DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 2005/68

Workshop on Greenland's diamond potential, 7-9 November 2005, in Copenhagen

Extended abstracts

Karsten Secher & Marianne N. Nielsen (eds)

GEOLOGICAL SURVEY OF DENMARK AND GREENLAND
MINISTRY OF THE ENVIRONMENT

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Contents

Introduction

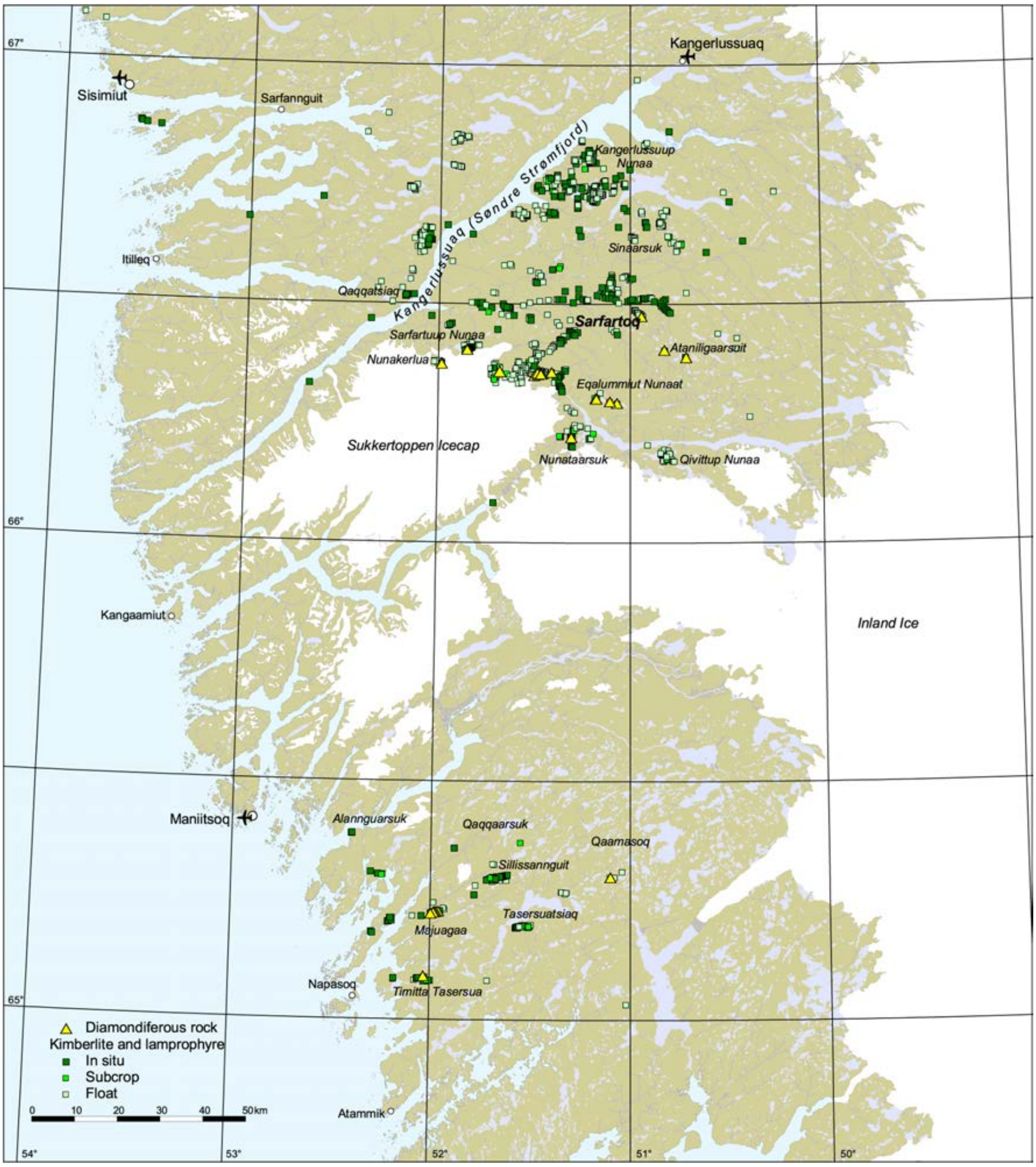
This workshop on Greenland's diamond potential is a milestone in GEUS' five-year project on 'kimberlite' geology. The project has been carried out in collaboration with the Bureau of Minerals and Petroleum (BMP) in Nuuk, Greenland. During these five years, GEUS' Department of Economic Geology conducted a new collection of data from West Greenland with relevance to distribution of rock types in the field of kimberlite, lamproite and ultramafic lamprophyre in the wide context, aiming at all aspects of the Greenland diamond potential. A number of reports and accounts on results from this work have been published so far, including a complete collection presented on DVD of all diamond exploration data produced by companies, universities and GEUS.

A wealth of new kimberlite occurrences and data relevant to kimberlites and their diamond potential have appeared over the last few years, and several research groups are at present working in collaboration with GEUS on new samples and data from the Sarfartoq and Maniitsoq regions. GEUS and BMP wish to convene the international workshop in order to give involved and interested parties an opportunity to exchange and discuss recent investigations and data and implications for exploration for diamonds in West Greenland and other Archaean cratonic regions in the northern hemisphere, especially those in glaciated terrain.

The presentations in this workshop report various results of GEUS' research in this field, as well as a number of invited accounts covering similar subjects from the North American and Atlantic with topics relating to the general discussion on kimberlites. The topics cover such wide issues as the lithospheric mantle under southern West Greenland, petrogenesis of kimberlite, geotectonic and structural setting, and exploration techniques and results.

This volume includes the abstracts delivered by the participants and contributions are printed as they are received. Only technical changes have been carried out by the workshop secretariat in order to match the format of the GEUS report. The abstracts are presented in alphabetical order.

Participants presenting material are thanked for their effort and enthusiasm directed toward this workshop. We look forward to a productive gathering with the Greenland diamond potential in focus.



Overview map of the Sarfartoq and Maniitsoq regions with place names, kimberlite and lamprophyre occurrences and localities of diamond-bearing rocks.

Old and/or thick lithosphere beneath NW and E Greenland

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Mantle xenoliths from NW Greenland (Ubekendt Ejland) and E Greenland (Wiedemann Fjord) have Re-depletion ages > 3 Ga. Coupled with indirect evidence of crust-formation ages from zircon dating this suggests that large portions of Greenland is underlain by Early Archaean lithospheric mantle. Igneous activity in the Early Palaeogene in NE Greenland requires a lithospheric thickness in excess of 200 km, demonstrating that in at least some parts of E Greenland the lithosphere is thick enough to host diamonds. The age and thickness of the Greenlandic lithospheric mantle thus imply that in SW Greenland a diamond potential exists in large areas in E and NW Greenland in addition to the known region.

Consequences of Phanerozoic episodes of burial and exhumation for erosional patterns in West Greenland

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in collaboration with Green, P.F.[2], Chalmers, J.A.[1] & Lidmar-Bergström, K.[3]

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The preserved Mesozoic–Cenozoic sedimentary and volcanic record of West Greenland makes this a key area for studying the uplift of passive continental margins. Large-scale landscapes near the passive continental margins around the northern North Atlantic are commonly erosion surfaces at high elevation. The landscapes often lack pre-Quaternary cover rocks and the details in the landscape are characterised by glacial scouring. The amount of erosion in the basement has been subjected to since the final dated metamorphic or intrusion events is therefore difficult to ascertain. We have combined apatite fission-track analysis (AFTA) data with landform analysis to investigate the development of West Greenland landscapes across areas with substantially different geology (Chalmers et al. 1999; Green et al. 2002; Bonow 2004, 2005; Japsen et al. 2005; Fig. 1a).

Thermal history constraints have been extracted from the AFTA data across central West Greenland (65–71°N). Data in individual samples typically define two (sometimes three) discrete paleo-thermal episodes. Synthesis of the timing constraints for individual cooling episodes identified in 70 samples suggests that at least six discrete episodes of cooling since the latest Proterozoic are required to explain all the AFTA results. The analysis shows that the basement rocks presently at outcrop have been buried below only a few kilometres of cover rocks during the Phanerozoic because palaeo-temperatures of 120°C or less are found for the palaeo-thermal events in this time interval at various locations across the area.

Identification and mapping of palaeosurfaces (preserved erosion surfaces) in West Greenland and analysis of the relationship between re-exposed relief, new relief and the Mesozoic-Palaeogene cover rocks, have made it possible to obtain relative age chronologies, to identify uplift events and to estimate the spatial distribution of erosion (Fig. 1). We find that the mountains of West Greenland are the end result of three Cenozoic phases of uplift and erosion. The first phase that began between 36 and 30 Ma created a planation surface during the Oligocene–Miocene. This surface was offset by reactivated faults, resulting in megablocks that were tilted and uplifted to present-day altitudes of up to 2 km in two phases one that began between 11 and 10 Ma and the second that began between 7 and 2 Ma (Fig. 2).

The amount of erosion since the onset of Neogene uplift has been estimated as the difference between the altitude of the planation surface and the present topography (Fig. 3). The area has been affected by differential erosion, even though the landscape is characterised by glacial scouring. Maximum erosion of 800-1300 m occurs along the fjords and valleys that cut through the highlands, while large areas within plateaux situated at high altitude are virtually unaffected. Areas dominated by gneiss in amphibolite facies are more eroded than areas with gneiss in granulite facies.

The multi-disciplinary approach taken here illustrates that it is possible to indicate when basement areas have been covered and when they have been exposed to erosion as well as to estimate the amount of erosion of basement rocks since uplift events.

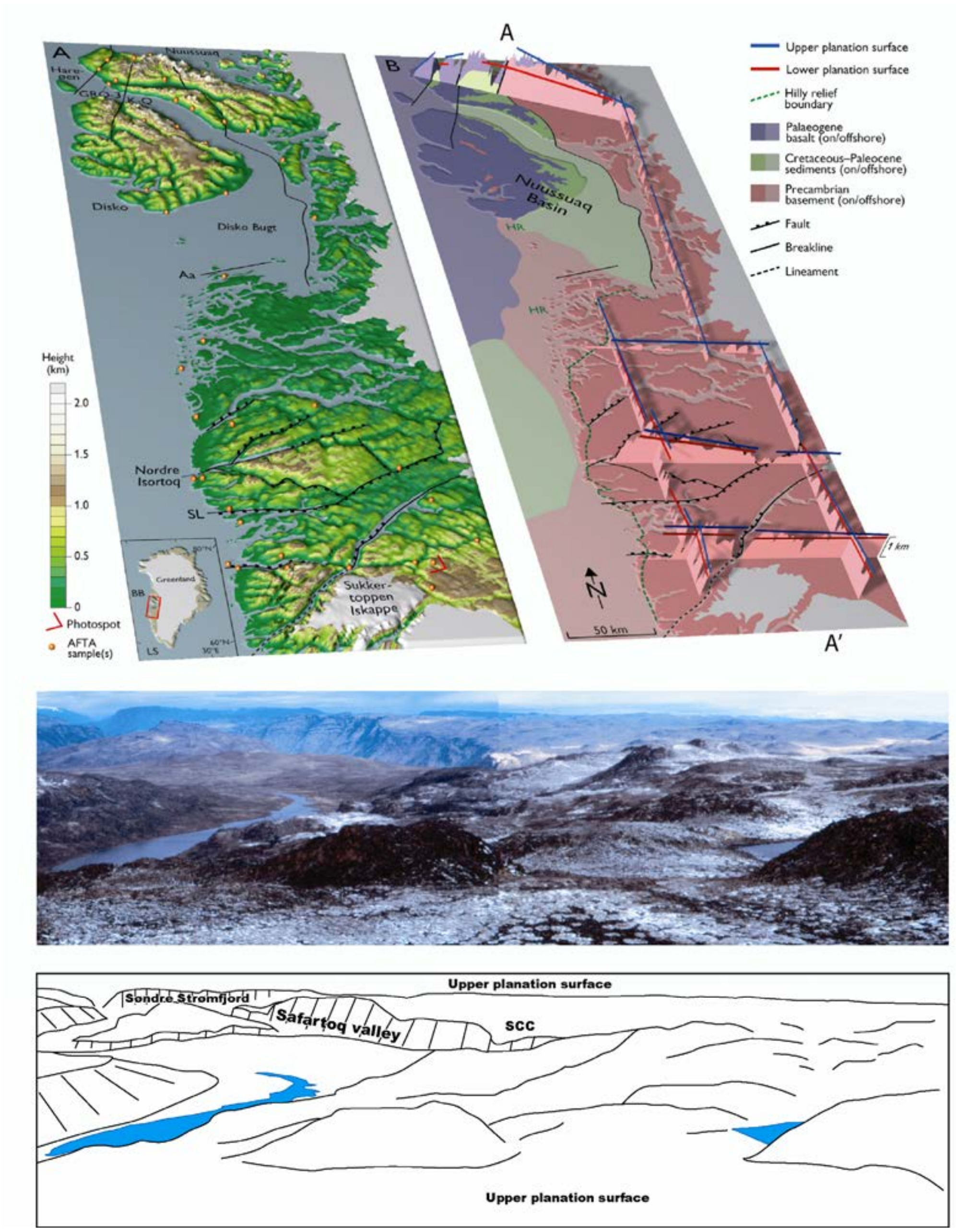

Figure 1. *Maps of the study area. Figure description on next page.*

(A) Topography. (B) Geology with topographical profiles (Chalmers et al. 1999; Bonow 2004, 2005). Two planation surfaces cut across Precambrian basement and Paleocene–Eocene volcanic rocks. Their formation was uniform across the study area and they must be younger than the Eocene basalts. The planation surfaces now dip in different directions and are offset by faults that displace them. Three significant faults and breaklines (changes in slope gradient) relative to the planation surfaces are (1) the N–S Kuugannguaq-Qunnilik (K-Q) fault on Disko and Nuussuaq, (2) an E–W fault just north of Aasiaat (Aa) where orthogneisses are separated from supracrustal rocks to the north (Garde et al. 2004); the fault separates the southwards-dipping planation surface on Disko from the northwards-dipping surface south of Disko Bugt, and (3) the E–W 'Sisimiut Line' (SL) that coincides with the Precambrian Ikertôq thrust zone. A hilly relief has been re-exposed from below

Cretaceous–Paleocene cover rocks on Nuussuaq, Disko and south of Disko Bugt. A-A' profile for fig. 2. LS: Labrador Sea, BB: Baffin Bay.
(C) Panorama towards west-north-west overlooking Sarfartoq. The upper planation surface, including wide and shallow valleys, can clearly be identified and appears as a line along the horizon. In detail the planation surface contains some undulating relief as seen in the foreground. The planation surface and the shallow valleys are distinct from the deeply incised valleys, here exemplified by the Sarfartoq valley.

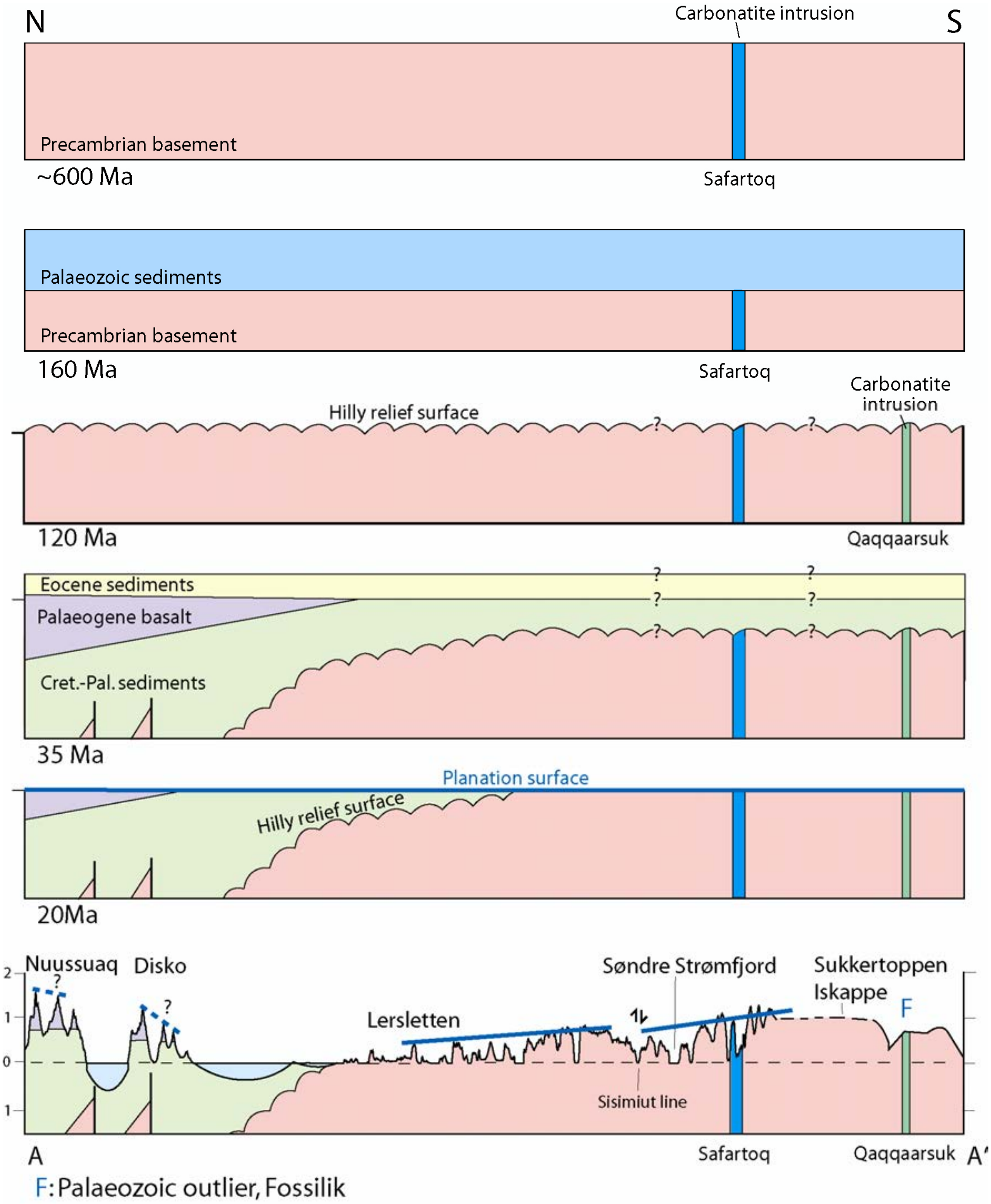

Figure 2. *Possible development of the relief in West Greenland. (a) 600 Ma, latest Proterozoic intrusion of the Sarfartoq carbonatite complex. (b) 160 Ma, Jurassic maximum burial before Jurassic–Cretaceous uplift. (c) 120 Ma, Cretaceous hilly relief. (d) 35 Ma, Pa-*

laeogene maximum burial before Eocene–Oligocene uplift. (e) 20 Ma, Oligocene–Miocene upper planation surface. (f) Present-day relief after second late Neogene uplift.

