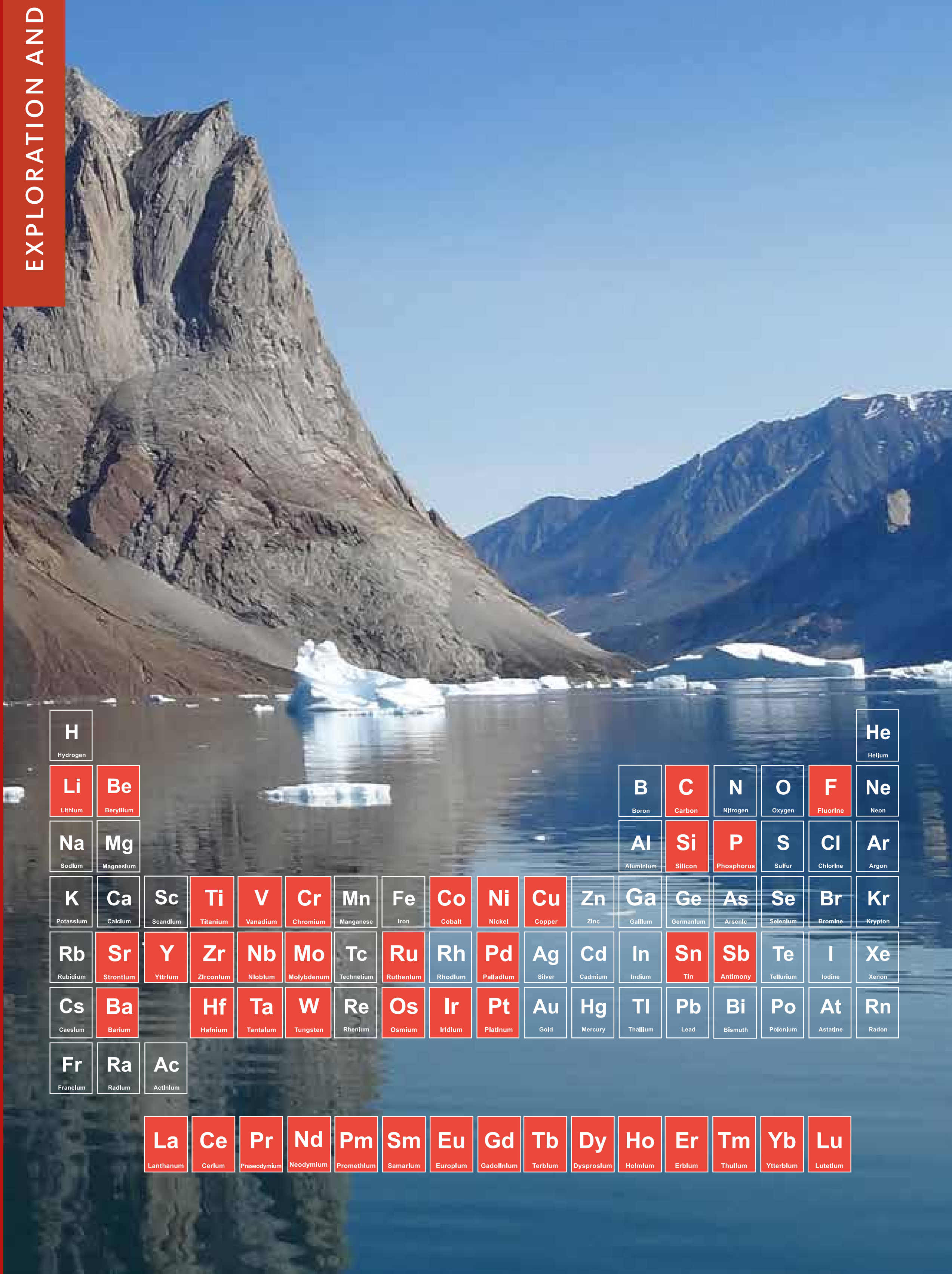
GEOLOGY AND ORE

EXPLORATION AND MINING IN GREENLAND

Critical raw material resources in Greenland



Critical raw material resources in Greenland

Critical Raw Materials (CRMs) are materials that have a large economic importance in industry and whose supply has a high risk of disruption. As such, these can be considered essential to society, namely as the building blocks for our green and digital economy.

