

# Kimberlites and other ultramafic alkaline rocks in the Sisimiut–Kangerlussuaq region, southern West Greenland

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The alkaline province of southern West Greenland includes swarms of dykes described as kimberlites and lamproites (Larsen 1991), and these rock types are widely distributed in the Sisimiut–Sarfartoq–Kangerlussuaq region (Figs 1, 2). Kimberlites and lamproites are potential carriers of diamond, and since the description of the Sarfartoq carbonatite complex and the kimberlitic dykes related to this complex (Larsen 1980; Secher & Larsen 1980), the Sisimiut–Sarfartoq–Kangerlussuaq region has seen several campaigns of commercial diamond exploration. The latest and most persistent stage of exploration began in the mid-1990s and has continued to date, with varying intensity. Numerous reports of diamond-favourable indicator min-

erals from till sampling, finds of kimberlitic dykes, and recovery of actual diamonds from kimberlitic rocks have emerged since 1995 (Olsen *et al.* 1999). A drilling programme in late 2001 confirmed the unusually great length and width of a magnetic kimberlitic dyke (Ferguson 2001).

The alkaline ultramafic dykes within the Sisimiut–Kangerlussuaq and Sarfartoq regions intrude the border zone between the Archaean craton and the Palaeoproterozoic Nagssugtoqidian orogen (van Gool *et al.* 2002, this volume). This border is defined as the southern boundary of Palaeoproterozoic reworking of the Archaean basement gneisses. The reworking has affected the Palaeoproterozoic Kangâmiut dolerite dykes, which

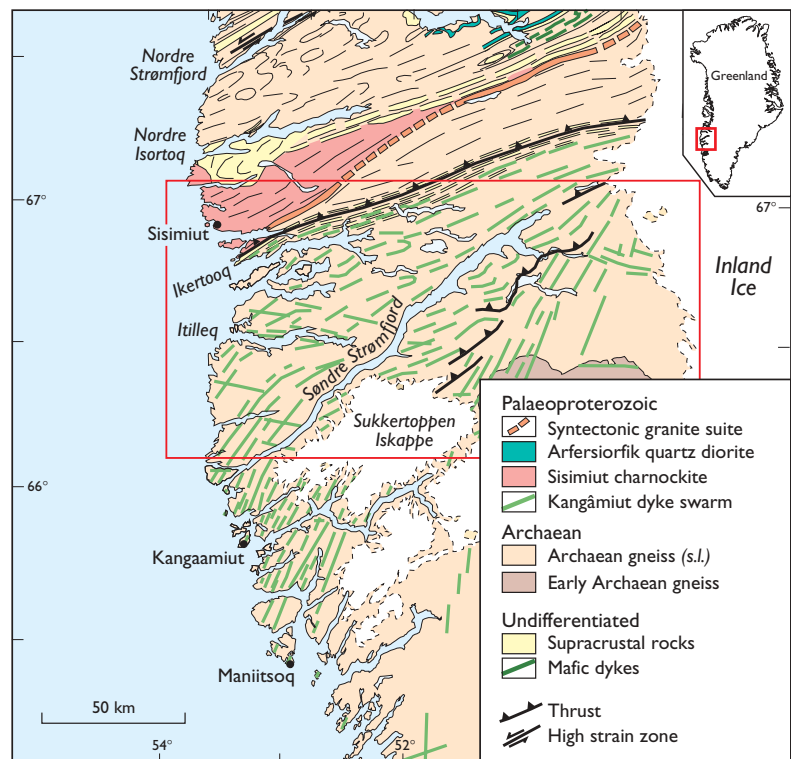


Fig. 1. Geological map of the region with the project area (Fig. 2) outlined in a red frame. Modified from Mengel *et al.* (1998).