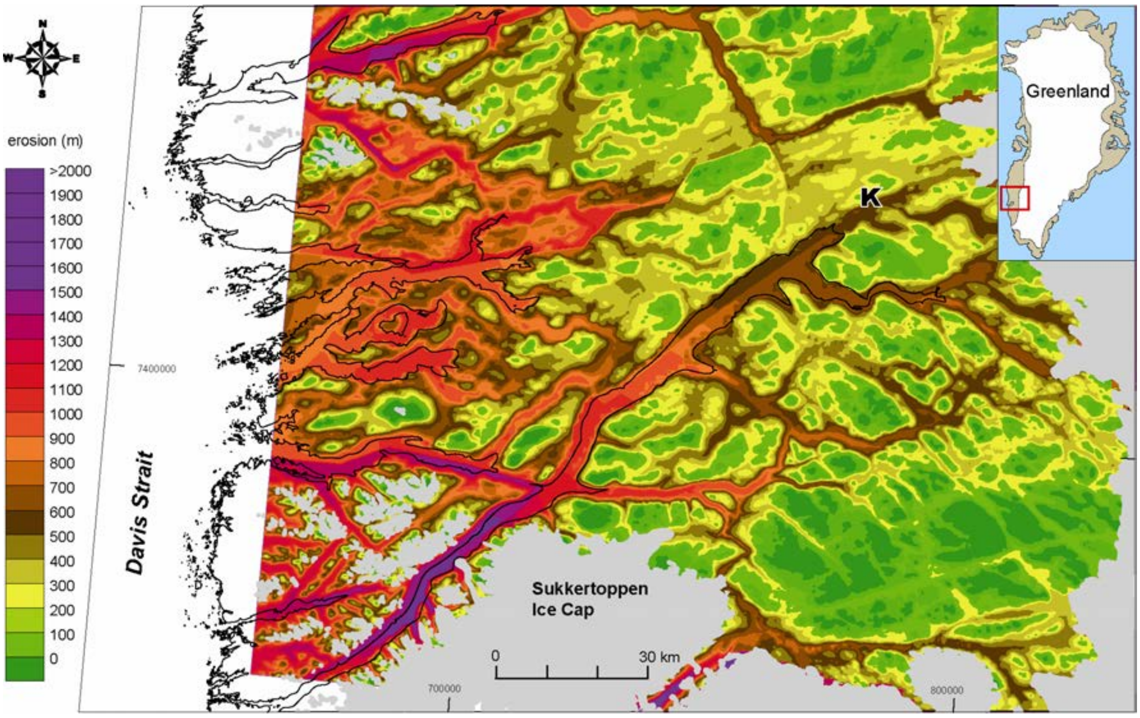

Figure 3. *Map showing the absolute amount of erosion in basement rock during the last c. 10 Ma, estimated as the difference between present topography and a reconstructed planation surface. The planation surface was formed close to a former base level (the sea) prior to differentiated uplift by events in the Neogene (starting c. 10 Ma). The planation surface has been dissected after uplift, first by fluvial systems and subsequently by glacial systems. The amount of erosion is highly variable across the area, from almost none in the SE to more than 1500 m in the high areas cut by fjords. Preservation of the planation surface occurs mainly in areas of a geographically high position and in the areas in front, as the high area has diverted eroding ice. Erosion is less within areas of gneiss in granulite facies than in areas of gneiss in amphibolite facies. K: Kangerlussuaq.*

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Crust and mantle information in Greenland from earthquakes

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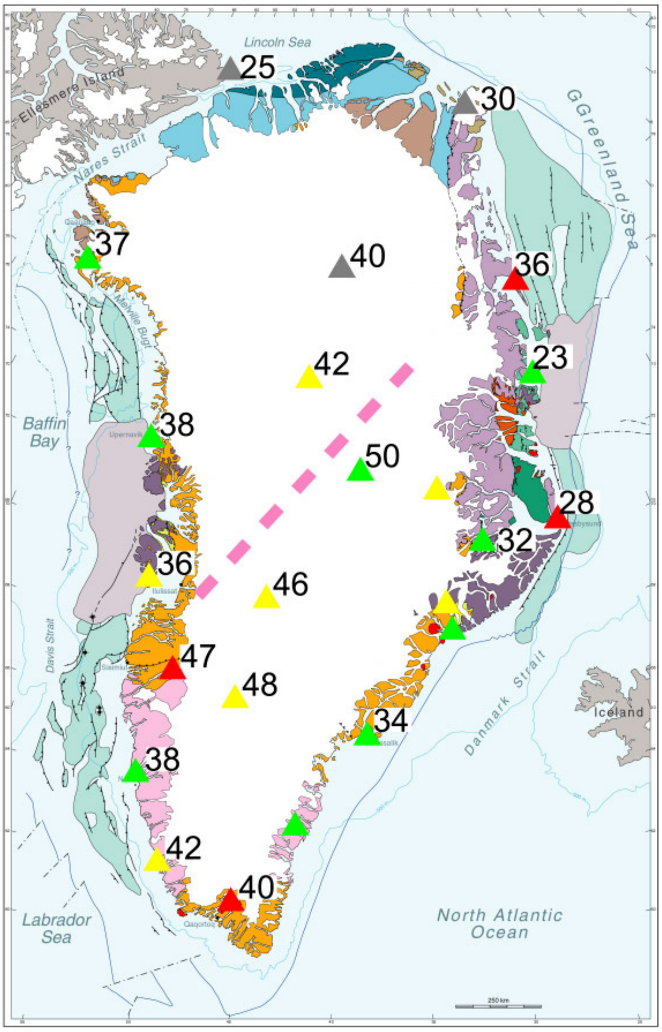

The GLATIS project (Greenland Lithosphere Analysed Teleseismically on the Ice Sheet) with collaborators have operated a total of 16 temporary broadband seismographs for periods from 3 months to two years distributed over much of Greenland from late 1999 to present. The very first results are presented in this paper where receiver function analysis has been used to map the depth to Moho in a large region where crustal thicknesses were previously completely unknown. The results suggest that the Proterozoic part of central Greenland consists of two distinct blocks with different depths to Moho. North of the Archean core in southern Greenland is a zone of very thick Proterozoic crust with an average depth to Moho close to 48 km. Further to the north the Proterozoic crust thins to 37-42 km. We suggest that the boundary between thick and thin crust forms the boundary between the geologically defined Nagssugtoqidian and Rinkian mobile belts, which thus can be viewed as two blocks, based on the large difference in depth to Moho (over 6 km). Depth to Moho on the Archean crust is around 40 km. Four of the stations are placed in the interior of Greenland on the ice sheet, where we find the data quality excellent, but receiver function analy-

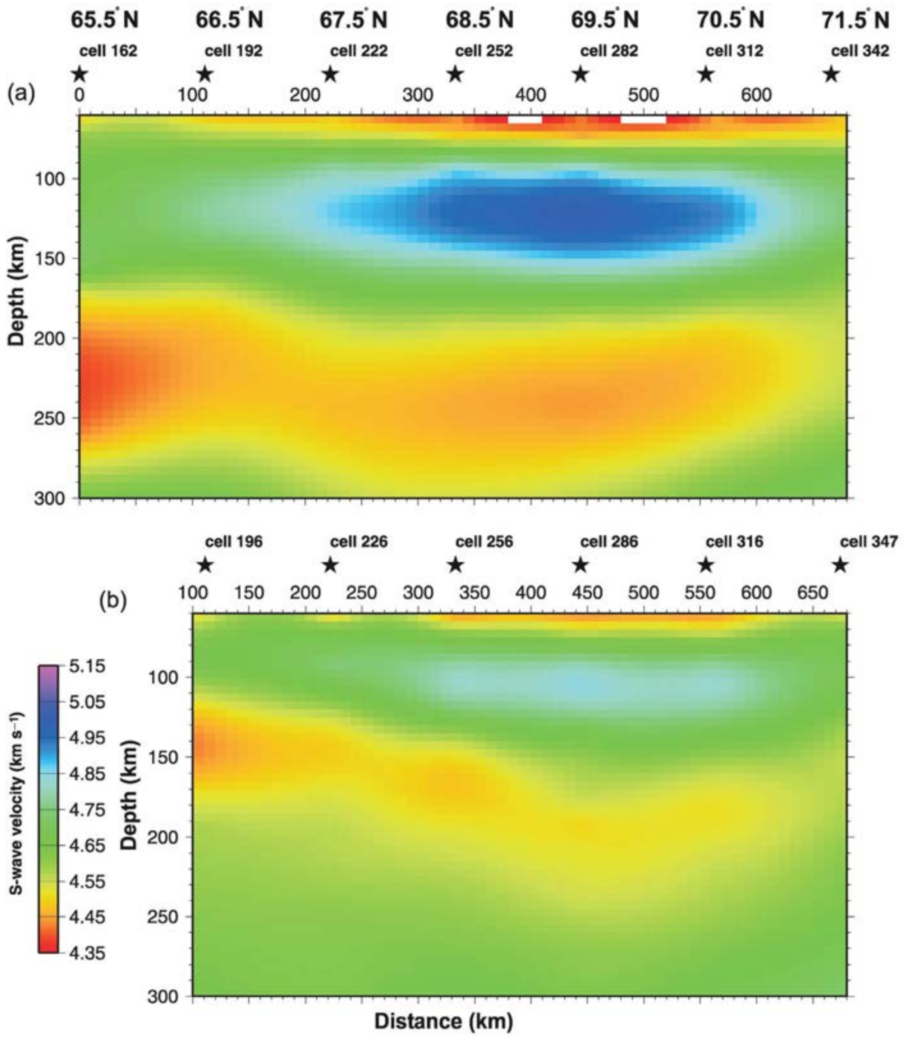

Figure 12. Shear wave velocity contour plot formed by interpolation of the models shown in Fig. 11, using GMT (Wessel & Smith 1991) routines: (a) western profile, (b) eastern profile. The positions of the 1-D models are marked as stars, and labelled with the appropriate cell number (see Fig. 8 for locations). The two contour plots are aligned according to latitude, which increases from left to right.

ses are complicated by strong converted phases generated at the base of ice sheet, which in some places is more than 3 km thick.

Rayleigh wave phase velocity dispersion curves were estimated for 45 two-station paths across Greenland, using data from large teleseismic earthquakes. The individual dispersion curves show characteristics broadly consistent with those of continental shields worldwide, but with significant differences across the Greenland landmass. Reliable phase velocity measurements were made over a period range of 25–160 s, providing constraint on mantle structure to a depth of ~300 km. An isotropic tomographic inversion was used to combine the phase velocity information from the dispersion curves, in order to calculate phase velocity maps for Greenland at several different periods. The greatest lateral variation in phase velocity is observed at intermediate periods (~50–80 s), where a high-velocity anomaly is resolved beneath central-southwestern Greenland, and a low-velocity anomaly is resolved beneath southeastern Greenland. The results of the phase velocity inversion were used to construct localized dispersion curves for node points along two parallel north–south profiles in southern Greenland (see figure). These curves were inverted to obtain models of shear wave velocity structure as a function of depth, again with the assumption of isotropic structure. A similar inversion was carried out for two twostation dispersion curves in northern Greenland, where the resolution of the phase velocity maps is relatively low. The models show a high-velocity ‘lid’ structure overlying a zone of lower velocity, beneath which the velocity gradually increases with depth. The ‘lid’ structure is interpreted as the continental lithosphere.Within the lithosphere, the shearwave velocity is ~4–12 per cent above global reference models, with the highest velocities beneath central-southwestern Greenland. However, the assumption of isotropic structure means that the maximum velocity perturbation may be overestimated by a few per cent. The lithospheric thickness varies from ~100 km close to the southeast coast of Greenland to ~180 km beneath central-southern Greenland.

Tracking glacially transported kimberlite erratics in Greenland

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Formerly glaciated mountain areas are generally areas of erosion, not deposition. Reconnaissance studies in the Angujartorfik area, West Greenland, have indicated that kimberlite erratics were mainly dispersed during the final phase of deglaciation, and were transported only over short distances (hundreds of metres). During this phase of deglaciation the thickness of the Greenland ice sheet over the area had decreased, and gradually the continuous ice margin had been transformed into local ice dispersal centres over upland areas. Radially from these dispersal centres small local glaciers flowed into existing valleys and fjords. The reconnaissance indicates that the erratics' complex pathways and source can be approximated by a combination of glacial geological field work, landscape analysis from air photos and satellite images, and dating of selected erratics by cosmogenic nuclides to provide a chronology for glacier movements.

Patterns of kimberlite emplacement – the importance of robust geochronology

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For the most part, North American kimberlite magmatism spans a period of time in excess of 1 billion years from 1.1 Ga Mesoproterozoic kimberlites in the Lake Superior and James Bay Lowlands region of Ontario to Eocene kimberlites in the Lac de Gras field, N.W.T. An exception to this is the Archean kimberlite-like deposits in the Wawa region. Nearly 25% of the known kimberlites in North America have robust emplacement ages and several patterns of kimberlite emplacement are emerging: 1) a Mesoproterozoic kimberlite province in central Ontario, 2) an Eocambrian/Cambrian Labrador Sea Province in northern Québec and Labrador, 3) an eastern Jurassic Province, 4) a central Cretaceous corridor and 5) a western mixed domain that includes two Type-3 kimberlite provinces. For some provinces the origin of kimberlite magmatism can be linked to known mantle heat sources such as mantle plume hotspots and upwelling asthenosphere attendant with continental rifting. For example, the timing and location of Mesoproterozoic kimberlites in North America coincides with and slightly precedes the timing of 1.1 Ga intracontinental rifting that culminated in the Midcontinent Rift centered in the Lake Superior region. The eastern Jurassic kimberlites record an age progression where magmatism youngs in a southeast direction from the ~200 Ma Rankin Inlet kimberlites to the 155-126 Ma Timiskaming kimberlites. The location of several kimberlite fields and clusters in Ontario and Québec lie along a continental extension of the Great Meteor hotspot track and represents one of the best examples in the world of kimberlite magmatism triggered by mantle plumes. The central Cretaceous (103-94 Ma) corridor extends for more than 4000 km from Somerset Island in northern Canada through the Fort à la Corne field in Saskatchewan to the kimberlites in central U.S.A. The possible westward younging of Cretaceous to Eocene corridors of kimberlite magmatism could reflect major changes in plate geometry during subduction of the Kula-Farallon plate.

Several periods of kimberlite/lamprøite emplacement are currently recognized in Greenland. Based on 24 new U-Pb perovskite and Rb-Sr phlogopite ages and previous geochronology, as many as five discrete events can be discerned; 1) Mesoproterozoic lamprøites (1284-1227 Ma), 2) three episodes of Eocambrian to Cambrian magmatism at 604-602 Ma (n=2), 585-577 Ma (n=9), and 568-556 Ma (n=9) and a younger Jurassic event at 164 Ma. Many of the kimberlites in the Eocambrian/Cambrian Labrador Sea Province in both Labrador/Quebec and Greenland were emplaced soon after the opening of the Iapetus Ocean at about 615 Ma and may be linked to mantle upwelling associated with continental rifting.

Geotectonic settings of diamond-producing cratons with implications for the diamond potential of southwest Greenland

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Judging from the regional distribution of economic 'primary' diamond deposits, xenoliths studies and geochronological evidence, most diamonds are 'old', and their major source rocks are garnet harzburgites, garnet lherzolites and eclogites located deep in the lithospheric roots of Archean cratons. There, the diamonds remain hidden, unless they are picked up by 'younger' kimberlites, lamproites, or other magmatic rocks originating deep enough to sample the source rocks and intruding fast enough for the diamonds to survive transport to the surface or near-surface emplacement site. The evolution of 'primary' diamond deposits is thus multi-stage. First is the formation of diamonds within ultrahigh-pressure ultramafic source rocks, a process that must be viewed as part of the craton assembly and formation of Archean cratonic roots, with the possible addition of diamonds to these roots during the Proterozoic. Diamonds are known to have formed at various times and by a number of processes, with individual diamonds preserving evidence for complex sequences of growth, resorption, brittle deformation and further overgrowth. Second is the long-term storage in the cratonic roots, during which the diamonds must survive all igneous and tectonic processes affecting the cratonic roots. Third is the formation of an appropriate igneous transport medium (kimberlite, lamproite, ultramafic lamprophyre) either within or below the cratonic roots. In order to yield a melt, the previously depleted source region requires a metasomatic enrichment in incompatible elements. Whereas the processes leading to the formation of 'primary' diamond deposits have operated worldwide, the timing of the individual diamond-forming events, source area enrichment, and the transport to the surface appear to be craton specific.

A comparison of Archean cratons worldwide suggests that not all are equally well endowed with 'primary' diamond deposits. This may be a consequence of differences in abundance and distribution of igneous transport media, differences in the chemical environment during transport, or differences in diamond contents within the craton roots, either as a consequence of root formation or preservation. It is likely that early root formation was more or less coeval with the earliest known diamond-forming episode at ~3.4±0.2 Ga which appears to have been a world-wide metasomatic event triggered by CO_2-rich, probably subduction-derived fluids that produced diamonds associated with garnet harzburgite. In a generally hotter Archean Earth, the low geothermal gradients and pressures necessary for diamond formation are thought to have been achieved through a build-up of early continental lithosphere by rapid tectonic stacking of imbricate slabs, whereby successively underplated slabs not only thickened the overlying stack, but also kept it relatively cool

(Helmstaedt and Schulze 1989; Gurney, Helmstaedt et al. 2005). Partial melting of hydrated oceanic crust in such a model would have yielded successive generations of tonalites, leaving behind an eclogitic residue within harzburgites into which carbon would have been preferentially partitioned (Ireland, Rudnick et al. 1994; Rapp 1995).

Taking into account the growing evidence from deep reflection seismic sections, that Archean cratons have grown by lateral tectonic accretion (Calvert, Sawyer et al. 1995; Calvert and Ludden 1999; White, Musacchio et al. 2003), it stands to reason that areas within the boundaries of the oldest domains of Archean cratons should have enhanced diamond potential over other on-craton and craton margin areas. This agrees with the surface geological record showing that the exposed parts of diamond-rich cratons are composite and always appear to contain tonalitic rocks older than 3 Ga. The label “archon”, meaning simply Archean craton without further qualification (Janse 1994), is thus not a sufficient description, synonymous with high diamond potential, as it would also include Neoarchean (2.7 to 2.5 Ga) juvenile granite-greenstone terrains which appear to have a lower diamond potential.

As all present Archean cratons are fragments of larger, earlier Archean cratons, craton margins after fragmentation were initially extensional, trans-tensional or transform. Latest during the Early Proterozoic, Archean cratons or their fragments became involved in plate motions and were built into Proterozoic cratons and continents which may have broken up again and rearranged several times before ending up in their present continental configuration. During accretion, the margins of Archean building blocks became convergent, transpressional or transform. During dispersal of Proterozoic or Phanerozoic continents or supercontinents, some Archean building blocks split again, but more often they preserved their integrity, as break-up occurred along earlier Proterozoic sutures. Each Archean terrain thus has its own complex post-Archean history, at every stage of which the diamond endowment in its root may have been affected. To remain diamond-prospective, an Archean craton or subprovince should not have fragmented below a certain minimum size (shortest dimension about 400 km). Kimberlites and related rocks emplaced prior to such fragmentation may have had a chance of picking up diamonds from the earlier root, however kimberlites following fragmentation and destruction of the earlier root stand only a slim chance of being diamondiferous. The minimum craton dimensions may not be obvious from the surface geology where craton margins are structurally modified and where Archean regions are tectonically buried by Proterozoic or later orogenic belts.

Diamond exploration in Greenland so far has focused mainly on western Greenland, in particular on the northwestern margin of the North Atlantic craton (Larsen 1991; Jensen, Secher et al. 2004), where ca. 600 Ma ultramafic dykes have yielded diamond indicator minerals as well as numerous small diamonds in the Sarfartoq and Maniitsoq areas (Olsen, Jensen et al. 1999; Jensen, Secher et al. 2004). Initially referred to as kimberlitic and lamprophyric (Larsen, Rex et al. 1983; Larsen and Rex 1992), these dykes were reclassified as melnoitic (Mitchell, Scott Smith et al. 1999), but a convincing case has now been made, that at least one of these dykes, the diamondiferous Majuagaa dyke in the Maniitsoq area, may be classified as a calcite-kimberlite (Nielsen and Jensen 2005).

As the oldest Archean building block of northeastern Laurentia, the composite North Atlantic craton (NAC) shows all the surface geological criteria and dimensions (>150,000 km^2) required of a diamond-rich craton, and it may be assumed that it developed an early diamondiferous root. Along its northern and western margins, the NAC was affected by the Paleoproterozoic Nagssugtoqidian and Torngat orogens, respectively. Tectonic fabrics indicate that convergence between the Disko craton and NAC across the broad Nagssugtoqidian orogen was mainly orthogonal, and tectonic reconstructions suggest that the northern edge of the NAC forms a northward-tapering tectonic wedge between the southerly-verging southern Nagssugtoqidian front and a postulated southward-dipping subduction zone (van Gool, Connelly et al. 2002). Deformation in the relatively narrow Torngat orogen, in the west (across Davis Strait in Labrador), appears to have been dominated by sinistral transpression and probably had little effect on the NAC exposed in West Greenland. Paleproterozoic preservation and modification of an Archean lithospheric root in this part of the NAC thus depends mainly on the extent of post-Archean rifting (as indicated by the ca. 2040 Ma Kangamiut dykes) and on the angle of subduction and southward extent of mantle wedge hydration above the subducting slab during collision with the Disko craton. On this basis, the strength of the Archean mantle-root signature of potential diamond hosts, as indicated by the presence and composition of harzburgitic diamond indicator minerals (G-10 garnets, chromite), should increase towards the south, away from the Nagssugtoqidian front.

Ages of alkaline ultramafic intrusive rocks in West Greenland have been reviewed by Larsen and Rex (1992). Latest Precambrian melnoite and kimberlite magmatism in the Sarfartoq and Maniitsoq overlaps in time with ages of numerous alkaline rocks of the North Atlantic alkaline province (Doig 1970), generally assumed to be related to rifting connected with the opening of the Proto-Atlantic (Iapetus) ocean. This also includes dykes of diamondiferous melnoites in Labrador (Torngat Mountains) (Digonnet, Goulet et al. 2000) and kimberlites and kimberlite-like rocks in the northern Quebec part of the Superior Province (Wemindji, Lac Beaver, Renard) recently referred to as Eocambrian/Cambrian Labrador Sea kimberlite province (Heaman, Kjarsgaard et al. 2004). It is interesting that the Renard igneous bodies, in the Otish Mountains of Quebec, although transitional between kimberlites and melnoites (Birkett, McCandless et al. 2004), appear to contain economic quantities of diamonds (Ashton Exploration, various press releases).

Little is known as yet about the age and isotopic compositions of the mantle sample of the Sarfartoq and Maniitsoq intrusions, and such information is needed to distinguish between the ages of possible diamond source rocks (harzburgites and eclogites), for assessing regional variations in ages and composition of the mantle sample and for fingerprinting the metasomatic event(s) preceding or accompanying the intrusive events. As for the overall diamond potential of the Sarfartoq and Maniitsoq provinces, it is encouraging to note that indicator mineral tests of the diamondiferous Majuagaa calcite-kimberlite dyke in the Maniitsoq area, in addition to yielding a fair number of harzburgitic garnets (G-10), also showed a relatively strong subgroup of Na_2O-rich eclogitic garnets (Jensen, Secher et al. 2004). This means that a significant part of the diamond budget of this dyke may be eclogitic, a possibility that could be tested by studying the carbon isotopes of the recovered diamonds.

The age of a younger kimberlite generation (ca.193-220 Ma) reviewed by Larsen and Rex (1992) approximately coincides with initial rifting related to the opening of the Atlantic Ocean. One dyke is located within Archean rocks in the southern part of the NAC in the Nigerlikasik (Frederikshåb = Paamiut) area, and numerous kimberlite sheets are found north of Ivittuut, in the slightly reworked Archean part of the Paleoproterozoic Ketilidian belt, near the southern border of the NAC. The occurrence of microdiamonds in these sheets suggests that the limited Mesoproterozoic rifting associated with the alkaline magmatism of the Gardar province (ca. 1350-1150 Ma), in southern Greenland, may not have eliminated the diamond potential of this area.

