GEOLOGY AND ORE

EXPLORATION AND MINING IN GREENLAND

Plutonic environments in Greenland – a potential for new discoveries

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Mineral deposits of plutonic complexes are among the most promising exploration targets in Greenland. Examples are the Malmbjerg molybdenum deposit, the Skaergaard intrusion gold and platinum group element deposit and the Ilimaussaq zirconium, rare-earth element (REE), thorium and uranium deposit. They are all three explored at present and have the potential to become large mining operations. However, many plutonic and hypabyssal provinces in Greenland are still significantly under-explored.

In 2002, GEUS published an overview of all the intrusive complexes in the Palaeogene province in East Greenland (GEUS report, 2002/113). The overview includes basic information and metadata on all the complexes allowing easy access to the basic geological data and non-confidential exploration records. The Palaeogene province in East Greenland is only one out of 23 defined plutonic provinces within the Archaean to Neogene evolution in Greenland. Basic geological data and exploration information on all plutons, sill complexes and dyke swarms in these provinces can be conveniently accessed on the Greenland Portal, at www.greenmin.gl. This issue of 'Geology & Ore' deals with the 23 plutonic provinces in summary outline.

The central part of the Mesozoic Qaqqaarsuk carbonatite complex, southern West Greenland.

Introduction

Intrusive rocks are an integrated part of the geological evolution of Greenland, and provinces of plutons and hypabyssal rocks can be defined in most geological periods. Table 1 lists all provinces in which the plutons, sills and dykes have preserved clear intrusive features and spatial integrity. The provinces are listed according to geological period, from Palaeogene to Archaean, and subsequently clockwise along the coast of Greenland starting in North-East Greenland. The identification number and the province are given in columns 1 and 2. Column 3 gives the main rock types and minor comments, column 4 gives examples of the most important commodities recorded within the province, and column 5 gives a suggestion for the geodynamic environment of the province. The four maps show the Palaeogene, the Mesozoic and Palaeozoic, the Proterozoic, and the Archaean provinces.

Palaeogene provinces

The Palaeogene provinces in East and West Greenland (# 1 and # 2, Map 1) are related to the continental breakup in the North Atlantic. It is a well-known geodynamic environment, often referred to as a Volcanic Rifted Margin (VRM). The tholeiitic flood basalts are among the most voluminous on Earth. The range in magma types in plutonic complexes, sill complexes and dyke swarms is significant, especially in East Greenland. The compositional