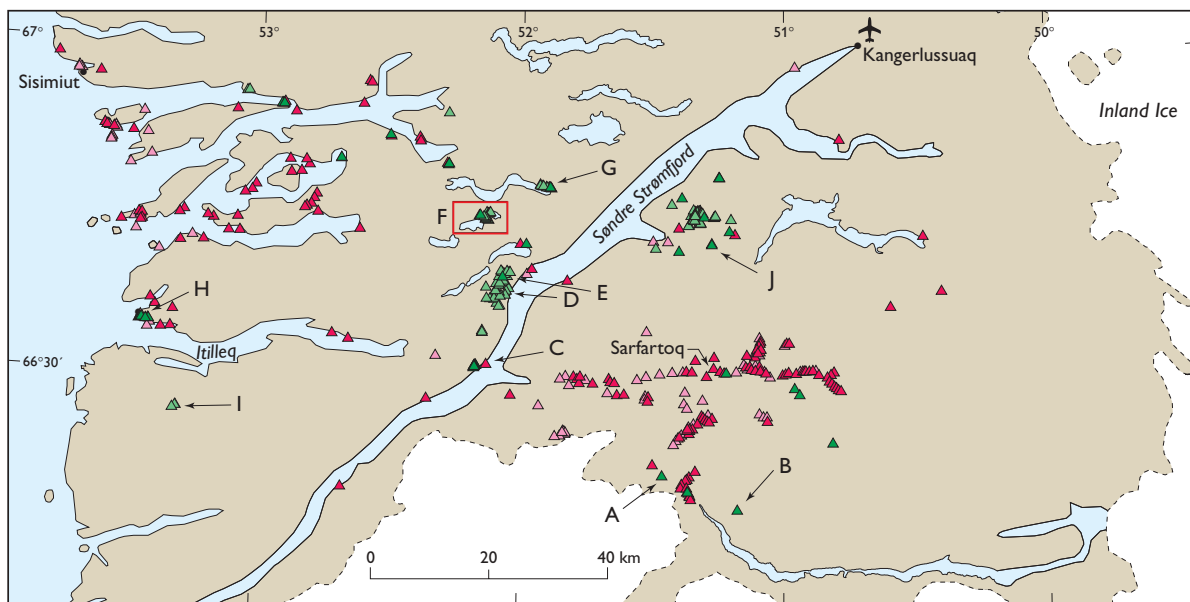


Fig. 2. Distribution of kimberlitic and lamprophyric occurrences within the project area. **A–J** are localities mentioned in the text. **Red triangles** are kimberlitic and lamprophyric dykes known prior to the present study: lamproites predominate in the region between Sisimiut and Itilleq, kimberlites in the Sarfartoq region (Larsen & Rex 1992). **Green triangles** are observations from the present study. **Heavy colouring** represents *in situ* finds and **light colouring** represents boulders (float).

were intruded into the Archaean gneisses prior to deformation and are now highly strained and boudinaged north of the boundary.

The intrusion of alkaline dykes appears to have taken place during two events. Lamproite dykes in the Sisimiut region are around 1.2 Ga old, whereas the Sarfartoq complex (Fig. 2) and a swarm of associated kimberlitic dykes have ages of around 0.6 Ga (Larsen & Rex 1992). A precise spatial relationship between the two intrusive events has not been established.

A project concerned with general scientific aspects of kimberlitic and related rocks in the Sisimiut–Kangerlussuaq region was established in 2000. The aim is to gather knowledge from companies' exploration activities and to incorporate Survey expertise such as petrology, structural geology, isotope geology, geochemistry, geophysics and the geographic information system (GIS). Field work was carried out in 2000 and 2001, with the Kangerlussuaq International Science Support (KISS) centre at Kangerlussuaq airport as logistical base. A combination of daily reconnaissance covering large areas using a helicopter, and fly camps of 2–3 days duration was applied.

The broad term 'kimberlitic' is used here in acknowledgement of the fact that the classification of the ultramafic dyke rocks of West Greenland is not resolved

with unanimity. Many of the dyke rocks resemble kimberlites and have previously been described as such (Larsen 1980, 1991; Scott 1981; Larsen & Rex 1992). Mitchell *et al.* (1999), however, take the view that the dyke rocks are not 'archetypal' kimberlites, but ultramafic lamprophyres that should be termed melnoites or aillikites. In the light of the actual occurrence of diamonds in the West Greenland dyke rocks, Mitchell *et al.* (1999) consider them to represent one of the few examples of diamond-bearing ultramafic lamprophyres. One of the aims of the present project is to contribute to a generally accepted classification of the West Greenland kimberlitic and related rocks.

### Distribution of kimberlitic and related rocks

Larsen's (1991) compilation of Greenland's kimberlite, lamproite and ultramafic lamprophyre occurrences proved to be a valuable initial guide to companies when the ongoing diamond exploration commenced in West Greenland in the mid-1990s (Olsen *et al.* 1999). The compilation includes data collected by earlier workers (e.g. Scott 1981), who typically operated by boat and thus were often restricted to working near the coast. As a

consequence, the known occurrences had an uneven distribution, and some areas appeared to be without occurrences.

Many of the occurrences of *in situ* dykes and boulders (float) in the Sisimiut–Sarfartoq–Kangerlussuaq region known at present are indicated in Fig. 2. The approximately 600 occurrences include those from Larsen's (1991) compilation and new localities added by exploration companies and recent field work by the Geological Survey of Denmark and Greenland (GEUS). It should be noted that the map does not include a large number of company localities that are at present confidential because they lie within active exclusive exploration licence areas. The map illustrates the concentration of occurrences in the vicinity of the Sarfartoq carbonatite complex, which Larsen (1980) interpreted as a swarm of kimberlitic cone-sheets centred on the carbonatite.

Bedrock exposure is generally poor in the study region, and dykes and sills of kimberlite, lamproite and carbonatite can be difficult to trace because they are thin, easily eroded and often covered by overburden and vegetation. Therefore, both stream geochemical data and aeromagnetic data are investigated with the aim of identifying geochemical and geophysical signatures reflecting occurrences of kimberlitic and related dykes.

### Field activities

Field work in 2000 consisted of one week's reconnaissance and visits to new dyke occurrences discovered

by exploration companies. The 2001 field work was focused on the spatial distribution of kimberlitic dyke rocks in areas with little or no previous information, and detailed studies on mantle xenoliths from the kimberlitic dykes. Studies of mantle xenolith-bearing rocks are described in a separate section below. The field work also included testing the ease of locating occurrences described in companies' assessment reports using various Global Positioning System (GPS) equipment and GIS methods.

Locality F (Fig. 2) provides an example of the density of new observations made in an area with no previously reported kimberlitic or lamproitic occurrences. Within the framed area 26 kimberlitic boulders and one new dyke were registered (Fig. 3). Three of the boulders measure about  $1 \times 1 \times 1$  m in size, indicating that the dyke or dykes from which they originated must be of substantial dimensions. Several large boulders were broken up into many smaller fragments, resulting in a much higher count of individual pieces of kimberlitic rock. The high number of kimberlitic boulders in this small area suggests they may have been derived from a nearby dyke outcrop. Similar observations were made at localities G and H (Fig. 2).

