Diamond exploration in southern West Greenland

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Kimberlite intrusions were discovered in Greenland in the late 1960s and the first microdiamonds were recovered from stream sediments in the early 1970s. By the 1980s over 500 occurrences of kimberlite, lamproite and ultramafic lamprophyre dykes and sheets had been located. The Lac de Gras discovery in Canada in 1991 caused a revival of interest in Greenland as prospective ground for diamonds. This interest was further stimulated by the discovery of kimberlite indicator minerals in stream sediment and overburden, and of a macrodiamond in a kimberlite dyke in 1997 (Minex, 1998).
The main activities related to diamond exploration undertaken by the Geological Survey of Denmark and Greenland (GEUS), by the Bureau of Minerals and Petroleum (BMP) and by private industry are summarised here.

Geological outline

Southern West Greenland is part of the Laurentian shield and is dominated by an Archaean craton which to the north and south have been affected by Palaeoproterozoic orogenies at around 1900 to 1800 Ma (Fig. 1). The proportion of new Proterozoic crust is small in the northern (Nagssugtoqidian) orogen and very large in the southern (Ketilidian) orogen. Gneiss complexes with only minor supracrustal units dominate the Archaean craton. Several terranes have been recognised which were assembled around 2700 Ma ago, and since that event the craton has escaped major tectonic reworking.

Investigations by GEUS and collaborating institutions

Registration of occurrences of rocks of alkaline mafic to ultramafic and carbonatitic character
The known localities of such rocks have been registered and their geographic coordinates are available from the Geological Survey of Denmark and Greenland (GEUS) in digital form (Larsen, 1991). Most new occurrences are found by exploration companies, and these cannot be included into the list until the information has been released by the licence-holders. The register distinguishes between kimberlites, lamproites, and various kinds of ultramafic lamprophyres. Chemical analyses of rock samples are stored in a GEUS database.
Occurrences of lamprophyres are found over most of West and South Greenland, while other rock types appear to form clusters in various parts of the Precambrian shield. Thus lamproites occur as two diatremes in the Disko Bugt area and as dykes near Sisimiut, and kimberlites are mainly found

in the region between Sisimiut and Maniitsoq. Major carbonatite complexes occur at Sarfartoq, near Maniitsoq and in South Greenland. From the point of view of diamond potential the kimberlites have attracted most attention (Sisimiut, Sarfartoq, Maniitsoq and SW Greenland groups, see Fig. 1). All the kimberlites form dykes and sheets, usually less than one metre, but locally up to ten metres thick.

Petrology, geochemistry, age and presumed setting of kimberlites.
A review of alkaline-ultramafic, potassic and carbonatitic magmatism in West Greenland was published by Larsen & Rex (1992). The emplacement ages span the period from 2500 Ma to the Tertiary, clustering around times of major plate tectonic events including Palaeoproterozoic orogeny at 1900 to 1800 Ma, continental rifting at 1200 Ma, opening of the Iapetus ocean at c. 600 Ma, and precursor events at 200 Ma to Cretaceous-Tertiary rifting in the Labrador Sea. Chemical and mineralogical investigations are reported in Larsen & Rex (1992) and in Mitchell et al. (in press). According to the latter, the chemistry of mica and spinel show that dykes previously regarded as kimberlites should be classified as ultramafic lamprophyres. However, their diamond potential remains unchanged. The term kimberlite is maintained here for practical reasons. The mineralogical and chemical characteristics of the dykes are summarised below for each of the four main kimberlite fields. The kimberlites of the three northern fields belong to the age group at ca. 600 Ma, while the kimberlite dykes in SW Greenland are about 200 Ma old.

Kimberlite field	Macrocrysts	Phenocrysts	Groundmass	Xenoliths
Sisimiut	olivine pyrope picroilmenite ilmenite	olivine phlogopite opaque oxide	carbonate phlogopite titanomagnetite ilmenite diopside apatite (perovskite)	dunite spinel lherzolite garnet lherzolite wehrlite harzburgite eclogite granulite
Sarfartoq	olivine pyrope picroilmenite ilmenite	olivine phlogopite opaque oxide	carbonate phlogopite titanomagnetite ilmenite perovskite apatite	dunite spinel lherzolite garnet lherzolite wehrlite glimmerite granulite
Maniitsoq	olivine pyrope opaque oxide ilmenite Cr-poor diopside	olivine phlogopite opaque oxide	carbonate titanomagnetite ilmenite phlogopite apatite	dunite
SW-Greenland	olivine	olivine phlogopite	carbonate titanomagnetite phlogopite clinopyroxene perovskite apatite serp	granulite garnet lherzolite spinel lherzolite phlogopite peridotite glimmerite

