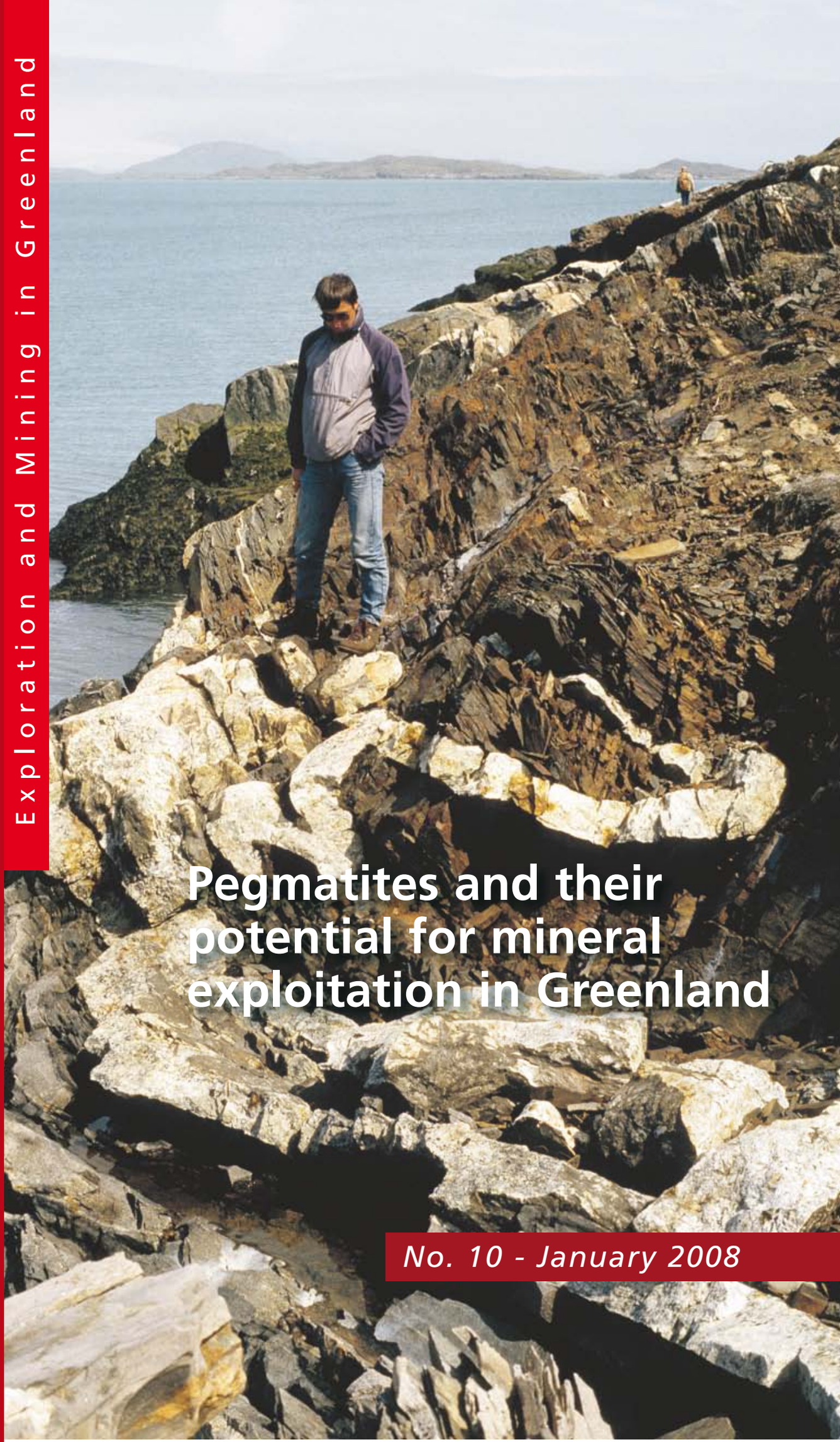
GEOLOGY AND ORE

Exploration and Mining in Greenland



Pegmatites and their potential for mineral exploitation in Greenland

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Pegmatites are important suppliers of many commodities world wide. In Greenland pegmatites are well-known, but their economic potential has only been explored at a few localities. This review provides an overview of the genesis and general economic potential of pegmatite occurrences in Greenland. Field observations, archive information as well as maps of stream sediment samples that are enriched in elements characteristic of pegmatites are the base for the presentation. The prospective areas for pegmatite-hosted mineral occurrences in Greenland are outlined, and examples of prominent pegmatite minerals are demonstrated.

