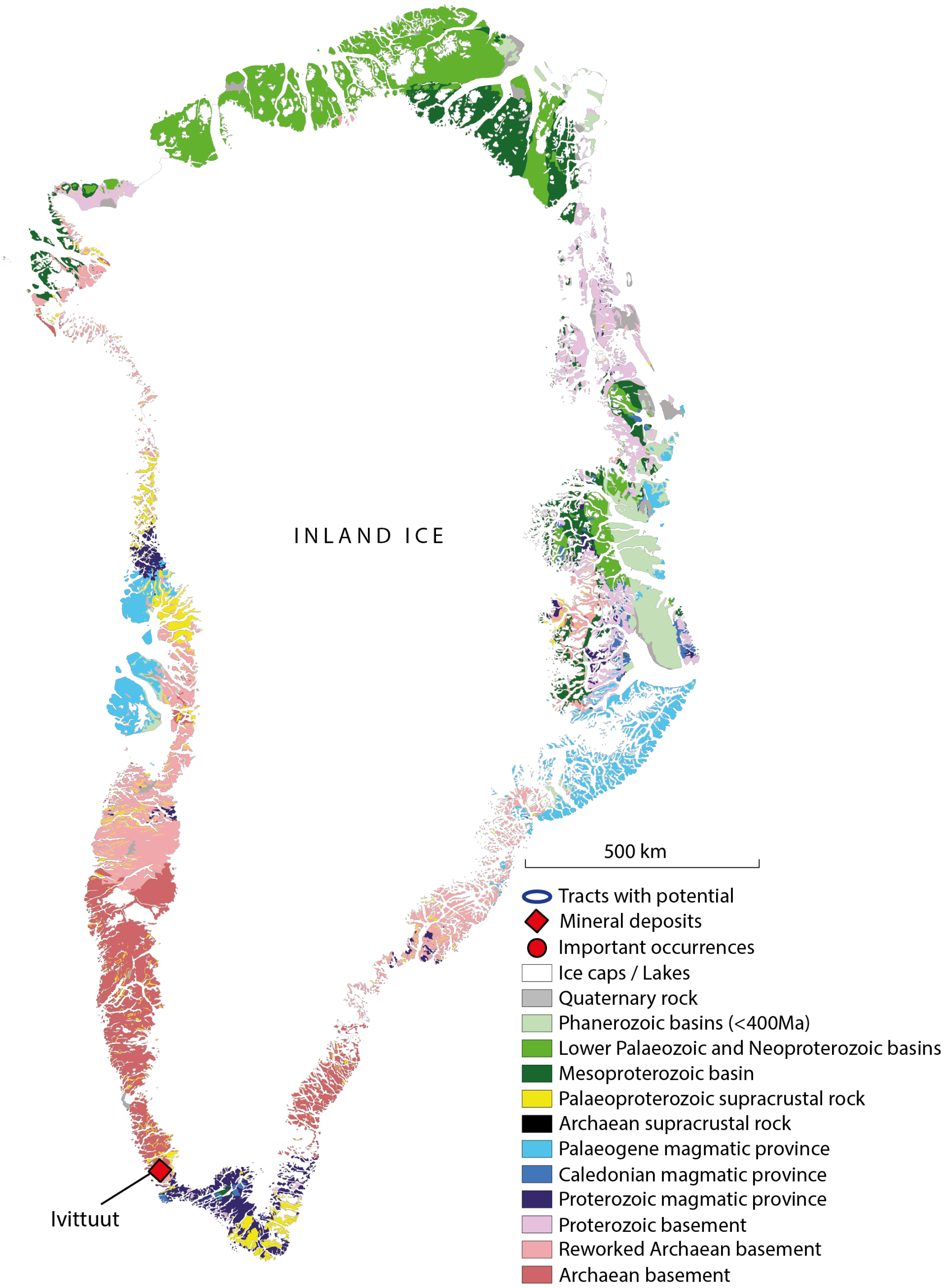

Figure 23 *Map of known silicon deposits. Simplified geological map is based on 1:2 500 000 geological map by Henriksen et al. (2009).*

3.23 Strontium [Sr]

Table 26 *Overview of the commodity strontium.*

Main application	The main application for strontium is for drilling fluids, used as celestite. A smaller proportion of the celestite is converted to strontium carbonate, -sulfate, and -nitrate, used as the raw material for the manufacture of pyrotechnics, ferrite magnets, alloys, pigments, zinc production and glass.
Annual production and leading producing countries	Global production in 2022 was 340,000 t contained metal (USGS 2023). Production is concentrated in Spain (38.2 %), Iran (32.4 %), China (23.5 %), and Mexico (6.5 %).
Main mineral	Celestite and strontianite are the only commercial sources of strontium. This mineral is mostly recovered from evaporite deposits and, more rarely, from hydrothermal veins where it can accompany fluorite, baryte, lead, and zinc sulphides and strontianite.
Resource/reserve	Reserve estimates are not available for most countries, but global resources are estimated to surpass 1,000 Mt of contained metal (USGS 2023).
Known resources in Greenland	9.8 Mt
Market constraints	Concentration of the production in a few countries. For the main use in drilling muds, celestite and baryte can both be used, and substitution depends on the relative price. However, for other uses, such as the production of ceramic ferrite magnets, substitution of strontium by barium compounds affects performance (USGS 2022).

Known strontium deposits and important occurrences (Figure 24)

Karstryggen, central East Greenland

Stratabound celestite mineralisation in Upper Permian carbonates has been identified at Karstryggen in Jameson Land. The celestite deposit is hosted by the Karstryggen Formation, a marine marginal carbonate and evaporite sequence, dominated by limestone deposited in a hypersaline shallow marine environment (Harpøth *et al.* 1986).

Mineralisation occurs in a lower 3–10 m thick algal-laminated limestone unit and in a > 50 m thick overlying karst breccia sequence (Harpøth *et al.* 1986). In the former unit, early diagenetic celestite substituting calcite and gypsum occurs, while in the latter sequence, celestite occurs as cement and fillings in the karst breccia and as pockets, lenses and veins in karst fractures and caves (Harpøth *et al.* 1986). Celestite occurs in an 80 km² area and over a thickness of several metres. An estimate made for an approximately 4 km^2 area, resulted in a resource of 120 Mt with an average grade of 20 % $SrSO_4$ (for an average thickness of 10 m), for mineralisation in the limestone breccia unit, and of 36 Mt with an average grade of 10–30% $SrSO_4$ (for an average thickness of 3 m), for mineralisation in the laminated limestone unit (Harpøth 1981). Scholle *et al.* (1990) report a potential for 25–50 Mt of $SrSO_4$, at a grade of 50–60 wt%, which places this deposit among the largest in the world.