The chemistry of the dykes vary much, as might be expected given the heterogeneity of the rocks and the volatile components, but generally the concentrations of major and trace elements compare

with kimberlites from other parts of the world (Larsen & Rex, 1992). In a MgO/CaO versus SiO_2/Al_2O_3 diagram a large number of the samples from each of the four kimberlite groups plot within the kimberlite field as defined by Hamilton & Rock (1990) and Rock (1991), see Fig. 2. Both the mineralogy and chemistry support the view that the magmas of the Greenland kimberlites originated by partial melting of an asthenospheric carbonated lherzolite source (Mitchell et al., in press).

Chemical studies of macrocrystic minerals and minerals in mantle xenoliths

Studies have been undertaken to estimate the composition, pressure and temperature conditions of the lithospheric mantle sampled by the alkaline ultramafic dykes. The results indicate that all the kimberlites in the unreworked Archaean craton originated in the diamond stability field (Larsen & Rønsbo, 1993). An investigation of garnet, chromite and ilmenite in mantle xenoliths and macrocrysts from the Maniitsoq, Sarfartoq and Sisimiut kimberlite fields was undertaken during a PhD project at University of Copenhagen in collaboration with CSIRO, Australia (Garrit et al., 1995; Griffin at al., 1995). The results have been used to characterise the lithospheric mantle beneath the three areas. The data obtained suggest that the base of the lithosphere is situated at a depth of ca. 200 km in the Sarfartoq and Maniitsoq regions and possibly shallower in the Sisimiut region. Signs of mantle reworking are found in the Sisimiut region and have been related to the Palaeoproterozoic Nagssugtoqidian orogen. Melt-related metasomatism with possible reduction of the stability field for diamonds was suggested in the Maniitsoq region. The report by Griffin et al. (1995) contains an estimate of the diamond grade for the three kimberlite fields. High prospectivity is estimated for the Sarfartoq region, less high for the Maniitsoq region, whereas the data did not permit an estimate for the Sisimiut region. G10 type garnets were found in both Sarfartoq and Maniitsoq kimberlites.

Investigation of archived stream sediment samples

The entire Precambrian shield of southern West Greenland has been covered by reconnaissance stream sediment surveys used for geochemical mapping (Steenfelt, 1994). The average sample density is one sample per 20 to 30 km^2. The samples have been sieved into three fractions, the coarse >1 mm fraction was discarded, the middle 0.1 to 1 mm fraction stored, and the fine < 0.1 mm fraction used for analysis. The occurrences of the alkaline rocks are reflected in geochemical maps of Nb (based on XRF analysis of the fine fractions).

When the boom for diamond exploration started, the exploration companies expressed an interest in examination of the stored middle fraction of stream sediment samples for kimberlite-indicator-minerals (KIM). An agreement was made in 1997 between GEUS and the interested companies on the processing of just over 3000 samples from southern West Greenland between 61° and 67° N latitude. The samples were treated at Overburden Drilling (screening and heavy mineral separation), at I. & M. Morrison Geological Services (IMM; hand-picking of suspected KIM), and at R. L. Barnett Geological (microprobe analysis).

The main concern before and during this investigation was the scarcity of material. The sample weights were typically between 70 g and 175 g. The resulting heavy mineral, non-magnetic concentrates weighed typically between 1.2 g and 5.5 g. Many samples contained organic matter which had to be removed and coatings on mineral grains required special treatment. Nevertheless, IMM was able to examine 2959 samples and found suspected KIM in 572 of those. Grains from ca. 100 samples many were probed for verification and calculation of pressure and temperature estimation parameters.
The samples from which suspected KIM were picked are plotted on Fig. 3. The dot size illustrates the number of grains found. The map shows clusters of dots where kimberlites are known, i.e. in the coastal and easily accessible areas around Maniitsoq, Sarfartoq, Sisimiut and SW Greenland. More importantly, there are many KIM in poorly known areas close to the Inland Ice east of Sarfartoq and Maniitsoq, suggesting the presence of many additional kimberlites yet to be located.
Additional maps, not included here, were produced to show the distribution of each of the minerals identified: pyrope, eclogitic garnet, chromite, olivine, chrome diopside and zircon.