Major plutonic provinces in Greenland

	Province	Type of magmatism	Observed commodities	Geotectonic environment
1	Palaeogene magmatism in East Greenland	Ultramafic, gabbro, diorite, monzonite, granite quartz porphyry, syenite, and ultramafic alkaline intrusions Picritic to rhyolitic swarms of dykes and sills	Mo, Au, PGE, Ti, Fe, V, Cu, Ni, P	Volcanic Rifted Margin
2	Palaeogene magmatism, W Greenland	Picritic to basaltic volcanics and dyke swarms; Gabbro and granophyre intrusion	Native Fe,sulphide, Ni-PGE, Au in related veins	Volcanic Rifted Margin
3	Caledonian granites, central E Greenland	Granodiorite and granite intrusions	W, Au, and base metals	Orogenic environment
4	Devonian granites and felsic volcanics, central E Greenland	Lavas, ultramafic alkaline and granite intrusions	W, Au, Ag, base metals, F, and U	Late to post orogenic
5	Mesozoic alkaline magmatism, SW Greenland	Carbonatite complexes, ultramafic lamprophyre and basalt dykes	Nb, Ta, U, REE and P	Continental to rift environmemt
6	Mesozoic lavas, dykes and plugs; N Greenland	Peralkaline lavas, dyke swarms, ultramafic plugs	None known	Related to continental rifting
7	Proterozoic intrusions and volcanics; Ammassalik region, SE Greenland	Syn to post kinematic gabbro, norite and granite intrusions and ultramafic to mafic volcanics and dyke swarms	Ni-Cu-PGE, bae metals, IOCG, and ornamental stone	Orogenic environment
8	Proterozoic Ketilidian intrusions and volcanics, S Greenland	Volcanics and gabbro, monzonite and rapakivi intrusions	Fe, Ti, V, Ni, Au, and U	Orogenic environment
9	Proterozoic Gardar province, SW Greenland	Mafic volcanics and dyke swarms; gabbro, granite, syenite, peralkaline syenite, and carbonatite intrusions	REE, Zr, cryolite, Nb, Ta, Th, U, P, Fe, Ti and V, and possible IOCG	Continental rifting
10	Palaeoproterozic dykes, SW Greenland	Mafic dyke swarms	Possible Ni potential	Continental environmemt
11	Proterozoic alkaline dykes, SW Greenland	Lamproite dyke swarm	None known	Continental environmemt
12	Neoproterozoic ultramafic magmatism, SW Greenland	Carbonatite complex, kimberlite, ailikite, and lamprophyr dykes	Nb, Ta, REE and diamonds	Continental environmemt
13	Proterozoic magmatism in W Greenland	Gabbro, diorite, charnokite and granite intrusions; basalt dyke swarms, lamproite plug	Cu and possible IOCG	Syn- to post-orogenic
14	Palaeoproterozoic in Thule district and Inglefield Land, NW Greenland	Mafic to felsic complexes; late granitoid and gabbwo intrusions	Possible IOCG, Fe	Late kinematic
15	Meso- to Neoproterozoic mafic magmatism, NW Greenland	Basaltic sills, dykes and volcanics	Ti, Fe, Au and base metals	Late kinematic
16	Mesoproterozoic basaltic magmatism; N and NE Greenland	Continental flood basalts and sill complexes	Native Cu	Continental platform
17	Archaean intrusions, Skjoldungen Alkaline Province, SE Greenland	Syn to post kinematic gabbro, granite, syenite, and mafic alkaline intrusions	Magnetite-apatite	Syn-kinematic
18	Archaean ultramafic, gabbro, and norite intrusions, and the tonalite, trondhjemite, granodiorite suite, SW Greenland	Ultramafic, gabbro, anorthosite, norite, and tonalite intrusions; mafic volcanics and dyke swarms	Ni-Cu-PGE, Cr, olivine, Al (anorthite) ruby and korneruppine	Accretional, continental
19	Archaean granites, SW Greenland	Granite and granodiorite intrusions	U and REE	Accretional, continental
20	Archaean carbonatite, SW Greenland	Carbonatite intrusion	Lazurite	
21	Archaean dykes, W Greenland	Mafic dykes	Diamond, Cu-Ni	Continental environmemt
22	Archaean intrusions, W Greenland	Tonalite, trondhjemite, granodiorite, diorite and anorthosite intrusions	None known	Continental environmemt
23	Archaean intrusions in Thule district, NW Greenland	Anorthosite, mafic to felsic, and diorite complexes	None known	Late kinematic

The rhythmic layered gabbros of the Palaeogene Skaergaard intrusion, South-East Greenland. The intrusion hosts a large tonnage of gold and platinum group element mineralisation.

range reflects the impingement of the Proto-Iceland Plume beneath the Greenland crust, the rapid transition from thick continental to relatively thin oceanic crust along the margin of the craton, and a more than 40 million-year duration of magmatism. The duration of the magmatism, the build-up of elevated temperatures, long residence times in feeder systems, and the large volumes of magma facilitated interaction with Archaean and Proterozoic crust. All this may explain the occurrence of molybdenum-bearing quartz-porphyry systems and epithermal mineralisation along the continental margin.

The repeated melting of mantle sources is suggested to be the reason for elevated platinum group element (PGE) contents in tholeiitic lavas, and in turn the formation of PGE reef structures in layered gabbro intrusions such as the Skaergaard intrusion. Magnesium-rich tholeiitic magmas and extensive sill complexes have prompted the search for sill-related Ni-Cu-PGE deposits.