Tracts with resource potential for strontium (Figure 24)

Significant Sr concentrations have been observed in the Karstryggen Formation (see below) but have also been described for the Sarfartoq and Tikiusaaq carbonatites (discussed under the Phosphorus and REE sections above). In the Sarfartoq, these concentrations are attributed to ancylite (strontium and rare earth carbonate). However, these most likely merely constitutes a mineralogical curiosity, rather than a significant strontium source.

Karstryggen Formation, central East Greenland

The tract displays the approximate extent of the Karstryggen Formation, a marine marginal carbonate and evaporite sequence, which is known to include significant quantities of celestite (Harpøth *et al.* 1986).

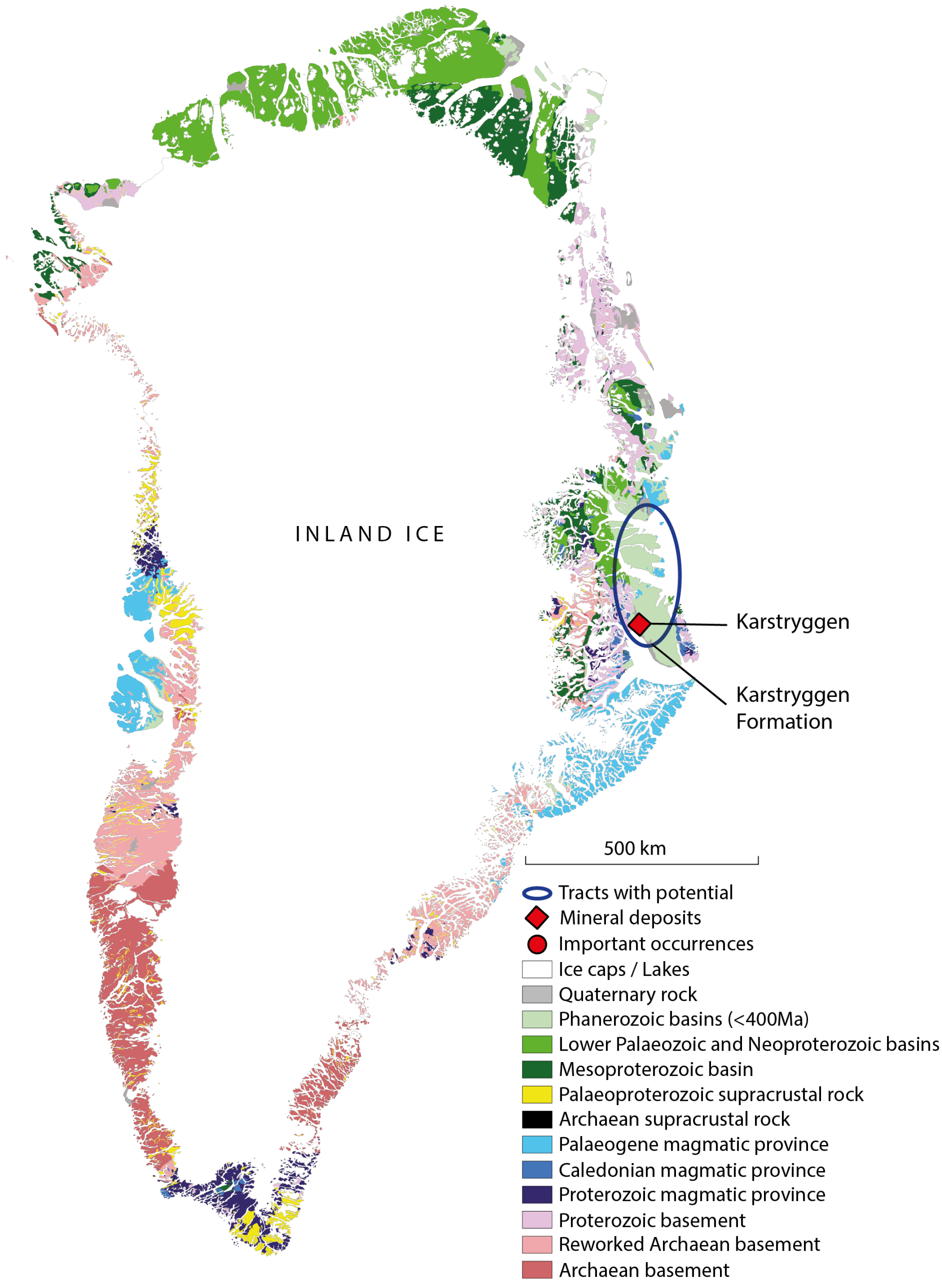

Figure 24 *Map of known strontium depositsand favourable tracts. Simplified geological map is based on 1:2 500 000 geological map by Henriksen et al. (2009).*

3.24 Tin [Sn] and Tungsten [W]

As tin and tungsten are often related to each other in the same deposits, this description deals with both commodities, although one of them might dominate in a given occurrence/deposit.

Table 27 *Overview of the commodity tin.*

Main application	Tin is used in many alloys, most notably bronze and tin/lead soft solders and for corrosion-resistant tin plating of steel. Tin is non-toxic and has therefore been used for food cans, but these are presently replaced by aluminium.
Annual production and leading producing countries	The total primary production in 2022 was *c.* 310,000 t, of which China was the dominant producer (31 %) followed by Indonesia (24 %), Burma (10 %), (9 %), Congo (6.5 %) Bolivia and Brazil (each 5.8 % of world production) (USGS 2022).
Main mineral	Most of the tin is mined as cassiterite (SnO_2). Only minor amounts of stannite (Cu_2FeSnS_4) are also produced.
Resource/reserve	The global reserves are 4.6 Mt of which Indonesia holds about 17 %, China 16 %, Burma 15 %, Australia 12 %, Rwanda 9.4 %, Brazil 9.1 % and Bolivia 8.7 % (USGS 2023).
Known resources in Greenland	No known resource estimation.
Market constraints	For most of its applications, substitution is limited or at the expense of cost and performance.