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Diamondiferous kimberlites from the Garnet Lake area, west Greenland: exploration methodologies and petrochemistry

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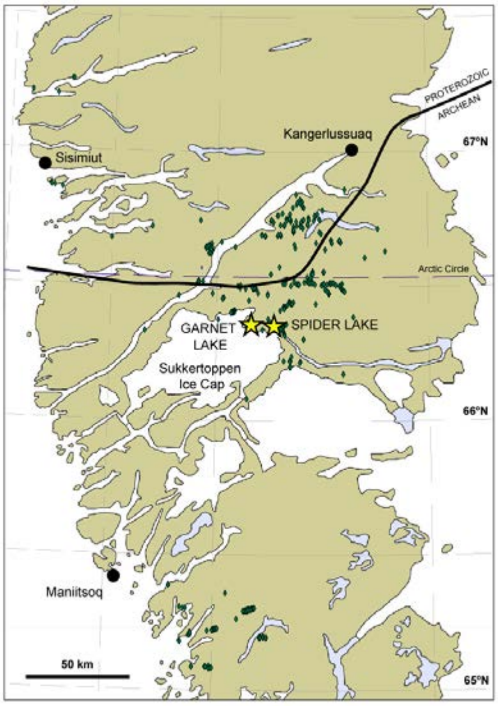
1. Introduction

Amongst the kimberlite-affinity rocks of West Greenland, of particular interest from the point of view of diamond prospectivity is the Garnet Lake locality that lies approximately 2 km to the north of the Sukkertoppen Ice Cap, Sarfartoq, West Greenland (Fig. 1). Reported here are the recovery of the largest diamond so far found in Greenland (1.90 x 1.70 x 1.42 mm) in addition to the largest calculated figures for metric carats of diamond per 100 tons (ct/100ton).



Diamond recovery data and geochemistry of mineral phases are presented, arising from samples of drill core and associated float recovered as part of the 2004 and 2005 exploration program of Hudson Resources, Inc. Comparison is made with mineralogy of diamond and non-diamond bearing rocks recovered from nearby localities principally within the same program with a view to clarify indications of diamond prospectivity.

Figure 1. *Map of locations of Garnet Lake and Spider Lake (yellow stars) with locations of in-situ kimberlite shown by green triangles after Jensen et al. (2004a).*

The Garnet Lake site is centred around WGS84 UTM22N grid reference (469922, 7360319). Also discussed are results from the Spider Lake site (479467, 735374) and associated Spider Hollow (479087, 7358613) approx. 10 km to the east and the Silly Kimberlite site (470219, 7360929) approx. 700 m to the north-east of Garnet Lake.

2. Geophysical exploration

The Garnet Lake site was discovered during 2004 ground reconnaissance following up on publicly available reports on indicator mineralogy (references in Jensen et al., 2004a) and an airborne DIGHEM resistivity / magnetic survey conducted at 100m line spacing for Hudson Resources Inc. by Fugro Airborne Surveys. The airborne magnetic survey in particular yielded a number of positive and negative semi-spherical and possible dipole anomalies which exhibited similarities with kimberlite pipes from elsewhere (e.g. Lockhart et al., 2004). Furthermore a number of strong linear basement features were seen to intersect each other within the Garnet Lake area.

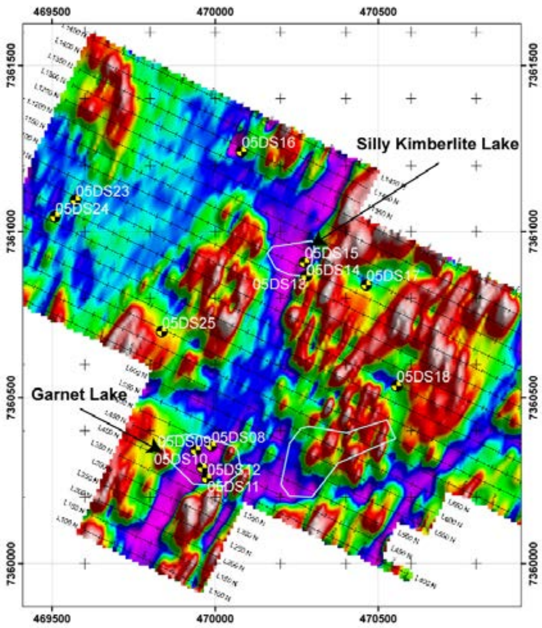


Figure 2. *Ground based geophysical survey of the Garnet Lake area – total field. UTM coordinate system is based on WGS84 Zone 22N. Drill site locations are indicated by black/yellow circles. Note that lake shapes and locations are approximate and lie in reality ~100 m W of the locations shown.*

Further to the successful recovery of diamonds from the Garnet Lake site, reported below, a 50 m line spacing ground-based magnetic survey was conducted around the Garnet Lake and Silly Kimberlite sites in order to direct drilling operations during 2005. Results are presented as total field data in Fig. 2. Within the field of view, the most prolific kimberlite-bearing sites lie at the SE corners of Garnet Lake and the Silly Kimberlite Lake at the eastern extent of a strong NE-SW trending magnetic low, interpreted as a basement feature. Furthermore, small linear features are seen to extend from these locations to the SE and it is believed that in-situ kimberlite which was subsequently drilled at these sites may have been emplaced preferentially along intersections of basement weaknesses indicated by the geomagnetic trends. This observation is commonly made for kimberlite fields worldwide (e.g. Stubley, 2004). Amongst other intersections elsewhere, six drill holes on Garnet Lake, three at Silly Kimberlite and six at Spider Lake were successful in intersecting kimberlite bodies, all thought to be sills, with the principal intersection at Garnet Lake having a 3.9 m interpreted uninterrupted true thickness.

3. Diamond recovery

Three samples of drill core and three larger samples of float taken from Garnet Lake were crushed and processed by caustic fusion for diamond separation at the SRC Geoanalytical Labs., Saskatoon, Canada. Results are presented in Table 1. The more voluminous float samples were found to yield the largest diamonds with the three most significant being 1.90 x 1.70 x 1.42; 1.98 x 1.34 x 0.98 and 1.56 x 1.40 x 1.16 mm. Figure 3 shows a slightly smaller colourless octahedral stone from float sample MHG9-7. Diamonds have been re-covered in total from 36 samples from West Greenland (references in Jensen et al., 2004a,b) with the largest previously reported being a single 1.62 x 1.53 x 0.22 mm stone from Pyramidefjeld (Geisler, 1974).

Figure 3. *Photograph of diamond recovered from Garnet Lake float sample MHG9-7.*

Calculations of ct/100t are presented as a means of rough comparison between samples (Table 1). Due to the small sample size however, figures should not be considered to be suitable for comparison with those quoted for producing mines. It is notable however that core 05DS12-D yields recovery figures most comparable with float. This core was taken from shallow depth within a few metres of the float sampling site whereas the other drill cores were from 35-100 m north. Values are much higher than those for diamondiferous samples previously recorded from Greenland with the exception of overlap with a 187 kg sample from east of Sukkertoppen Ice Cap (Bizzarro and Plouffe, 1999) which yielded 55 ct/100ton. Diamond recovery values for other sites from the current program were also comparably smaller. Aside from a number of diamond-free samples, three micro-diamonds were recovered from 41.05 kg Spider Lake core, two microdiamonds in 57.8 kg of float were recovered from the Silly Kimberlite and two in 64.45 kg from another site nearby. Garnet Lake diamond recovery in comparison with other diamondiferous rocks from West Greenland, therefore suggests that this is a site from which a useful diamond prospectivity methodology may be constructed.

Table 1. *Weights and numbers of diamonds recovered from Garnet Lake float and drill core.*

Sample	Sample wt.	#	Diamond wt.	ct/100t
05DS08-D	14.4	6	0.269	9.3
05DS10-D	14.15	6	0.098	3.5
05DS12-D	10.95	15	0.662	30.2
MHG9-5	29.65	71	6.654	112.2
MHG9-7	21.2	28	4.269	100.7
MHG9-13	57.05	52	9.696	85.0
TOTALS	**147.4**	**178**	**21.648**	**73.4**

Samples prefixed by 05DS are drill core samples; samples prefixed by MHG are float samples; Sample weight in kg; diamond weight in mg; # :- number of diamonds. Note that ct/100t values are not statistically robust due to the small sample sizes involved.

3. Mineralogy

Compositions of kimberlite and xenolith phases have been measured using standard EPMA techniques (Univ. Copenhagen JEOL 733) from samples of heavy mineral separates recovered from crushed float and core and from polished thin sections taken from both float and core. Mineral separation was conducted at the SRC Geoanalytical Labs., Saskatoon, Canada.

3.1 Olivine

Olivines have been analysed in abundance from both mineral separates and groundmass and xenolith-hosted grains from thin sections. Strong trends in Ni at constant Fo content are apparent for Garnet Lake samples particularly at Fo content of 0.86, 0.90 and 0.92. Although there is a dominance of analyses within the proposed diamond field of Fo > 0.90 and Ni > 2250 ppm (Jago, 2004), no strong differences are observed between Garnet Lake olivines and olivines from nearby less diamondiferous localities.

3.2 Ilmenite

Ilmenites from Garnet Lake samples are almost exclusively picro-ilmenites although with variable Cr_2O_3-content up to 6.78 wt%. The occurrence of ilmenites with MnO greater than 1 wt% is highly variable with some samples having no such grains and one thin section having only Mn-rich ilmenites. Variability in Mg, Cr and Mn is not strikingly different between Garnet Lake and other samples in this study with perhaps the exception of Silly Kimberlite samples which are typically more Cr_2O_3-rich (up to 16.5 wt%) and yield no Mn-rich examples.

3.3 Garnet

Following the classification scheme of Grütter et al. (2004), Garnet Lake samples are rich in harzburgitic G10D and particularly eclogitic G3D and G4D diamonds in comparison with samples from other localities. G10D and G3D-G4D garnets comprise 10% and 11% respectively in comparison with for example Spider Lake with 11% (the most comparable G10D occurrence) and no eclogitic garnets. Garnet Lake garnet compositions in terms of a

Cr_2O_3/CaO discriminatory diagram (Fig. 4) demonstrate the proliferation of G10D and eclogitic garnets in core and float mineral separates. Thin sections of float and core show a similar spread of data and also include a single G12 wehrlitic garnet.

The Na_2O content of Garnet Lake garnets is unusually high (averaging 0.19 up to 0.518 wt% and up to 0.28 wt% for G4D garnets in an eclogitic garnet-bearing xenolith from Garnet Lake drill core). The only Greenlandic samples otherwise reported with the range of Na approaching this trend is the Majuagaa kimberlite, Maniitsoq (Nielsen and Jensen, 2005), however their highest Na_2O content is reported as 0.18 wt%.

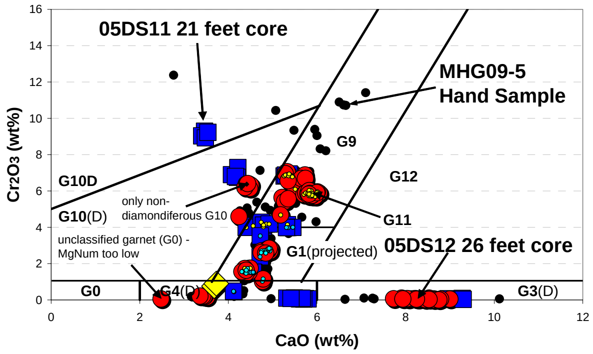


Figure 4. *Compositional variation of garnets from Garnet Lake samples expressed as Cr_2O_3 versus CaO (wt%). Yellow diamonds:- 05DS07-162 foot thin section G4D eclogitic garnets.*

3.4 Spinel

A variety of spinel compositions have been recovered from Garnet Lake, involving Ulvöspinel, magnetite and magnesioferrite components to varying degrees. Notably however few chromites have been recovered, unlike at Spider Lake and Spider Hollow where chromites are common. Compositions of chromites from Garnet Lake and other localities from this study are presented as a projection onto the reduced spinel prism (Fig. 5). Individual grains are grouped separately according to sample with different legend sizes corresponding to different samples. Where trends in composition are apparent these are annotated on the diagram. There is a significant spread in the data, partly due to the involvement of magnetite and Mg-rich spinel, however it is apparent that examples of both T1 and T2 trends of Mitchell (1995) plus a mixed trend for Garnet Lake sample T1 occur (similar to that described in Mitchell et al., 1999). Mitchell (1995) describes the T1 trend as being kimberlitic and the T2 trend as being orangeitic.

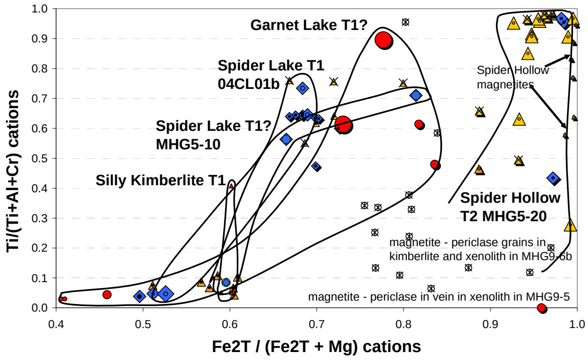


Figure 5. *Compositional variation of spinels projected onto the front face of the reduced spinel prism: expressed as Ti/(Ti+Al+Cr) cations versus (Fe2T i.e. total Fe calculated as Fe^{2+})/(Fe2T+Mg) cations. Red circles are Garnet Lake samples, red triangles are from the Silly Kimberlite, yellow diamonds are from Spider Hollow and flesh-coloured triangles are from Spider Lake samples.*

3.5 Mica

Individual samples from Garnet Lake, as from the other localities studied show a range in mica compositions. Of particular use for classification are the variations in Al, Ti and Fe. Mica compositions in terms of Al and Ti wt% oxide are presented in Figure 6. Individual grains are typically significantly homogeneous with the exception of rims of tetra-ferriphlogopite. The Garnet Lake samples distinguish themselves in being particularly Ti-rich (also compared to Greenlandic micas published elsewhere, e.g. Nielsen and Jensen, 2005). Their trend towards tetra-ferriphlogopite can be considered to be orangeitic (Mitchell, 1995). It is notable that Spider Lake and Spider Hollow compositions have a similarity with those from the Majuagaa calcite-kimberlite despite Spider Hollow in particular having otherwise an orangeitic character (e.g. in terms of spinel composition).

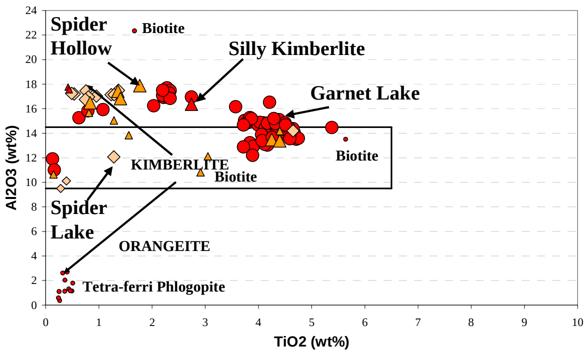


Figure 6. *Compositional variation of phlogopites from Garnet Lake and Spider Lake samples expressed as Al_2O_3 versus TiO_2 (wt%). Tetra-ferriphlogopite rims on micas from three Garnet Lake float samples are shown as small red circles.*

4. Geothermobarometry

Calculations of equilibration pressure and temperature of a Garnet Lake sample was undertaken using data from phases in a garnet lherzholite xenolith taken from float sample MHG9-6 (Figure 7). A four phase assemblage calculation is considered preferable to calculations based on fewer phases and the commonly used technique of using mineral compositions from mineral separates. The latter method allows no confidence of mineral equilibration and can result in misleading conclusions.

Two calculations were carried out using the Al in Opx barometer of Brey and Köhler (1990) and the following thermometers:

1. Ellis and Green (1979) Fe-Mg exchange in garnet-cpx
2. Brey and Köhler (1990) Na in Opx-Cpx
3. Brey and Köhler (1990) Cpx-Opx solvus

The first calculation used averaged analyses of touching grains considered most likely to be in chemical equilibrium. The second calculation used averaged analyses for grains of opx, cpx, olivine and garnet taken from within the unaltered centre of the xenolith.

Equilibrium conditions are calculated to lie within the range P=61.4 to 66.7 kbar and T=1352°C to 1327°C. Comparison with the fields of Greenland till samples calculated after data in Jensen et al. (2004a) which cuts off at ~1270°C, indicates that the depth of origin of the xenolith from the diamond-bearing Garnet Lake locality is greater than generally observed previously. Admittedly equilibration within till sample grains, as described previously, may not be assured. Data from Garnet Lake is also consistent with a similar cold geotherm, as in for example the Kaapvaal craton (references in Nixon, 1987).

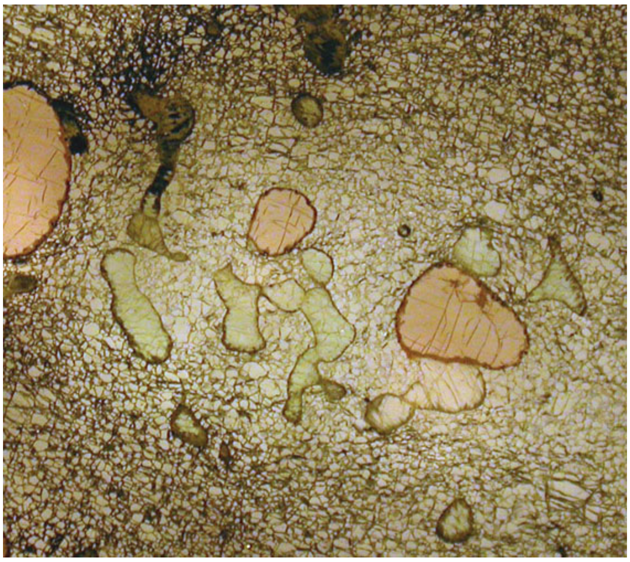


Figure 7. *Transmitted light photomicrograph of garnet lherzolite xenolith sample tsMHG06b. Field of view is approximately 2 cm. Green macrocrysts are cpx, colourless are opx, orange are garnet. Finer grains are almost exclusively olivine.*

5. Discussion and conclusions

Similarities in terms of diamond recovery and mineral compositions between Garnet Lake core and float, in and in contrast with data from nearby samples (e.g. Fig. 4) strongly suggests that the Garnet Lake float can be considered to be close to in-situ. It is reasonable therefore to accommodate data from float into discussion of the significance of mineralogy of Garnet Lake samples in general.

	h11	h12	t7C	t7F	h9-5	t9-2	t9-3	t9-5	t9-6a	t9-6b
Olivine ***Macrocrysts***	?p	?p	-	-	?p	-	-	-	-	-
Phenocrysts	**O**	**O**	?c	?c	**?c**	**O**	**O**	**O**	?-	**K**
Mica ***Groundmass***	?p	?p	**O**	**K**	**K**	-	-	**O**	**O**	**O**
Macrocrysts	?p	?p	?p	?p	**?p**	**O**	**O**	**O**	**O**	**O**
Spinel	?p	?p	-	-	-	-	-	**K** (ulv, T1?)	**K** (ulv, T1?)	-
Perovskite	?p	?p	**O**	**K**	?p	<<	<<	<<	<<	<<
Apatite	?p	?p	- ?c	**K** ?c	-	-	-	-	-	-
Carbonate	?p	?p	**O***	**K**	-	?c	?c	?c	?c	?c
K-richterite	<<	<<	<<	<<	<<	<<	<<	<<	**O?**	<<
Mn-ilmenite	**K**	**K**	**K**	**K**	**K**	-	**O**	**K**	**O**	-
REEphos-phates	?p	?p	<<	**O**	?p	<<	<<	<<	<<	<<
Barite	?p	?p	**K**	**K**	?p	<<	<<	<<	<<	<<
Ni sulphide	?p	?p	**K**	<<	?p	<<	<<	<<	<<	**K**
lowCr,Ti macro.	**K**(G1)	**K**(G1)	?p	?p	**K**(G1)	<<	<<	<<	**K**(G1)	**K**(G1)
K or O affinity	**K**	**K**	**O**	**K**	**K**	**O**	**O**	**O/K**	**O/K**	**K**

Table 2. *Orangeite and Kimberlite Affinities of Najaat samples – Garnet Lake core and associated float h11 and h12 :- heavy mineral separates from cores 05DS11-21 and 05DS12-26 respectively; t7F :- thin section 05DS07-155b (apahanitic); t7C :- thin sections 05DS07-155-a and –c (macrocrystal); h9-5 :- heavy mineral separate from MHG9-5; t9-2. t9-3. t9-5, t9-6a and t9-6b :- thin sections MHG9-2, MHG9-3, MHG9-5, MHG9-6a and MHG9-6b respectively. Orangeite and Kimberlite characteristics after Mitchell (1995); K :- kimberlite; O :- Orangeite; ülv :- ulvöspinel; macro: :- macrocrysts; * :- contains olekminskite; ?c :- composition unknown; ?p :- proportion unknown; << not abundant, however absence can't be stated with confidence; - :- phase present but observed characteristics do not allow for distinction between rock types; T1 and T2 :- spinel magmatic trends T1 and T2 respectively.*

Garnet Lake samples distinguish themselves from neighbouring diamond-poor kimberlitic rocks by the following characteristics:

- implied high diamond grade;
- commonly visible garnet megacrysts in the matrix;
- dominance of diamond-stable peridotitic garnets;
- abundance of diamond-stable Na-eclogitic garnets;
- deep solution to geothermobarometry calculations

The closest analogy reported elsewhere may be the Majuagaa calcite-kimberlite (Nielsen and Jensen, 2005). Its diamond content of 125 microdiamonds in 1060 kg (Jensen et al., 2004b) is higher than most tested Greenlandic kimberlites but is still significantly lower than

Garnet Lake samples. Majuagaa does contain significant eclogitic garnets and concentrations of Na in garnet overlap the lower end of the Garnet Lake range.

In terms of classification, there has been some significant debate as to how to describe the Greenlandic kimberlitic rocks (e.g. Mitchell et al., 1999 and Nielsen and Jensen, 2005). Table 2 summarises the mineral compositional data described above in association with additional observations in the context of Mitchell's (1995) orangeite/kimberlite classification scheme. It is apparent that the mineralogical and geochemical characteristics of most of the samples studied would lead to a classification of either kimberlite or orangeite depending on which is considered to be the most important criteria. Garnet Lake samples often contain low Cr, Ti-macrocrysts, occasional Ni-sulphide and Mn-ilmenites are rare. These are all characteristics of kimberlite. On the other hand tetra-ferriphlogopite rims on phlogopite are seen in many samples, olekminskite (Sr,Ba,Ca carbonate) is reported and olivine phenocrysts are typically Fo-rich. These are all characteristics of orangeite. Such conflicting characteristics are not confined to mineral separates but are also seen in thin section. Similar mixed characteristics are seen in Spider Lake, Spider Hollow and Silly Kimberlite samples. Indeed a single core section from Garnet Lake (05DS07-262) consists of a coarse grained rock with strong orangeitic affinity abutting a fine grained perovskite-rich rock of strong kimberlitic affinity.