Mesozoic and Palaeozoic provinces

The Mesozoic in Greenland is a comparatively stable period with basin formation and crustal relaxation leading to the formation of dyke swarms and typical continental magmatism (# 5, map 2). Carbonatite complexes and related swarms of ultramafic lamprophyre dykes characterise the Mesozoic of southern Greenland. In the northernmost part of Greenland, in Peary Land, peralkaline and ultramafic magmatism (# 6, map 2) is suggested to be related to the initiation of break-up and sea-floor spreading of the Polar Basin. Initiation of continental separation between Greenland and Canada may be reflected in dyke swarms along the coasts of South-West Greenland.

The Palaeozoic in Greenland is dominated by the formation of the Caledonian Fold Belt along the east coast of Greenland. Two main periods of mainly S-type granite emplacement (# 3, map 2) one in the Neoproterozoic, around 900 Ma ago, and another in the Palaeozoic, around 450–400 Ma ago, account for most of the magmatism related to the Caledonian evolution. The granite complexes are syn- to late kinematic and the geodynamic environment is orogenic. Minor intermediate to felsic volcanics formed during the Caledonian. Vein-type mineralisation is commonly related to the Caledonian granites. Tungsten is a common commodity in these mineralisations.

A younger postkinematic Devonian suite of granitic intrusions (# 4, map 2) was emplaced during relaxation and basin formation in areas affected by the Caledonian. Significant mineralisations are related to these intrusions. Wide zones of epithermal alteration and mineralisation may be related to even small granitic stocks.

Proterozoic provinces

The Proterozoic Ammassalik Mobile Belt (# 7, map 3) hosts early, syn-, and late kinematic gabbroic to granitic plutons. A prominent suite of synkinematic norite intrusions is located centrally in the mobile belt. The norites are emplaced into supracrustal successions

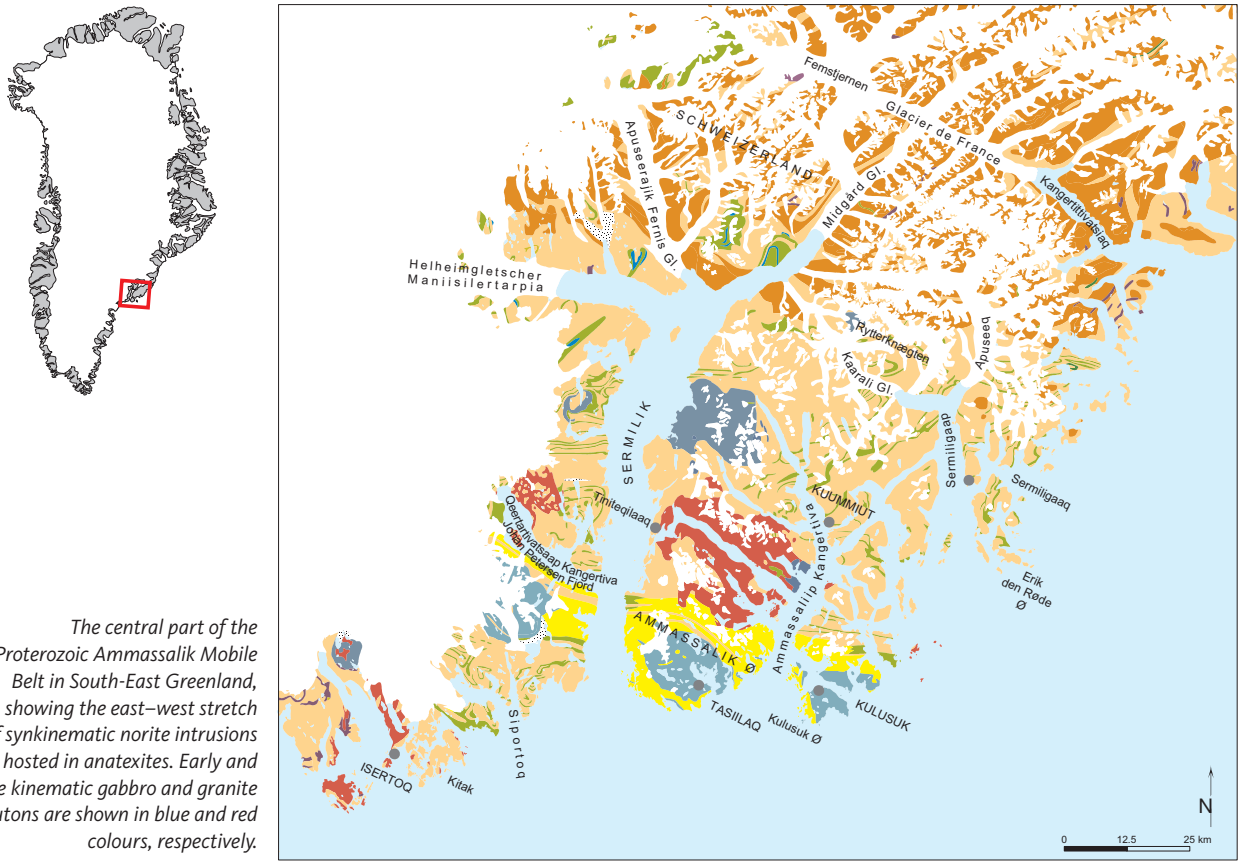
View along creek with exposed sheets of carbonatite into mafic host rock of the Tikiusaaq complex. Intense fracturing with rusty coating characterise the impact zone as seen in the background. Nuuk region, southern West Greenland.