The Center for Minerals and Materials (MiMa) under the Geological Survey of Denmark and Greenland (GEUS) has reviewed the CRM resource potential of Greenland. This highlighted the Gardar alkaline province in South Greenland as an exceptional accumulation of CRMs. This is documented by the known rare earth element deposits, some also hosting very significant lithium, fluorite, tantalum, niobium, hafnium and/or zirconium resources, namely the very large deposits at Kvanefjeld/Kuannersuit, Kringlerne/Killavaat Alannguat and Motzfeldt. East Greenland stands out by hosting the very large Malmbjerg molybdenum deposit and the large platinum group metals, gold, titanium and vanadium Skaergaard deposit, both related to Palaeogene intrusions, as well as the very large evaporitic Karstryggen strontium 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 potential for granite-related tungsten, tin, and antimony, as well as sedimentary copper mineralisation. The West Greenland Palaeogene Province is thought to hold a large potential for conduit-type nickel-copper-cobalt-platinum group metals mineralisation. West Greenland also hosts the large feldspar deposits at Majoqqap Qaava and Qaqortorsuaq and the large rare earth element and phosphorus Sarfartoq deposit. The Palaeoproterozoic terranes in West, South and East Greenland, have a substantial 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, illustrated by the Moriusaq deposit. Finally, the Palaeozoic Franklinian Basin of North Greenland has a very significant potential for zinc and lead deposits, from which gallium and germanium can be possible by-products.

What are critical raw materials?

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. 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, and various definitions of mineral criticality have been suggested. 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.

The European Commission (EC) carried out its first criticality analysis for raw materials in 2010, with its latest revision in 2023. The methodology for the EC criticality assessment is based on the criteria of supply risk (SR) and economic importance (EI), with thresholds of SR > 1.0 and EI > 2.8 (plot on page 4). In the latest EC assessment, 67 individual raw materials and three materials groups were assessed, of which 32 surpassed the CRMs thresholds and were therefore considered as critical. In addition, even though Cu and Ni do not meet the thresholds for CRMs, these were designated by the EC as strategic raw materials, and were therefore included in the CRM list, adding up to 34 (shown in red in plot on page 4). Furthermore, whereas Cr, Mo, Sn and Zr are not strictly considered as critical, these are economically important metals with a relative high supply risk and were therefore considered as near-critical and included in the assessment carried out by GEUS (shown in green in plot on page 4), summarised here. As a result, this summary encompasses 38 CRMs.

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, assessment 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.

Detailed geological maps as well as comprehensive geophysical and geochemical data exist for most of the ice-free areas of Greenland. Furthermore, decades of mineral exploration campaigns undertaken by the mineral exploration companies have provided a wealth of detailed data, namely resource estimates of known deposits. Most of this data can be accessed in publicly available reports from the Geological Survey of Denmark and Greenland (GEUS) and the Ministry of Mineral Ressources (MMR) on the Greenland Mineral Resource Portal found on the webpage www.greenmin.gl. Finally, GEUS and MMR have since 2009 held annual regional mineral resource assessments (MRAP) workshops on selected commodities. These workshops, which provided insights into the potential for undiscovered resources, coupled with the resource estimates of known deposits carried out by exploration companies, constituted the backbone for the assessment summarised here.

It should be noted that some CRMs can be of economic interest by themselves, while others constitute by-products obtained during mineral beneficiation or further downstream supply chain steps. 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, 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, was in some instances merely based on the identification of favourable geological contexts.

Known CRM deposits of Greenland

The wide concept of mineral occurrence covers any locality where a useful mineral or material is found. This includes mineral deposits, 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.

Table 1 summarises the known resource for each CRM in Greenland. The quantified resources are considerable for many of CRMs, often even in a global context. However, it is important to note that the resource estimates for most (78 %) of the deposits are historical, non-compliant assessments. Thus, the estimated CRM tonnages are often associated with large uncertainties and need further verification through resource evaluations that are up to modern standards.