As the orangeite classification relies heavily on southern African samples, it is perhaps not surprising that the terminology has questionable direct application to Greenlandic rocks. However the natural question which arises is whether or not Garnet Lake, and other kimberlitic rocks from Greenland represent a mixing of true primary orangeite with kimberlite in the source region, or whether some genetic spectrum of kimberlite-orangeite primary magma is possible. Significantly more work is required to fully address this issue. It is at least safe to say at this stage however, that notwithstanding uncertainty on classification, Garnet Lake samples demonstrate that Greenlandic kimberlitic rocks can be substantially diamond-bearing.

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Disclaimer: Non-Greenlandic place names are informal. This publication reflects the author's views and the European Community shall not be held liable for any use of the information contained herein.

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Regional distribution and chemistry of indicator minerals from *in situ* rocks and surficial deposits in the Maniitsoq and Sarfartoq regions

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Introduction

A core activity of recent work on Greenland's diamond potential by the Geological Survey of Denmark and Greenland (GEUS) has been the compilation of data submitted to Greenland's Bureau of Minerals and Petroleum (BMP) according to the standard terms for mineral exploration licences. The data were amassed over a period of more than 30 years, with the vast majority of data being from 1994 and younger. This work resulted in a digital data package first published in 1993 (Jensen *et al.* 2003), and a major update and revision of the compilation was published the following year (Jensen *et al.* 2004). The data, extracted from 164 assessment reports, consist primarily of indicator mineral analyses (ca. 96 000) from till and stream sediment sampling programmes covering the whole Archaean craton of southern West Greenland. The numbers of mineral grains analysed and reported by exploration companies and GEUS prior to 2004 are given in Table 1.

On a regional scale, the populations and chemistries of the indicator minerals outline relatively well-defined areas as potentially prospective for diamonds, both in the Sarfartoq and Maniitsoq regions. However, it has been the experience of GEUS, and presumably of several exploration companies, that tracing diamond-favourable indicator minerals from till back to a kimberlite or lamprophyre source was not straightforward where it has been attempted, i.e., chiefly in the Sarfartoq region. There was an apparent lack of potential *in situ* kimberlite source rocks to explain the relatively high numbers of indicator minerals with favourable chemistry. Although the sampling density for till and stream sediment in the Maniitsoq region was fairly even and high, and despite the existence of a clearly defined linear trend with garnets and other indicator minerals with diamond-favourable chemistry, as well as some diamondiferous kimberlites, the amount of follow-up tracking of kimberlite has been very limited and few potential source rocks was studied in any detail here.

GEUS sampling project, 2004

In 2004 GEUS, in a collaboration project with BMP, launched new field and laboratory investigations to address the following questions:

1. Are the numbers and chemistries of indicator minerals reported by various exploration companies reproducible and are they inter-comparable?

2. Do the large numbers of indicator minerals reflect local *in situ* sources, or are they derived from distant sources (possibly below the Inland Ice)?

3. Is the linear trend of diamond-favourable garnets from till samples in the Maniitsoq region reproducible, and are the areas outside the trend really barren?

4. Is the empirical observation from available descriptions and own field reconnaissance that the dykes from the Maniitsoq region are closer in composition to 'real kimberlites' than those of the Sarfartoq region verifiable by detailed petrography and mineral chemistry?

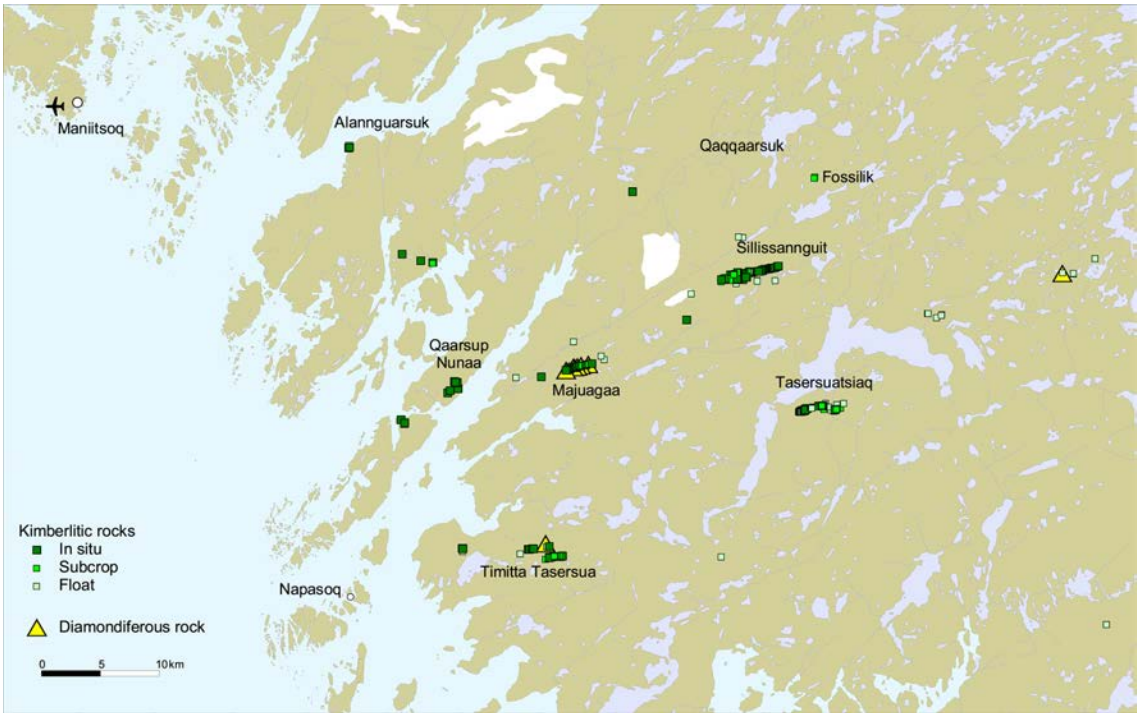

Figure 1. *Kimberlite dykes and occurrences of the Maniitsoq region, several of which were found during GEUS fieldwork in 2004.*

Thus, in 2004, new till samples were collected and a number of kimberlite and lamprophyre dykes were sampled with a view to separation and analysis of heavy minerals. Because of the paucity of data from potential source rocks it became a key element in the new investigation to separate and analyse mineral grains from a fair number of kimberlites and lamprophyres, and to examine the dispersal of indicator minerals in 'down-ice' directions relative to the outcrops.

A total of 131 till samples and 41 rock samples were included in the study. The amount of sample material submitted for heavy mineral separation was approximately 20 kg of <4 mesh (ca. 6.3 mm) material for till and sediment samples, and 3–5 kg of rock for kimberlite and lamprophyre samples. The heavy mineral separation and picking was conducted by Overburden Drilling Management in Nepean, Ontario, and the subsequent mounting and microprobing of grains by GEUS. The numbers of mineral grains analysed to date from these samples are given in Table 2. Publication of the new mineral chemistry data is planned for January 2006 in conjunction with the Mineral Exploration Roundup in Vancouver. A few preliminary conclusions are presented as an appetiser here.

Table 1. ***Mineral grains microprobed prior to 2004 (Jensen et al. 2004)***

Mineral group	Sample medium	
	Rock	Till
	n = 31	*n = 15295*
CHR (chromite, spinel)	1058	11332
CPX (clinopyroxene)	205	15069
GAR (garnet)	1106	8875
ILM (ilmenite)	833	43318
OPX (orthopyroxene)	20	732
OL (olivine)	472	12333

Table 2. ***Mineral grains microprobed from GEUS' 2004 sampling programme, excluding in situ grains in kimberlite reported by Nielsen & Jensen (2005)***

Mineral group	Sample medium	
	Rock	Till
	*n = 27**	*n = 133*
CHR (chromite, spinel)	841	390
CPX (clinopyroxene)	333	235
GAR (garnet)	2524	1417
ILM (ilmenite)	446	672
OPX (orthopyroxene)	96	20

** Results from 14 samples pending*

The 2004 fieldwork resulted in the recognition of much larger kimberlite dyke systems than had been previously reported from the Maniitsoq region (Figure 1), and these new localities were included in the latest digital data compilation (Jensen *et al.* 2004). For example, in one field area (Sillissannguit), where a very small kimberlite dyke had been previously reported, new dykes with a combined length of more than 10 km were found, and in another area near the coast (Timitta Tasersua E), what is believed to one of the largest kimberlite dyke exposures known in Greenland was found in a steep gully above a stream with numerous large boulders of kimberlite. Mineral chemistry data for these occurrences, along with several occurrences in the Sarfartoq region, have only recently become available, and it is now possible to address the provenance of the indicator minerals from till and stream sediment.

The discovery of new dykes in 2004 was a first indication that the dispersion of indicator minerals 'down-ice' from outcropping kimberlite is very limited in the Maniitsoq region. A regional, remarkably linear belt defined by diamond-favourable garnets in till, for example, is interpreted to closely reflect the occurrence of kimberlite. All of the areas that have been checked for outcropping kimberlite, based on the distribution of diamond-favourable garnets in till, have been found to have kimberlite dykes or boulders a short distance N or NE of the till sampling sites. This reflects an apparently uniform direction of ice movement of

240° (SW) in the region. In the Sillissannguit area glacial striation on the surface of a kimberlite dyke has been observed. It is suggested that the source of indicator mineral grains in till is to be sought, most likely within 1–2 km distance, NE of the till sampling sites.

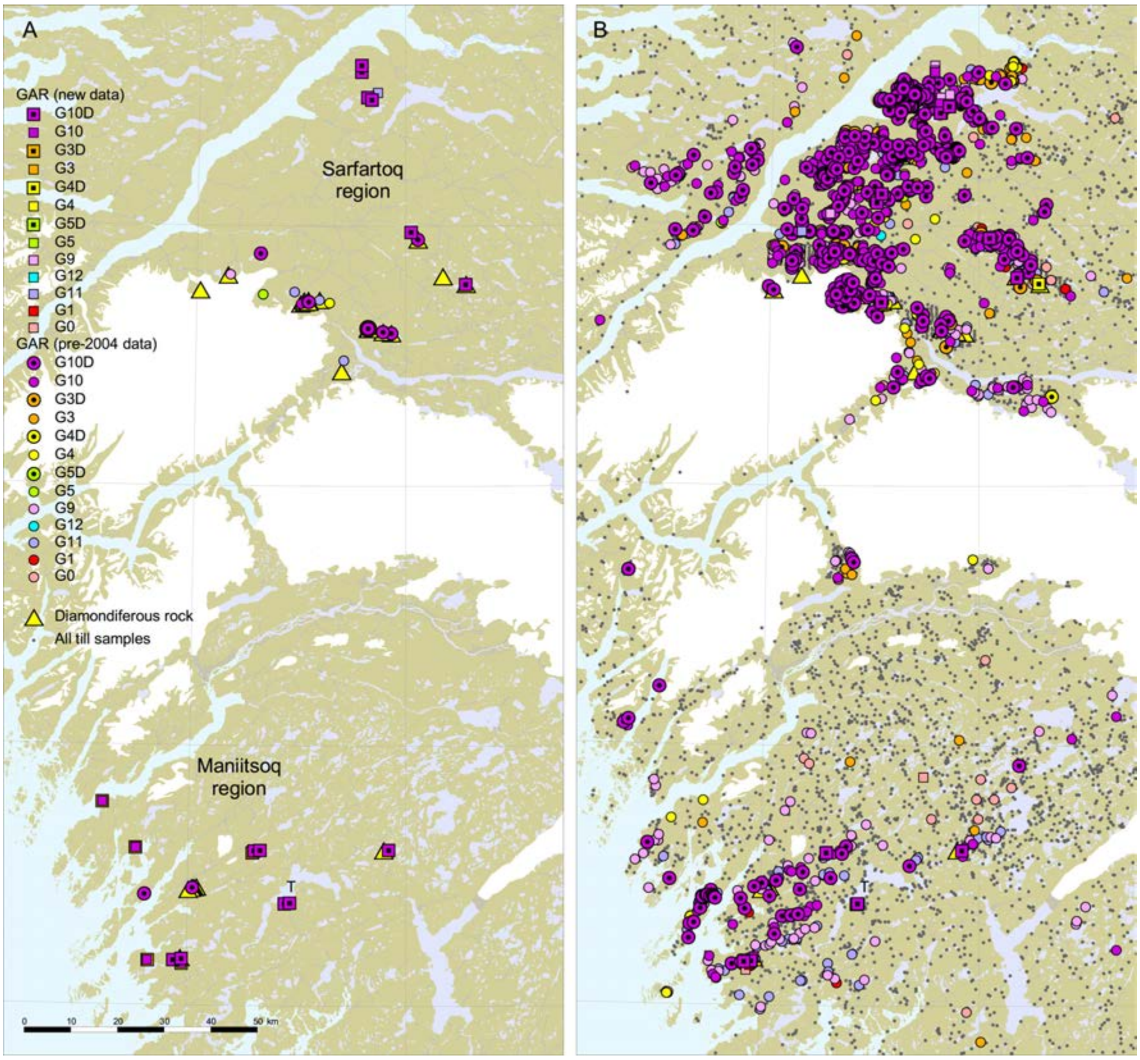

Figure 2. *Diamond-favourable garnets (G10D class of Grütter et al. 2004 plotted as top layer) from (A) in situ rock samples, and (B) till samples.*

Distribution of diamond-favourable indicator minerals

Peridotitic garnets from the 2004 till sampling occur in comparable numbers, locations and classes as in earlier sampling (Figure 2), but a new area was added with diamond-favourable G10D (Grütter *et al.* 2004) garnets near a 2 km long kimberlite dyke system at Tasersuatsiaq in the Maniitsoq region (Figure 1, 2), where previous sampling was sparse. Peridotitic garnets from *in situ* rocks appeared in the pre-2004 data to be concentrated in the SW part of the Sarfartoq region, and almost exclusively within the undeformed Archaean craton. With the addition of data from the 2004 investigation, the *in situ* kimberlites of the Maniitsoq region appears to have a comparable, if not higher, frequency of G10D garnets (Figure 2). Another important result of the 2004 sampling is that several *in situ* rocks in the N part of the Sarfartoq region also are now also seen to contain G10D and G10 garnets, although generally in modest numbers. This possibly explains the widespread occurrence of these garnet types in till samples from the area.

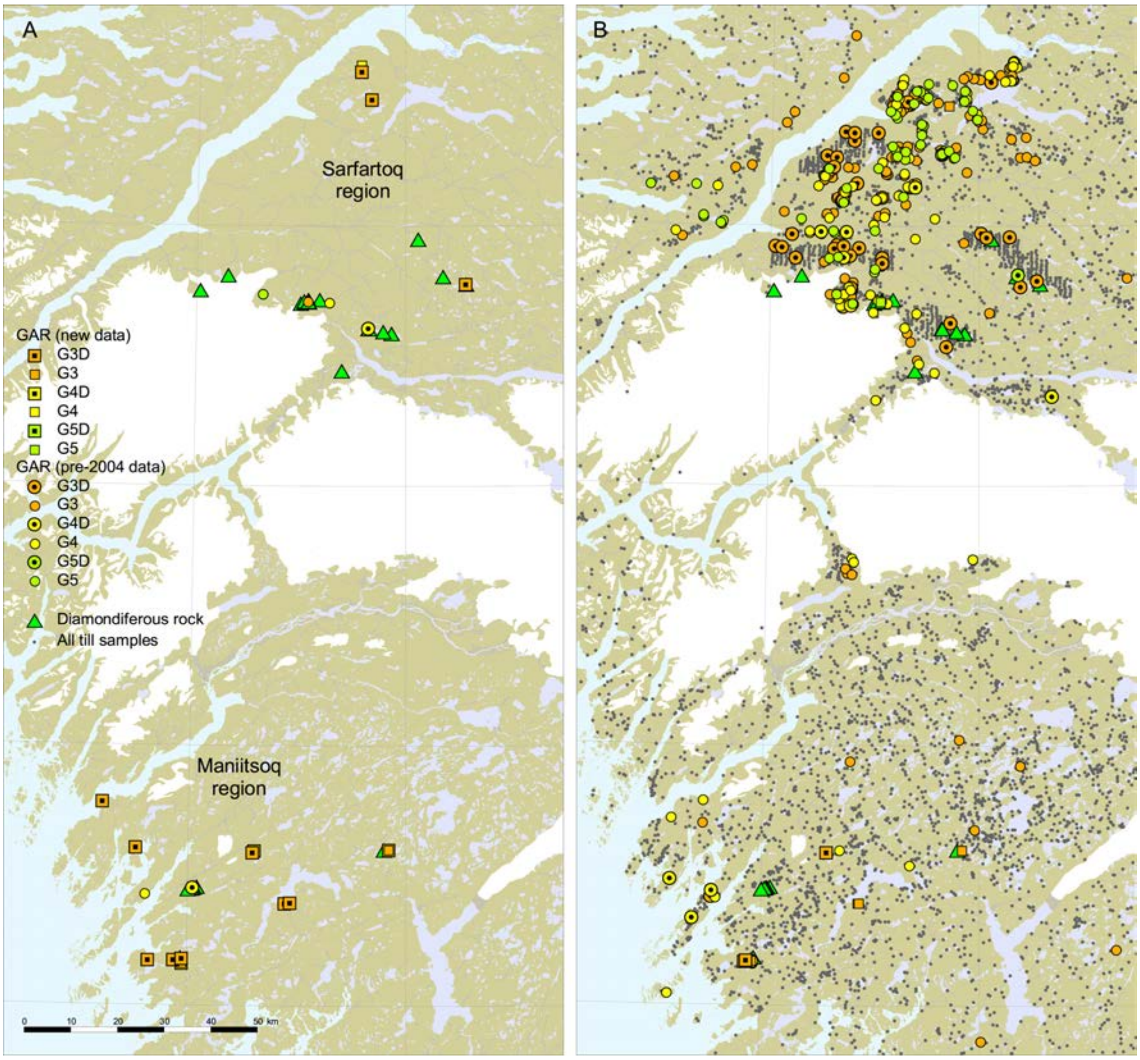

Figure 3. *Diamond-favourable eclogitic garnets (G3D class of Grütter et al. 2004 plotted as top layer) from (A) in situ rock samples, and (B) till samples.*

Eclogitic garnets of diamond-favourable class G3D (Grütter *et al.* 2004) occur in most of the *in situ* rocks sampled in 2004, both in the Sarfartoq and Maniitsoq regions, but in the new till samples mainly in the Maniitsoq region (Figure 3). The pre-2004 data showed the opposite trend, and this may tentatively be explained by picking bias towards purple (peridotitic) garnets by the exploration companies that operated in the Maniitsoq region and the SW part of the Sarfartoq region; the picking of indicator minerals from samples in the rest of the Sarfartoq region apparently recorded a more fair representation of purple and orange (eclogitic) garnets.

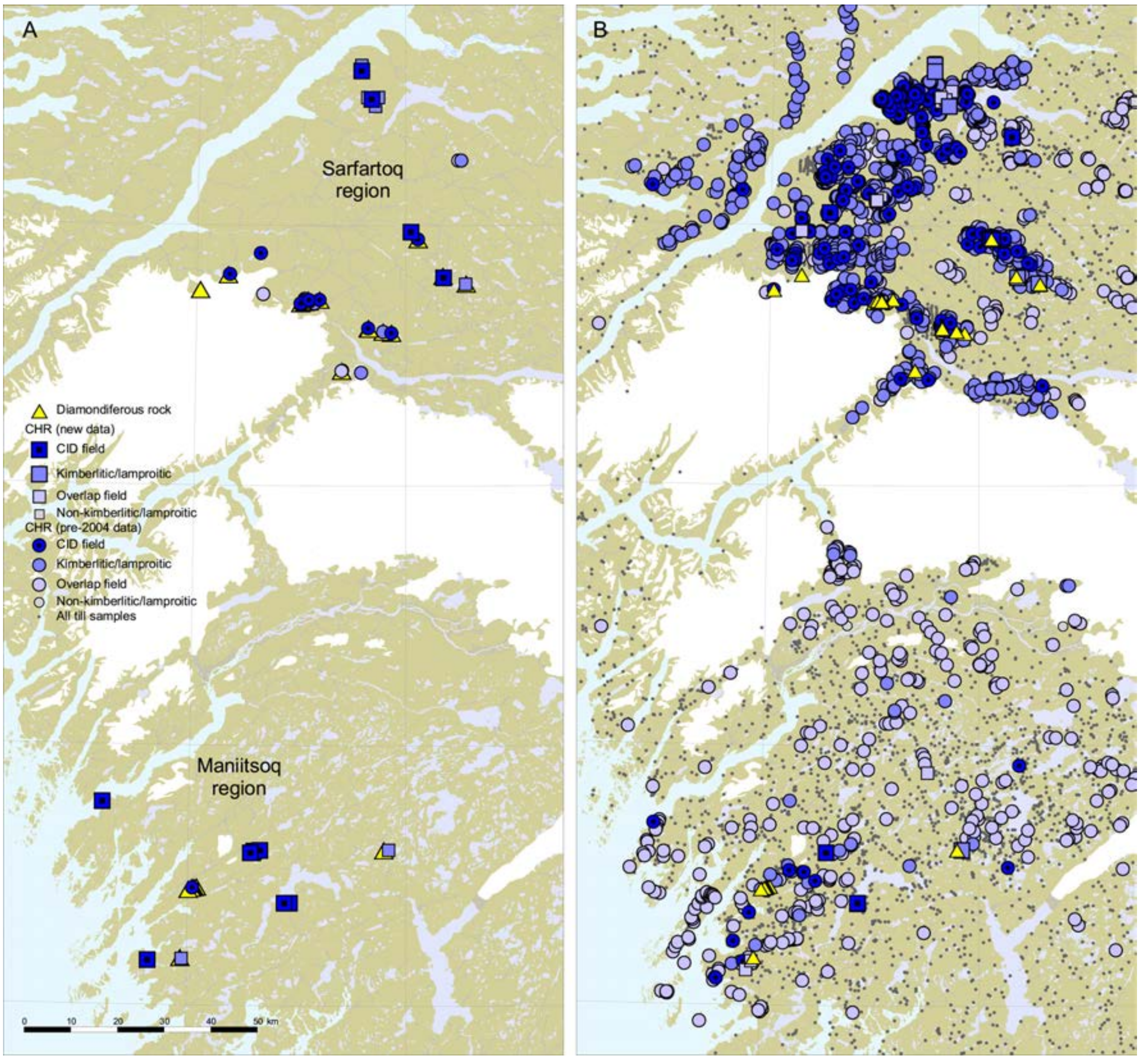

Figure 4. *Diamond-favourable chromites (chromite-inclusion-in-diamond class, Cr2O3–TiO2 diagram of Fipke 1994, plotted as top layer) from (A) in situ rock samples, and (B) till samples.*

Spinel populations (mainly chromite) include a small, but possibly significant number of grains with high Cr_2O_3 and intermediate MgO, considered to be typical of chromite inclusions in diamond (Fipke 1994). These chromites also plot in the chromite-inclusion-in-diamond fields in Cr_2O_3 *vs* TiO_2 diagrams of Fipke (Fipke 1994; Fipke *et al.* 1995) and (Grütter & Apter 1998). The pre-2004 data showed that chromite-inclusion-in-diamond grains from *in situ* rocks were sparse, but tended to coincide with diamondiferous localities (Figure 4). The 2004 rock sampling added several new localities with diamond-favourable chromites (Cr_2O_3 *vs* TiO_2 diagram of Fipke 1994) in the Maniitsoq region, confirmed their overall distribution in the S part of the Sarfartoq region, and added new localities in the N part of the Sarfartoq region. The new chromite data from till samples largely confirms the distribution seen in the pre-2004 data.