that were transformed into anatexites, and host massive Ni-Cu-PGE mineralisation. The possibility for IOCG (iron oxide-copper-gold) type mineralisation has been suggested. Very little is known about the suites of early kinematic and late kinematic mafic to felsic intrusions.

The Ketilidian orogen (# 8, map 3) in South Greenland is the continuation of the Makkovikian in eastern Canada and together they constitute the Makkovikian– Ketilidian orogen. In Greenland the southern parts of the orogen are characterised by large and voluminous syn- to late kinematic rapakivi granite sheets and minor gabbro and granite plutons. The northern part of the Ketilidian is characterised by the Julianehåb batholith that records an extended period of felsic plutonism and deformation. Only late plutons have escaped significant deformation. The Cordilleran-type orogen includes supracrustal lava successions, both tholeiitic foreland successions and a classic calc-alkaline within-belt succession. The Ketilidian areas are commonly referred to as a gold province due to

The spectacular face of a Caledonian granite intrusion with rafts of host rocks, central East Greenland.

Caledonian monzonite (423 Ma) hosted in migmatised Proterozoic metasediments and granites in Renland, central East Greenland. The rutile-rich monzonite is the wide, dark coloured band one third up the 1800 m high face.



The central part of the Proterozoic Ammassalik Mobile Belt in South-East Greenland, showing the east–west stretch of synkinematic norite intrusions hosted in anatexites. Early and late kinematic gabbro and granite plutons are shown in blue and red colours, respectively.

the many gold-bearing vein mineralisations related to basaltic lithologies, e.g. the Nalunaq gold mine. The Ketilidian formations are also known for uranium mineralisation. Large rafts of supracrustals entrained in rapakivi granites show significant concentrations of uraninite. The batholith granites are in some areas gold-bearing, and gabbros host sulphide and Fe-oxide mineralisation.

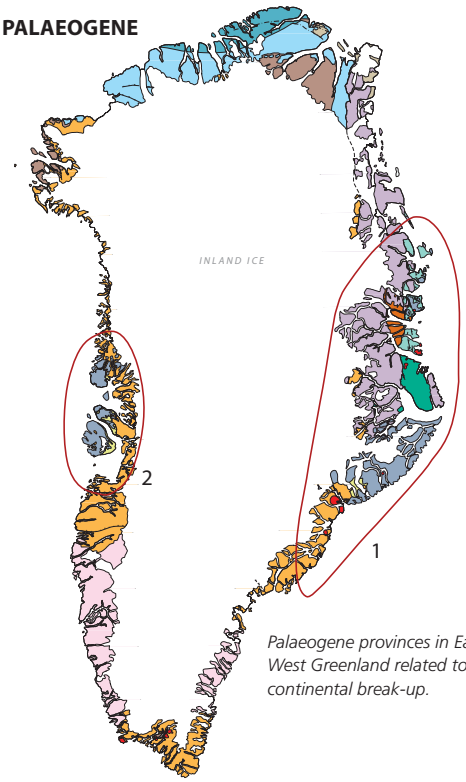
The continental rift environment in the Gardar Province (# 9, map 3) in South-West Greenland is in many respects well-described and has seen significant exploration due to the many highly alkaline intrusions enriched in a variety of rare metals and uranium. The uncommon rock types have for many years attracted significant interest, from both academics and exploration. An example is the Ivittuut cryolite mine. The uranium, the zirconium and the rare-earth element (REE) potential of the Ilimmaasaq intrusion, the niobium and tantalum potential of the Motzfeldt complex, and the possibilities for massive iron and/or sulphide mineralisation in mafic dykes of the province have all received significant attention.