Pink pegmatite related to the Qôrqut granite complex. Godthåbsfjord, Nuuk region

Introduction

Pegmatites are suppliers of rare metals like beryllium, lithium and tantalum. Pegmatites also represent an important source of gemstones such as emerald and tourmaline, and some pegmatites are even mined for their large, clean crystals of quartz and feldspar. Pegmatites are abundant in Greenland, but few have been described or studied in detail and hence their economic potential is largely unknown at present.

In a broader sense, the term pegmatite is used for any coarse-grained vein of granitic composition, with or without a connection to an intrusive complex. Medium- to coarse-grained granitic to pegmatitic veins may be derived from partial melting of their host rocks during progressive high-grade metamorphism. Such veins are also termed migmatitic veins.

Mineralogically, pegmatites are termed simple when they essentially consist of quartz, feldspar and biotite, and complex when they carry a range of accessory minerals like tourmaline, fluorite, lepidolite, spodumene or beryl. Also molybdenite, scheelite, uraninite and rare earth element-bearing minerals may occur in complex pegmatites.

Pegmatites in exploration and exploitation

Exploration is generally straightforward, because large, potentially economic pegmatites are often easily recognised in the field, and they are often shown on geological maps. Furthermore, pegmatites may sometimes be located directly from aerial photographs due to their distinct appearance. In the geological mapping of the Precambrian basement of Greenland, coarse-grained veins are commonly termed pegmatites when their dimensions exceed 0.5 m in width and 2 m in length, regardless of their origin.

Of economic importance are especially minerals containing lithium, beryllium, scandium, uranium and REE, which are commodities with a variety of high-technology uses. Quartz, feldspars and mica are used as industrial minerals. Several pegmatite mineral species may also be used as gemstones.

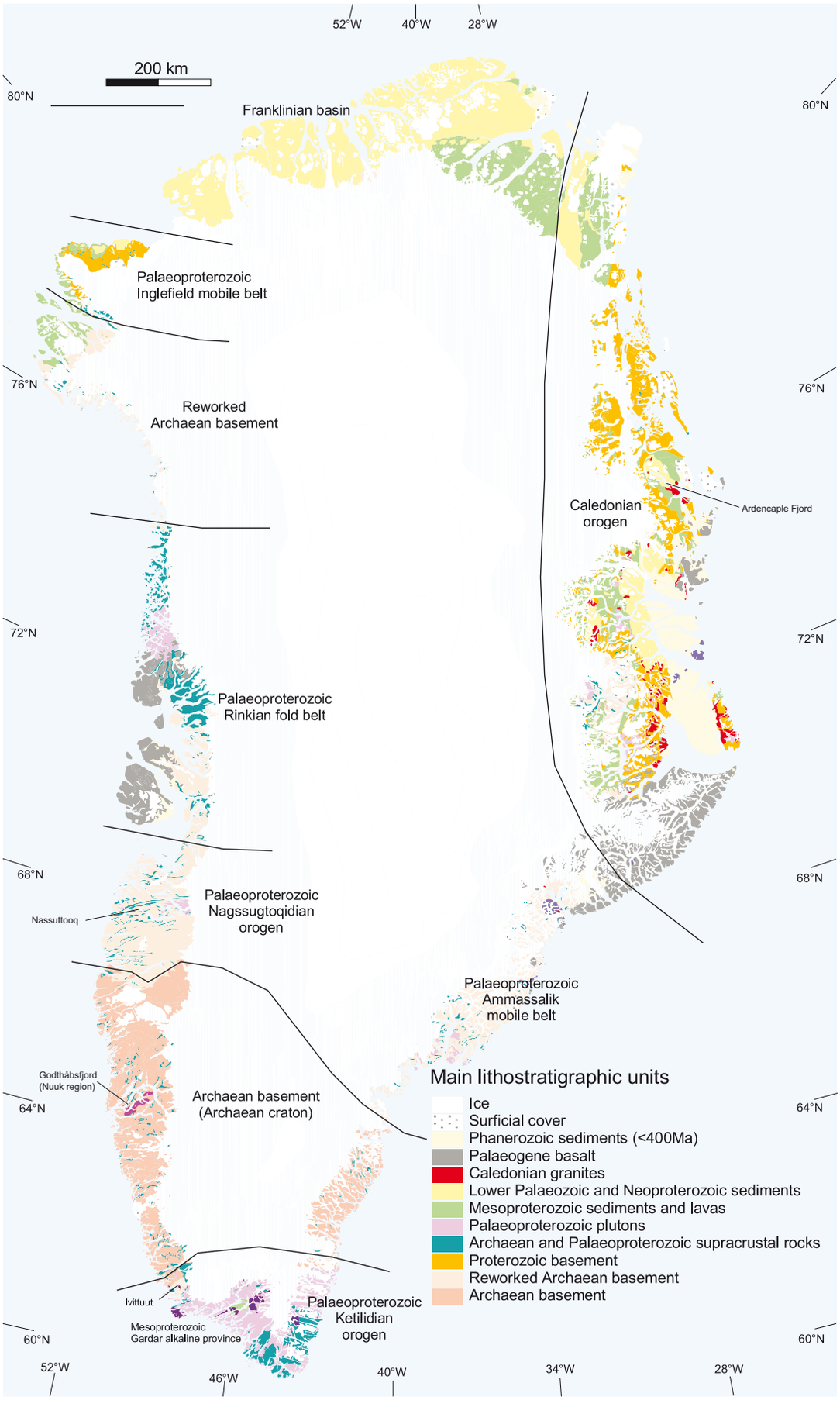
Greenland itself only comprises one example of pegmatite exploitation which is however outstanding, namely the cryolite deposit adjacent to an alkaline granite of Mesoproterozoic Gardar age at Ivittuut in South Greenland. This deposit supported an extremely profitable mining operation for around 130 years. Apart from this hallmark of pegmatite use in Greenland only limited pegmatite exploration has been carried out.