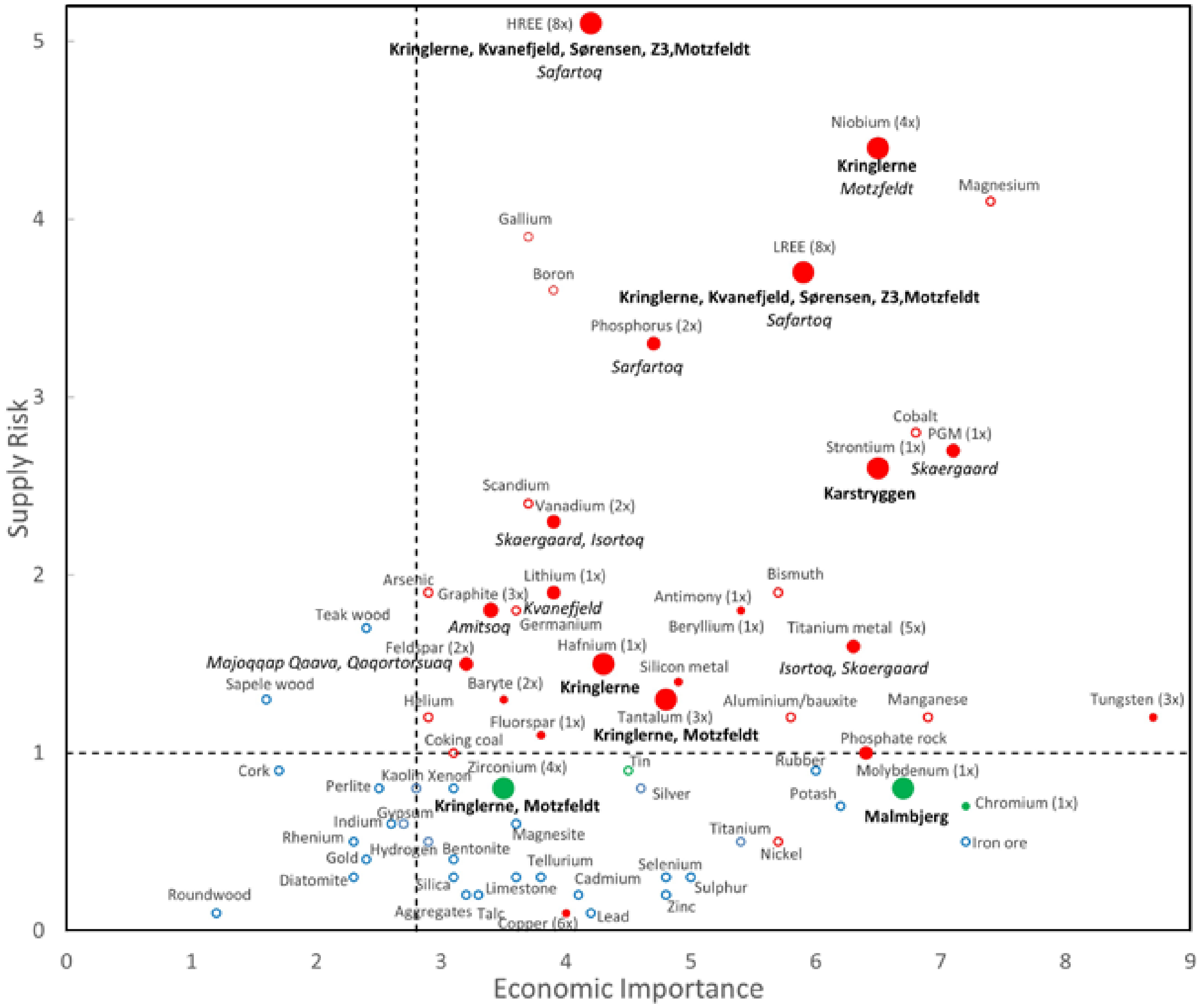
Table 1 *Overview of known CRM resources in Greenland*

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 (Cu)	75,200	Silicon metal (Si)	2,800,000
Feldspar	111,500,000	Strontium (Sr)	9,800,000
Fluorite ($CaFl_2$)	250,000	Tantalum (Ta)	916,000
Graphite (C)	6,000,000	Titanium (Ti)	11,500,000
Hafnium (Hf)	108,000	Tungsten (W)	26,200
Lithium (Li)	235,000	Vanadium (V)	179,000
Molybdenum (Mo)	323,541	Zirconium (Zr)	57,100,000