All of the Archaean core in Greenland (# 10, map 3) hosts widely spaced Palaeoproterozoic basaltic dykes, referred to as the MD (metadolerite) dykes. The dykes are widely spaced and emplaced during relaxation of the craton. Only minor sulphide contact mineralisation is observed in relation to these dykes. An E–W-oriented swarm of Mesoproterozoic lamproite dykes in the Sisimiut area (# 11, map 3) attracts significantly more interest. The lamproitic magmatism and related metasomatism of lithospheric mantle lithologies may be a pre-requisite for the Neoproterozoic swarms of diamond-bearing ailikite and kimberlite dykes in the Sisimiut, Sarfartoq and Maniitsoq regions, and the Sarfartoq carbonatite complex (# 12, map 3). Diamonds recovered from the Garnet Lake property of the Sarfartoq region are of gem quality and up to 2.5 carats in size.

A major swarm of Mesoproterozoic transitional basalt dykes (# 13, map 3) is hosted in the Proterozoic Rinkian Fold Belt along the north-west coast of Greenland. The dyke swarm can be followed more than 1000 km with individual dykes being >100 m wide. Significant volumes of magma have been emplaced in the crust, but no significant mineralisation has been recorded in connection with these dykes. In the same area occurs the large Prøven granite (or charnokite).

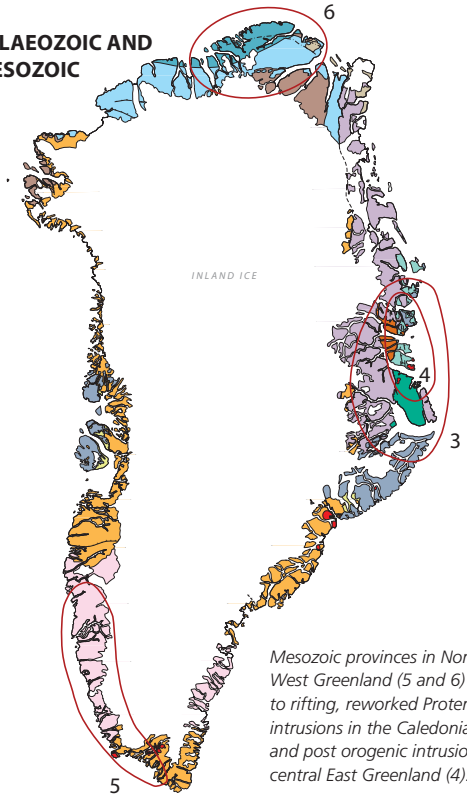
North-West and North Greenland host a wide range of Proterozoic plutons and hypabyssal rocks. The Palaeoproterozoic plutons (# 14, map 3) include multiphase complexes of gabbro, diorite, monzonite and microsyenite, and more uniform gabbro and granite complexes. Exploration has been very limited, but the gabbros hold an iron-oxide potential. All of the Thule district and the areas to the north host Mesoproterozoic to Neoproterozoic suites of basaltic sills and dykes, which in part can be correlated into northern Canada. Two types of mineralisation are related to these hypabyssal rocks. Many of the sills are rich in ilmenite and are the source for extensive ilmenite placer sands in the Thule district. Sulphide mineralisation is also recorded at the contacts of sills. In North-East Greenland the Mesoproterozoic Midsommersø