Geochemical criteria for identifying economic pegmatite occurrences

The regional distribution of certain elements may indicate where pegmatites are located. Large parts of Greenland outside the Inland Ice have been covered by stream sediment surveys. Most samples have been analysed by neutron activation, and several of the elements that are easy to determine by this method are usually concentrated in pegmatites; the elements of interest in this context are Cs, Mo, La, Yb, Hf, Ta, Th and U.

The distribution of Cs reflects the distribution of granitic and syenitic rocks, and the highest values suggest areas favourable for finding pegmatites. These high values form clusters in meta-sedimentary rocks in several geological environments in Greenland.

Major lithostratigraphical and tectonic division of Greenland.



Large black crystals of arfvedsonite up to 60 cm long are intergrown with equally large crystals of white feldspar. Pegmatite in the margin of the alkaline Ilímaussaq complex, South Greenland.

Lithium (Li) is the most economically valuable of the lithophile elements because of its rarity and use in the electronics industry. The Geological Survey (GEUS)' stream sediment database does not contain data for Li, but the distribution of Cs serves as a good indicator of environments generally enriched in lithophile elements including Li. In South Greenland, both granitic and alkaline intrusions have high Cs contents; hence the possibility of finding concentrations of Li minerals seems to be good.

The Ta distribution patterns show that the Gardar province is strongly enriched in Ta, but interestingly, high Ta is also found in samples from streams draining metasedimentary and sedimentary rocks in East Greenland. The few scattered stream sediment samples with high Ta in West Greenland coincide with known occurrences of Ta-Nb bearing carbonatites (i.e. not pegmatites).

In simple pegmatites related to granites the minerals allanite and monazite are commonly enriched in REE (rare earth elements), whereas a whole range of rare REE minerals occurs in alkaline pegmatites. The light REE La and Ce are geochemically very similar, so that a high concentration of La also indicates high Ce. The heavy REE Yb is similar to Y, which is economically more interesting. There is an interesting difference in the distribution patterns of the light and heavy REE, exemplified by La and Yb. Thus, in metasedimentary environments, La is enriched in the Rinkian fold belt, while Yb is enriched in south-eastern Ketilidian and Caledonian orogens. Many of the Gardar rock units are enriched in both light and heavy REE.

Granitic pegmatites

The most common pegmatites in the Precambrian basement of Greenland are approximately granitic in composition. They essentially consist of very coarse-grained quartz, alkali feldspar and mica; the amount and variety of additional minerals depend on the origin of the pegmatite in question. Magnetite, zircon and allanite are commonly seen, while minerals such as monazite, tourmaline, fluorite, apatite, sulphides, uraninite, beryl or topaz are rarer.