Clinopyroxenes (chrome-diopside) from the till and stream sediment have apparent P–T compositions (Nimis & Taylor 2000) within the diamond stability field as defined by Kennedy & Kennedy (1976) in widespread areas of Western Greenland, also in some areas where no kimberlite or lamprophyre sources are known (Jensen *et al.* 2004). However, on a regional scale, the distribution of 'diamond-stable' clinopyroxenes largely coincides with the two main regions with kimberlite and lamprophyre intrusions. In the Maniitsoq region, only sampling sites close to kimberlites appear to contain 'diamond-stable' clinopyroxenes (Figure 5); they are notably absent from till samples from the areas of two major dyke systems. This is interpreted to reflect that no samples have been collected within a few kilometres of the dykes in the regional 'down-ice' direction SW. In the Timitta Tasersua area, the 'diamond-stable' clinopyroxenes appear to be absent from till only about 1 km W of the large dyke outcrops.

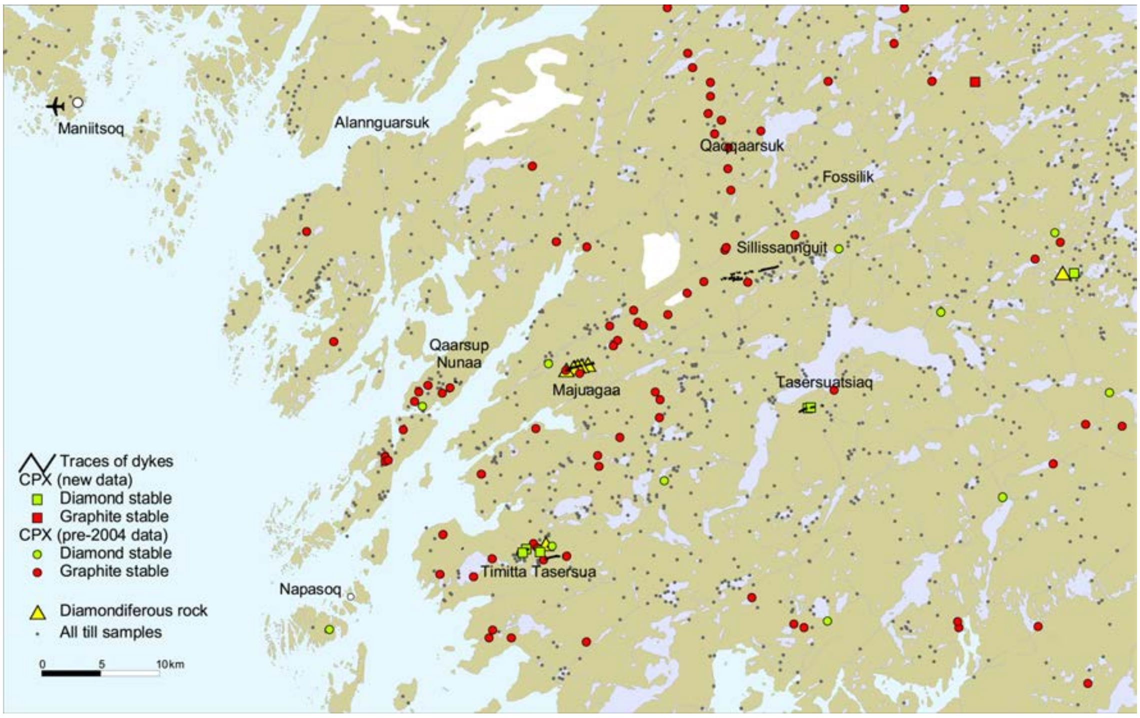

Figure 5. *'Diamond-stable' clinopyroxenes (Kennedy & Kennedy 1976; Nimis & Taylor 2000) in till samples from of the Maniitsoq region.*

Orthopyroxene is not an abundant mineral in the Greenland kimberlites and lamprophyres, and this is reflected in low numbers of grains recovered from both rock and till samples. In the Sarfartoq region, pre-2004 orthopyroxene analyses with diamond-favourable compositions, those falling within the 'diamondiferous harzburgite' and 'diamondiferous lherzolite' fields of Ramsay & Tompkins (1994), were from localities south of the Palaeoproterozoic deformation front, where diamonds had actually been found. The 2004 sampling added new localities with diamond-favourable orthopyroxenes in the N part of the Sarfartoq region. The impression from the previously available data that these orthopyroxenes are very rare in the kimberlites of the Maniitsoq region was confirmed with the new data, and it is interesting to note that no orthopyroxenes were recovered from samples of two major dykes systems (Sillissannguit and Tasersuatsiaq).

Ilmenite is the most common of the indicator minerals analysed prior to 2004, and thus constitutes about half of all the analyses available. A very high proportion (about 90 %) of the ilmenites are 'kimberlitic' in the recent classification scheme of Wyatt *et al.* (2004), i.e., Mg-rich, with generally more than 6 wt% MgO. In till samples 'kimberlitic' ilmenites are ubiquitous and therefore not very diagnostic of specific kimberlite or lamprophyre sources. However, as do the clinopyroxenes, on a regional scale, ilmenites from till with 'kimberlitic' composition outline areas that coincide well with areas of known kimberlite or lamprophyre occurrences. The contribution of ilmenite grains to the till from crustal rocks, for example the voluminous Kangâmiut dolerite dykes of the Sarfartoq region, appears to be minimal. This, and the observation that the Greenland tills have higher heavy mineral content than average tills from the Slave Craton (Overburden Drilling Management, personal communication), may help explain the relationship between fairly high numbers of indicator minerals in till and numerous, but generally small outcrops of possible source rocks.

Conclusions

The separation, picking and analysis of heavy minerals from *in situ* kimberlite and lamprophyre occurrences has lent support to the hypothesis that the dispersion of indicator minerals 'down-ice' from their source is limited to a few kilometres in most areas of southern West Greenland. This seems especially convincing in the Maniitsoq region, where glacial transport appears to have been uniformly to the SW (240°). Kimberlite float and the most diamond-favourable indicator minerals are always found on the S side of these, generally WSW–ENE striking dyke systems. The fact that the recently found kimberlite dykes in the Maniitsoq region have remained unknown until 2004 is largely due lack of previous systematic follow-up on indicator mineral results. That most of the kimberlite localities in the Maniitsoq region contain abundant diamond-favourable peridotitic and eclogitic garnets, along with diamond-favourable chromites and clinopyroxenes adds weight to the suggestion that those dykes not already tested for diamond content should be sampled and subjected to caustic dissolution.

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The Diamond Potential of West Greenland: some Global Insights

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Deep seated magmas capable of transporting diamond to the surface include kimberlite, ultramafic lamprophyre, and olivine lamproite. Typically, economic diamond mines are observed in areas of Archean crust, which are underlain by Archean mantle. From this perspective West Greenland is an interesting exploration area for diamonds based on: 1) the existence of bonafide kimberlite at Maniitsoq, as typified by their 'Trend 1' spinels, in contrast to ultramafic lamprophyres (UML, var. aillikite) which are now recognized to have a diagnostic spinel population which lies intermediate between 'Trend 1' and 'Trend 2'; 2) the Maniitsoq kimberlites are emplaced through Archean crust, which preliminary studies have shown to be underlain by a thick lithospheric root (>190 km) with a cool paleogeotherm (36 – 40 mW/m^2), and; 3) the lithospheric mantle in the Maniitsoq area contains subcalcic harzburgite. However, it must be noted that: 1) large variations in mantle stratigraphy (and hence diamond potential) can occur over very short distances (<50 km) as seen in the Kaapvaal craton (S. Africa) and the Slave and the Superior cratons (Canada), and; 2) that within kimberlite fields, and specifically within individual kimberlite bodies there can be large variations in diamond grade that are specifically related to geochemically and temporally discrete 'diamond transporting events' as observed in Canadian (and Southern African) kimberlites. For West Greenland, it is suggested that a structural analysis for areas of Archean crust would provide insights about possible boundaries between mantle "microblocks", as well as pathways/zones of weakness for intruding kimberlite or UML magmas. Further, there is probably an intimate relationship between 'diamondiferous' kimberlite bodies and specific structures, and also that these 'diamondiferous' kimberlite bodies will also have diagnostic geochemical and age characteristics, which distinguish them from weakly- or non-diamondiferous kimberlites.

Mapping of the lithosphere beneath the Archaean craton and Proterozoic mobile belt in West Greenland

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Minerals in mantle xenoliths and separated garnet and oxide megacrysts in kimberlite and aillikite dykes were investigated from three areas in West Greenland: the Maniitsoq (Sukkertoppen) area well within the Archaean craton, the Sarfartoq area at the boundary between the Archaean craton and the Nagssugtoqidian mobile belt, and the Sisimiut (Holsteinsborg) area well within the mobile belt. The mobile belt was formed during a Proterozoic continental collision event that reworked the Archaean terranes. The alleged collision suture is located about 80 km north of Sisimiut.

The minerals were analysed for major elements by electron microprobe and for trace elements by proton microprobe and laser-ICP-MS. The work was carried out as a PhD project in the period 1994-2000.

No xenolith material was at the time available from the Maniitsoq area; however the kimberlite samples contained frequent garnet megacrysts. From the Sarfartoq area, the xenolith population (208) consisted of dunite, harzburgite, lherzolite (all three with or without garnet), wehrlite and glimmerite. Spinel-bearing types were rare, as were granulites. From the Sisimiut area, the xenolith population (24) consisted of spinel lherzolite, dunite, granulite, wehrlite, glimmerite and rare garnet lherzolite; only few dykes contained garnet megacrysts.

Garnet, chromite and ilmenite separates were analysed for 4 samples (543 garnets) from the Maniitsoq area, 12 samples (1560 garnets) from the Sarfartoq area, and 3 samples (96 garnets) from the Sisimiut area. There is in general a dearth of garnets in the Sisimiut area.

Based primarily on the methods developed by W. L. Griffin and coworkers, sections through the lithosphere in the Maniitsoq and Sarfartoq areas were constructed, whereas there was not enough data from the Sisimiut area, primarily because the garnets there derive only from specific intervals. The sections show that the lithosphere in the Maniitsoq and Sarfartoq areas are of similar thickness (c. 235 km) though the base of the lithosphere at 235–190 km depth is strongly influenced by melt metasomatism. The two areas contain similar lithologies though in different proportions. The most frequent rock type in the lithosphere is garnet lherzolite. The amount of harzburgite at depths of diamond stability goes up to 40% in the Maniitsoq area and is only c. 10% in the Sarfartoq area. In both areas the lithosphere is layered, most strongly in the Sarfartoq area where the upper part is dominated by depleted harzburgites typical of Archaean cratons. Whereas the lithosphere in the Maniitsoq area is of Archaean aspect throughout, the lower lithosphere in the Sarfartoq area is dominated by lherzolites and metasomatised lherzolites similar to some Proterozoic sections. In both areas, but particularly in the Sarfartoq area, there is extensive phlogopite metasomatism around 150 km depth. The Sarfartoq carbonatite complex is probably genetically related to this layer.

REE patterns of garnets and clinopyroxenes show evidence of repeated depletion and enrichment events in the mantle. No truly primitive mantle is present in West Greenland. Some of the re-enrichment events are of ancient Archaen age, as judged from the primary metamorphic and undisturbed texture of the xenoliths.

The lithosphere beneath the Maniitsoq and Sarfartoq areas is similar in mineralogy and average chemical composition to Archaean lithosphere in other parts of the World. As far as the data allow conclusions, the lithosphere beneath the Sisimiut area is less depleted than in the other two areas, and the metasomatic processes seem to be different. This may be connected to mantle disturbances during the Proterozoic collision event.

Indicator mineral signatures in basal till surrounding the Lahtojoki and Seitaperä kimberlites, eastern Finland

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Abstract

Since the 1980's diamondiferous kimberlitic rocks have been discovered in eastern Finland. In order to further the ongoing diamond exploration in the country, the Geological Survey of Finland carried out detailed heavy mineral surveys of basal till around two of the known kimberlitic bodies. The Lahtojoki kimberlite in Kaavi and the Seitaperä kimberlite in Kuhmo have different geological and mineralogical characteristics. The kimberlitic indicator grains down-ice from the Lahtojoki kimberlite form a well-defined fan, extending for at least 2 km. The fan has been formed as a net effect of two known ice-flow events in the region. The indicator dispersal trail from the Seitaperä kimberlite is shorter (~1 km) and more vague than that at Kaavi. This is mainly due to the low indicator content in the Seitaperä kimberlite, as well as a large population of background chromites in till. These chromites are probably derived from the Archean Kuhmo greenstone belt. Results of this study contribute to the overall understanding of the Quaternary history of the Kaavi and Kuhmo areas, and provide tools to diamond exploration in glaciated terrains.

1 Introduction

A commonly used diamond exploration method in recently glaciated terrains is to track kimberlitic indicator mineral grains dispersed in glacial sediments *(e.g. Gurney, 1984; Atkinson, 1989; McClenaghan & Kjarsgaard, 2001)*. The classic indicator suite includes Cr-pyrope, Ti-pyrope and eclogitic garnet, Cr-diopside, Mg-ilmenite (picroilmenite) and high-Cr, high-Mg chromite.

Diamondiferous kimberlites occur in eastern Finland around the Kaavi-Kuopio and Kuhmo areas *(Tyni, 1997; O'Brien & Tyni, 1999)*. Major part of the Karelian Craton is, in fact, prospective for diamond based on the empirical evidence necessary for diamond preservation (Fig. 1). Active diamond exploration in Finland has been ongoing for over two decades *(Tyni, 1997)* but systematic glacial dispersal studies around the known kimberlites have not been published to date.

In 2001-2003 the Geological Survey of Finland (GTK) carried out sampling of Quaternary till around two kimberlitic bodies in Finland, the Lahtojoki pipe (Pipe 7) in Kaavi and the Seitaperä dyke swarm (Dyke 16) in Kuhmo. The selection of targets was based on their different geological and mineralogical characteristics, as well as differences in the surrounding bedrock and Quaternary deposits. The objective was to study their indicator mineral signatures in the surrounding basal till. The ultimate aim of the work was to gather information that can be applied to diamond exploration in similar areas. This study has been described in greater detail in *Lehtonen et al. (in press)*.

Figure 1. *Map illustrating the diamond prospective area of Fennoscandia characterized by a) low heat flow (Kukkonen & Jõeleht, 1996) and b) lithosphere thicker than 170 km based on seismic data (Calcagnile, 1982). The Archean/Proterozoic boundary marks the subsurface extent of the Archean craton. The black diamonds represent diamond-bearing kimberlite/lamproite clusters. The localities of this study are underlined.*

2 Targets of study

2.1 The Lahtojoki kimberlite

The Lahtojoki kimberlite in Kaavi belongs to the 600-Ma Kaavi-Kuopio Kimberlite Province situated at the edge of the Karelian Craton, see Figure 1 *(Tyni, 1997; O'Brien & Tyni, 1999; O'Brien et al., 2005)*. At least 19 kimberlite pipes have been emplaced into Archean (3.1-2.6 Ga) basement gneisses and Proterozoic (1.9-1.8 Ga) metasediment sequences *(Kontinen et al., 1992)*.

The bedrock in Kaavi is mainly composed of mica schists, gneisses and intercalated black schists *(Huhma, 1975)*. The Quaternary deposits consist of basal till (e.g. drumlin fields), ablation till, outwash and glaciolacustrine sediments. The ablation till unit commonly rests directly upon the basal till, altogether forming a till cover that rarely exceeds 3 m in thickness. There are two known ice flow directions in the region *(Hirvas & Nenonen, 1987)*, the older from 280° to 100° and the younger (main) from 335° to 155°.

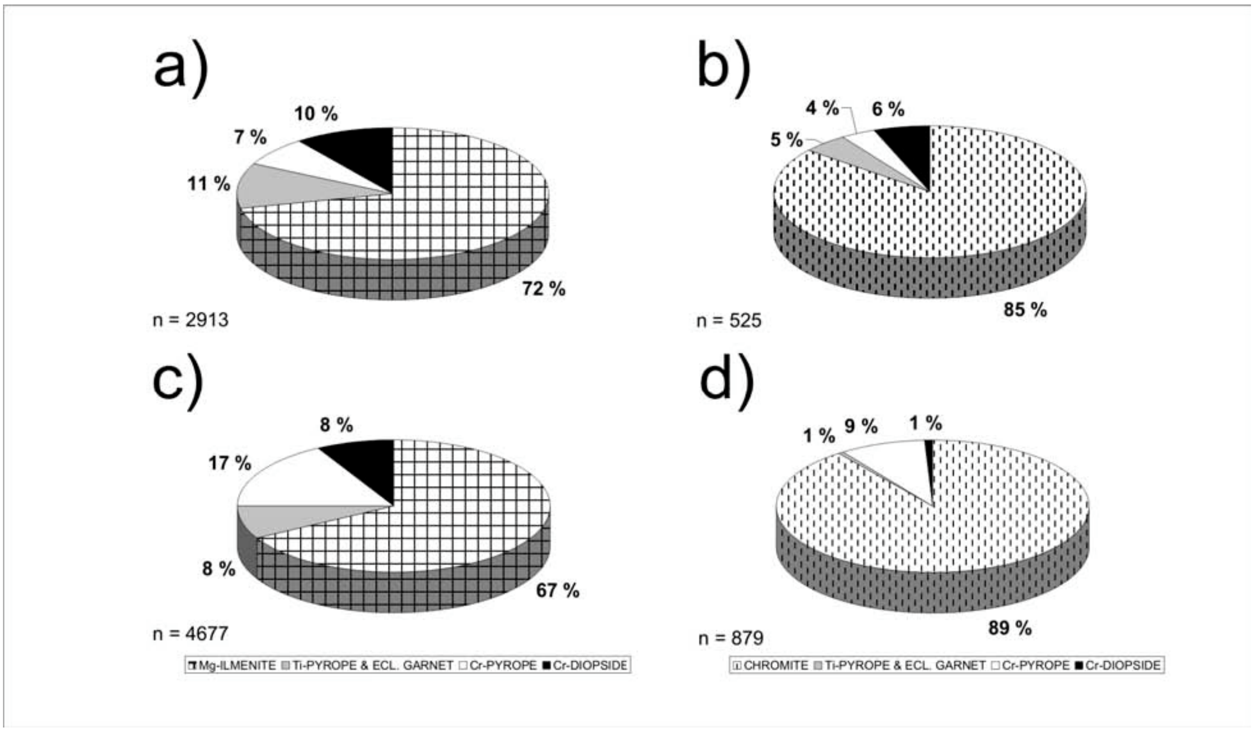

Figure 2. *Pie graph showing the relative abundances of indicator minerals in the 0.25-1.0 mm fraction of: a) the Lahtojoki kimberlite; b) the Seitaperä kimberlite; c) till samples from Lahtojoki; and, d) till samples from Seitaperä. Visual identification of indicator minerals was confirmed using SEM-EDS and/or electron microprobe.*

The 2-ha Lahtojoki kimberlite is a classical Group I kimberlite. The kimberlite is mainly composed of macrocrystal tuffisitic kimberlite and subordinate tuffisitic kimberlite breccia with rare hybabyssal kimberlite. An average diamond grade of 26 ct/100 t has been reported for the pipe *(Tyni, 1997)*. The indicator minerals are abundant and include Mg-ilmenite, Cr-pyrope, Ti-pyrope, eclogitic garnet and Cr-diopside (Fig. 2). The body is covered by 13-20 m of glacial deposits and peat.

2.2 The Seitaperä kimberlite

The Seitaperä kimberlite is located in Kuhmo (Fig.1), 200 km NE from Kaavi, closer to the center of the Karelian craton. The bedrock in the area is composed of Archean gneisses, migmatites and granites (3.1-2.6 Ga) through which runs the N-S trending Kuhmo greenstone belt (3.0-2.7 Ga) *(e.g. Piirainen, 1988)*. The district is characterized by similar type and age of Quaternary deposits as Kaavi, although there are some regional distinctions. The glacial stratigraphy in the area consists of basal till covered by ablation till and/or a widespread unit of glaciolacustrine sediments *(Saarnisto et al., 1980)*. The main ice flow direction in the region was from 300° to 120°. The till cover usually exceeds 3 m in thickness.