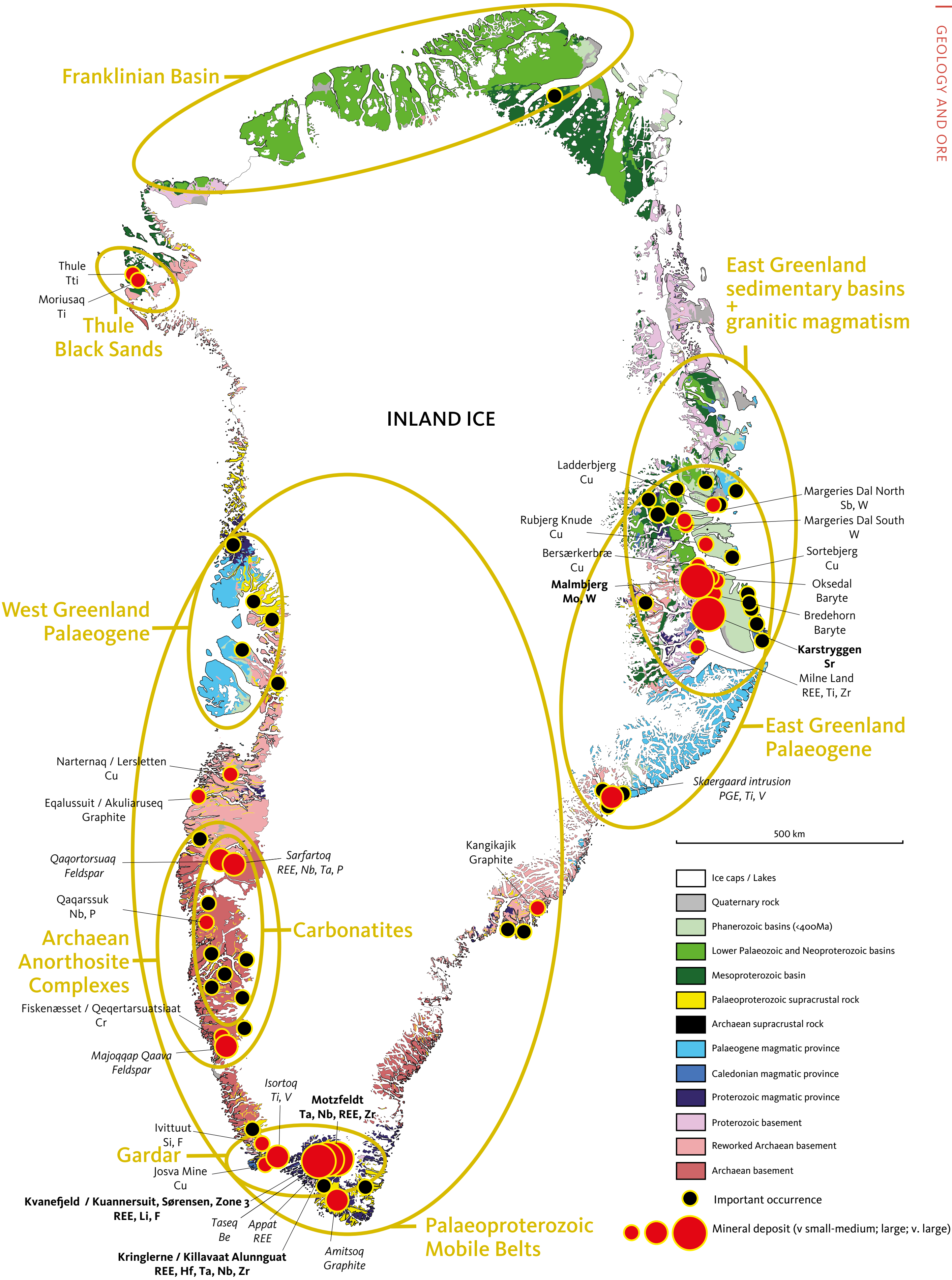
In total there are 33 deposits with resource estimates, many of which for multiple CRMs, and their geographical distribution is shown in the Map on page 5. Although better quantification of resource numbers is warranted, it is already possible to point out some deposits that are particularly relevant in terms of their CRM potential. The plot below shows the magnitude of these estimates for different CRMs.