1 PALAEOGENE



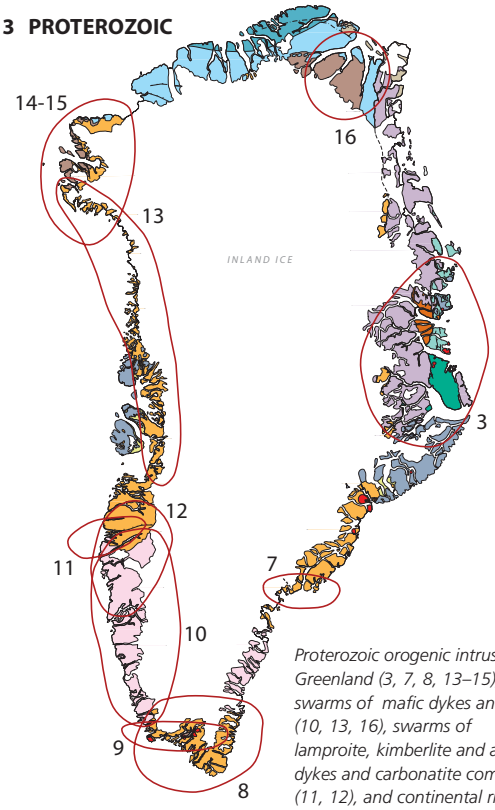
Palaeogene provinces in East and West Greenland related to continental break-up.

2 PALAEOZOIC AND MESOZOIC



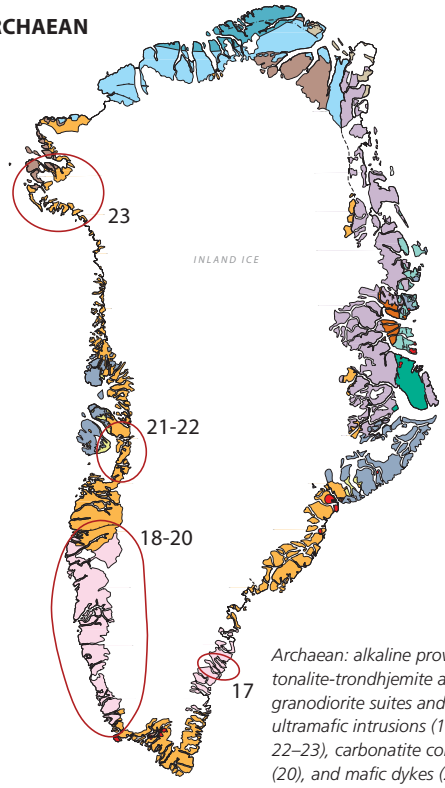
Mesozoic provinces in North and West Greenland (5 and 6) related to rifting, reworked Proterozoic intrusions in the Caledonian (3), and post orogenic intrusions in central East Greenland (4).

3 PROTEROZOIC

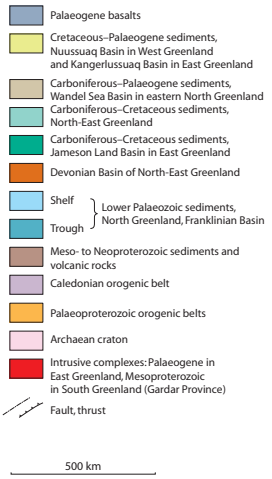


Proterozoic orogenic intrusions in Greenland (3, 7, 8, 13–15), swarms of mafic dykes and sills (10, 13, 16), swarms of lamproite, kimberlite and ailikite dykes and carbonatite complex (11, 12), and continental rift related alkaline province (9).

4 ARCHAEAN



Archaean: alkaline province (17), tonalite-trondhjemite and granodiorite suites and mafic to ultramafic intrusions (18–19, 22–23), carbonatite complex (20), and mafic dykes (21).