### Stream sediment geochemical anomalies reflecting alkaline rocks

Geochemical reconnaissance-scale stream sediment surveys have been carried out over large parts of West Greenland, including the project region considered here. The chemical analyses have been compiled and



Fig. 3. View of the area of locality F. A small outcrop of a new kimberlitic dyke (**arrow**) is located in the lineament marked by **dotted line**. Length of dotted line is approximately 200 m.

**Table 1. Range of Nb concentrations of various rock types in the Sisimiut–Sarfartoq–Kangerlussuaq region**

Rock type	Age	Nb ppm
Gneiss	Archaean	0.5–11
Charnockite	1.9 Ga	1–25
Syenite	1.9 Ga	5–25
Lamproite	1.2 Ga	95
Kimberlite	0.6 Ga	163–311
Beforsite	0.6 Ga	151
Carbonatite	0.6 Ga	2.3–22

From Larsen & Rex (1992) and GEUS database (unpublished).

calibrated (Steenfelt 1999, 2001a), and presented in a geochemical atlas of West and South Greenland (Steenfelt 2001b). The atlas displays element distribution patterns for 43 major and trace elements based on analysis of the < 0.1 mm grain size fraction of stream sediment samples collected systematically with a density of about one sample per 30 km<sup>2</sup>. The atlas also includes maps of high-pressure mineral phases of assumed mantle derivation, so-called kimberlite indicator minerals, identified in the 0.1 to 1 mm fraction of stream sediment samples collected between latitudes 61°N and 67°N.

The Sarfartoq carbonatite complex comprises rocks enriched in P, Ba, Sr and rare-earth elements (REE), and hosts a niobium-rich pyrochlore mineralisation (Secher & Larsen 1980). In the geochemical maps, the

Sarfartoq complex is easily recognised as a local but very pronounced anomaly with high concentrations of P, Ba, Sr, Nb and REE, as well as Mo, Ta and Th.

Kimberlites and lamproites have olivine- and carbonate-rich groundmass (high Mg and Ca) and high concentrations of the trace elements Ba, Cr, Ni, Nb, Sr, P, Ti and light REE. In view of the particular mineralogy and chemistry of the alkaline rocks, their presence within the gneiss-dominated Archaean basement should be readily detectable in the stream sediment geochemical survey. However, because of the small volume of alkaline rocks, their geochemical imprint on the stream sediment composition may be obscured by the presence of other igneous rocks that have intruded the tonalitic gneisses in the same region. Gabbroic inclusions within the gneisses, and the Palaeoproterozoic Kangâmiut dolerite dyke swarm, release so much Ni, Cr and Ti to the streams that the contribution of these metals from alkaline ultramafic rocks is easily disguised. Furthermore, Palaeoproterozoic intrusions within the Nagssugtoqidian domain comprise considerable volumes of charnockite and syenite, enriched in Ba, Sr, P and REE (Steenfelt 1997), which give rise to anomalies that are similar to those expected to be caused by kimberlites and lamproites.

However, one element, niobium, has proved convincing as a ‘pathfinder’ for kimberlites and lamproites. Table 1 illustrates the high Nb concentrations of kimberlites and lamproites relative to Archaean gneisses; even the Palaeoproterozoic syenites have relatively low

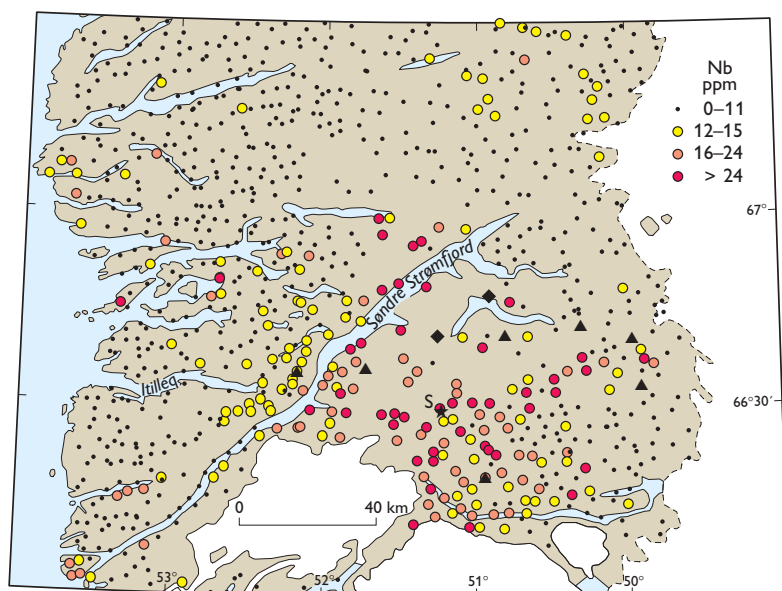


Fig. 4. Distribution of Nb in the < 0.1 mm fraction of stream sediments. **S**: Sarfartoq; **black triangles**: high-Mg, high-Cr chromite; **black diamonds**: high-Cr, low-Ca pyrope garnet.

contents of Nb. The regional stream sediment anomaly pattern for Nb in the study region (Fig. 4) does, in fact, coincide with the province of known kimberlites and lamproites.

It was recognised at an early stage that the Sarfartoq complex and surroundings were characterised by a regional stream sediment Nb anomaly (Steenfelt 1991). The anomaly was then attributed partly to Nb mineralisation, and partly to the known ultramafic alkaline dykes. As more stream sediment data became available (Steenfelt *et al.* 1993) and more kimberlite occurrences were registered, the apparent spatial relationship between the high Nb in stream sediments and occurrences of ultramafic alkaline dykes was strengthened.