Table 28 *Overview of the commodity tungsten.*

Main application	Most tungsten (60–70 %) is used for cemented carbides (hard metals) used in special tools. Additionally, tungsten is used for creep-resistant steels and alloys, for electrodes, wires, and chemicals.
Annual production and leading producing countries	The global mine production in 2021 was 84,000 t, of which China was the dominant producer (85 %) followed by Vietnam (5.7 %), and Russia (2.7 %), and minor productions in a number of other countries (USGS 2023).
Main mineral	Wolframite ($(Fe,Mn)WO_4$) and scheelite ($CaWO_4$).
Resource/reserve	The world mine reserves are *c.* 3.8 Mt of which about 47 % is located in China, followed by Russia (11 %) and Vietnam (2.6 %) (USGS 2022).
Known resources in Greenland	26,200 t. 'Undiscovered resources' at a regional scale has been estimated by Rosa *et al.* (2014) to 244,000 t.
Market constraints	For most of its applications, substitution is limited or at the expense of cost and performance.

Known tin and tungsten deposits and important occurrences (Figure 25)

Tin and tungsten occurrences in Greenland are not well known but are normally reported to be associated with Caledonian or Palaeogene magmatic activity in central East and North-East Greenland.

Malmbjerg, central East Greenland

Malmberg is a Climax-type molybdenum-porphyry deposit related to a Palaeogene composite alkali granite intrusion (Schønwandt 1988). The deposit is dome shaped with an outside diameter of up to 600 m and a height of approximately 150 m, and extensive hydrothermal altered. A resource estimate of 150 Mt @ 0.23 % MoS_2 and 0.02 % WO_3, at a 0.16 % MoS_2 cut-off, was reported by Harpøth *et al.* (1986), with wolframite and cassiterite described to occur in greisen veins, which postdate the stockwork Mo mineralisation and are hosted both by the granite stock and hosting meta-sedimentary rocks. A NI43-101 compliant resource estimation has been published by the current license holder Greenland Resources (see Paragraph 3.16 Molybdenum [Mo]), however, this estimate does not refer to tungsten or tin. Nevertheless, significant W and Sn concentrations are reported to be found in test tailings, but these appear to not be amenable to be efficiently recovered (Greenland Resources 2022).

Margeries Dal, North-East Greenland

The deposits of Margeries Dal, in Ymer Ø, are related to fault zones in Upper Eleonore Bay Supergroup metasediments and do not appear to be spatially related to granitic rocks. The ores are hosted by brecciated carbonates, in minor fault zones, with scheelite, stibnite and tetrahedrite (Hallenstein 1981; Hallenstein & Pedersen 1982; Pedersen & Stendal 1987). There appears to be a crude zonation with scheelite and stibnite at higher stratigraphic levels and pyrite, galena, sphalerite, chalcopyrite and, locally, arsenopyrite with gold at lower stratigraphic levels (Pedersen & Stendal 1987). The emplacement age of the bulk of the scheelite has been determined to be at 382 ± 39 Ma (Stendal & Frei 2008), so that the mineralising event took place during the latest stages or after the emplacement of the majority of Caledonian granites at around 425 Ma. Genetically, it is proposed that fault zones acted as channels for hydrothermal solutions and that limestone and dolomite horizons 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 Margeries Dal North indicates 42,000 t grading 0.7 wt% W and 108,000 t with 3.5 wt% Sb (Harpøth *et al.* 1986); high-grade scheelite is restricted to the thicker part of the breccia zone in which individual half metre sections contain up to 24 wt% W in drill cores. In Margeries Dal South, a vein carries 82,000 t grading 2.3 wt% W (Harpøth *et al.* 1986). Locally the fault related mineralisation has quartz veins with some arsenic and gold contents (Pedersen 1993).

Occurrences in the East Greenland Caledonides, central East, and North-East Greenland

Central East and North-East Greenland comprises the Caledonian fold belt and is regarded as being the area with most potential for tungsten and tin deposits. 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. In any case, the area comprises several known tungsten deposits and occurrences, where the tungsten is found in the mineral scheelite.

Some of the scheelite occurrences are related to fault zones in Upper Eleonore Bay Supergroup metasediments without any apparent spatial relation to granitic rocks. These include, in addition to the Margeries Da deposits described above, the Panoramafjeld, Eleonores Bugt and Noa Dal occurrences.

Most of the known scheelite occurrences, however, are related to the presence of favourable granitic intrusions and host rocks. Stendal & Frei (2008) found a heterogeneous, probably local, source of tungsten, and support a genetic link to Caledonian magmatic activity. In addition, this study indicates that hydrothermal fluids interacted with both Archaean-Palaeoproterozoic crystalline basement and Mesoproterozoic-Neoproterozoic sedimentary rocks. Thus, tungsten may have been deposited from fluids associated with Caledonian granites, which also provided heat sources for local hydro-thermal circulation cells. Forced into faults, thrusts and fractures, the fluids were trapped by dominantly Ca-rich sediments. Within this setting, scheelite occurrences are known in Upper Proterozoic metasediments, spatially associated with Caledonian or older granitic intrusions (Kalkdal, East Milne Land, Knivbjergdal, Gemmedal and Eremitdal), or in the Lower Eleonore Bay Supergroup sediments, up to 7 km from outcropping Caledonian granites (Bersærkerbræ, Skjoldungebræ, Trekantgletscher, Galenadal, Scheelitdal and Randenæs).