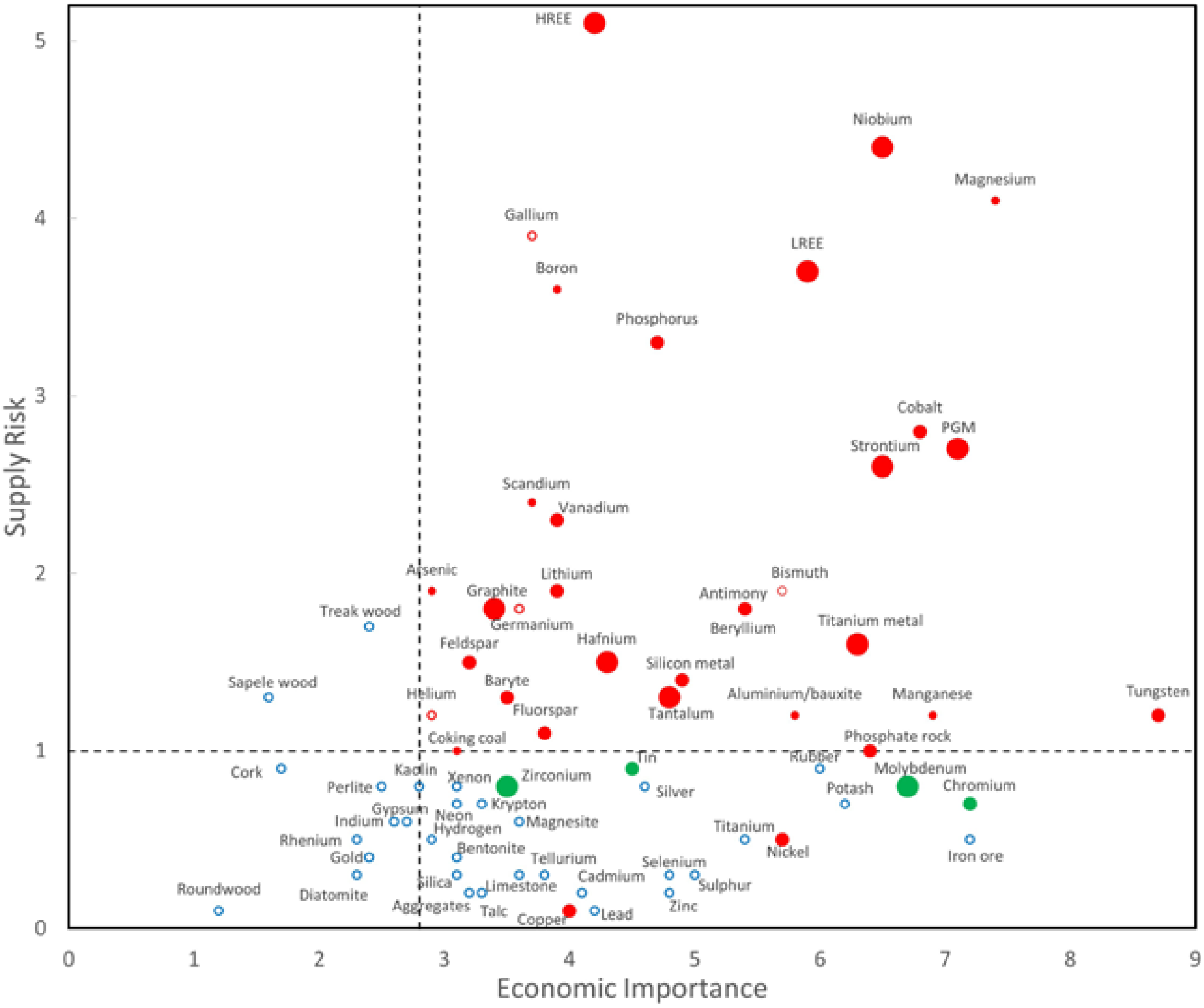
Among the most outstanding deposits are the very large, REE deposits, some also hosting very significant Li, F, Ta, Nb, Hf and/or Zr resources, at Kringlerne/Killavaat Alannguat, Kvanefjeld/Kuannersuit, Sørensen, Zone 3 (of the Illímaussaq intrusion) and Motzfeldt, in South Greenland. East Greenland stands out by hosting the very large Malmbjerg Mo deposit, the very large Karstryggen Sr deposit, and the large PGM-Au-Ti-V Skaergaard deposit. Also significant are the large feldspar deposits at Majoqqap Qaava and Qaqortorsuaq and the large REE-P Sarfartoq deposit (southern West Greenland), as well as the large Amitsoq graphite deposit and the large Ti-V Isortoq deposit (South Greenland).

Geographical distribution of known CRM occurrences and deposits in Greenland. Deposit symbols are sized according to Inspire deposit size categories for most important commodity at each deposit: very small to medium, large (deposit names in italics), or very large (deposit names in bold). Yellow ellipses show extent of provinces discussed in the text.



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, whereas those shown in green were considered as near-critical and considered in the CRM assessment made by GEUS. Raw materials shown in blue are not considered critical and are therefore not part of the assessement. Filled symbols sized according to EU Inspire deposit size categories for each given commodity at the largest known Greenlandic deposit: very small to medium, large (deposit names in italics), or very large (deposit names in bold), empty symbols-unassessed/unknown deposits in Greenland. Numbers in brackets are the number of deposits with resource estimates.


Franklinian Basin
Thule
Tti
Moriusaq
Ti
Thule
Black Sands
INLAND ICE
East Greenland
sedimentary basins
+
granitic magmatism
Ladderbjerg
Cu
Rubjerg Knude
Cu
Bersærkerbræ
Cu
Malmbjerg
Mo, W
Margeries Dal North
Sb, W
Margeries Dal South
W
Sortebjerg
Cu
Oksedal
Baryte
Bredehorn
Baryte
Karstryggen
Sr
Milne Land
REE, Ti, Zr
East Greenland
Palaeogene
Skaergaard intrusion
PGE, Ti, V
West Greenland
Palaeogene
Narternaq / Lersletten
Cu
Eqalussuit / Akuliaruseq
Graphite
Qaqortorsuaq
Feldspar
Sarfartoq
REE, Nb, Ta, P
Qaqarssuk
Nb, P
Archaean
Anorthosite
Complexes
Carbonatites
Kangikajik
Graphite
Fiskenæsset / Qeqertarsuatsiaat
Cr
Majoqqap Qaava
Feldspar
Isortoq
Ti, V
Motzfeldt
Ta, Nb, REE, Zr
Ivittuut
Si, F
Gardar
Josva Mine
Cu
Kvanefjeld / Kuannersuit, Sørensen, Zone 3
REE, Li, F
Taseq
Be
Appat
REE
Kringlerne / Killavaat Alannguat
REE, Hf, Ta, Nb, Zr
Amitsoq
Graphite
Palaeoproterozoic
Mobile Belts
500 km
Ice caps / Lakes
Quaternary rock
Phanerozoic basins (<400Ma)
Lower Palaeozoic and Neoproterozoic basins
Mesoproterozoic basin
Palaeoproterozoic supracrustal rock
Archaean supracrustal rock
Palaeogene magmatic province
Caledonian magmatic province
Proterozoic magmatic province
Proterozoic basement
Reworked Archaean basement
Archaean basement
Important occurrence
Mineral deposit (v small-medium; large; v. large)