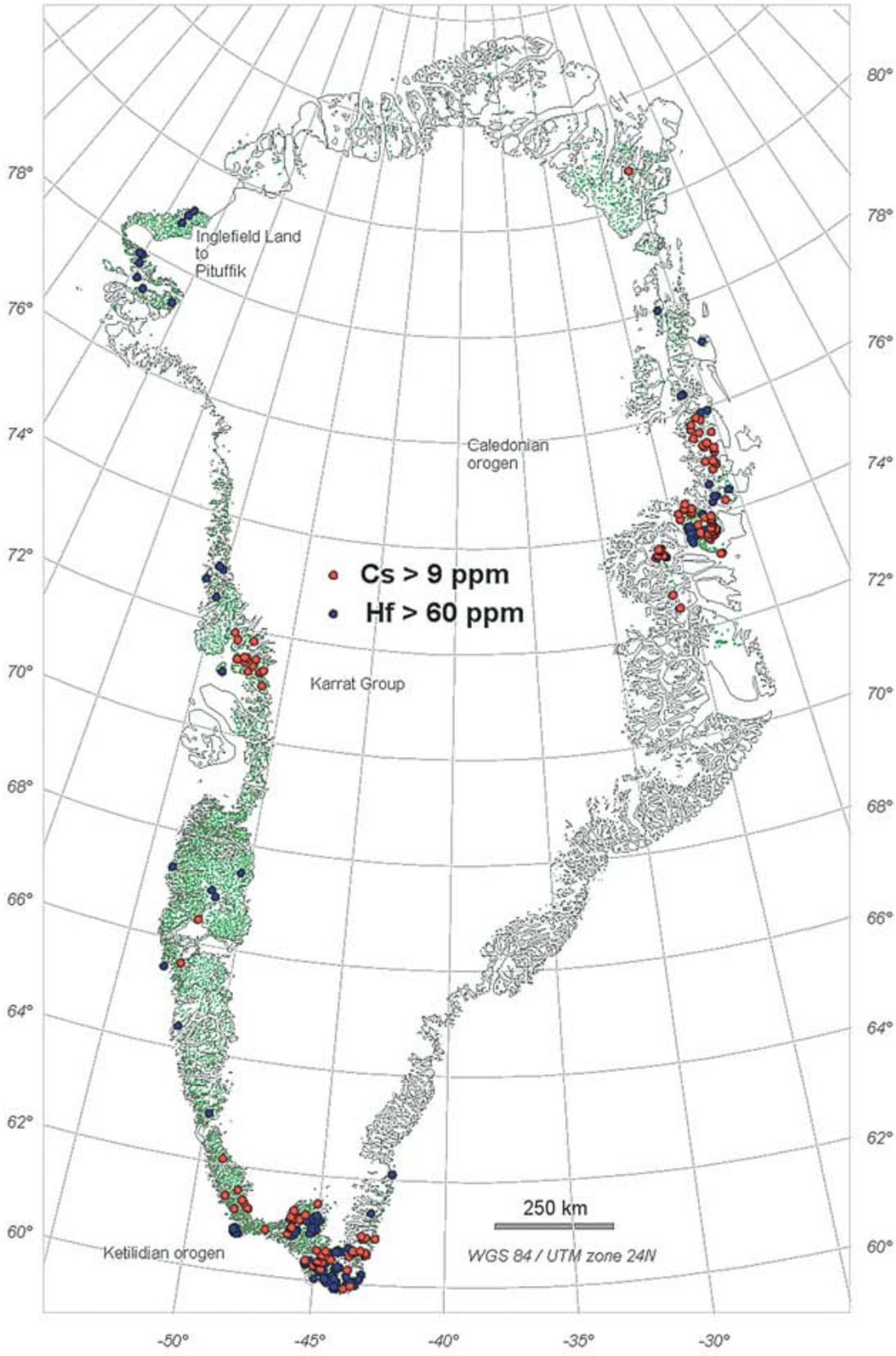
Genetically, most pegmatites in the Precambrian basement are results of melting during prograde metamorphism. Their mineralogy and economic potential depend to a large extent on the character of the source rock. Pegmatites derived from reworking of tonalitic to granitic orthogneiss usually have a simple mineralogy of quartz, alkali feldspar and biotite, and are commonly named as simple pegmatites.

Prograde metamorphism of clastic sedimentary rocks with significant contents of clay minerals leads to progressive dehydration and generation of metamorphic fluids, and when high amphibolite facies conditions are reached, pegmatites are commonly formed. They are more aluminous than the simple pegmatites and therefore typically also contain muscovite, tourmaline and garnet in addition to quartz, alkali feldspar and biotite. Besides common accessory minerals such as magnetite, apatite and zircon, which are also found in simple granitic pegmatites, they may comprise additional beryl, topaz and fluorite in order to accommodate minor elements like B, Be or F from their pelitic precursors. These pegmatites are therefore often named as complex pegmatites. Some of the minerals found in this group may potentially be of gem quality.

Alkaline pegmatites

Alkaline magmatic rocks result from crystallisation of melts generated in the lithospheric mantle and are often associated with crustal-scale rifting. Magmas formed in this way are often silica-undersaturated and characterised by high concentrations of the alkali metals K and Na. Related pegmatites are enriched in high field strength elements such as Y, Zr, Hf, and Nb, Ta and REE. The concentration of these elements may reach economically interesting levels both in pegmatites and in non-pegmatitic rock units in the surroundings of the alkaline complexes. Alkaline rocks contain rare minerals that have a value as specialised industrial minerals or in the mineral collectors' market. In addition, certain minerals have found use as semi-precious stones, e.g. amazonite and tugtupite.
I

Locations of stream sediment samples with high concentrations of Cs and Hf in the < 0.1 mm fraction. Green dots mark location of samples analysed by neutron activation.