Geophysical surveys
GEUS has carried out airborne surveys of magnetic and electro-magnetic properties over most of the Archaean part of the Precambrian shield in the period 1994-1998. The funds for the surveys were provided by the Government of Greenland. An article by Thorning & Stemp (1998) contains a review of the surveys with specifications of survey parameters and maps produced. A report by Stemp (1996) outlines the principles for applying airborne geophysical data to exploration for kimberlite pipes and identifies some targets in the Maniitsoq area. The geophysical data has been used mostly by the private exploration companies. The geophysical maps and data may be purchased from GEUS.

Other
A study of field methods for locating and concentrating indicator minerals by panning is reported in Appel (1994).

Information service
"Greenland MINEX News" is a newsletter issued jointly by GEUS and BMP. Highlights of activities and results related to diamond exploration in Greenland have been referred in the newsletter issues from 1995 onwards. The newsletter is available from GEUS on request, free of charge.

Activities by exploration companies

In the first years of interest, 1994 to 1997, almost all of the Archaean part of the Precambrian shield were covered by mineral exploration licences, many of which were related to diamond exploration. The main exploration strategy has been to try to discover hidden or unknown kimberlite pipes.

Although Greenland is celebrated for excellent rock exposures along the coast and fjords, the fact is that such conditions do not prevail in the inland areas. There is substantial coverage by scree, till and glaciofluvial sediments which hide the rocks, although the thickness of till and residual soil is commonly less than one metre. As kimberlites weather more easily than their host gneisses they are not often seen in the field. The methods used in the search for the hidden kimberlite bodies on a regional scale have included (1) studies of topography to identify round depressions or lakes, (2) identification of round geophysical anomalies and (3) collection of samples of overburden and stream sediment with subsequent identification of KIM. On a detailed scale some of the identified targets have been drilled, and large bulk samples of kimberlite have been analysed for diamonds. The results have so far been encouraging, in as much as diamonds have been recovered from several kimberlite bodies, and the KIM investigations have outlined new prospective areas. There appears to have been less success with the identification of kimberlite pipes. Press releases have disclosed the finding of only one small pipe. The present exploration activities are focused on the four kimberlite fields originally outlined. Judged by the size of the present licensed areas, only the Sarfartoq kimberlite field appears to have been increase significantly in size compared to what was known prior to 1994.

Status and future activities

A diamond potential was already indicated for Greenland prior to the diamond rush which started in southern West Greenland in the mid 1990s. Mineral chemical data suggested that large proportions of the lithospheric mantle below the Archaean craton were within the diamond stability field, and kimberlite dykes were present to transport any diamonds to the surface. In SW Greenland two microdiamonds had been found. This diamond potential has now been confirmed by the finding of good quality microdiamonds and one macrodiamond in dykes in the Sarfartoq-Maniitsoq region. The search for kimberlite pipes continues and may have a positive outcome. Future investigations by GEUS and BMP and collaborators will be directed at gaining more information on the properties and architecture of the lithosphere through structural analyses of dyke patterns, teleseismic measurements, chemical and isotopic analysis of rocks and minerals, and more age determinations.

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Fig. 1. Known occurrences of kimberlites and diamonds in southern West Greenland.