The Seitaperä kimberlite has characteristics of both olivine lamproite and Group II kimberlite (O'Brien & Tyni, 1999). The rock is mainly (~70%) composed of phlogopite microphenocrysts while macrocrysts other than olivine are virtually absent. The kimberlite is known to contain diamonds at extremely low contents, 1 ct/100 t. The SW-NE kimberlite dyke swarm intrudes a 300 x 600 m area, with approximately 20% of the area being kimberlitic. The thickness of glacial sediments varies between 3 and 12 m.

Ar-Ar measurements from phlogopite microphenocrysts have resulted in age of ca. 1200 Ma for the kimberlite (Hugh O'Brien, personal communication). The most abundant indicator mineral in the relatively indicator-poor kimberlite is chromite with rare pyrope and Cr-diopside (Fig. 2).

3 Methodology

3.1 Sampling areas

3.1.1 Lahtojoki, Kaavi

Till sampling was carried out in Lahtojoki in 2001-2002. The results of a GTK heavy mineral survey conducted in 1994 in the area were also included in this study. Indicator mineral data on previous claims reported by exploration companies to the Ministry of Trade and Industry were used as background information (Fig. 3). The GTK sampling program consisted of 46 excavator pits, resulting in 84 samples. The initial sample size was 20 kg. The first sample was taken from the uppermost layer of basal till, i.e. the C-horizon usually at ~ 1 m depth, and the following in 1-2 m intervals. 30 pits reached the bedrock with an average overburden thickness of 2.3 m. The older basal till bed was encountered in only one sampling site.

The objective of the longest sampling profile (Line 1L) parallel to the main ice flow was to measure the length of the dispersal fan (Fig. 4A). Perpendicular profiles (Lines 2L and 3L) were made in order to determine the width of the fan. A few samples were taken from the distal areas to estimate the regional background indicator concentration.

In the vicinity of the kimberlite a drill rig was used for sampling due to the thick glacial deposits. 25 holes were drilled to form two crossing lines (4L and 5L). Altogether 87 till samples were recovered from the drill cores representing 1 m layers of the till bed and weighed up to 9 kg apiece.

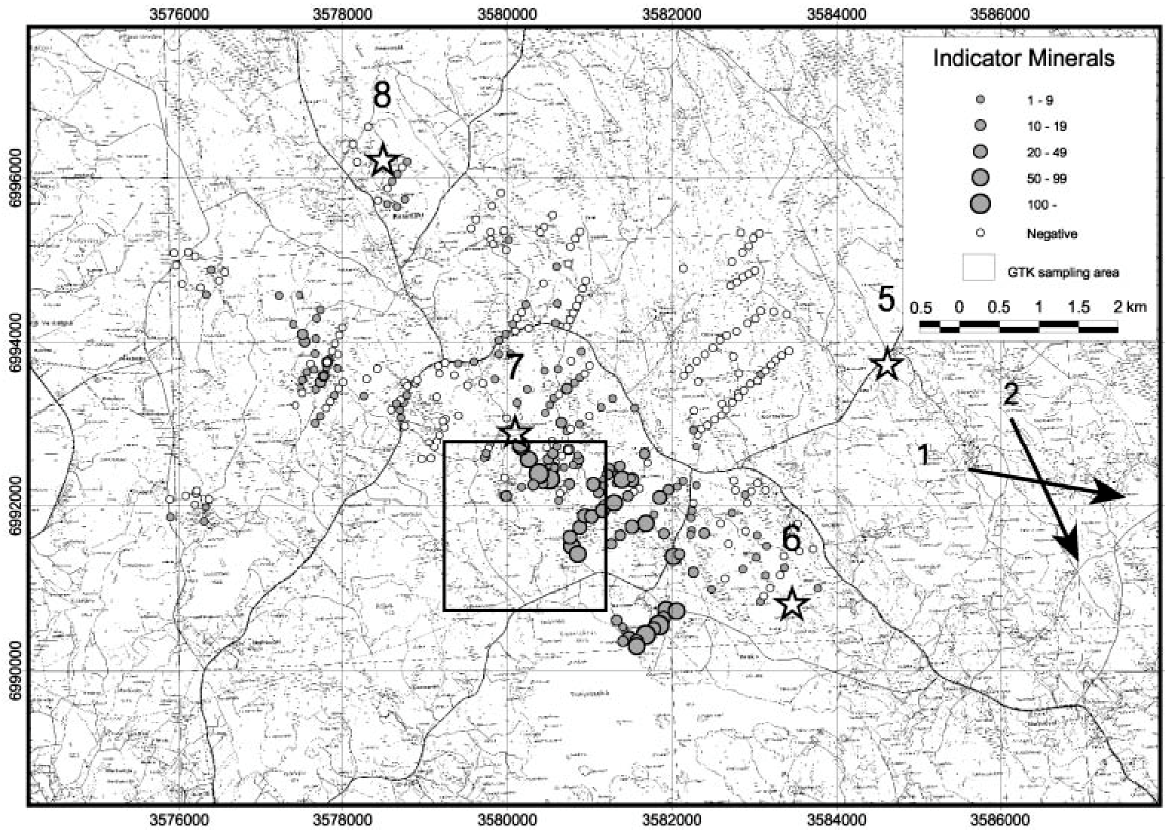

Figure 3. *Indicator distribution in till in the Kaavi area. Data compiled from expired claims reported to the Ministry of Trade andIndustry. The known kimberlite pipes in the area are marked as stars. Indicator counts are normalized to 10 kg and consist ofgrains below 1.2 mm in diameter. The arrows point to the main (2) and the older ice flow (1) directions in the region.*

3.1.2 Seitaperä, Kuhm

Till sampling was carried out in Seitaperä in 2002-2003 using an excavator and the same methodology as in Lahtojoki. The sample size was increased to 60 kg due to the lower indicator content of the Seitaperä kimberlite compared to that of the Lahtojoki pipe. A 2-km profile (Line 1S) was sampled down-ice from the kimberlite parallel to the main ice flow (Fig. 4B). A shorter perpendicular profile (Line 2S) was placed at the greatest extent on Line 1S where indicators were still found in concentrations above background. In total 42 pits were excavated, resulting in 98 till samples. 21 pits reached the bedrock with an average overburden thickness of 2.5 m. Occasionally thick ablation till unit prevented sampling of basal till.

In order to study the influence of the Archean ultramafics of the Kuhmo greenstone belt on the regional chromite content in till, two pits were excavated on both up- and down-ice of the voluminous Näätäniemi serpentinite massif. The massif is located approximately 30 km up-ice from Seitaperä.

3.2 Sample processing and analysis

The till samples were initially screened down to <1.0 mm grain size to reduce their volume. Selected coarser fractions were also studied for indicators and kimberlite fragments. Preconcentrates were made from screened 15 kg (Lahtojoki) and 45 kg (Seitaperä) excavator and 4-6 kg drilled (Lahtojoki) till samples using a GTK modified 3''Knelson Concentrator *(Chernet et al., 1999)*. The preconcentration reduced the 15 kg and 45 kg excavator samples into 200-300 g and 700-900 g, respectively, and the drilled till samples into 100-200 g. The preconcentrates were separated by heavy medium (d=3.2 gcm^{-3}). A dry low intensity drum magnetic separator was applied to remove magnetite. Finally the 0.25-1.0 mm size indicator grains were hand picked under binocular microscope. In order to confirm their identification, all indicator grains were analyzed using an EDS equipped Jeol JSM-5900LV scanning electron microscope. Accurate mineral compositions from selected indicator grains were determined by a Cameca Camebax SX50 electron microprobe.

4 Results

4.1 The Lahtojoki indicator fan

Down-ice from the Lahtojoki kimberlite a well-defined indicator fan exists, parallel to and symmetrically distributed around the main ice flow direction (Fig. 4A). The highest concentration of indicator grains is found nearly 1.2 km down-ice from the pipe. At this distance the indicator fan is approximately 600 m wide and the highest concentration of indicators usually exists at the base of the till bed. Further away the indicators are slightly enriched in the uppermost part of the basal till. The further-most sampling site, 2 km from the kimberlite, is still enriched in indicators and suggests that the fan extends further.

While studying the pipe area by drilling, another small kimberlitic body of yet unknown size was discovered 300 m down-ice from the main pipe. The satellite kimberlite intersection of 9 m from a 45° dipping drill hole is composed of tuffisitic kimberlite breccia and bounded on both sides by country rock. The intrusion is clearly related to the main pipe both spatially and mineralogically. The till indicator population corresponds very closely to that of the main Lahtojoki kimberlite (Fig. 2), suggesting that it is the main contributor of the dispersal fan. The small satellite kimberlite must have its impact on the shape and indicator content of the fan as well but this effect cannot be readily identified.

4.2 The Seitaperä indicator fan

The indicator content in till down-ice from the Seitaperä kimberlite is much lower than that in Lahtojoki, as expected based on the different indicator concentrations in the kimberlites themselves. The indicator maximum exists in samples directly over the kimberlite and immediately down-ice from it, after which the concentration drops rapidly (Fig. 4B). The indicators also seem to be enriched in the upper part of the basal till very soon after the kimberlite contact.

Special attention was paid to distinguishing kimberlitic till chromites from non-kimberlitic background chromites. A separation method was applied based on chromite major element composition (Cr, Ti, Mg). Altogether 1581 till chromites were microprobed and 559 of them were categorized as kimberlitic. Figure 5 illustrates how the till chromite population evolves as the transport distance from the kimberlite 16 increases. The strongest background population can be identified as a group of chromites with ca. 35-53 wt% of Cr_2O_3, 0.3-1.4 wt% of TiO_2 and 6-12 wt% of MgO. It is present literally in all till samples but not in the kimberlite. Based on regional geology, the most probable sources for these chromites are the Archean ultramafic rocks of the Kuhmo greenstone belt, such as the Näätäniemi serpentinite massif and associated metavolcanics. As expected, the basal till samples taken down-ice from the Näätäniemi massif contain chromite in relatively high concentrations, >200 0.25-1.0 mm grains/45 kg, whereas up-ice of the massif, the chromite contents are very low (5-10 grains/45 kg). Most importantly, the bulk of the down-ice till chromites agrees in terms of composition with the Seitaperä background chromite population.

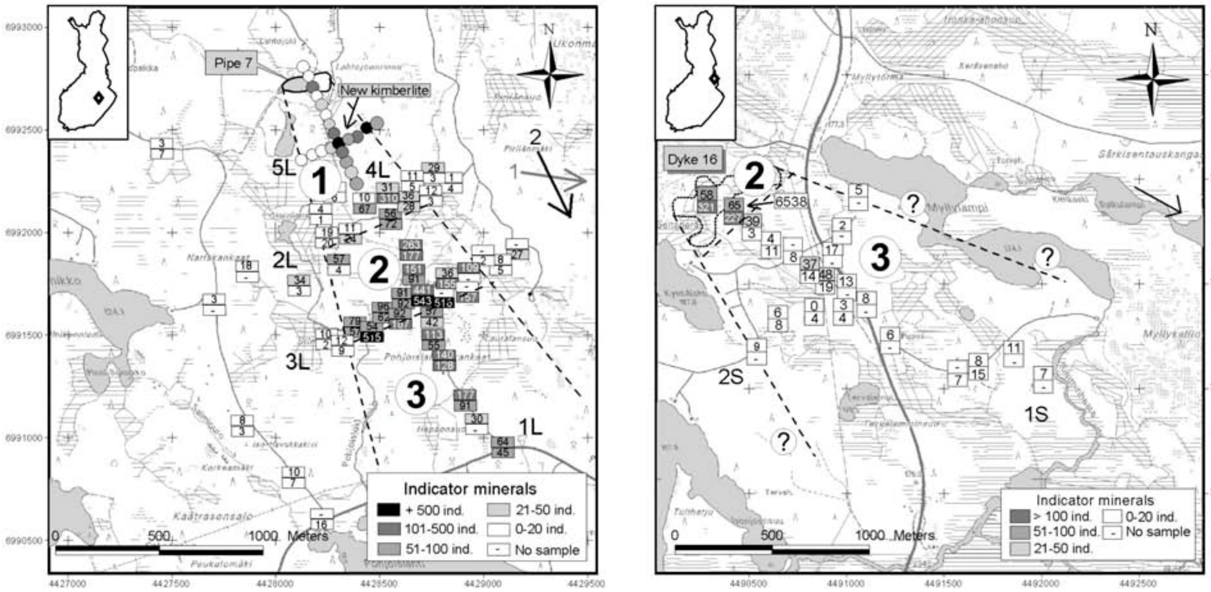

Figure 4A and 4B. *Indicator dispersal fans from the Lahtojoki (Pipe 7) and the Seitaperä (Dyke 16) kimberlites subdivided (1-3) according to the content of kimberlitic material in till. The arrows point to the ice flow directions in the regions. The indicatormineral (0.25-1.0 mm) counts in 15 kg (Lahtojoki) and 45 kg (Seitaperä) till samples from excavated sites are marked in double boxes. The lower box represents the base of and the upper the surface of the basal till bed. The drilling sites in Lahtojoki are marked with dots, the shades of which indicate the indicator abundance in the deepest 2-4 m layer of till.*

5 Discussion

5.1 The Lahtojoki case study

The results of the previous sampling programs (Fig. 3) combined with the outcome of this study (Fig. 4A) suggest that the Lahtojoki dispersal fan has been formed as a net effect of the two known ice flow events in the region (older ~W-E and younger ~NW-SE). Out of the two ice flow events, the younger appears to have had more prominent effect on the shape of the fan. During the latest glaciation the older till was reworked, transported and redeposited along the younger ice flow. The older till bed was virtually destroyed in the process.

The distance of the indicator maximum in till from the kimberlite is generally a function of the kimberlite type and/or the availability of soft kimberlite regolith for the glacier to erode *(McClenaghan et al., 2004)*. The Lahtojoki kimberlite is mainly composed of soft diatreme facies rocks with minor, more resistant hybabyssal component. On top of the pipe there occasionally exists a several meters thick soft weathered kimberlite horizon whereas in other parts glacial erosion has exposed fresh kimberlite. This variance in kimberlite resistance probably explains the relatively long distance of the indicator maximum down-ice from the kimberlite. In general it is not exceptional that the maximum for sand-sized indicators in till exists some distance away from the kimberlite *(e.g. McClenaghan et al., 2002)*.

The Lahtojoki dispersal fan parallel to the main ice flow can be roughly divided into three zones (Fig. 4A): (1) The proximal zone extending approximately 500 m down-ice, characterized by abundant kimberlitic fragments, and a high concentration of kimberlitic material at the base of the till bed. (2) The intermediate zone starts where clearly elevated numbers of indicator grains have reached the till surface, i.e. at ca. 500 m distance from Pipe 7. This is probably mainly due to the effect of grain liberation from coarser kimberlite fragments. The indicator maximum at 1.2 km distance marks the end of zone 2. (3) The distal zone extends from this point further down-ice until the lake in the south (ca. 3 km). Zone 3 shows decreasing numbers of indicator grains, with the highest concentrations occurring in the upper parts of the basal till. Zone 3 is expected to dilute down-ice to background levels of kimberlitic indicators.

5.2 The Seitaperä case study

In contrast to the Lahtojoki case, the mineral grain liberation from coarser kimberlite fragments in Seitaperä has taken place immediately at the kimberlite contact (Fig. 4B). Dilution from country rock has rapidly replaced the kimberlitic material from the base of the till bed and soon reached also its upper parts. At 800 m distance the dilution is already so strong that it is difficult to estimate the width of the dispersal fan.

The silicate indicator population in till does not correspond to that of the kimberlite (Fig. 2); Cr-diopsides and Ti-pyrope and eclogitic kimberlitic garnets are considerably underrepresented in the till whereas purple Cr-pyropes are found in low concentrations (<5 grains in 45 kg of till) over the entire sampling area. This evidence suggests that the silicate indicators in till most likely represent a regional feature.

The chromite content and composition in till samples strongly indicate that the Archean ultramafics of the Kuhmo greenstone belt are the source for the bulk of the background chromites. The distance between the Näätäniemi serpentinite massif and the Seitaperä study area is approximately 30 km. The bulk of the till (i.e. the coarser material) has traveled generally less than 10 km from its source based on various studies in Finland *(e.g. Hellaakoski, 1930; Virkkala, 1971; Perttunen, 1977; Saarnisto et al., 1980; Salminen, 1980; Salonen 1986)*. However, studies on till size fractions indicate that finer material is transported far longer than coarser fractions *(e.g. Peltoniemi, 1985)*. *Saarnisto et al. (1980)* demonstrated that the proportion of 6-20 cm material originating from the Kuhmo greenstone belt decreases almost to zero within a kilometer, but the 2-6 cm pebbles still contain about 5% material from the greenstone belt at a distance of 15 km. Chromite grains in this study are even considerably finer-grained than that, overwhelmingly 0.25-0.5 mm in size.

Thus, it is reasonable to assume that they have endured in glacial transport all the way from the greenstone belt.

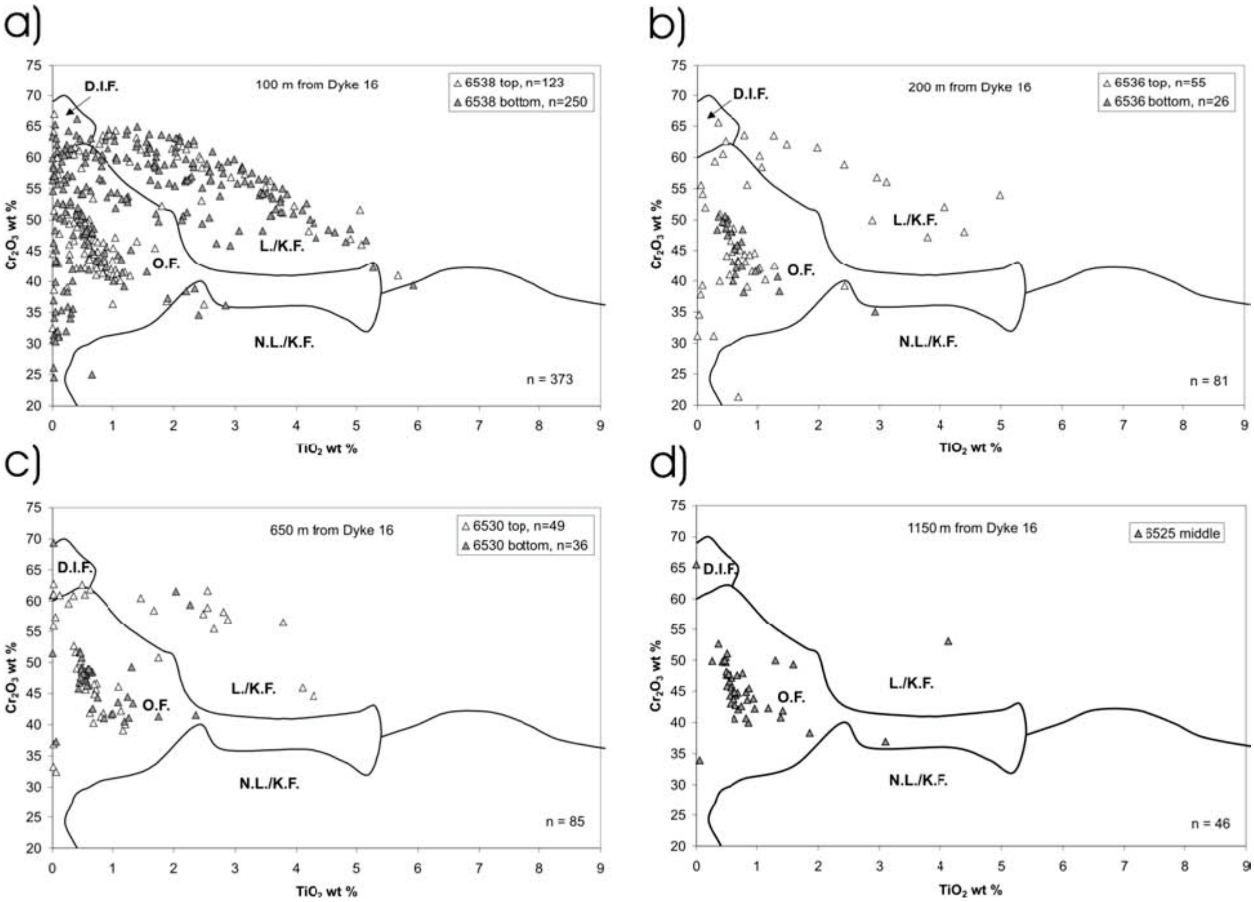

Figure 5. *Chromite analyses from the Seitaperä till samples plotted in a Cr_2O_3-TiO_2-diagram redrawn after Fipke et al. (1995). Analyses from the upper (top), middle and lower (bottom) parts of the basal till bed are denoted: a) till sample 6538, 100 m southeast (down-ice); b) 6535, 200 m southeast; c) 6530, 650 m southeast; and d) 6525, 1150 southeast from the Seitaperä kimberlite. The field unique to lamproites and kimberlites is labelled as L./K.F., diamond inclusion and intergrowth field asD.I.F., the nonlamproitic/kimberlitic field as N.L./K.F., and the overlap field for kimberlitic and non-kimberlitic rocks as O.F.*

6 Conclusions and implications for diamond exploration

At least in theory, the implications from this work seem to be easily applicable for diamond exploration in Fennoscandia as well as in any other recently glaciated terrain. Most importantly, the methodology described here can be used in all till-covered regions. The ultimate aim of commercial till heavy mineral surveys is, of course, to identify kimberlitic dispersal fans. This study illustrates that defining a solitary fan requires a detailed indicator mineral study with dense sample spacing, ~1 sample / 0.25 km^2. The discovery of the Lahtojoki satellite kimberlite emphasizes the significance of a dense sampling grid. The case studies of Lahtojoki and Seitaperä show that the fans can, for a number of reasons, be different in morphology, size, indicator content and internal structure.