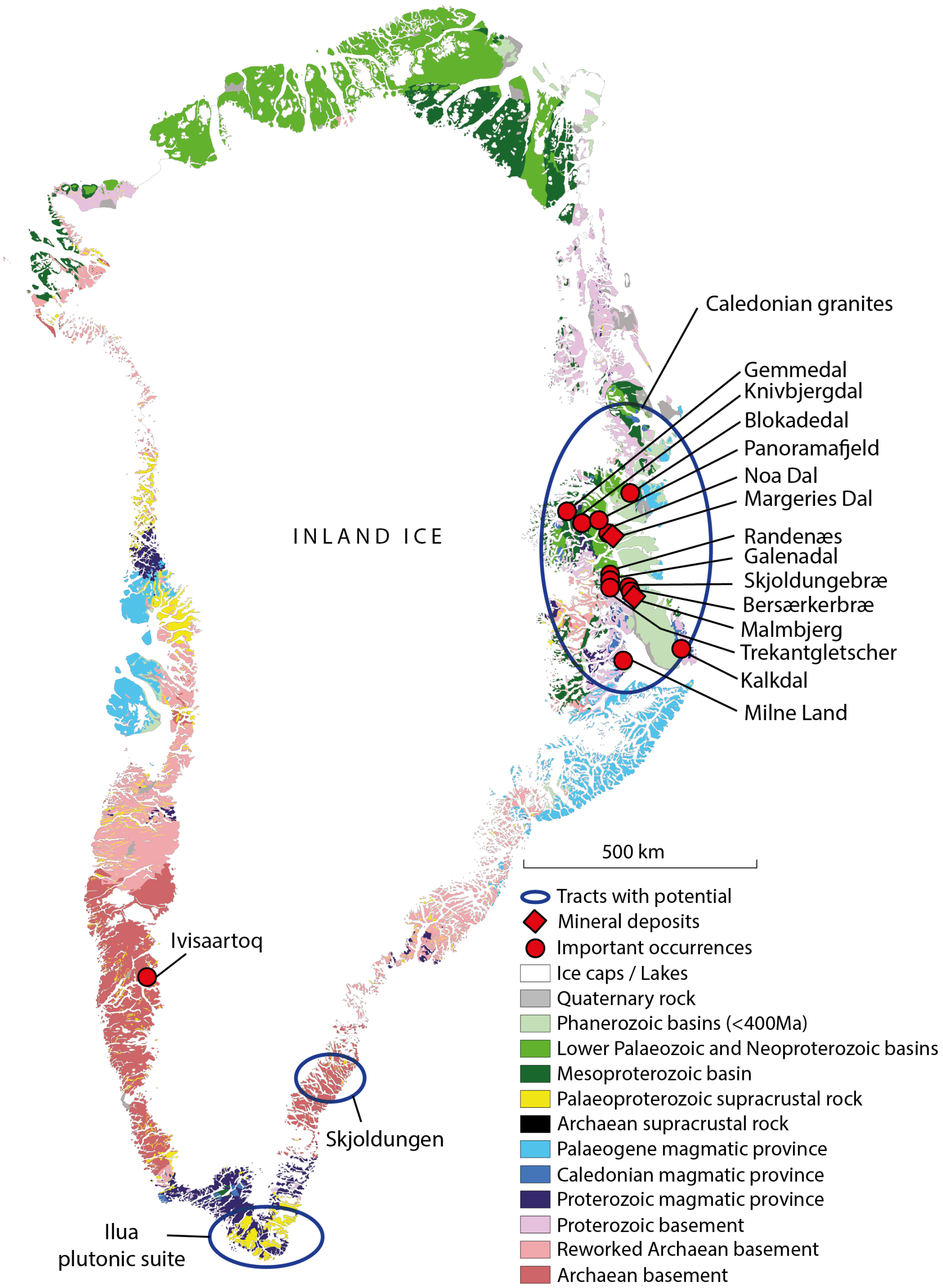

Figure 25 *Map of known tin and tungsten deposits, significant occurrences, and favourable tracts. Simplified geological map is based on 1:2 500 000 geological map by Henriksen et al. (2009).*

Finally, cassiterite occurrences are also known. At the Blokadedal greisen occurrence, Devonian granite has intruded Eleonore Bay Supergroup shales which are contact metamorphosed into hornfels aureole around the intrusion. The granite is a medium- to coarse-grained, leucocratic, biotite-hornblende granite with local areas of feldspar-porphyritic phases containing abundant aplite fragments. Indications og hydrothermal activity are pronounced and hematization is common.

Seconly, epidotization and argillization is widespread. Hydrothermal veins are widespread, with up to dm-thick quartz-fluorite veins and to a minor extent as silicified zones. Cassiterite is recorded in panned samples. Porphyritic granite boulders have up to dm-thick tin-tungsten-bearing tourmaline-quartz greisen veins. Very pronounced tin anomalies in pan samples indicate an area with granite associated Sn-W-Mo-Bi-Nb-Ta-REE-F mineralization (Lind 1981; Harpøth 1984; Harpøth et al. 1986).

Ivisaartoq, southern West Greenland

The Nuuk region hosts a major tungsten province with scheelite occurring in virtually every greenstone enclave. The Mesoarchaean Ivisaartoq greenstone belt 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 (~ 3.08 Ga), 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 tin and tungsten (Figure 25)

Geologically the tracts described comprise central East and North-East Greenland including geological units of pre-Devonian age. The other tracts shown in Figure 25 are based on geochemical data and not on known tungsten occurrences in these areas.

Caledonian granites, central East, and North-East Greenland

Caledonian intrusions (granites) and faults in central East and North-East Greenland are considered to hold a potential for tin and tungsten. Even though only limited exploration has been carried out, the example provided by the Margeries Dal tungsten deposits confirms that these settings may hold potential for additional mineralisation.

Ilua plutonic suite, South Greenland

Tungsten-rich deposits are related to reduced ilmenite-bearing, S-type granites that crystallise 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 granites of the 1755–1720 Ma Ilua plutonic suite (Steenfelt *et al.* 2016), emplaced in the Psammite and Pelite zones of the Palaeoproterozoic Ketilidian orogen in South Greenland, were formed in this setting and may therefore hold a potential for tungsten deposits. Significant tungsten concentrations were identified in heavy mineral concentrates deriving from the Ketilidian batholith in South Greenland.

Skjoldungen, South-East Greenland

During fieldwork by GEUS in 2012, a quartz vein with wolframite and molybdenite, with 1.6 wt% tungsten, 0.26 % molybdenum and 54 ppm rhenium, was identified (Rosa & Ulrich 2015). Furthermore, stratabound scheelite mineralisation (up to 0.5 wt% 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.

3.25 Titanium [Ti] and Vanadium [V]

Table 29 *Overview of the commodity titanium.*

Main application	Titanium mineral concentrates are used as raw materials for TiO_2 pigments used in paint, paper, and plastics. A smaller proportion of titanium mineral concentrates are used for production of titanium metal and alloys for the steel and aerospace industries, for welding-rod coatings and in manufacturing carbides and other chemicals.
Annual production and leading producing countries	Global production is 9.5 Mt of titanium mineral concentrates (approximately 94 % ilmenite and 6 % rutile), with Australia, China, and South Africa as leading producers and accounting for over half the global production (USGS 2023).
Main mineral	Ilmenite and rutile, predominantly from placers.
Resource/reserve	Global reserves of ilmenite and rutile total approximately 700 Mt, with Australia, China, and India accounting for more than half, and resources being more than 2,000 Mt (USGS 2023).
Known resources in Greenland	12.1 Mt
Market constraints	In 2021, China imported approximately 3.6 Mt of titanium mineral concentrates, which in addition to the domestic Chinese production, makes China the dominant global TiO_2 pigment producer. Only Ti metal is regarded as a critical commodity, TiO_2 pigments are not critical.