Pegmatite of residual granitic origin with pink feldspar, white quartz and black biotite from the Ndr. Strømfjord (Nassuttooq) area.

In Greenland, the largest and most important group of alkaline rocks is the Mesoproterozoic Gardar province in South Greenland. Others include the Palaeogene alkaline province in East Greenland.

Selected pegmatite occurrences

Most of the information about pegmatites in Greenland is found in the published geological maps and field diaries in the archives of the Survey. The regions addressed in the following are selected due to a demonstrated and/or expected potential.

Rinkian fold belt

The Palaeoproterozoic Karrat Group comprises large areas of amphibolite to granulite facies metagreywacke of the Nukavsak Formation together with quartzite and marble. Pegmatites are most abundant in the northern part close to the Prøven igneous complex. A swarm of peraluminous granite pegmatite dykes cuts gneiss and Karrat Group rocks in the central part of the southern Rinkian fold belt. The pegmatites have quartz-rich centres and are associated with quartz veins, and are composed of quartz, muscovite, biotite, feldspar, garnet and variable tourmaline. Molybdenite is commonly found close to the margins of the veins, and 0.1 – 0.5 % MoS_2 has been recorded.

The Nagssugtoqidian orogen

The Nagssugtoqidian orogen in central West Greenland mainly comprises Archaean crust that has been partly reworked during Palaeoproterozoic heating and deformation, besides Palaeoproterozoic supracrustal rocks and remnants of two magmatic arcs. Both Archaean and Palaeoproterozoic pegmatites occur, and examples of both simple and complex pegmatites are known.

Aggregate of black allanite crystals in red pegmatite from the Ndr.Strømfjord (Nassuttooq) area. Scale bar: 1 cm.

Pink pegmatites are common in the outer fjord zone from Kangaatsiaq to south of Attu, where the Archaean orthogneiss is intruded by granite and simple pink pegmatites of un-known age. The pegmatites occur mostly as discordant up to metre-thick bodies within the gneiss, commonly

Monazite in biotite rich pegmatite from the Ndr.Strømfjord (Nassuttooq) area. Scale bar: 1 cm.

Black tourmaline crystals (dravite) from pegmatite on the island of Sermitsiaq, Nuuk, region. Scale bar: 1 cm.

at contacts between major lithological units. The dominant minerals are coarse-grained K-feldspar, quartz, biotite and subordinate allanite, titanite, apatite, magnetite and Fe-sulphides.
White pegmatites are generally concordant to the foliation of the adjacent country rocks. The white pegmatites are 5–20 m wide and 50–200 m long, with a general trend of NW–SE all over the Nordre Strømfjord and Ussuit areas, and normally contain plagioclase and biotite with accumulations of monazite.

Pegmatite dykes, veins and schlieren occur throughout the southern Nagssugtoqidian boundary area, and vary considerably. Locally, simple quartz-feldspar-pegmatites host garnet and apatite.

Archaean basement in the Nuuk region

The Nuuk region represents the highest crustal level of the North Atlantic craton in southern West Greenland, and pegmatites are abundant and voluminous in some areas, especially within supracrustal rocks at the western part. Pegmatites were formed during several thermal episodes in the time interval c. 2750–2600 Ma, and again at around 2550 Ma in connection with the intrusion of multiple Qôrqut granite sheets.

Pre-Qôrqut granite pegmatites are leucocratic and dominated by quartz and white feldspar, and they contain a variety of accessory minerals including biotite, mag-

Brown siderite, grey cryolite and white quartz in a pegmatite vein from the cryolite deposit of the alkaline granite at Ivittuut, South-West Greenland.

White pegmatites within Archaean supracrustal rocks on central Storø, Nuuk region.

netite, garnet, tourmaline, allanite and uraninite. Pegmatites in the Ivisaartoq area to the east are known for local finds of beryl (var. aquamarine), which at one locality has delivered large, well-shaped crystals of up to 4 x 17 cm. Tourmaline (var. dravite) is well known from the Sermitsiaq island and in the southern part of the Nuuk region around Ameralik. A typical feature of this tourmaline is its black colour; the well-developed crystal faces with shiny surfaces and the large sizes. Crystals of up to nearly 2 kg each have been recorded.

Archaean basement in the Fiskenæsset–Paamiut region

In the southern part of the Archaean craton, quartz- and plagioclase-rich pegmatites intrude both the orthogneisses and the Fiskenæsset anorthosite complex, where they typically form conformable bodies along lithological contacts within the complex. Numerous light coloured quartz-plagioclase-biotite pegmatites with varying sizes up to 30 m wide often have accessory (up to 10 vol%) allanite.