CRM resource potential of Greenland (known deposits and undiscovered resources): empty symbols-unassessed/unknown; filled symbols sized according to potential: low, moderate or high.

Drilling at the Majoqqap Qaava anorthosite deposit (Photo: Greenland Anorthosite Mining)

CRM resource potential of Greenland

Looking beyond the known deposits resource estimate figures, namely by also considering the potential for undiscovered resources suggested by the MRAP workshops, resulted in a wider assessment of CRM resource potential (plot above). As a result of this evaluation, the resource potential in Greenland for As, bauxite, borate, coking coal, Sc (from bauxite), Mn and Mg was generally considered low, the lack of known deposits of these CRMs being a reflection of that. For Bi, Ga, Ge and He there is a potential, but its magnitude is not known. For the remainder 27 commodities assessed, Greenland is estimated to hold moderate to high resource potential (plot above). Naturally, CRMs for which Greenland hosts well known, very large and/or large deposits, discussed above, translate into high resource potential for REE, Nb, Ta, Zr, Hf, PGM, Sr, Mo, Ti and graphite. But additionally, Ni, Co, Cu, V, Cr, P, W, Sn, Li, Sb, fluorite, and silicon also emerge as commodities for which Greenland is thought to have a moderate potential.

Carbonatite in Sarfartoq drill core (Photo: Hudson Resources Inc)

Main provinces and deposits

Archaean anorthosite complexes, southern West Greenland

Anorthosites are a source for high quality feldspar with low levels of impurities that is used in demanding and expanding industries such as fiberglass and could be a possible resource for alumina in the future. The highest concentration of anorthosite complexes in Greenland is found in the core of the Archaean block around Nuuk, which includes two large feldspar deposits. The Qaqortorsuaq (White Mountain) deposit was discovered in the 1940s by the Geological Survey of Greenland and today Lumina Sustainable Materials has a fully permitted mining project for anorthosite, with a 43-101 resource model outlining 27 Mt of indicated and 32 Mt of inferred resources at Na2O cut-off of 2.5 wt%.

The Majoqqap Qaava is part of the Fiskenæsset (Qeqertarsuatsiaat) Complex which is a single stratiform intrusion with anorthosites, gabbros and ultramafic rocks. Majoqqap Qaava represents the best preserved and most continuous part of the complex which has been intensively metamorphosed and folded. An indicated/inferred resource of 52.5 Mt has been defined by Greenland Anorthosite Mining (CIM standard terms). In addition to feldspar, the Fiskenæsset complex also hosts resource potential for Cr, PGM, Ti and V.

Amitsoq graphite deposit (Photo: Greenroc Mining plc)

Carbonatites, southern West Greenland

Carbonatites were emplaced between the Archaean and the Jurassic, of which several hold a potential for CRMs, typically as pyrochlore (REE, Nb, Ta) and apatite (P). The 565 Ma old Sarfartoq Complex is situated between the Archaean block and the Nagssugtoqidian mobile belt. The complex consists of a dolomite-rich core zone of carbonatites surrounded by a fenitzed aureole zone that is cut by carbonatite veins, breccias and agglomerates. The younger Qaqarssuk carbonatite was emplaced around 170 Ma ago into Archaean basement, accompanied by extensive fenitization. The complex consists of a central unit of olivine søvite, and rauhaugite ring dykes and a late-state outer suite of fine-grained rauhaugite and søvite sheets.

Other mineralised carbonatites complexes in this province include the Tikiussaq and the Grønnedal-Ika complex. However, no resource estimates have been defined for these occurrences.