Table 30 *Overview of the commodity vanadium.*

Main application	About 90 % of the vanadium production is used as high strength 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 2022 amounted to 100,000 t, of which the major producers were China (70 %), Russia (17 %), South Africa (9.1 %), and Brazil (6.2 %) (USGS 2023).
Main mineral	Vanadium is primarily produced as a by-product from processing of titanomagnetite ores, but also from uranium-vanadium ores, bauxites, and phosphates.
Resource/reserve	The total worldwide reserve of vanadium is 26 Mt, of which China holds 37 %, Australia 28 %, Russia 19 %, and South Africa 13 % (USGS 2023).
Known resources in Greenland	179,000 t
Market constraints	China, Russia, and South Africa are dominating with regards to the reserves of vanadium as well as the annual production.

Known titanium and vanadium deposits and important occurrences (Figure 26)

Moriusaq, North-West Greenland

The ilmenite-rich placers of the Thule Black Sand Province (Dawes 1989) were evaluated at Moriusaq by Dundas Titanium. This company reports a JORC compliant mineral resource of 117.3 Mt, grading 1.7 % Ti (Bluejay Mining plc 2020).

Thule Black Sands, North-West Greenland

The ilmenite-rich placers of the Thule Black Sand Province (Dawes 1989) have been licensed to the northwest of Moriusaq by GreenRoc Mining Plc. This company provided a resource of 19 Mt with 8.9% ilmenite, which would translate to approximately to 2.8% Ti (GreenRoc Mining Plc. 2022).

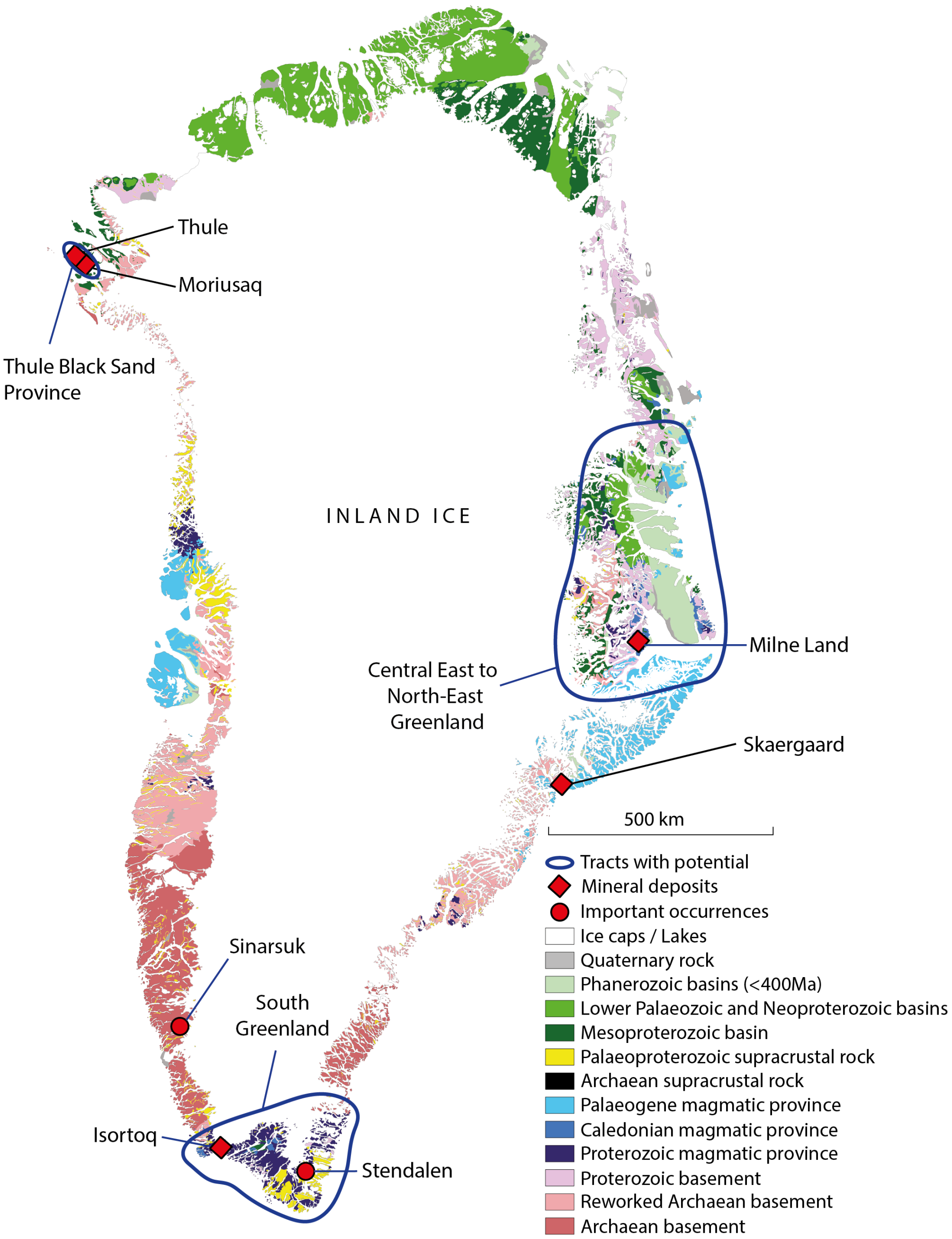

Figure 26 *Map of known titanium and vanadium deposits, significant occurrences, and favourable tracts. Simplified geological map is based on 1:2 500 000 geological map by Henriksen et al. (2009).*

Milne Land, central East Greenland

In Milne Land, in Central East Greenland, Jurassic palaeoplacers containing ilmenite, rutile, zircon, monazite and garnet have been identified by Nordmine (Harpøth *et al.* 1986). The heavy mineral sands occur as irregularly distributed 10–40 cm thick lenses within a *c.* 20 m thick unit of arkosic sandstone (Harpøth *et al.* 1986). In 2013, CGRG outlined an area with a potential for *c.* 4 Mt grading 3–6 wt% of TiO_2, in addition to Zr and REO (CGRG 2019).

Skaergaard Intrusion, southern East Greenland

Titanomagnetite from the layered Skaergaard Intrusion in southern East Greenland is found to be enriched in vanadium with values of 1.11 to 1.22 wt% (Platina Resources Ltd. 2007). Sørensen *et al.* (2016) provide a resource of 104 Mt with 4.68 % Ti and 0.12 % V. For further description of the Skaergaard intrusion please see section 3.19.

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 troctolite dyke at Isortoq has Ti-V-Fe mineralisation. This dyke 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 the inland ice. An inferred global resource of 70.3 Mt grading 29.6 wt% Fe, 10.9 wt% TiO_2 and 0.144 wt% V_2O_5 using a cut-off of 15 wt% 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.

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 section 3.5 Chromium [Cr].

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. Later the license was taken over by 21st North that in in the early 2010s carried out detailed geological mapping and channel sampling at Sinarsuk. However, 21st North did not continue to work in the area.