Molybdenite and beryl are rarely seen, and the pegmatites are considered barren in an economic geological context.

Palaeoproterozoic Ketilidian orogen

The evolution of the Palaeoproterozoic Ketilidian orogen and the subsequent Mesoprotero-zoic Gardar igneous province in South Greenland has favoured the formation of pegmatites, both simple ones related to granitic magmas, simple and complex pegmatites formed by melting of metasedimentary rocks, and pegmatites related to alkaline intrusions. The most interesting pegmatite-forming events are late-kinematic Ketilidian granites related to the Julianehåb batholith and the granites contemporaneous with the late- to post-kinematic rapakivi suite, both of Palaeoproterozoic age, and the Mesoproterozoic Gardar magmas.
The late to post-kinematic rapakivi intru-

sive suite of granites also comprises small volumes of microcline granite and biotite granite. Pegmatites and aplites associated with these granites are locally enriched in gold, and have a potential of being enriched in Li as they have high concentrations of the other lithophile elements Rb and Cs. The type locality for allanite is Aluk in South Greenland, located within the rapakivi suite.

Mesoproterozoic Gardar province

A number of the Gardar intrusions have attracted various grades of exploration. The Ilímaussaq intrusive complex and the Ivittuut granite stock appear to have the best potential for economic use of their pegmatites.

Ilímaussaq intrusive complex

The Ilímaussaq intrusive complex comprises a series of syenites formed by crystallisation of silica-undersaturated, alkaline to peralkaline magmas rich in volatiles. The pegmatites were formed as networks of veins near the roof and along the sides of the chamber within the early naujaite-foyaite stage of nepheline syenites. The pegmatites are commonly rich in the Zr mineral eudialyte and other minerals containing Nb, Ta and REE, and pegmatites rich in Li and Be minerals occur locally. In the late magmatic lujavrite (mafic nepheline syenite) stage, other pegmatites were developed as irregular veins and patches, and they are particularly enriched in F, U and Th, Be, Li, Zr, Nb and Ta. The Ilímaussaq complex has become famous among mineral connoisseurs for its large number of rare mineral species, which are commonly found in its pegmatites.

Ivittuut alkaline granite stock

The Gardar intrusion at Ivittuut comprises a stock of alkaline granite (Ivigtût granite) with a pegmatitic facies developed into cryolite-, quartz- and quartz-feldspar pegmatites. The now totally exploited cryolite ore body had the shape of an irregular, flattened dome measuring about 50 x 155 m horizontally and 70 m in depth. The main ore body of cryolite and siderite was followed downwards by a siderite zone, which was mixed with a fluorite shell to the west. At still deeper levels a huge mass of more or less pure quartz with accessory sulphide minerals separated the body from the underlying granite. Late feldspar-quartz pegmatites have been recognised in the upper part of the ore body. Typical complex pegmatite minerals such as topaz, cassiterite, columbite and wolframite occur, together with a suite of rare and unusual fluoride and oxide minerals, around 100 different minerals in all.

The cryolite deposit was mined from 1856–1987, with at total production of 3.7 million t of ore averaging 58% cryolite. The mode of formation of the cryolite mass adjacent to the Ivigtût granite is still a matter of discussion. One of the accepted theroies considers the cryolite to represent an extreme pegmatitic and/or pneumatolytic phase derived from the crystallising granitic magma. This unique occurrence was the result of accumulated fluorine-rich gases trapped in the central upper part of the already solidified granite stock.

The major cryolite, cryolite/siderite and

Close-up of white pegmatite, clearly intrusive into deformed grey gneiss, central Storø, Nuuk region.

Bluish green amazonite and graphic granite with grey quartz and white feldspar, from a pegmatite associated with the Nunarssuit alkaline complex, South-West Greenland. Scale bar: 1 cm.

quartz phases of the cryolite deposit are considered to have crystallised in close succession, while subsequent fluorite-cryolite- and fluorite-dominated phases were formed when late fluids reacted with previously crystallised rocks.