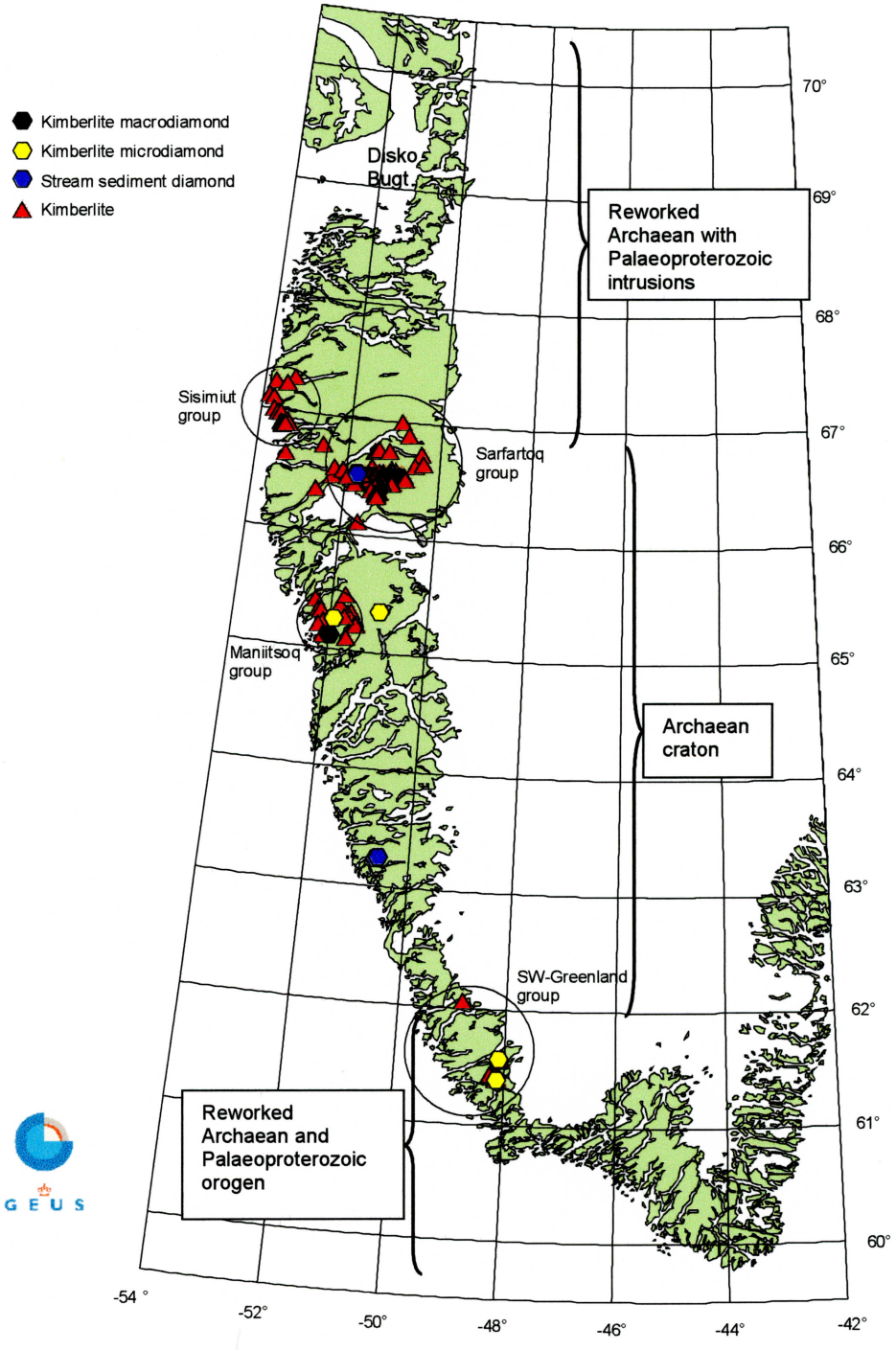

Fig. 2. Discrimination diagram for kimberlites and ultramafic lamprophyres, after Hamilton & Rock (1990) and Rock (1991). The diagram is based on chemical data compiled by one of the authors (L.M.L.).

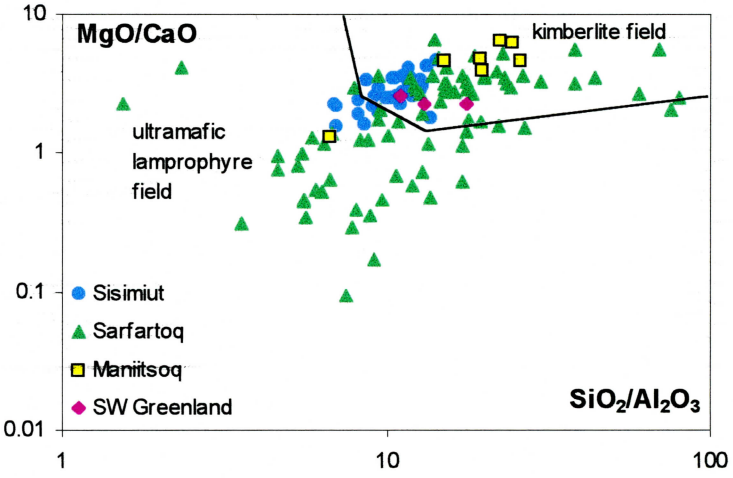

Fig. 3. Distribution of stream sediment samples with kimberlite indicator minerals.