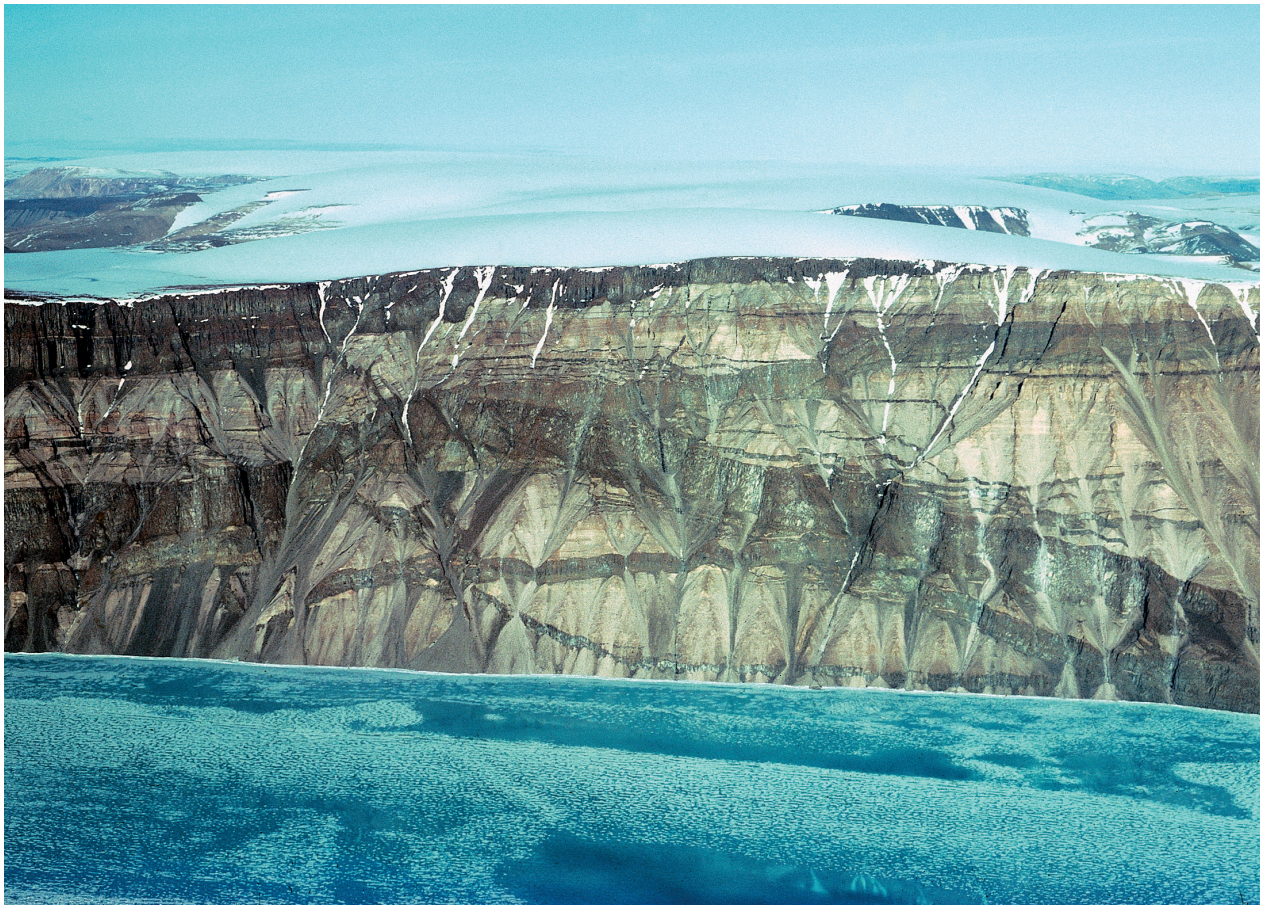
The Gardar Province, South-West Greenland. One of the most exotic resources in the Gardar Province is the now exhausted cryolite deposit at Ivittuut. The cryolite pegmatite body formed in the roof of a granitic stock.

Dolerites exhibit spectacular sections of mafic sills with associated re-melting of sediments. The magmatism is related to the Zig-Zag Dal flood basalts. Native copper is seen in mineralisation related to the sill complex.