Field visits to high-Nb stream sites were carried out in 2000 and 2001 to test the validity of high Nb in stream sediments as an indicator of kimberlite and lamproite. At one site with a very high Nb value a lamproite dyke was seen in outcrop in a stream gorge, and at other sites boulders of kimberlite were observed along the stream course. Outcrops or boulders of kimberlite or lamproite were not found in all the high-Nb sites visited. However, it is worthy of note that thin dykes and float of befor-site have been recorded some distance from the Sarfartoq carbonatite complex; befor-site is a magnesiocarbonatite rock with high concentrations of Nb and LREE, which probably contributes to the Nb-enriched province.

Stream sediment samples with high Nb and high-pressure chromite have been collected in areas east and south-east of known kimberlite occurrences suggesting a wider extent of the kimberlite field than recognised hitherto. A small cluster of high Nb values in the north-eastern part of Fig. 4 is at present unexplained. Kimberlites or lamproites have not so far been recorded here. However, the generally poor exposure in the stream surroundings would hinder ready recognition of alkaline dykes or other rocks with high Nb such as granitic pegmatites.

High concentrations of P, REE, Ba and Sr are recorded in stream sediment samples collected in a 15 × 15 km area near the coast south of Itilleq (locality I, Fig. 2). The geochemical signature of these samples is similar to that obtained in streams draining Palaeoproterozoic syenitic intrusives in the Nagssugtoqidian domain (Steenfelt 1998). It is noteworthy that the Nb concentrations are as low as in the Nagssugtoqidian syenites, and hence it was not expected to find kimberlites, but some other kind of alkaline rock.

Two field days were spent in a valley upstream from the most pronounced stream sediment anomaly. The area is dominated by a gneiss complex intruded by a

10 to 15 m wide Kangâmiut dyke and numerous thin, less than 0.5 m wide, dykes and sills of grey lamprophyre and a brown dolerite with star-shaped aggregates of phenocrystic plagioclase. Blocks of a coarse-grained alkaline ultramafic rock were frequently seen in the moraines of the valley glacier and were particularly abundant in the screes covering the southern valley slopes. The alkaline rock is dominated by black, shiny amphibole and has variable to large amounts of brown phlogopite and light green apatite. The finds explain the geochemical anomaly and enlarge the province of known alkaline rocks in this part of Greenland.

### Mantle xenoliths in kimberlitic rocks

Mantle xenoliths are widely used in studies of the mantle lithosphere (Menzies & Hawkesworth 1987; Nixon 1987, 1995), and are here used to shed light on how the plate-tectonic history affected the deeper parts of the lithosphere across the Archaean–Proterozoic transition in the Sisimiut–Sarfartoq–Kangerlussuaq region. An extensive collection of xenoliths from several kimberlitic occurrences in the unworked Archaean terrane south of Søndre Strømfjord was made in 2000, and two kimberlitic dykes containing abundant mantle xenoliths (localities A and B, Fig. 2) were visited and sampled in 2001. At least 90% of the xenoliths encountered have peridotitic or pyroxenitic compositions, and range in size from less than 1 cm to 15 cm across. Some xenoliths contain visible purple pyrope garnet (Fig. 5) and green Cr diopside, minerals that – given the right



Fig. 5. Kimberlitic dyke with many different types of mantle xenoliths (locality A, Fig. 2). Note purple garnets indicated with **arrows**; hammer and pencil for scale.

chemical composition – may indicate  $P$ - $T$  conditions within the diamond stability field.

In the Palaeoproterozoic reworked Archaean terrane north of Søndre Strømfjord another kimberlitic dyke reported by exploration companies was visited (locality C, Fig. 2). The dyke consists of a 5–10 m wide, *c.* 500 m long train of kimberlitic boulders and outcrops in banded grey gneiss. Peridotitic and pyroxenitic xenoliths are abundant, ranging in size from less than 1 cm to around 10 cm. Dunitic (ol), harzburgitic (ol + opx) and lherzolitic (ol + opx + cpx ± gt) xenoliths were identified in the field. The Survey campaign located two further dykes north of Søndre Strømfjord (localities D and E, Fig. 2). The locality D dyke is vertical, 2–5 m wide and can be traced for *c.* 1.5 km. Xenoliths are much less abundant here than in the dykes south of Søndre Strømfjord, and their sizes range from less than 1 cm to about 5 cm. Macroscopically, the peridotitic xenolith types are dunite (ol) and lherzolite (ol + cpx + opx). The locality E dyke is a gently dipping (16–20°S), 30–50 cm thick sheet, and contains small xenoliths that are mostly less than 2 cm in diameter.

## Preliminary results

Seven xenoliths from the locality A dyke have been analysed for major element mineral chemistry by electron microprobe at the Geological Institute, University of Copenhagen, and garnets in three of them have been subjected to reconnaissance laser ablation analyses at the Survey. Garnets in the same three xenoliths were subjected to high-precision analysis of Ni by electron microprobe, and the xenolith rock types (Table 2) have been determined from their mineral assemblages and estimated mineral proportions (e.g. LeBas & Streckeisen 1991).