Based on this study, a sample size of at least 60 kg of basal till is recommended for indicator mineral work in diamond exploration at reconnaissance and regional scale. It is also important to take samples from different horizons of the basal till bed, because the vertical distribution of indicators within the till may vary considerably as seen in both study areas. Ideally this variance can be used to estimate the transport distance.

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Kimberlites and ultramafic lamprophyres in West Greenland: regional constraints

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Mitchell et al. (1999) noted regional differences in the mineral chemistry of ultramafic lamprophyres from the Sisimiut-Maniitsoq region in West Greenland. The Majuagaa dyke (Nielsen et al., this volume) has now been shown to be a kimberlite (s.s.) and the distribution of kimberlites and ultramafic lamprophyres could be of importance for the evaluation of the diamond potential in the West Greenland province.

Thirty occurrences of ultramafic lamprophyres and kimberlites throughout the province have been selected for detailed studies. The compositions of groundmass phlogopite, spinel and ilmenite and the presence or absence of cognate clinopyroxene can be used for the identification of kimberlites (s.s.) (Mitchell, 1995 and Tappe et al, 2005). The ultramafic lamprophyres from a single occurrence may, however, show several mineralogical characteristics corroborating with a kimberlitic affinity, but one or more of the critical constraints do not comply with the strict definition of kimberlite (see e.g. Hutchison, this volume). Whether this reflects a gradation between kimberlite and ultramafic lamprophyre or mixing of lamprophyre, ultramafic lamprophyre and kimberlitic melts is not clear.

A first step in the investigation of this problem is the establishment of a large database for the compositions of the groundmass minerals that forms the backbone of the classification of kimberlites and ultramafic lamprophyres. This investigation has been initiated and some preliminary results are presented. All occurrences investigated to date, except for the Maniitsoq swarm (see below), are according to the current classifications ultramafic lamprophyres, but many may have characteristics of kimberlites. It is hoped that ultramafic and mafic “endmember” types of dyke rocks can be identified and investigated in great detail.

A subsequent step would be a systematic investigation of the correlations between the groundmass mineral chemistry and the occurrence of diamonds in the West Greenland province and diamond-producing kimberlites and ultramafic lamprophyres world-wide. It is a preliminary suggestion, but the data at hand do suggest that the prospectivity of the West Greenland dykes is ***not*** dependent on the dykes being kimberlite (s.s.) or ultramafic lamprophyre.

Kimberlites in the Maniitsoq region

The Majuagaa dyke of the Maniitsoq region is concluded to be a genuine kimberlite (see Nielsen et al., this volume). This is based on the compositions of groundmass phlogopite, spinel and ilmenite and the absence of clinopyroxene. The same characteristics are seen in new data from the so-called MK02 occurrence mentioned in Mitchell et al. (1999) from close to Maniitsoq. The characteristic of the kimberlites from these localities is that the dyke rocks are phlogopite-poor (no brown phlogopite to be seen in hand specimens and thin section) and carbonate-rich. Dykes collected from further in land in the E-W Maniitsoq swarm of nodule-bearing dykes appear to be of the same type and it is suggested that the Maniitsoq dyke swarm is dominated by kimberlites (s.s.). Lamprophyric dykes occur in the same swarm, but are easily identified in hand specimens. They have grains of brown phlogopite. One lamprophyre dike has been investigated in more detail and the phlogopites are zoned towards tetraferriannite (Fe-rich biotite). Such dykes also occur in the Sarfartoq region.

Ultramafic lamprophyres with kimberlitic affinities in the Sarfartoq region

Hutchison (this volume) clearly demonstrates the problems of classification of the ultramafics from the Garnet Lake diamond prospect. Individual samples from the same occurrence have few or more mineral kimberlitic charateristics. It becomes difficult to classify the occurrence. Is this a kimberlite occurrence diluted to variable extends with ultramafic lamprophyre and/or lamprophyre components? A similar complication is observed in the Sarfartuup nuna (S) occurrence SE of Garnet Lake. Phlogopite trends in the “Jesper Blow” can show one ore more compositional trends, even within the same thin section. One option is to see the occurrence as the result of the mixing of magmas. A second possibility is that the compositional trends of groundmass phlogopite reflect very local geochemical environments, such as volatile content, and composition (CO_2/H_2O ratio) and oxygen fugacity. If so, the fundation for the classifications of kimberlites may be questioned. It seems imperative for an understanding of the diamond-related ultramafic magmatism and the diamond prospectivity to understand the details of variability in the composition of groundmass phases and their margins.

A call for co-operation

The observations in the West Greenland occurrences raise questions regarding the classification and the genesis of the ultramafic rocks. The aim of this presentation is to ask for support for three investigations.

1: Is it important for diamond prospectivity if the host rocks are kimberlites, or ultramafic lamprophyres including orangeites and such rock types? The investigation should study samples from a larger suite of occurrences (50?) that have or do produce diamonds. The groundmass minerals should all be analysed and the occurrence classified according to Mitchell (1995) and Tappe et al. (2005). It is tentatively believed that the investigation would show that petrographic type is irrelevant, as long as the “carrier” liquid originates from a depth below the level at which diamond can form. All samples should be investigated by the same standart methods and by the same group of researchers to ensure that the data is comparable.

2: What are the compositions of the “carrier” melts of the ultramafic lamprophyres and kimberlites? It is argued that most of the matrix and megacrystic olivine in the Majuagaa dyke is xenocrystic. This opens for the possibility for an evaluation of the composition of the “carrier” melt. Does this apply to other kimberlite occurrences? The olivines of the Wesselton kimberlite (Mitchell, 1973) show a compositional variation similar to that of the Majuagaa dyke. It is suggested to study a suite of classic kimberlites and ultramafic lamprophyres along the lines described in Nielsen and Jensen (2005). The investigation should comprise morphological characterisation of the olivine grains and analysis of euhedral and anhedral matrix grains, megacrysts and nodules. How much of the olivine in the kimberlites can be interpreted as cognate? The amount of xenocrystic olivine should be evaluated and the bulk recalculated to give an estimate of the “carrier” melt. What is the composition of the carrier melt? A continuum of melts from magnesium-rich carbonatite to CO_2-bearing high Mg# silicate melt along the lines suggested by Dalton and Presnall (1998)? The investigation requires the study of hypabysal and very well preserved, unaltered, kimberlites in which the morphologies of olivine can be interpreted.

3: Are the evolutionary trends in groundmass minerals directly related to the magma type? Can marginal differences in CO_2/H_2O and oxygen fugacity change the evolutionary trends in, e.g., phlogopite? Detailed investigations of single samples from well-described occurrences should be used, e.g. Garnet Lake. Are groundmass mineral trends the results of marginal differences and/or local geochemical environments during the final crystallisation? If so, what would that suggest for the classification of kimberlites?

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The Majuagaa calcite-kimberlite dyke

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Introduction

The Greenland diamond exploration is focused on swarms of ultramafic dykes in the Sisimuit – Maniitsoq region in West Greenland. The dykes have traditionally been referred to as lamprophyres and "kimberlitic" dykes (e.g. Larsen, 1980). More detailed investigations of the mineral chemistry, however, let Mitchell et al. (1999) to conclude that the dykes were best referred to suites of ultramafic lamprophyre grading into carbonatite. The dykes are not referred to kimberlites, because the compositions of groundmass phlogopite, spinel and ilmenite do not conform with kimberlites as defined in Mitchell (1995). The rationale behind this conclusion is that the type of magma that transported nodules, megacrysts and diamonds to upper crustal levels is revealed by the compositions of the minerals that crystallised in the groundmass of the dykes.

The ultramafic dykes vary significantly in petrography and mineral chemistry from phlogopite-rich and clinopyroxene-bearing in the Sisimiut region to phlogopite-rich or phlogopite-poor in the Sarfartoq region to phlogopite-poor in the Maniitsoq region. Individual dykes may be composed of several segments, which may comprise several pulses of contrasting types of ultramafic magma. The observations suggest that the magmas that carried nodules and megacrysts to the surface varied and that individual dyke systems can represent melts from several source regions, and may even be mixed melts with both astenospheric and lithospheric origins.

A consistent description of the ultramafic magmatism in West Greenland apparently requires identification and detailed descriptions of the different petrographic types. The Majuagaa dyke from the Maniitsoq region (Jensen & Secher, 2004; Nielsen & Jensen, 2005) is a diamond-bearing and phlogopite-poor ultramafic dyke, which in all field criteria should be referred to as kimberlite.

The Majuagaa dyke

The Majuagaa dyke is 2.5 km long and up to 2 m wide. It consists of a number of "en echelon" segments. The proportions of megacrysts and nodules vary, but the groundmass appears quite uniform and composed of small, euhedral to anhedral grains of olivine in a groundmass of calcite, serpentine, minor colourless or weakly greenish phlogopite, small grains of spinel and ilmenite. Perovskite and apatite are rare and no clinopyroxene or monticellite has been encountered. The proportion of carbonate varies and late carbonatite veins are common.

The dyke rocks are a mixture of xenolithic and xenocrystic material and a “carrier” melt. It is the composition and mineralogy of the “carrier” melt that allows the classification of a given sample. This investigation of the petrography and the mineral chemistry of the Majuagaa dyke focuses on: (1) the compositional variation in olivine and (2) the compositions of groundmass phlogopite, spinel and ilmenite. The aim of the olivine investigation is an evaluation of the proportion of liquidus olivine (as opposed to the xenocrystic olivine). If the proportion and composition of xenocrystic material can be determined it is possible to correct the bulk compositions to give an estimate of the composition of the “carrier” melt. The aim of the investigation of the groundmass minerals is to determine the affinity of the “carrier” magma.

Olivine

Small grains of olivine dominate the groundmass of the samples and can be divided into euhedral crystals and anhedral grains. Euhedral crystals are rare to very rare. Systematic analyses of all morphologies of olivine reveal that euhedral grains have $Fo_{90\text{-}89}$ cores and $Fo_{89\text{-}88}$ margins, whereas anhedral grains have $Fo_{94\text{-}85}$ cores, in some cases with margins similar to those of the euhedral olivines. It is suggested that the equilibrium olivine has a starting high-T composition of $Fo_{90\text{-}89}$ and a margin composition of $Fo_{89\text{-}88}$. Similar core and margin compositions are described from Canadian kimberlites (Fedortchouk and Canil, 2004). Liquidus compositions between Fo_{90} and Fo_{88} conforms with liquidus olivine of kimberlite (s.s.). Note should be taken that the compositions of cores and margins of Majuagaa olivine (euhedral as well as anhedral) are very similar to compositions of olivines from the classic Wesselton kimberlite (Mitchell, 1973).

Compositions of olivine megacrysts and nodules overlap with the cores of the anhedral groundmass olivine. Only a single nodule has olivine with compositions similar to those of the cores of euhedral olivine grains. This appears to demonstrate that the anhedral groundmass grains are xenocrystic and that a dominant proportion of groundmass olivine is xenocrystic.

Ilmenite

Large rounded ilmenite megacrysts are common in the Majuagaa dyke. They show a small compositional range and have on average 56% ilmenite and 44% geikielite. The groundmass ilmenite has a much higher geikielite component (up to 70%). The ilmenite megacrysts are xenocrystic and contributed little to the groundmass of the dyke. The groundmass ilmenite conforms with ilmenite of kimberlite (s.s.).

Spinels

The groundmass of the Majuagaa dyke does not contain chromite. All spinels are poor in Cr, but rich in Mg. They belong to the ***magmatic trend 1*** and are Mg-rich Ti-magnetites. Some margins are quite rich in MgO. Such margins are known from spinels of calcite-kimberlites (Mitchell et al, 1999). The spinels of the Majuagaa dyke conform with compositions from kimberlites (s.s).

Phlogopite

Phlogopite is rare and is often found in small areas of late residual calcite-rich material. The phlogopite is pale or weakly greenish. The centres and the margins of the small grains are very similar in composition, except for BaO. The phlogopite is TiO2-, FeO- and Fe2O3-poor, but rich in Al2O3. No tetraferriphlogopite is observed. Margins of the groundmass grains show a strong increases in BaO, up to wt. 7.5%. Cores and margins all plot in the fields of groundmass phlogopites of kimberlites (s.s.) and the enrichment in Ba in the margins conforms with observations from archetypal kimberlites (Mitchell, 1995).

Bulk composition

Nineteen samples with small proportions of megacrysts and nodules have an average composition in the field of kimberlites. The average composition is relatively low in SiO2, but compares to, e.g., the Benfontein kimberlite. The trace element compositions conform with kimberlite. The REEs compare with classic kimberlites such as Wesselton and the spidergram shows a composition very similar to that of Namibian kimberlite. The bulk composition conforms with compositions of kimberlite (s.s.).

The bulk composition is a mixture of xenocrystic olivine and ilmenite and a melt. An accurate proportion of xenocrstic olivine is not at hand and the proportion of xenocrystic olivine has been estimate by assuming that the Ni content of the quite carbonatitic “carrier” melt was comparatively low (<200 ppm). Likewise the TiO_2 content is assumed to be low (<0.5%). Subtraction of 33% olivine (average of megacrystic olivine) and subtraction of a further 10% of megacrystic ilmenite results in a composition in agreement with the experimental melt compositions of Dalton and Presnall (1998). The estimated melt lies on the borderline between kimberlite and silico-carbonatite. Addition of xenocrystic olivine makes the bulk composition kimberlitic.

Discussion

The compositions of groundmass minerals and the absence of clinopyroxene conforms with the definition of kimberlite (s.s.). Based on the criteria in Mitchell (1995) and the classification scheme suggested by Tappe et al (2005) the Majuagaa dyke classifies as a kimberlite. Some may hesitate to accept this conclusion, as the groundmass is calcite-rich and poor in serpentine. The groundmass points towards carbonatitic rather that a CO_2-rich silicate melt.

It is clear that all types of olivine grains, irrespectively of their origin, can have margins in equilibrium with the melt. They are not surrounded by serpentine or altered to serpentine. It is suggested that the volatile component of the Majuagaa dyke had a high CO_2/H_2O ratio and that the low proportion of silicate (serpentine) in the groundmass is due to the growth of olivine margins rather than primary groundmass serpentine.

It is with reference to the spinel compositions and the calcite-rich nature of the groundmass concluded that the diamond-bearing Majuagaa dyke is a calcite-kimberlite, with characteristics referring to classic kimberlites such as Wesselton and Benfontein.

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A Greenland petrographic atlas of kimberlites and ultramafic lamprophyres

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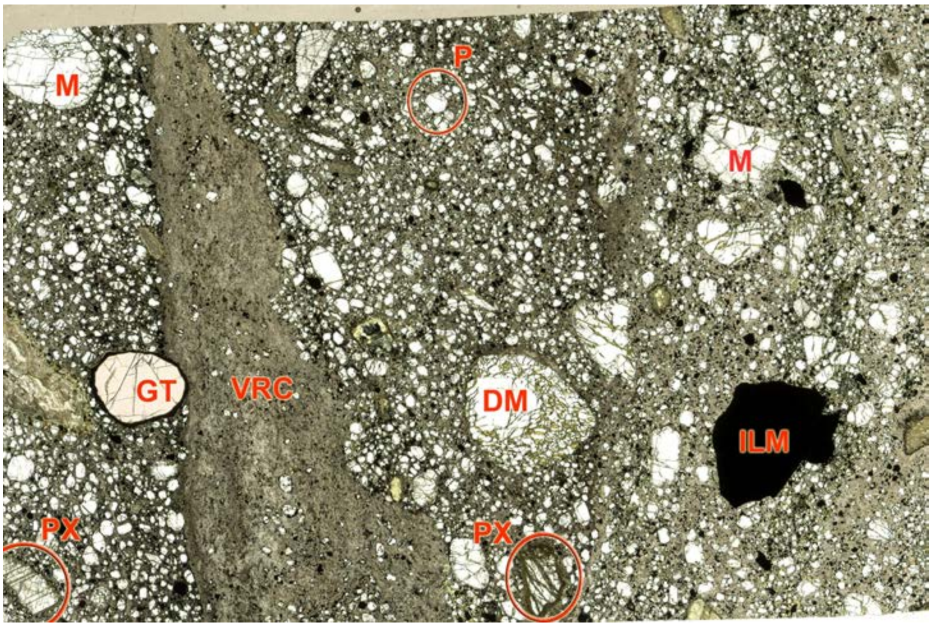
An introduction to the great diversity of kimberlites, ultramafic lamprophyres and lamproites in Greenland is proposed in the form of a petrographic atlas. The Atlas contains schematic information and thin sections of a range of alkaline dyke rocks from the collections of the GEUS archives.

An example of a page display from the proposed Atlas is introduced.



Locality number	2004KSE076			**Locality name**		Majuagaa						
Latitude	64,500		**Longitude**		-52,00			**Sample no.**		48642		
Groundmass	CAR	OL	PHL	GAR	ILM	SPI	CPX	OPX	PER	LEU	MEL	SER
	x	x	x		x	x		x	x			
Megacrysts		OL	PHL	GAR	ILM	SPI	CPX	OPX				
		x		x	x	x	x					
Xenoliths	Harzburgite		Lherzolite		Wehrlite		Dunite		Eclgite		Basement	
	x		x						x			
Diamonds	Tested +		Tested –		Not tested		Size (mm)		Carats			
	1						0,56		0,0001			
Remarks	Exceedingly rich in mantle xenoliths											

Assessment of diamond potential using kimberlitic indicator minerals: key principles and applications

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Introduction

Most of the common indicator minerals (i.e. garnet, Cr-spinel, Cr-diopside, picro-ilmenite, forsterite and enstatite) represent fragments of mantle material sampled and brought to surface by volcanic intrusions such as kimberlite. The type, abundance and composition of these minerals, recovered from surface sediment and kimberlite rock samples, provide critical information at several stages in diamond exploration programs. In particular, indicator mineral compositions provide a means of: 1) assessing regional diamond prospectivity; 2) identifying and locating primary diamond source rocks; and 3) evaluating the diamond potential of source rocks. This contribution focuses on the use of indicator mineral composition data to assess the diamond potential of kimberlites. The principles discussed are applicable to other deep-seated intrusives that have potential to sample the diamond stability field (e.g. olivine lamproites and group 2 kimberlites / orangeites) and may be used to assess the regional prospectivity of terrains in which kimberlites or related rocks occur.

The basic premise

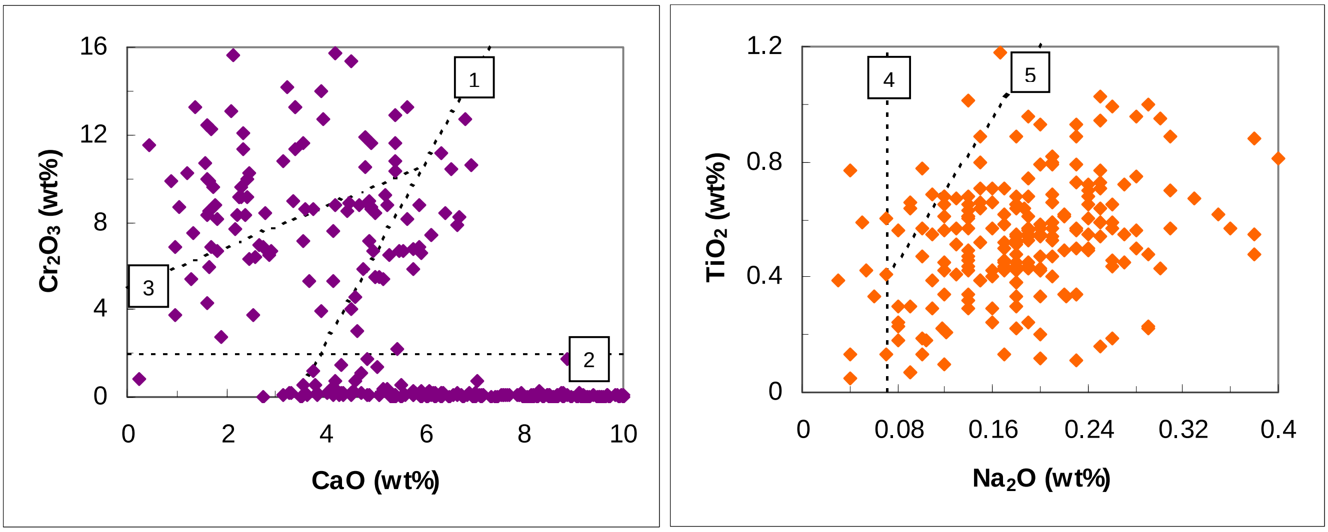
Most of our understanding of the link between indicator minerals and diamonds stems from studies of inclusions in diamonds as well as of diamond-bearing upper-mantle xenoliths from kimberlites. Such studies have defined the two well known diamond “parageneses”, i.e. sub-calcic garnet- and/or chromite-bearing harzburgite and high-pressure eclogite. In the mantle sample within kimberlite, these are primarily represented by specific garnet types – G10 and group 1 eclogitic garnets.

The key diagnostic compositional characteristics of diamond-inclusion (DI) garnets are illustrated in Figure 1. Approximately 85 % of all diamond inclusions of peridotitic garnet (>2 wt% Cr_2O_3) are sub-calcic, plotting to the left of the G10-G9 divide, as defined by Gurney (1984). These compositions correspond with those of garnets from mantle harzburgite (i.e. clinopyroxene-free peridotite) or dunite. If one considers that the proportion of harzburgite and dunite in average cratonic lithosphere, as represented by xenoliths and xenocrysts in kimberlites, only ranges up to approximately 15 %, the high proportion of peridotitic DI garnets with such compositions demonstrates a striking preferential association of diamond with this material. Peridotitic chromite inclusions in diamond define a similarly unique compositional range (at least for mantle-derived chromite) and are characterized by very high Cr and moderately high Mg contents. As in the case of G10 garnets, these chromite compositions are indicative of derivation from a peridotite with a specific bulk composition, i.e.

harzburgite or dunite. In contrast to the harzburgite / dunite association, diamonds occur in eclogite with a wide range of bulk compositions (Grütter and Quadling, 1999). However, eclogitic garnets associated with diamond (i.e. as diamond inclusions or in diamond-bearing eclogite xenoliths) are characterized by relatively high Na contents (McCandless and Gurney, 1989; Figure 1b), indicative of high pressures of equilibration. This also applies to relatively rare websteritic garnets included in diamond.