Palaeoproterozoic terranes South, West and 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

Rhythmic cumulates in kakortokite, Kringlerne REE, Ta, Nb, Zr, Hf deposit (Photo: P. Kalvig)

material, under appropriate metamorphic conditions, has been transformed into graphite. This has been reported from many localities, with Amitsoq, Akuliaruseq and the Kangikajik deposits being the most important deposits.

The Amitsoq deposit, South Greenland has been mined from 1915 to 1924, producing about 6,000 tons graphite ore averaging 21 % Cg. Recently, Greenroc Mining Plc has identified a JORC compliant resource of 23 Mt at an average grade of 20.4 wt% Cg, giving a total contained graphite content of 4.7 Mt.

The Akuliaruseq (also referred to Eqalussuit) graphite deposit, West Greenland, is characterised by accumulation of graphite within a supracrustal sequence composed of foliated biotite garnet ± graphite ± sillimanite gneiss, locally interlayered with amphibolite. Graphite Field Resources Ltd. estimated a graphite resource of 12.6 Mt grading 6.3 wt% Cg including a high-grade zone encompassing 8.9 Mt grading 7.6 wt% Cg.

Finally, flake graphite is known from the Kangikajik deposit, South-East Greenland, with an estimated resource of about 500,000 t of graphite at 9 wt% Cg.

Motzfeldt Ta-Nb REE deposit (Photo: P. Kalvig)

Mesoproterozoic Gardar Province, South Greenland

The 1300–1140 Ma Gardar period involved continental rifting, sedimentation, and alkaline magmatism. Numerous dykes and 14 intrusion complexes were formed. Residual magmas and fluids resulting from extreme magmatic differentiation, possibly combined with assimilation of older crust, created large mineral deposits of predominately specialty metals. Of particular interest is the Ilímaussaq intrusion, which is unusual in terms of the enrichment of REE, Nb, Be, Zr, Li, F U and Th, reflected in the number of minerals recorded. This intrusion hosts two different types of REE deposits; Kvanefjeld/Kuannersuit, dominated by lujavrites, and Kringlerne/Killavaat Alannguat, dominated by kakortokite cumulates. Total resources of REE from the Kvanefjeld and the Kringlerne deposits amount to over 24 Mt and 8.8 Mt, respectively; with the former also having resources of F, Li, Zn, U, and Th and the latter containing resources of Hf, Nb, Ta and Zr.

Other important deposits in the Gardar Province include Ivittuut which was mined for cryolite (Na_3AlF_6) in 1854-1987 and has resources of F and high-quality quartz (a possible source for silicon metal) as well as the Motzfeldt Ta-Nb-REE deposit at in the Igaliko complex. Finally, the Gardar Province has mafic dykes of which some have potential for

Ti-V(-Fe) mineralisation, as exemplified by the Isortoq deposit with an estimated resource of 70.3 Mt grading 10.9 wt% TiO_2 and 0.144 wt% V_2O_5.

Franklinian Basin, North Greenland

The Franklinian Basin in North Greenland evolved along a passive continental margin during the early Phanerozoic and features a southern, shallow shelf dominated by carbonates, reaching 3 km in thickness, and a northern slope with moderate water depth leading to a deep water through sediments, characterized by siliciclastic rocks with thickness of approximately 8 km. The Franklinian Basin is thought to host a significant potential for Zn-Pb mineralisation (as Mississippi Valley-type and sedimentary-exhalative deposits), from which Ge and Ga can be possible by-products.

Turesø Formation, hosting Mississippi Valley-Type mineralisation, Franklinian Basin (Photo: D. Rosa)

East Greenland sedimentary basins

The Neoproterozoic Eleonore Bay Supergroup comprises a thick succession of shallow-water sedimentary rocks, with stratabound Cu occurrences in eight stratigraphic levels found along more than 300 km. Several very small Cu deposits have been identified, however, due to its remote location, only limited exploration efforts have been conducted.

Neoproterozoic Eleonore Bay Supergroup, as seen in Antarctic Sund, East Greenland (Photo: M. Sønderholm)

The Permo-Triassic Jameson Land Basin, related to continental breakup, consists of conglomerates, sandstones, shales, carbonates, and evaporites, with reduced-facies Cu deposits. Copper occurrences within the Ravnefjeld Formation are widespread and have been compared with the European Kupferschiefer. Stratabound celestite (a source of Sr) and baryte mineralisation has been identified in the Karstryggen Formation, a marine marginal carbonate and evaporite sequence, dominated by limestone deposited in a hypersaline shallow marine environment.