Generally, the major element compositions of minerals within individual xenoliths are homogeneous

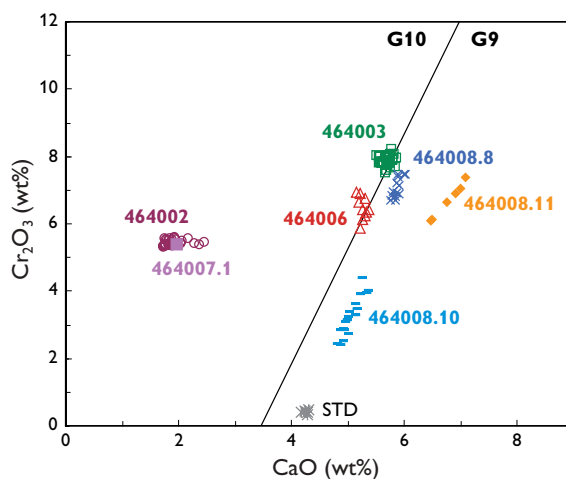


Fig. 6. Garnet compositions in xenoliths from the locality A dyke, analysed by electron microprobe. The **G9–G10** boundary line is from Gurney (1984) and Gurney & Zweistra (1995), and **STD** is a reference garnet analysed along with microprobe standards. GGU 464xxx numbers refer to sample material in the files of the Geological Survey of Denmark and Greenland.

(Table 2). The average forsterite (Fo) content of the olivines ranges from Fo87 to Fo92; garnet wehrlites contain the olivines with the lowest Fo, garnet harzburgites and garnet lherzolites the olivines with the highest Fo. Average Ni contents are within the range of 2900 ± 360 ppm reported by Ryan *et al.* (1996) for garnet peridotites. Orthopyroxenes contain less than 1.6 wt% CaO and have relatively low Al<sub>2</sub>O<sub>3</sub>, the lowest values being from ilmenite-free garnet lherzolites (0.49–0.53 wt%). Clinopyroxene Mg/(Mg + Fe<sup>2+</sup>) ratios correlate positively with Cr<sub>2</sub>O<sub>3</sub>. Garnet Mg/(Mg + Fe<sup>2+</sup>) ratios tend to correlate positively with Fo contents of olivine. CaO and Cr<sub>2</sub>O<sub>3</sub> contents of garnets show limited variation within individual xenoliths but large overall variations (Fig. 6), and the garnets from two harzburgite xenoliths clearly

Table 2. Calculated temperatures and pressures for xenolith minerals from the locality A dyke

Mineral analysed	GGU sample	464002.2	464003	464006	464008.10	464008.11
	Rock type	gt hzb	gt lhz	gt lhz	gt lhz	gt weh
	Minerals	ol-opx-gt	ol-opx-cpx-gt	ol-opx-cpx-gt	ol-opx-cpx-gt-ilm	ol-cpx-gt
cpx	$T$ (°C) *		1039 ± 30	1194 ± 30	1124 ± 30	1030 ± 30
cpx	$P$ (kbar) *		48.9 ± 2.3	57.8 ± 2.3	68.7 ± 2.3	52.5 ± 2.3
gt	$T_{Ni}$ (°C) †	1143 ± 42	1101 ± 18	1221 ± 30		

$T$ ,  $P$  and  $T_{Ni}$  calculated according to: \* Nimis & Taylor (2000), † Ryan *et al.* (1996).

ol: olivine, opx: orthopyroxene, cpx: clinopyroxene, gt: garnet, ilm: ilmenite, hzb: harzburgite, lhz: lherzolite, weh: wehrlite. The GGU numbers refer to material from Greenland in the files of the Geological Survey of Denmark and Greenland.

plot within the G10 field of Gurney (1984) and Gurney & Zweistra (1995). G10-class pyrope garnets are considered to be strongly indicative of conditions favourable for diamond stability.

Equilibration temperatures ( $T$ ) and pressures ( $P$ ) for the clinopyroxene-bearing xenoliths were calculated using the Nimis & Taylor (2000) single clinopyroxene thermobarometry equations (Table 2), and these temperature estimates are comparable to  $T_{Ni}$  values calculated using the high-precision Ni analyses and the empirical Ni-in-garnet thermometer of Ryan *et al.* (1996).

Variations of Zr vs. Y in garnets of three xenoliths from the locality A dyke are shown in Fig. 7, and averaged chondrite-normalised REE patterns for garnet and clinopyroxene in each xenolith in Fig. 8. The very low Zr and Y contents in garnets of a garnet harzburgite xenolith (sample GGU 464002.2) are consistent with their low-Ca character (Fig. 6) and indicate that this xenolith represents original lherzolite mantle depleted by partial melting (Griffin *et al.* 1992). The garnet in sample GGU 464002.2 is more depleted in the middle and heavy REE than the garnets in lherzolites from samples GGU 464003 and 464006. The sinuous pattern resembles that of low-Ca garnet in a harzburgite xenolith from the Sarfartoq area (Garrit 2000). The low REE contents support the idea that the garnet is hosted in a rock depleted by partial melting, whereas the sinuous shape may indicate post-depletion metasomatic enrichment processes (Hoal *et al.* 1984) or disequilibrium garnet growth (Shimizu & Sobolev 1995). Garnet lherzolites from samples GGU 464003 and

464006 have much higher Zr and Y concentrations in the garnets, and their chondrite-normalised REE patterns are more like those of typical LREE-depleted and MREE- to HREE-enriched garnets of primitive mantle (e.g. Haggerty 1995). Garnets from samples GGU 464003 and 464006 plot within fields indicating phlogopite and melt metasomatism of previously depleted mantle, respectively (Fig. 7). Phlogopite occurs in the xenoliths as part of kelyphitic rims on garnets, and in sample GGU 464003 also as a minor phase away from garnets. Ti contents of garnets, which follow Zr in some metasomatic processes (Griffin *et al.* 1999), show no significant zoning. This may indicate that if metasomatic processes affected garnet compositions, there was sufficient time for equilibration with the metasomatising agents.