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).

Stendalen, South Greenland

The Stendalen gabbro is part of Julianehåb Batholith (1850–1800 Ma) of the Ketilidian orogen. It is a folded, sheet-like body at least 8 km in length and several hundred metres thick (Garde *et al.*

1997). It is composed of gabbro, leucogabbro, and diorite, locally with primary banding and divided into two main units: a lower layered gabbro unit and an upper homogeneous gabbro to diorite unit.

A magnetite-rich zone separates the lower layered gabbro from the upper homogeneous gabbro. The zone varies in thickness and reaches a maximum width of 20 m. The magnetite-rich zone contains sulphide-rich bands variably enriched in pyrrhotite. About 5 m of the zone is semi-massive and contains 20 vol.% ilmenite, 10 vol.% magnetite and 5 vol.% pyrrhotite, and less than 1 % chalcopyrite (Birkedal 1998). Samples of the ilmenite-magnetite horizon carry about 0.26 % V_2O_5 (Armitage 2011).

Tracts with resource potential for titanium vanadium mineralisation (Figure 26)

Thule Black Sand Province, North-West Greenland

This province, defined by Dawes (1989) encompasses ilmenite-rich placers, related to active, raised, and drowned beaches, known from along the coast of North-West Greenland, between Kap Edvard Holm (76°N) and Kap Alexander (78°N). These placers are enriched in ilmenite and/or magnetite derived from Neoproterozoic titanium-rich dolerite sills and dykes in the immediate hinterland of the beaches. Two ongoing projects, discussed above, focus on these placers.

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

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

4. Conclusions and outlook

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

The carried-out review confirms that the endowment of several CRMs of Greenland can be considered plentiful. The geographical distribution of this endowment is shown in Figure 27, whereas Table 31 summarizes the known resource in Greenland for each CRM. In total there are 35 deposits with resource estimates, many of which for multiple CRMs (Appendix 1 CRM deposits in Greenland). The quantified resources are considerable for many of CRMs (Table 31), often even in a global context. However, it is important to note that the resource estimates for most of the individual deposits are historical, non-compliant assessments (n = 43 of 55, corresponding to 78 %). Thus, the estimated CRM tonnages are associated with large uncertainties and need further verification through resource evaluations that are up to modern standards.

Although better quantification of resource numbers is desirable, it is already possible to point out some deposits that are particularly interesting due to their large CRM potential. Among the most outstanding deposits are the very large, rare earth element (REE) deposits, some also hosting very significant Li, F, Ta, Nb, Hf and/or Zr resources, at Kringlerne/ Killavaat Alannguat, Kvanefjeld/Kuannersuit, Sørensen, Zone 3 (of the Illímaussaq intrusion) and Motzfeldt, in South Greenland. Further large REE and P resources, have been identified at Sarfartoq southern West Greenland. East Greenland stands out by hosting the very large Malmbjerg Mo deposit, the very large Karstryggen Sr deposit, and the large PGM-Ti-V Skaergaard deposit. Also significant are the large feldspar deposits at Majoqqap Qaava and Qaqortorsuaq (southern West Greenland), the large Amitsoq graphite deposit (South Greenland), and the large Ti deposits at Isortoq (South Greenland) and Moriusaq (North-West Greenland), the former also hosting significant V.

The established endowment can be considered, in many cases, comparable to that found in well-established mining regions such as Australia, Canada, and Scandinavia. However, in contrast to these regions, mining in Greenland has to date only taken place in a few sites or at a relatively modest scale. This is partly due to the fact that Greenland faces some specific challenges, e.g., harsh and remote Arctic conditions, lack of infrastructure and high operational costs, which to some extend have hindered development of mining projects (Thaarup *et al.* 2020, Christiansen *et al.* 2022). However, these challenging conditions do not not necessarily have to be a limiting factor for mining operations in Greenland, as the revenue of well-founded projects should be more than capable of offsetting these relatively higher costs (Thaarup *et al.* 2020). Particularly with dwindling resources and high future demands of CRMs (e.g., Hund *et al.* 2020; Watari *et al.* 2021), which most likely will increase commodities prices, Greenlandic deposits could become more economically viable in the future.

Due to its relatively underexplored status, Greenland should be considered to still hold a very significant potential for yet undiscovered deposits. The present review has demonstrated that the mineral deposits and occurrences are in many ways similar to those found world-wide, meaning