Nunarssuit alkaline complex

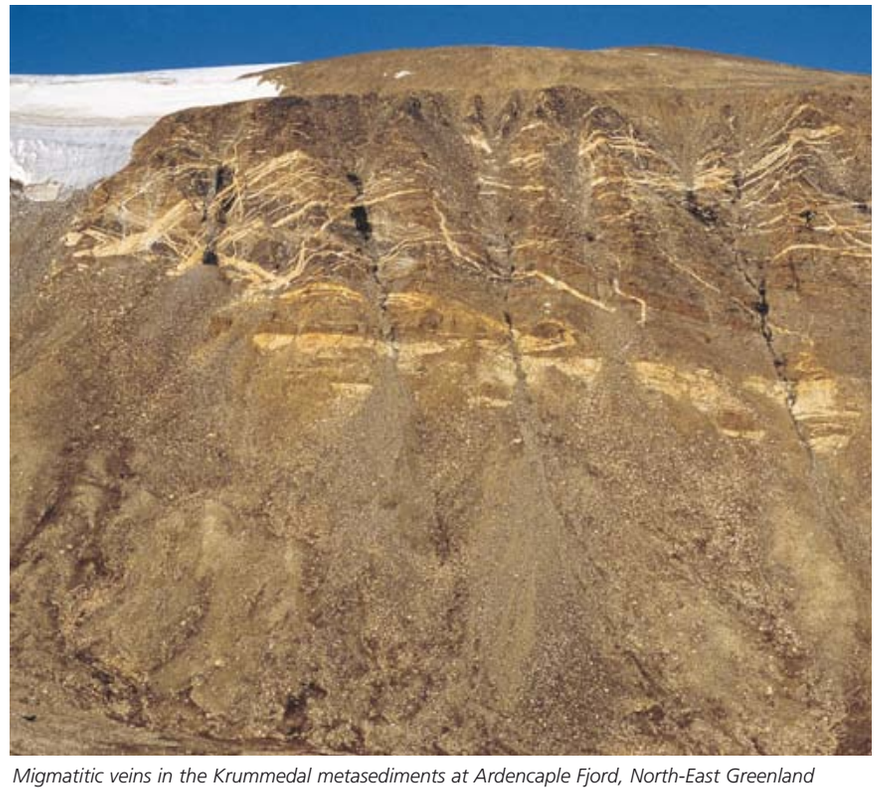
This large intrusive complex comprises several intrusive phases of saturated to oversaturated alkaline rocks. Very high Y and Yb concentrations in stream sediment suggest that pegmatites with yttrium minerals may occur in the intrusive complex. Well crystallised amazonite occurs in several pegmatites of the complex, and a limited exploitation has been carried out directed to its use as gemstone.

Igaliko alkaline complex

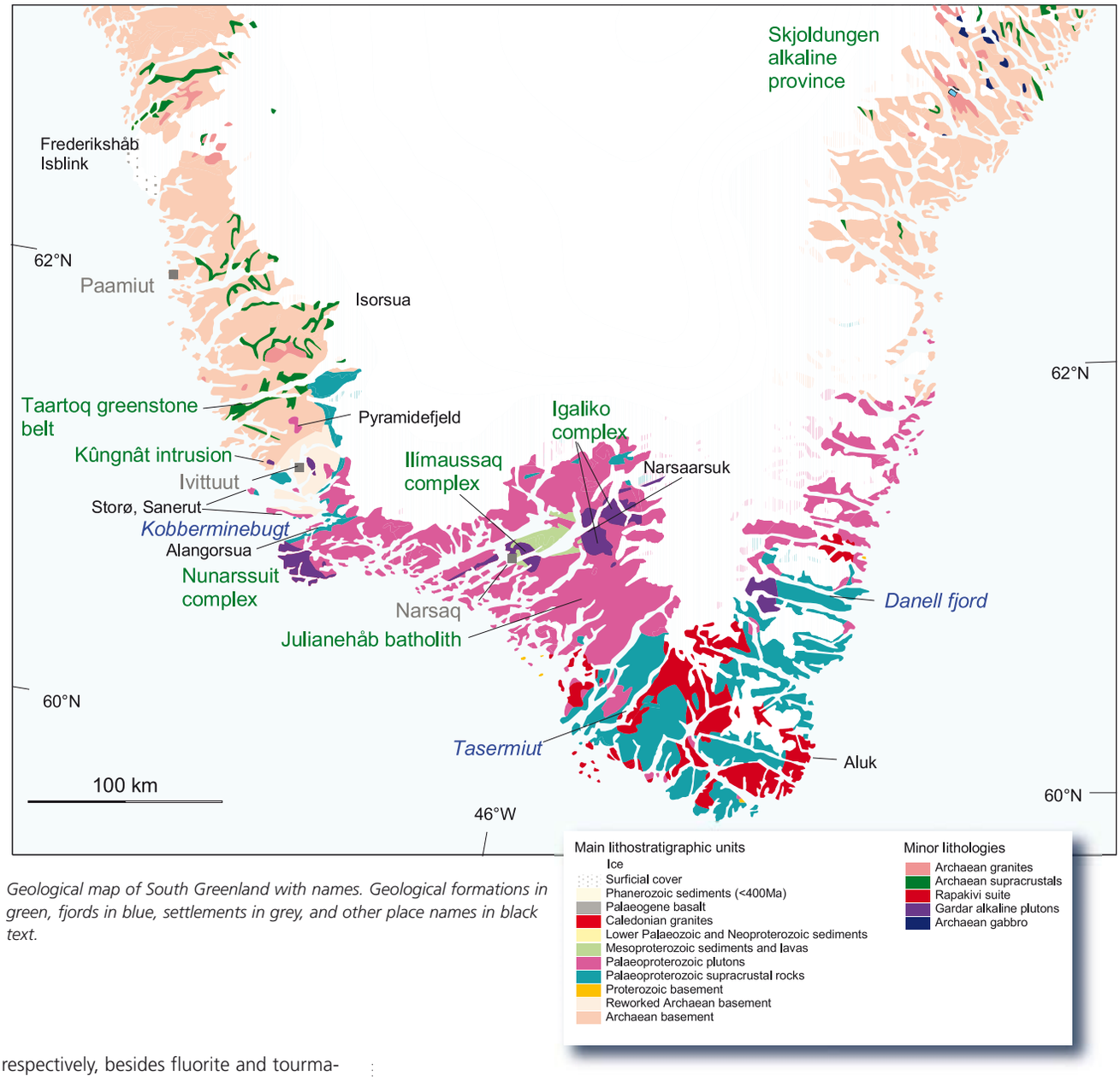
A pegmatite at the locality Narsaarsuk has been famous for a large number of new and very rare minerals with REE.