## Geophysical properties of kimberlites

Airborne geophysical surveys play an important role in diamond exploration, as kimberlites are often hidden under surficial deposits but also often have magnetic properties that make them distinguishable from the country rocks (e.g. Keating 1995; Macnae 1995). Since 1996 several helicopter-borne surveys have been commissioned by exploration companies to cover their licence areas in the Maniitsoq and Kangerlussuaq regions (Olsen *et al.* 1999). Data from the latest helicopter-borne survey in the Kangerlussuaq region in 2000 were used to outline targets for the drilling that led to the

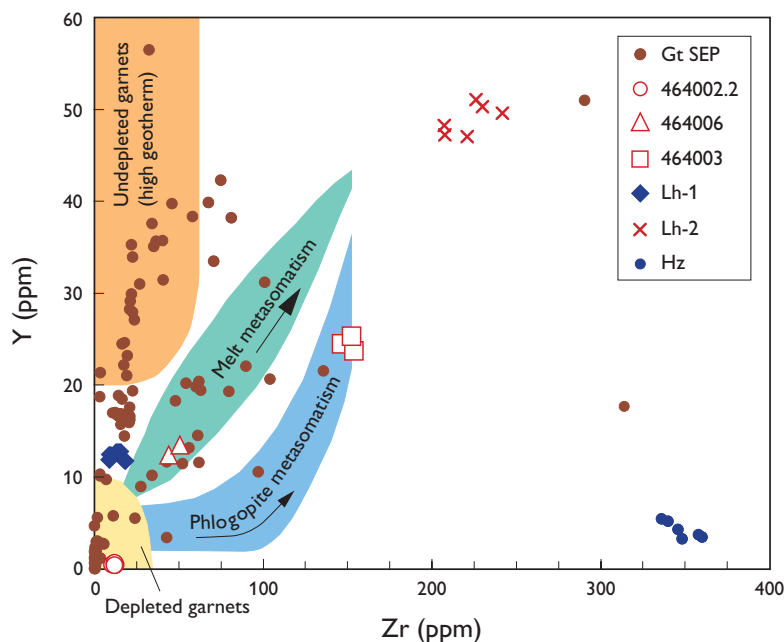


Fig. 7. Laser ablation ICP-MS analyses of Zr and Y in garnets from xenoliths in the locality A dyke (this study, data from GEUS), garnet lherzolite and garnet harzburgite xenoliths from the Sarfartoq area (Garrit 2000, data from Memorial University, Canada) and in garnet separates from the Sarfartoq area (**brown dots**: Garrit 2000, data from Macquarie University, Australia). The **coloured fields** are from Griffin & Ryan (1995) and Griffin *et al.* (1999), and **arrows** indicate core-to-rim zonation direction in metasomatised garnets of Griffin *et al.* (1999).

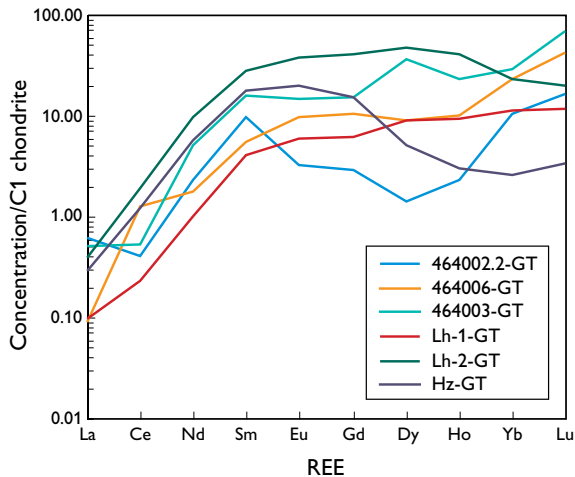


Fig. 8. Chondrite-normalised REE patterns of garnets in xenoliths from the locality A dyke (this study) and of garnets in Sarfartoq xenoliths (Garrit 2000). Laser ablation ICP-MS analyses, same sources as in Fig. 7.

confirmation of a 5 km long and 20 m wide kimberlitic dyke in late 2001 (locality J, Fig. 2; Fig. 9; Ferguson 2001).

The petrophysical properties of 22 representative kimberlitic samples collected in 2001 have been determined by the Geological Survey of Finland, and these data will be used in modelling the geophysical response obtained in the airborne surveys. It is planned to collect further samples for petrophysical measurements in 2002.

## Conclusions and plans for further work

Field work in 2000 and 2001 in poorly known areas has added approximately 50 samples of kimberlitic dykes and more than 300 kimberlitic boulders to the existing databank.

Niobium in the fine fraction (< 0.1 mm) of stream sediments has proved to be a convincing 'pathfinder' element for kimberlites and lamproites in the Sisimiut–Sarfartoq–Kangerlussuaq region. Nb anomalies and the presence of high-pressure chromite in the stream sediment samples in the eastern and south-eastern part of the study area warrant follow-up.

The different xenolith types from the locality A dyke and their distinctive mineral compositions clearly demonstrate the heterogeneous character of the West Greenland lithospheric mantle, with a vertical zonation of depleted and metasomatised zones beneath the Archaean craton. Temperature and pressure calculations suggest that all xenoliths were derived from within the diamond stability field at a depth interval of 49–69 kbar, corresponding to approximately 150–215 km.