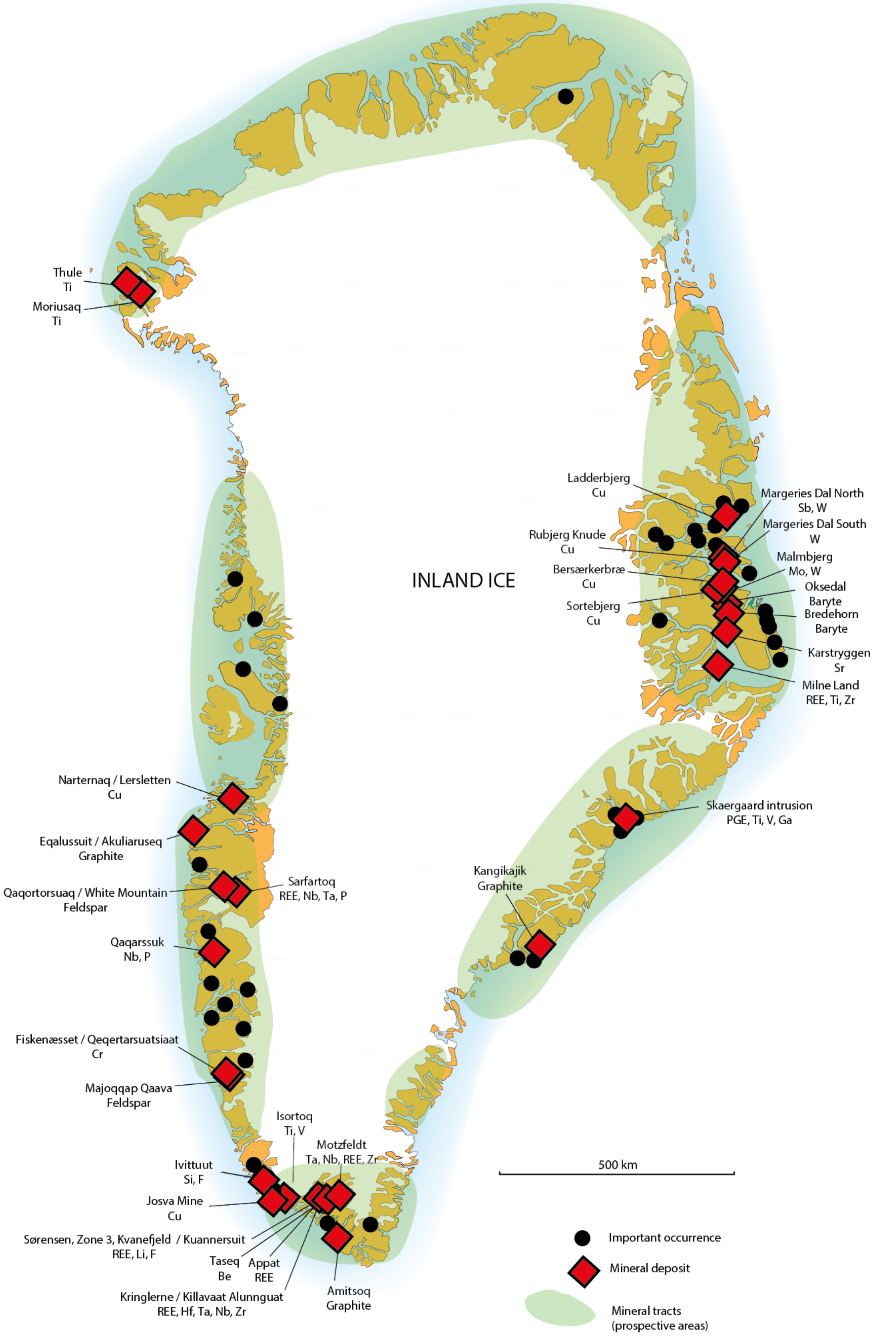

Figure 27 *Summary map showing locations of deposits, important occurrences, and areas with assumed potential for additional CRM resources in Greenland. The map is based on Figures 3-26.*

that the potential for new mineral discoveries which can sustain mining are excellent. Naturally, such potential encompasses CRM in the areas for which resources have already been established, listed above. But the potential for undiscovered deposits can also be extended to W, Sn, and Sb in veins, skarns and greisens, or sedimentary Cu in Eastern Greenland. A significant potential for undiscovered Ni, Cu and Co in magmatic deposits is expected in Western Greenland, whereas undiscovered Zn and Pb deposits, from which Ge and Ga can be possible by-products, are predicted in North Greenland. Finally, undiscovered graphite deposits are thought to exist in Palaeoproterozoic terranes (West, South and East Greenland).

Table 31 *Overview of known CRM resources in Greenland.*

Commodity	Contained resource (t)	Commodity	Contained resource (t)
Antimony (Sb)	3,780	Niobium (Nb)	5,900,000
Baryte (Ba)	480,000	Phosphorus (P)	11,500,000
Beryllium (Be)	65	Platinum group metals (PGM)	576
Chromium (Cr)	560,000	Rare earth elements (REE)	36,100,000
Copper (Cr)	108,000	Silicon metal (Si)	2,800,000
Feldspar	80,800,000	Strontium (Sr)	9,800,000
Fluorite ($CaFl_2$)	250,000	Tantalum (Ta)	916,000
Gallium (Ga)	152,000	Titanium (Ti)	12,100,000
Graphite (C)	6,000,000	Tungsten (W)	26,200
Hafnium (Hf)	108,000	Vanadium (V)	179,000
Lithium (Li)	235,000	Zirconium (Cr)	57,100,000

Rounded total resources of the CRMs assessed in this report based on summed resource estimations of individual deposits given in Appendix 1.

Clearly the fact that most of Greenland is covered by areas with assumed potential for additional CRM resources (Figure 27) highlights a possibly large untapped mineral potential that needs to be further explored. Despite the large potential for CRMs in Greenland documented here, it is concluded that the knowledge base for most of the CRMs in Greenland remains poor and essential data and information is missing. Thus, if Greenland shall contribute to meet the future CRM needs, it is recommended that further research which can support CRM exploration and mining is established. This could include (but is not limited to) more modern geophysical and/or geochemical mapping, in combination with geological mapping, which could facilitate to constrain the mineral potential, define prospective areas, and assist in attracting mineral exploration companies.

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Appendix 1 CRM deposits in Greenland

Commodity	Deposit name	Alternative name	Latitude	Longitude	Status	Resource tonnage (Mt)	Contained resource (t)	Reporting standard	Size category[1]
Antimony	Margeries Dal North		73.2242	-24.8446	Unexploited	0.11	3,780	Historical, non-compliant	Medium sized deposit
Baryte	Oksedal		72.0691	-23.4814	Unexploited	0.44	264,000	Historical, non-compliant	Medium sized deposit
Baryte	Bredehorn		71.8553	-24.0120	Unexploited	0.30	216,000	Historical, non-compliant	Medium sized deposit
Beryllium	Ilímaussaq, Taseq		60.9500	-45.9670	Unexploited	0.18	65	Historical, non-compliant	Very small deposit
Chromium	Fiskenæsset	Qeqertarsuatsiaat	63.2730	-50.0410	Unexploited	2.50	560,000	Historical, non-compliant	Medium sized deposit
Copper	Bersærkerbræ		72.2415	-24.6120	Unexploited	0.1	2,500	Historical, non-compliant	Very small deposit
Copper	Sortebjerg		72.0931	-24.0306	Unexploited	0.22	1,540	Historical, non-compliant	Very small deposit
Copper	Josva Mine		60.8666	-48.1414	Closed mine	0.0025	88	Historical, non-compliant	Very small deposit
Copper	Ladderbjerg		73.5539	-22.0164	Unexploited	2.5	3,750	Historical, non-compliant	Very small deposit
Copper	Naternaq	Lersletten	68.4073	-51.9437	Unexploited	3.6	97,200	Historical, non-compliant	Small deposit
Copper	Rubjerg Knude		72.6802	-23.6129	Unexploited	8.5	2,550	Historical, non-compliant	Very small deposit
Feldspar	Majoqqap Qaava		63.2748	-50.0632	Unexploited	21,800,000	21,800,000	CIM	Large deposit
Feldspar	Qaqortorsuaq	White Mountain	66.5349	-52.3080	Mine	59,000,000	59,000,000	NI 43-101	Large deposit
Fluorite	Ivittuut		61.2003	-48.1454	Unexploited	0.50	250,000	Historical, non-compliant	Medium sized deposit
Gallium	Skaergaard intrusion		68.1819	-31.6690	Unexploited	1,520	152,000	Historical, non-compliant	Medium sized deposit
Graphite	Amitsoq		60.2910	-45.1190	Closed mine	23.1	4,704,505	JORC 2012	Large deposit
Graphite	Eqalussuit	Akuliaruseq	67.6460	-53.5820	Unexploited	12.6	793,800	Historical, non-compliant	Medium sized deposit
Graphite	Kangikajik		66.0980	-35.9250	Unexploited	5.56	500,400	Historical, non-compliant	Medium sized deposit
Hafnium	Ilímaussaq, Kringlerne	Killavaat Alannguat	60.8683	-45.8377	Unexploited	4,300	107,500	Historical, non-compliant	Very large deposit
Lithium	Ilímaussaq, Kvanefjeld	Kuannersuit	60.9727	-45.9989	Unexploited	124	235,000	Historical, non-compliant	Large deposit
Molybdenum	Malmbjerg		71.9540	-24.2710	Unexploited	315	323,541	NI 43-101	Very large deposit
Niobium	Ilímaussaq, Kringlerne	Killavaat Alannguat	60.8683	-45.8377	Unexploited	4,300	5,409,400	Historical, non-compliant	Very large deposit
Niobium	Motzfeldt		61.1984	-44.9397	Unexploited	340	442,000	Historical, non-compliant	Large deposit