Archaean provinces

The Skjoldungen Alkaline Province in South-East Greenland (# 17, map 4) hosts some twenty syn- to late tectonic intrusions. The petrographic range is significant and includes ultramafic, gabbroic, monzonitic, syenitic, granitic and strongly alkaline intrusions. In addition the province includes significant areas of syenitic gneiss. Apart from two complexes, the Ruinnæsset gabbro complex and the Singertât ijolite complex, most of the Skjoldungen Alkaline Province has only received little investigation. The Ruinnæsset gabbro hosts minor magnetite-apatite veins. The region is strongly underexplored. Initial investigations suggest a compositional similarity with the intrusions of the Haliburton-Bancroft Province

Mining operation in the Ketilidian in South-West Greenland. The Nalunaq gold mine was located in a gold-bearing quartz vein system.



The impressive Midsommersø dolerites emplaced into Proterozoic sediments, North-East Greenland.

in Canada and the intrusions of the Seiland Province in northern Norway. The magmatism is tentatively seen as a compressive regime.

The core of the Archaean craton in southern West Greenland is for large parts composed of orthogneiss. Some of the late intrusions have preserved many intrusive features. The plutons include the classic suite of ultramafic plugs and ultramafic to gabbroic, norite and leucogabbro to anorthosite intrusions, and tonalite, trondhjemite and granite plutons of the tonalite-trondhjemite and granodiorite (TTG) suite. One small carbonatitic complex has also been located. The large, mostly deformed and disrupted, layered ultramafic, gabbroic, and anorthositic complexes have seams rich in chromite, and do in several occurrences show significantly elevated concentrations of platinum group elements (PGE). The Fiskenæsset anorthosite and the Amikoq complexes are presently targets for PGE exploration. Little can be said about the geodynamic environment, but almost by definition, a late to postkinematic environment has to be suggested.

Further north along the west coast of Greenland, Archaean intrusions are preserved in the Disko Bugt region (# 21 and # 22, map 4), in a region of preserved Archaean lithologies sandwiched between the Nagssugtoqidian orogen to the south and the Rinkian Mobile Belt to the north. The Archaean intrusions include anorthosite and diorite, in addition to the TTG suite. The region also hosts Archaean mafic dykes, one of which recently has been shown to be diamondiferous. All of these intrusive rocks are late to postkinematic.

Archaean anorthosite, so common to large parts of Greenland is also preserved in the Thule district in North-West Greenland (# 23, map 4). The region hosts Archaean, anorthosite, mafic to felsic, and dioritic complexes. They are all late kinematic. No detailed investigation has been conducted and no mineralisation has yet been observed.

Concluding remarks

Greenland hosts intrusions of all ages and many types of composition in many types of geodynamic environment. Some regions have seen significant exploration, whereas others are only superficially known. Classic regions such as the Gardar Province (# 9, map 3) and parts of the Palaeogene Province in East Greenland (# 1, map 1) have been investigated and explored in significant detail. The Palaeogene Skaergaard intrusion in East Greenland is one of the most studied mafic intrusions on Earth. However, many other intrusions and complexes, also in these two regions, are only superficially known and have not been subject to exploration.

The conclusion is that the majority of intrusions in Greenland are underexplored. Data on all plutons, sill complexes and dyke swarms of 23 plutonic provinces, available at www.greenmin.gl, is an invitation to explore the economic potential of plutonic environments in Greenland.

Evening scenery in Kattertooq fjord in the kjoldungen Alkaline Province. The syenitic gneiss areas are characterised by large screes.

Layered Archaean anorthosite with layers of chromitite. The anorthosite and related ultramafic layered rocks hold a platinum group element potential

Large tonnages of dunite in Archaean layered mafic intrusions used for production of olivine at the Seqi deposit, southern West Greenland.

The layered kakortokites of the Ilimaussaq intrusion, Gardar province. The kakortokites are zircomium-rich cumulates.

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Kimberlite dyke (Neoproteozoic age) in the Archaean basement, southern West Greenland.

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No. 14 March 2024

Front cover photograph
The face of Gabbrofjeld (1200 m) in the Palaeogene Skaergaard intrusion, South-East Greenland. The three leucocratic layers of the Triple Group can be seen below the top of Gabbrofjeld. The gold and PGE mineralisation is located in the lower part of the Triple Group.

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Graphic design
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Photographs
GEUS unless otherwise stated

Printed
March 2024 ©GEUS
Reprint of Feburary 2009 issue

Printers
Stibo Complete

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