Although magnetic data have been used with some success in the search for kimberlitic dykes in the Kangerlussuaq region, there is a need for establishing a database with petrophysical properties of both kimberlitic dykes and host rocks in order to fully utilise the geophysical data available. Magnetic profiling at ground

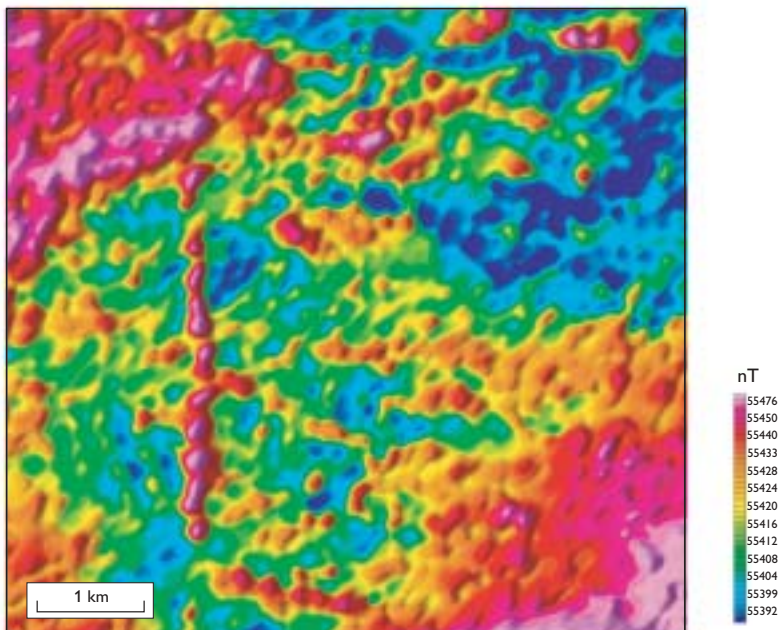


Fig. 9. Magnetic total field anomaly of locality J (Fig. 2), where a 5 km long and 20 m wide kimberlitic dyke shows up as pronounced linear feature. Data from helicopter-borne DIGHEM survey carried out for Dia Met Minerals Ltd., reproduced with permission.



level should be conducted at selected kimberlitic dyke occurrences in future field work.

Exploration companies have produced a large volume of data relevant to diamond exploration since 1995. The data include mineral analyses of heavy minerals recovered from till samples, dyke and boulder distribution maps, helicopter-borne geophysical surveys, results of diamond testing of mini-bulk sampled dykes, drill logs, etc. Compilation and publication of all non-confidential company data submitted in assessment reports to the Bureau of Minerals and Petroleum, Government of Greenland, is planned for 2002. A compilation of this type covering the North Slave Craton in Nunavut, Canada (Armstrong 2002) has received very positive response from industry.

The ultramafic alkaline rocks observed within the region north-west of the Sarfartoq cone sheet structure (Larsen 1980) have not been proved to be diamondiferous. However, the finds of diamonds in kimberlitic dykes of the Torngat orogen (Derbuch 2001) – the Canadian counterpart of the Nagssugtoqidian orogen – is an encouragement for further exploration in West Greenland.

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## References

Armstrong, J.P. 2002: Diamond exploration data, North Slave Craton, Nunavut. NU Open Report **2002-01**, 1 CD-ROM. Iqaluit, Canada: Department of Indian Affairs and Northern Development.

Derbuch, H. 2001: Twin Mining's Torngat results advance project. News Release, 3 pp. Toronto, Canada: Twin Mining Corporation (issued 5 April, 2001).

Ferguson, J. 2001: Citation confirms large kimberlitic dyke in Greenland. News Release **2001-8**, 1 pp. Vancouver, Canada: Citation Resources Inc. (issued 27 September, 2001).

Garrit, D. 2000: The nature of Archaean and Proterozoic lithospheric mantle and lower crust in West Greenland illustrated

by the geochemistry and petrography of xenoliths from kimberlites, 289 pp. Unpublished Ph.D. thesis, University of Copenhagen, Denmark.

Griffin, W.L. & Ryan, C.G. 1995: Trace elements in indicator minerals: area selection and target evaluation in diamond exploration. In: Griffin, W.L. (ed.): Diamond exploration into the 21st century. *Journal of Geochemical Exploration* **53**(1–3), 311–337.

Griffin, W.L., Gurney, J.J. & Ryan, C.G. 1992: Variations in trapping temperatures and trace elements in peridotite-suite inclusions from African diamonds: evidence for two inclusion suites, and implications for lithosphere stratigraphy. *Contributions to Mineralogy and Petrology* **110**, 1–15.

Griffin, W.L., Shee, S.R., Ryan, C.G., Win, T.T. & Wyatt, B.A. 1999: Harzburgite to lherzolite and back again: metasomatic processes in ultramafic xenoliths from the Wesselton kimberlite, Kimberley, South Africa. *Contributions to Mineralogy and Petrology* **134**, 232–250.

Gurney, J.J. 1984: A correlation between garnets and diamonds in kimberlites. In: Glover, J.E. & Harris, P.G. (eds): Kimberlite occurrence and origin: a basis for conceptual models in exploration. *Publication* **8**, 143–166. Perth: Geology Department & University Extension, The University of Western Australia.

Gurney, J.J. & Zweistra, P. 1995: The interpretation of the major element compositions of mantle minerals in diamond exploration. In: Griffin, W.L. (ed.): Diamond exploration into the 21st century. *Journal of Geochemical Exploration* **53**(1–3), 293–309.

Haggerty, S.E. 1995: Upper mantle mineralogy. *Journal of Geodynamics* **20**, 331–364.

Hoal, K.E.O., Hoal, B.G., Erlank, A.J. & Shimizu, N. 1984: Metasomatism of the mantle lithosphere recorded by rare earth elements in garnets. *Earth and Planetary Science Letters* **126**, 303–313.

Keating, P. 1995: A simple technique to identify magnetic anomalies due to kimberlite pipes. *Exploration and Mining Geology* **4**(2), 121–125.