Caledonian orogen in East Greenland

The basement to the Caledonian orogen in central East Greenland is dominated by grano-dioritic to tonalitic orthogneisses of Archaean and Palaeoproterozoic age, respectively, north and south of 73° N. Palaeoproterozoic granites are known, e.g. a body of pegmatitic muscovite granite near the margin of the Inland Ice at Charcot Land. The granite/ pegmatite body intrudes both basement and supracrustal rocks. In Milne Land a pegmatite several metres wide with large crystals of tourmaline and beryl (var. aquama-rine) is hosted by Proterozoic migmatitic gneiss and possibly related to nearby Caledonian granite. Scheelite and cassiterite with W and Sn,



Migmatitic veins in the Krummedal metasediments at Ardencaple Fjord, North-East Greenland



Geological map of South Greenland with names. Geological formations in green, fjords in blue, settlements in grey, and other place names in black text.

respectively, besides fluorite and tourmaline have been recorded in a sub-concordant pegmatite presumed to be associated with a Cale-donian granite at Forsblad Fjord. Here also Li (200 ppm), Be (50 ppm). up to 2 ppm Au (in arsenopyrite) occur in samples from the contact zone between pegmatite and metasedimentary rocks. The finding suggests that pegmatites related to the Caledonian granites have a potential for Li minerals.

Palaeogene alkaline intrusions in East Greenland

Mineral research related to the Palaeogene alkaline intrusions in central East Greenland has mostly been attracted by hydrothermal alteration that is very pronounced within and around preserved roof zones of several large intrusions. Many pegmatites have however also been observed, and in general terms they have a potential for rare minerals enriched in Li, Be, Zr, Hf, Nb, Ta, REE and Y, U and Th.

The Gardiner intrusion comprises many pegmatites, and pegmatites also occur in the nearby Kangerlussuaq intrusion. An undersaturated alkaline pegmatite occurs at Bagnæsset. At Kræmer Island, a quartz vein contains large crystals of aegirine, arfvedsonite, astrophyllite, and abundant small zircon crystals and amazonite. The Caledonian alkaline intrusion at Batbjerg contains large pegmatites with crystals of Cr-diopside, phlogopite and 'moonstone' feldspar.

Concluding remarks

Favourable areas in West Greenland for complex pegmatites of granitic composition with economic potential occur where partial melting of metasedimentary rocks has taken place. Published geological maps at scale 1:100 000 show the distribution of supracrustal rocks and pegmatites. Additional information is provided by stream sediment geochemical maps, which can be used to outline areas favourable for concentrations of specific elements within complex pegmatites. Favourable units with this potential could be the fore-arc basin of the Ketilidian orogen in South Greenland. Other units considered favourable are underlain by Archaean supracrustal rocks e.g. in the Nuuk region in the Archaean craton.

Alkaline pegmatites occur abundantly within the Gardar alkaline province in South Greenland and the intrusions of the Palaeogene igneous province in East Greenland. Successful exploitation of pegmatites in Greenland has so far only been related to alkaline rocks. However, commodities of interest hosted by alkaline rocks are not confined to pegmatites, so that the entire alkaline complexes are target areas for detailed exploration for specific elements or minerals.

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Front cover photograph
Folded pegmatite in a metavolcanic sequence of the supracrustal rocks from the northern Ketilidian Border Zone in Kobberminebugt, South-West Greenland.

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