East Greenland granitic magmatism

Caledonian plutonic rocks have been emplaced between Scoresby Sund and

Blokadegletscher with Parkinson Bjerg granite intrusion in background, East Greenland (Photo: D. Rosa)

Macrorhytmic layering in the Skaergaard intrusion, East Greenland, containing the PGM-Au-Ti-V Platinova Reef deposit (Photo: C. Tegner)

Bessel Fjord. Reduced Silurian and Devonian granitic intrusions are considered fertile and to hold a potential for W, Sn, Bi, Be, Mo in pegmatites, skarns, greisens and veins. Several small occurrences are known, but no significant deposits have yet been identified.

East Greenland Palaeogene Province

The East Greenland Palaoegene volcanic rifted margin which is part of the North Atlantic Igneous Province (NAIP), formed from 63 to 13 Ma. Evidence of magmatism is manifested by voluminous flood basalts, dyke and sill complexes and more than 60 intrusions. Although felsic intrusions constitute an important component, mafic to ultramafic intrusions are most dominant.

The 55 Ma old Skaergaard intrusion, world-famous for its spectacular magmatic layering, hosts a significant orthomagmatic stratiform PGM-Au deposit referred to as the 'Platinova Reef' with a resource of more than 364 Mt grading 1.46 g/t Pd and 0.11 g/t Pt, and significant Au, Ti and V.

The Malmbjerg deposit, which is related to an alkali granite, is dome shaped with an outside diameter of up to 600 m and a height of approximately 150 m,and is extensively hydrothermally altered. Ore resources have been estimated to 315 Mt grading 0.18 wt% MoS2 and the deposit is also endowed in W and Sn.

West Greenland Palaeogene Province

A significant potential for conduit-type Ni-Cu-Co-PGM mineralisation related to picrite and/or tholeiitic basalt dyke-sill complexes is suggested by the low contents of these elements in some crustally contaminated lavas at Disko Island, Nuussuaq and Svartenhuk Halvø. Mineral exploration in this region dates back to the 1870s when the Ni-sulfide bearing Igdlukunguaq dyke was discovered. Massive sulfide from this dyke contains 6.86 wt% Ni, 0.55 wt% Co, 3.71 wt% Cu and 2 ppm PGM. The West Greenland Palaeogene Province shares similarities with the Norilsk system; however, in the West Greenland system, sulfide saturation occurred at a shallower level in the Earth's crust.

Thule Black Sands Province, North-West Greenland

The Thule Black Sands Province, consists of magnetite and ilmenite-rich placers, including the Moriusaq and Thule deposits. The placers are related to active, raised, and drowned beaches along the coast of North-West Greenland. The beach deposits consist of grey to black silt and sand, with imenite and magnetite varying in size between 0.3 and 1.0 mm, with the magnetite containing elevated Co, in addition to the Ti and Fe. The ilmenite is derived from Neoproterozoic Ti-rich dolerite sills and dykes in the immediate hinterland of the beaches.

500 m high mountain slope of iron-rich basalt layers in the southern part of Disko Island, central West Greenland (Photo: A.K.Pedersen)

Rusty hydrothermal alteration halo around the Malmbjerg porphyry Mo deposit (Photo: B. Thomassen)

Conclusions

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.

Confirming this potential are the very large, REE deposits, some also hosting very significant Li, F, Ta, Nb, Hf and/or Zr resources, at Kringlerne/ Killavaat Alannguat, Kvanefjeld/Kuannersuit, Sørensen and Zone 3 (of the Illímaus-saq intrusion) and Motzfeldt, in South Greenland. East Greenland stands out by hosting the very large Malmbjerg Mo deposit, the very large Karstryggen Sr deposit, and the large PGM-Au-Ti-V Skaergaard deposit. Also significant are the large feldspar deposits at Majoqqap Qaava and Qaqortorsuaq and the large REE-P Sarfartoq deposit (southern West Greenland), as well as the large Amitsoq graphite deposit and the large Isortoq Ti-V deposit (South Greenland).

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 because 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. However, these challenging conditions do 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.

Furthermore, due to its relatively under-explored status, Greenland should also be considered to hold a very significant potential for yet undiscovered deposits. 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 East Greenland. A significant potential for undiscovered Ni, Cu, Co and PGM in magmatic deposits is expected in West 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).

Ilmenite-rich black sands in Moriusaq (Photo: Dundas Titanium)

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No. 34 Nov 2023

Front cover photograph
Periodic table of elements with critical and near-critical raw materials, for which Greenland is estimated to hold a moderate to high potential, highlighted in red. Background photograph is the Inukassaat Sulluat fjord in West Greenland.
Photo: P. Guarnieri

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Diogo Rosa, Per Kalvig, Henrik Stendal og Jakob Kløve Keiding

Editor
Kristine Thrane, GEUS

Graphic design
Tegnestuen, GEUS

Printed
November 2023 ©GEUS

Printers
Stibo Complete

ISSN
1602-818X (print)
2246-3372 (online)