Larsen, L.M. 1980: Lamprophyric and kimberlitic dykes associated with the Sarfartôq carbonatite complex, southern West Greenland. *Rapport Grønlands Geologiske Undersøgelse* **100**, 65–69.

Larsen, L.M. 1991: Occurrences of kimberlite, lamproite and ultramafic lamprophyre in Greenland. *Open File Series Grønlands Geologiske Undersøgelse* **91/2**, 36 pp.

Larsen, L.M. & Rex, D.C. 1992: A review of the 2500 Ma span of alkaline-ultramafic, potassic and carbonatitic magmatism in West Greenland. *Lithos* **28**, 367–402.

LeBas, M.J. & Streckeisen, A.L. 1991: The IUGS systematics of igneous rocks. *Journal of the Geological Society of London* **148**, 825–833.

Macnae, J. 1995: Applications of geophysics for the detection and exploration of kimberlites and lamproites. In: Griffin, W.L. (ed.): Diamond exploration into the 21st century. *Journal of Geochemical Exploration* **53**(1–3), 213–243.

Mengel, F. *et al.* 1998: Archaean and Palaeoproterozoic orogenic processes: Danish Lithosphere Centre studies of the Nagssugtoqidian orogen, West Greenland. *Geology of Greenland Survey Bulletin* **180**, 100–110.

- Menzies, M.A. & Hawkesworth, C.J. (eds) 1987: Mantle metasomatism, 472 pp. London: Academic Press.
- Mitchell, R.H., Scott Smith, B.H. & Larsen, L.M. 1999: Mineralogy of ultramafic dikes from the Sarfartoq, Sisimiut and Maniitsoq areas, West Greenland. In: Gurney, J.J. *et al.* (eds): Proceedings of the VIIth International Kimberlite Conference **2**, 574–583. Cape Town: Red Roof Design cc.
- Nimis, P. & Taylor, W.R. 2000: Single clinopyroxene thermobarometry for garnet peridotites. Part I. Calibration and testing of a Cr-in-Cpx barometer and an enstatite-in-Cpx thermometer. *Contributions to Mineralogy and Petrology* **139**, 541–554.
- Nixon, P.H. (ed.) 1987: Mantle xenoliths, 864 pp. Chichester: John Wiley & Sons.
- Nixon, P.H. 1995: A review of mantle xenoliths and their role in diamond exploration. *Journal of Geodynamics* **20**, 302–329.
- Olsen, H.K., Jensen, S.M., Schönwandt, H.K. & Helmstaedt, H.H. 1999: Review of diamond exploration in Greenland. North Atlantic Minerals Symposium, Dublin, Ireland, 19–22 September, 1999. Extended abstracts volume, 166–168.
- Ryan, C.G., Griffin, W.L. & Pearson, N.J. 1996: Garnet geotherms: pressure–temperature data from Cr-pyrope garnet xenocrysts in volcanic rocks. *Journal of Geophysical Research* **101**, 5611–5625.
- Scott, B.H. 1981: Kimberlite and lamproite dykes from Holsteinsborg, West Greenland. *Meddelelser om Grønland Geoscience* **4**, 24 pp.
- Secher, K. & Larsen, L.M. 1980: Geology and mineralogy of the Sarfartôq carbonatite complex, southern West Greenland. *Lithos* **13**, 199–212.
- Shimizu, N. & Sobolev, N.V. 1995: Young peridotitic diamonds from the Mir kimberlite pipe. *Nature* **375**, 394–397.
- Steenfelt, A. 1991: Reconnaissance geochemical mapping of southern West Greenland from 62°30' N to 64°00' N – 1991 results. Open File Series Grønlands Geologiske Undersøgelse **91/9**, 21 pp.
- Steenfelt, A. 1997: High Ba–Sr–P–REE components in Early Proterozoic magmas within the Nagssugtoqidian orogen, West Greenland. Posters and Abstracts. 9th EUG symposium. *Terra Nova* **9**, 360 only.
- Steenfelt, A. 1998: The Nagssugtoqidian orogen imaged by geochemical maps. In: Wilson, J.R. (ed.): 23. Nordiske geologiske vintermøde, Aarhus, Denmark, 13–16 January, 1998. Abstract volume, 234 only. Aarhus, Denmark: University of Aarhus.
- Steenfelt, A. 1999: Compilation of data sets for a geochemical atlas of West and South Greenland based on stream sediment surveys 1977 to 1997. Danmarks og Grønlands Geologiske Undersøgelse Rapport **1999/41**, 33 pp.
- Steenfelt, A. 2001a: Calibration of stream sediment data from West and South Greenland. A supplement to GEUS Report 1999/41. Danmarks og Grønlands Geologiske Undersøgelse Rapport **2001/47**, 43 pp.
- Steenfelt, A. 2001b: Geochemical atlas of Greenland – West and South Greenland. Danmarks og Grønlands Geologiske Undersøgelse Rapport **2001/46**, 39 pp. + 1 CD-ROM.
- Steenfelt, A., Dam, E. & Nielsen, J.P. 1993: Reconnaissance geochemical mapping of map sheets 67 V.1 and 68 V.1 (66° to 68° N, 51°25' to 54°W), West Greenland. Open File Series Grønlands Geologiske Undersøgelse **93/1**, 18 pp.
- van Gool, J.A.M. *et al.* 2002: Precambrian geology of the northern Nagssugtoqidian orogen, West Greenland: mapping in the Kangaatsiaq area. *Geology of Greenland Survey Bulletin* **191**, 13–23 (this volume).

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