Commodity	Deposit name	Alternative name	Latitude	Longitude	Status	Resource tonnage (Mt)	Contained resource (t)	Reporting standard	Size category[1]
Niobium	Qaqarssuk	Qeqertaasaq	65.3602	-51.6701	Unexploited	1.20	6,710	Historical, non-compliant	Small deposit
Niobium	Sarfartoq		66.4762	-51.2944	Unexploited	0.06	2,490	Historical, non-compliant	Small deposit
Phosphorus	Qaqarssuk	Qeqertaasaq	65.3602	-51.6701	Unexploited	0.80	30,026	Historical, non-compliant	Very small deposit
Phosphorus	Sarfartoq		66.4762	-51.2944	Unexploited	750	11,456,025	Historical, non-compliant	Large deposit
PGM	Skaergaard intrusion		68.1819	-31.6690	Unexploited	364	576 [2]	NI 43-101	Large deposit
REE	Ilímaussaq, Appat		70.9020	-51.7510	Unexploited	3.20	25,600	Historical, non-compliant	Medium sized deposit
REE	Ilímaussaq, Kringlerne	Killavaat Alannguat	60.8683	-45.8377	Unexploited	4,300	24,080,000	Historical, non-compliant	Very large deposit
REE	Ilímaussaq, Kvanefjeld	Kuannersuit	60.9727	-45.9989	Unexploited	673	5,787,800	JORC 2012	Very large deposit
REE	Ilímaussaq, Sørensen	Kuannersuit	60.9833	-45.9833	Unexploited	242	2,105,400	JORC 2012	Very large deposit
REE	Ilímaussaq, Zone 3	Kuannersuit	60.9667	-46.0000	Unexploited	95.0	902,500	JORC 2012	Very large deposit
REE	Milne Land		70.6853	-25.9195	Unexploited	4.00	36,000	Historical, non-compliant	Medium sized deposit
REE	Motzfeldt		61.1984	-44.9397	Unexploited	340	3,060,000	Historical, non-compliant	Very large deposit
REE	Sarfartoq		66.4762	-51.2944	Unexploited	8.40	126,000	NI43-101	Large deposit
Silicon metal	Ivittuut		61.2003	-48.1454	Unexploited	6.63	2,797,860	Historical, non-compliant	N.A. [3]
Strontium	Karstryggen		71.5550	-24.6840	Unexploited	37.5	9,836,250	Historical, non-compliant	Very large deposit
Tantalum	Ilímaussaq, Kringlerne	Killavaat Alannguat	60.8683	-45.8377	Unexploited	4,300	881,500	Historical, non-compliant	Very large deposit
Tantalum	Motzfeldt		61.1984	-44.9397	Unexploited	340	34,000	Historical, non-compliant	Very large deposit
Tantalum	Sarfartoq		66.4762	-51.2944	Unexploited	0.10	147	Historical, non-compliant	Very small deposit
Titanium	Isortoq		60.9632	-47.4396	Unexploited	70.3	4,569,500	NI43-101	Large deposit
Titanium	Milne Land		70.6853	-25.9195	Unexploited	4.00	108,000	Historical, non-compliant	Small deposit
Titanium	Moriusaq		76.7753	-70.0850	Unexploited	117	2,038,674	JORC 2012	Large deposit
Titanium	Thule		76.8440	-70.7954	Unexploited	19.0	532,000	Historical, non-compliant	Medium sized deposit
Titanium	Skaergaard intrusion		68.1819	-31.6690	Unexploited	104	4,867,200	Historical, non-compliant	Large deposit
Tungsten	Malmbjerg		71.9540	-24.2710	Unexploited	150	24,000	Historical, non-compliant	Medium sized deposit
Tungsten	Margeries Dal North		73.2242	-24.8446	Unexploited	0.04	294	Historical, non-compliant	Very small deposit
Tungsten	Margeries Dal South		73.0933	-24.6516	Unexploited	0.08	1,886	Historical, non-compliant	Small deposit
Vanadium	Isortoq		60.9632	-47.4396	Unexploited	70.3	56,240	NI43-101	Large deposit

Commodity	Deposit name	Alternative name	Latitude	Longitude	Status	Resource tonnage (Mt)	Contained resource (t)	Reporting standard	Size category[1]
Vanadium	Skaergaard intrusion		68.1819	-31.6690	Unexploited	104	122,341	Historical, non-compliant	Large deposit
Zirconium	Ilímaussaq, Appat		70.9020	-51.7510	Unexploited	3.20	25,600	Historical, non-compliant	Medium sized deposit
Zirconium	Ilímaussaq, Kringlerne	Killavaat Alannguat	60.8683	-45.8377	Unexploited	4,300	55,900,000	Historical, non-compliant	Very large deposit
Zirconium	Milne Land		70.6853	-25.9195	Unexploited	4.00	44,000	Historical, non-compliant	Medium sized deposit
Zirconium	Motzfeldt		61.1984	-44.9397	Unexploited	340	1,156,000	Historical, non-compliant	Very large deposit

[1]Size classifications are based on the EU Inspire specifications https://inspire.ec.europa.eu/documents/Data_Specifications/INSPIRE_DataSpecification_MR_v3.0_rc2.pdf except very small deposits that corresponds to the occurrence category in Inspire.
[2]PGMs in the Skaergaard intrusion constitue 533 t Pd and 43 t Pt.
[3]N.A. – Not Available (no size categories are defined for silicon metal in the Inspire system).

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