These observed direct relationships between certain indicator minerals and diamond are borne out in studies of xenocryst suites in kimberlites. In particular, as far as the authors are aware, there are no significantly diamondiferous kimberlites worldwide that do not contain one or more of these diamond-associated mineral types. This provides diamond explorers with a very powerful tool, i.e. it implies that the presence and amount of diamond-indicator minerals are directly related to the diamond content of their source rock. However, there are complexities and additional factors that need to be considered in order to ensure reliable predictions of diamond potential.

Figure 1. *Diagnostic composition plots of diamond inclusion garnets (from internal Mineral Services database of published data).* ***a)*** *Cr_2O_3 vs CaO plot of all garnets (n = 566) – dashed lines show the Gurney (1984) G10-G9 divide (1), the 2 wt% Cr2O3 cut-off (2) and*



the Cr-Ca graphite diamond constraint (Grütter et al,, 2004); ***b)*** *TiO_2 vs Na_2O plot of low-Cr (< 2 wt% Cr_2O_3), eclogitic garnet (n = 238) - dashed lines represent the 0.07 wt% Na_2O cut-off (4) and the approximate lower limit of the TiO_2-Na_2O compositional field defined by garnet megacrysts (5).*

When is a G10 not a diamond indicator?

The compositional criteria used to identify diamond-associated G10 garnets (or chromites) primarily reflect the bulk composition of the source rocks and a very strong association with carbon in the mantle, but do not do not indicate whether the garnets are derived from the diamond stability field or not. Recent studies have demonstrated that G10 garnets can be derived from shallow depths in the graphite stability field (e.g. Griffin *et al*., 1999). In addition, where hot geothermal gradients prevail, elevated temperatures can place deep, high-pressure mantle peridotite outside of the diamond stability field. In these instances, the presence of G10 garnets (or associated DI chromites) may not have any relationship to the diamond content of their kimberlite hosts. It is therefore critical to know the pressure-temperature conditions at which these minerals equilibrated.

Equilibration temperatures for peridotitic garnet can be determined directly by Ni thermometry (e.g. Ryan *et al.*, 1996) which requires measurement of Ni concentrations at trace levels. A less precise, but useful alternative approach has been developed based on Mn content (Grütter *et al*., 1999; Grütter *et al.,* 2004), which can be determined by high-quality electron microprobe analysis. Unfortunately, equilibration pressure cannot be determined reliably for single garnet grains. High-pressure G10 garnet can be broadly identified by relatively high Cr content and this has been used by Grütter *et al.* (2004) to provide a constraint on likely diamond-associated (G10D) grains (Figure 1a). However, the Cr content of garnet only provides an indication of the minimum pressure under which it is likely to have equilibrated. Thus, while high Cr contents in G10 garnets indicate a high-pressure origin, the reverse is not necessarily true (i.e. low-Cr garnets may be derived from high pressure if they were not in equilibrium with chromite). An alternative approach is therefore commonly required to confirm the likely proportion of G10 garnets derived from the diamond stability field.

Equilibration pressures for garnets can be determined indirectly by projection of the garnet temperature onto a known geothermal gradient (geotherm). The geotherm is most reliably determined using well established thermobarometers that are based on co-existing mineral pairs in xenoliths. However, these are commonly not available in the early stages of exploration or kimberlite evaluation and typically it is necessary to rely on single-grain thermobarometry techniques. The most reliable published method is the clinopyroxene thermobarometer of Nimis and Taylor (2000). An alternative approach, proposed by Ryan *et al*. (1996), permits estimation of the geotherm based only on peridotitic garnet compositions. This is a statistical approach (i.e. cannot determine pressures for individual grains and relies on garnet population characteristics and assumptions about co-existence of garnet with chromite) and, under typical cratonic conditions, significantly underestimates the geothermal gradient (Grütter and Sweeney, 2000). Nonetheless, in the absence of suitable pyroxene minerals, it can provide a useful indication of the likely geotherm. Where present, orthopyroxene provides a very useful qualitative indicator of the geothermal gradient.

The eclogite problem

It is not possible to calculate equilibration temperatures or pressures for single grains of eclogitic garnet. Inferences can be made on the likely P-T range for the eclogitic component of kimberlite xenocryst suites based on associated peridotitic minerals but this is an indirect and potentially unreliable approach. Thus the Na content of eglogitic garnet is the primary indicator of equilibration depths and likely association with diamond. However, high-Na garnet is also observed in graphite-bearing eclogite xenoliths (Grütter and Quadling, 1999) indicating that the relationship between Na content and diamond in eclogite is not straightforward. In addition, diamond-bearing eclogites with relatively low Na contents (i.e. below the 0.07 wt% threshold typical of diamond inclusion compositions) have been documented (Cookenboo *et al.*, 1997). These discrepancies do not negate the importance of eclogitic garnet in assessing diamond potential, but demonstrate that care needs to be taken in interpreting their compositions. Assessments of eclogitic diamond potential based on Na-Ti relationships need to be refined by consideration of bulk compositional factors that influence the relationship between Na and equilibration pressure.

Diamond inclusion chromites – some imposters

Diamond inclusion chromites are derived from highly depleted, high-pressure mantle peridotite. However, chromites of equivalent compositions can occur in other, non-diamond associated parageneses. In particular, chromite phenocrysts/microphenocrysts crystallizing from kimberlite, and certain non-kimberlitic chromites from mafic to ultra-mafic crustal rocks may have compositions that overlap with the DI chromite field. These "imposters" generally occur in association with other non-mantle chromites that display specific compositional trends. Thus they can generally be accounted for when evaluating large populations of chromites. However, it is important to be cognizant of these alternative possible sources of "DI type" chromites when interpreting data for individual grains or grains from small populations where such trends may not be evident.

The relationship between indicator mineral abundance and diamond content

In general, it can be assumed that the diamond content of a kimberlite is related to the concentration of diamond indicator minerals. This is broadly true and it is therefore critical to not only measure the composition of indicator minerals recovered from kimberlite, but also their abundance. In order to reliably interpret results, it is essential that procedures used to extract and analyse indicator minerals provide quantitative and representative abundance and composition data.

Reliable interpretation of indicator mineral abundance data in terms of diamond potential requires cognizance of two key factors:
Only the specific mineral types indicative of the presence of diamond count (i.e. G10 garnets and DI chromites from the diamond stability field, group 1 eclogitic garnets or Na-rich websteritic garnets). The abundance of other mantle mineral types is not relevant.
The relationship between the abundance of specific diamond indicator minerals and that of diamond is not constant and needs to be calibrated for different kimberlite fields and types.

Applications

Application of the above described principles will be illustrated with examples of indicator mineral datasets from Greenland and elsewhere.

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The North Atlantic alkaline rocks – probes for testing continuity of subcontinental lithospheric mantle

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It has been 35 years since Doig (1970) published his paper titled "An alkaline rock province linking Europe and North America", wherein he presented the North Atlantic Alkaline Igneous Province (NAAIP) extending over an area from eastern Canada to European Russia. Since that time a large body of age, petrological, geochemical and isotopic information has been acquired on NAAIP rocks allowing us to "image" compositional and mineralogical reservoirs in the subcontinental lithospheric mantle of the area. The main limitation of this method is that information is only available for those specific time slices when there was significant province-wide alkaline magma activity.

Three Mesoproterozoic alkaline intrusive fields, ca. 1200 Ma in age, are discussed here: Western Greenland, Kalix in N. Sweden and the Kuhmo (Finland) and Kostomuksha (Russia) area. Even though the rock type names used for these localities range from lamproite (Greenland) to ultramafic lamprophyre (Kalix) to K2L [Group II kimberlite-Lamproite hybrid](Kuhmo, Kostomuksha), there are, nevertheless, a number of similarities between these occurrences. These include: 1. Mineralogy – All of these rocks are Ti-phlogopite rich. 2. Major and trace element chemistry – these show clear similarities 3. Intrusive habit – nearly all occur as relatively narrow dikes with a dominant N-S orientation.

The Neoproterozoic alkaline intrusive fields, ca. 600 Ma in age, within the NAAIP are more numerous and include (from East to West): Kaavi-Kuopio Group I kimberlites in Eastern Finland, alnöites from the type locality of Alnö in Eastern Sweden, damtjernites of the Fen complex in Southern Norway, the West Greenland UMLs and kimberlites, the Aillikites from Aillik in Labrador and the Torngat UML in Labrador and Quebec. This group is more diverse, mineralogically and geochemically but still shows a number of similarities, particularly in terms of isotopic composition.

The use of alkaline magmas as mantle probes allows similarities and differences of the lithospheric mantle to be discerned, as well as secular variations. This information, coupled with the paleomagnetic plate reconstructions presented in Pesonen et al (this volume), provide significant tests for plausible craton correlations in the North Atlantic.

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Age, depth and composition of the W. Greenland lithospheric mantle root and implications for diamond prospecting

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Introduction

Alkaline magmatic activity across W. Greenland provides a record of lithosphere evolution over the last 500 Ma. Kimberlite magmatism in particular has erupted an exceptional inventory of mantle xenoliths allowing a detailed look at the lithospheric root beneath both the exposed craton and the re-worked Archean terrane of the Nagssugtoqidian, 500 Ma ago. This is complimented by less numerous xenoliths erupted during Tertiary times further North and East, such that we can begin to understand the possible impact of a major plume on the ancient lithospheric root. We are undertaking a major study aimed at constraining the age, depth and composition of the lithospheric mantle root at the time of kimberlite eruption, for the cratonic and circum-cratonic regions. This should enable us to provide primary information on the likely diamond potential of the W. Greenland lithospheric mantle.

Petrography

Peridotites are the dominant lithology in the xenolith suite studied by us. Despite detailed field investigations no eclogites were encountered in xenoliths from the reworked Archean terrane or from the Archean terrance immediately South of the craton margin. Eclogite has previously been reported from a dyke S. of the Sukkertoppen ice cap (Jensen et al., 2004). Detailed petrography has yet to be completed but field and petrographical observations indicate that the following generalisation can be made from initial data. Samples from within the re-worked Archean terrane more commonly have diopside plus garnet, i.e. are more lherzolitic whereas highly depleted harzburgites and dunitic lithologies are prevalent amongst xenoliths erupted through the undisturbed Archean craton. We note that an abundance of dunite is a feature of the peridotite xenolith suite from Weidemann Fjord studied by Bernstein et al (1998). Modal orthopyroxene is mostly in the range 0 to 20%, i.e., significantly less than values observed for Kaapvaal craton peridotites.

Bulk compositions

20 peridotites have so far been analysed for bulk composition. Samples selected are as far as possible taken from >500 g coarse crush to ensure representative sampling an accurate calculation of modes. The range in depletion indicated from modal mineralogy is reflected in the major element compositions of the W. Greenland peridotites. Some dunitic samples clearly have very low Al and Ca, as expected. Harzburgites are also depleted in CaO (most <1 wt %) and Al_2O_3 (most < 1wt%) and on this basis are as depleted as the those from Wiedemann Fjord and cratonic peridotites from the Kaapvaal craton.

Mg/Si values are high and indicate, along with modal analysis that the W. Greenland mantle has not experienced significant SiO_2 enrichment, a feature also observed by Bernstein et al. The low bulk SiO_2 contents suggest particularly orthopyroxene poor protoliths. This contributes to growing evidence that the Kaapvaal cratonic lithosphere is the exception rather than the rule in terms of craton lithosphere bulk compositions and evolution. FeO contents of some W. Greenland peridotites are in the range shown by cratonic peridotites but some extend to considerably higher values (> 9wt%) and, combined with elevated TiO_2 are indicative of metasomatic enrichment. This complicates the interpretation of major elements in terms of likely depths and environment of melting. Compatible trace element analyses will be undertaken to try to resolve this issue.

Re-Os isotopes

A selection of dunitic, harzburgitic and lherzolitic lithologies have been analysed for Re-Os isotopes. Some dunites have extremely low osmium contents, possibly due to reaction with melt dissolving osmium-rich phases. Harzburgites and lherzolites have Os contents more typical of melt residues and have unradiogenic Os isotope compositions. Os isotope ratios of peridotites from dykes erupted through the Archean basement give Archean model melt depletion ages (oldest T_{RD} age currently 3 Gyr). No clear age variation with depth is evident so far. Analysis of peridotites from the re-worked Archean terrane will be reported.

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Mantle stratigraphy of the Karelian craton – implications for diamond prospecting

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Mantle-derived xenolith and xenocryst studies indicate that the subcontinental lithospheric mantle of the Karelian craton shows considerable variation from margin to core. At the margin, the mantle is stratified into at least three distinct layers labeled A, B, and C. Shallow *layer A* (at ~60–110 km depth) has a knife-sharp lower contact against layer B indicative of a shear zone implying episodic construction of the SCLM. Layer A peridotites have "ultradepleted" arc mantle -type compositions, and have been metasomatised by radiogenic $^{187}Os/^{188}Os$, presumably from slab-derived fluids.

Xenoliths derived from the middle *layer B* (at ~110–180 km depth), which is the main source of harzburgitic garnets (G10) in Finnish kimberlites, are characterised by an unradiogenic Os isotopic composition. $^{187}Os/^{188}Os$ shows a good correlation with indices of partial melting implying an age of ~3.3. Ga for melt extraction. This age corresponds with the oldest formation ages of the overlying crust, suggesting that layer B represents the unmodified SCLM stabilised during the Paleoarchean.

The underlying *layer C* (at 180–250 km depth) is the main source of Ti-rich pyropes of megacrystic composition, which however, lacks G10 pyropes. The osmium isotopic composition of the layer C xenoliths is more radiogenic compared to layer B, yielding only Proterozoic T_{RD} ages. Layer C is interpreted to represent a melt metasomatised equivalent to layer B. This metasomatism most likely occurred at c. 2.0 Ga when the present craton margin formed following break-up of the proto-craton.

The mantle stratigraphy of the craton core, in the area of Kuhmo 150 km to the NE, shows less variation. Layer A is absent. Layer B begins with the lowest temperature pyropes at an inferred depth of 70 km and continues to a depth of about 250 km showing a relatively homogenous distribution of harzburgite and lherzolite pyropes throughout. Differences in craton core layer B compared to craton edge layer B include: 1. Wehrlite garnet is very rare, as is chrome diopside. 2. The G10 to G9 ratio in both exploration samples and hardrock sources is considerably higher implying core layer B is relatively harzburgite-rich. Thus far there is only a weak indication of a G10 pyrope-free Layer C. However, Ti-rich megacryst composition pyropes are very common, so evidence for a deep 250-300 km Layer C may become available with further sampling.

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Kimberlites and lamproites in continental reconstructions – implications for diamond prospecting

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Kimberlitic and lamproitic rocks are well known in every Precambrian Shield. The ages of kimberlite/lamproite dykes vary from Mesoproterozoic to Cretaceous. Since all hardrock economic diamond deposits occur in these rock types, it is worthwhile, from the prospecting point of view, to determine whether kimberlite/lamproite occurrences form either continuous belts or distinct provinces at various times in supercontinent assemblages. For this purpose we initiated a new project where kimberlites and lamproites will be compiled into a database, which allows the continuities of kimberlite/lamproite belts to be studied in former supercontinents. In the testing stage of the project we focus on two Precambrian age intervals of kimberlite/lamproite magmatism: the 580-600 Ma interval and the 1200 Ma activity, respectively. In the database we compile the ages of kimberlite/lamproite dyke swarms (and pipes), their widths and orientations, their distances to known orogenic belts as well as their geochemical (particularly trace element) and isotopic signatures. Using paleomagnetic data of coeval rocks (such as mafic dyke swarms and other intrusions and occasionally the kimberlite dykes themselves) we first make the continental reconstructions using the techniques outlined in Pesonen et al. (2003). We will then plot the kimberlite/lamproite dykes and pipes onto these supercontinent reconstructions to delineate possible continuous belts or provinces. The paleomagnetically made global reconstructions of continents with kimberlite/lamproite occurrences at 600 Ma and 1200 Ma will be presented and compared with those made on traditional geological grounds. The implications for diamond prospecting will be discussed.

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Magnetic signatures of circular geological features with special emphasis on kimberlite prospecting

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1. Introduction

The magnetic anomaly patterns of idealistic 3-dimensional geological structures are investigated in an aim to find observable diagnostic features and to identify the type of structure from the magnetic data. The analyzed structures - kimberlite pipe, kaolin deposit, gabbroic intrusion, and meteorite impact structure - may all have circular or nearly circular plan view. Because their shapes in vertical plans and their physical properties are different, they produce specific residual geophysical anomalies. The diagnostic features, as shape of the anomaly, magnitude, amplitude, and derivatives, allow making first approaches in determination of the source body based on the magnetic map.

2. Methods

Four hypothetical models, one for every particular geological case, were created. All the models consist of several vertical and symmetrical prism-like bodies with 16 corner points on a plan view. To compare the modeling results, each structure has a diameter of 1 km, i.e., the uppermost prism is always 1 km in diameter. The thickness, horizontal extent, and physical properties of the prisms are different for every model. For comparison purposes, the natural remanent magnetization (NRM) always has the direction that corresponds to an age of 500 Ma at the Fennoscandian Shield. The magnetic anomalies for each case are calculated for both polarity options of this 500 Ma remanence vector, hereafter called normal and reversed polarity.

The background rock has a magnetic susceptibility of 3300×10^{-6} SI, typical to the granite-gneiss basement in Finland (Puranen, 1989). The induced magnetic field corresponds to that of a central location of Fennoscandia and is taken from Pesonen et al. (1994). The magnetic anomalies of these four bodies were calculated over a 2 $\times$ 2 km area using the ModelVision Software Package by Encom Technology Pty Limited, Australia (1995).

We defined **kimberlite** as a deep undeformed carrot-shaped body (Fig. 1), which has obtained a strong and homogeneous thermal magnetization during the fast cooling at 500 Ma. We didn't consider post-intrusion changes of the magnetic properties (oxidation, weathering, metamorphism etc.). The model, for calculation purposes, contains 8 vertical prisms, which have different thickness and diameter. The lowermost prism extends to the depth of

5 km. All prisms possess similar magnetic properties, derived from Korhonen and Kivekäs (1997), as mean values of kimberlites in the central Baltic Shield.

In the model of **kaolin**, the low magnetizations are assigned to a lens-like body that extends to the depth of 180 m (Fig. 2). We assumed that the remanent magnetization is of chemical origin, produced by the weathering of the underlying basement. The **gabbro** model has lens-like shape with a maximum diameter of 1250 m in a depth of 250 - 300 m (Fig. 3). The vertical extent is 700 m. All the prisms possess similar magnetic properties (Table 1), derived from Korhonen et al. (1993), whereas the NRM is of thermal origin. To describe the magnetic field above the **simple impact** structure two units, which are different in their magnetic properties, were created. The uppermost 140 m thick unit simulates crater filling post-impact sediments and possesses low magnetization (Fig. 4). Another unit is the 300 m thick impact breccia lens, located around and below the sediments. Due to the shock effects, the magnetization of the breccias is usually higher than in sediments, and the NRM is dominating (e.g. Iso-Naakkima, Finland; Järvelä et al., 1995) over induced magnetization (Q>1).

3. Results

Magnetic sources in the upper part of the crust produce anomalies (A), which depend on depth (h) of the source structure, its orientation (O), shape (S) and volume (V):

$$A = (1/h)^3 \times \Delta M \times F(O, S, V),$$

where ΔM is magnetization contrast of the source body and its host rock and is calculated as a vector sum of the induced and remanent magnetization. Thus, the amplitude of a magnetic anomaly decreases rapidly in 3rd power with depth thus reducing the depth and height sensitivity of magnetic methods. The detectable magnetic sources are confined to the uppermost few kilometers of the crust (Henkel and Reimold, 1997). Moreover, vector nature of the magnetization will produce complex magnetic anomalies, which have both positive and negative parts. Due to the very steep (72 - 77°) inclination and moderate declination (2-12°; Pesonen et al., 1994) of the Earth's magnetic field, highly magnetic bodies at the Fennoscandian Shield produce intensive positive anomalies followed by a negative side on the northern edge. The anomalous picture is overturned if K is negative, i.e. the magnetization of background is higher that those of the anomalous body, or the highly magnetic source body possesses the reversed polarity.

The circular positive magnetic anomaly, due to a normally polarized kimberlite pipe with dimensions and physical properties given in Fig. 1, reaches the maximum value of 580 nT. Due to the eastwards directed NRM, acquired at 500 Ma, the central maximum is shifted slightly to south-east. The narrow negative ring, most intensive in the northern side of the structure surrounds the positive part of the anomaly. The vertical and horizontal gradients (Fig. 1c) show great variations at the edges of the model, and reach values of several thousands $nTkm^{-1}$. In the case of reversed polarity of the NRM, the magnetic anomaly of kimberlite shows minimum of -260 nT in its central part, shifted sligthly to north-west from the center. The gradients are up to 2300 $nTkm^{-1}$, which are more than 2 times less than in the case of normal polarity.

Compared to other modeled structures, the residual magnetic anomalies over the kimberlite bodies are most similar to that of the gabbroic intrusions showing the most intensive anomalies up to thousands of nT (Fig. 3). Due to high magnetization, their anomalies are positive in the case of normally polarized NRM, and vice versa in the case of reversed magnetization. The amplitudes of the anomalies are much higher in the normal polarity case. In a case the magnitude of the NRM is approximately equal and oppositely directed to the induced magnetization, the resulting magnetization is zero and the source is invisible in the magnetic data.

The magnetic anomalies of the meteorite impact structure (Fig. 4) and kaolin deposit (Fig. 2) may be similar to each other in amplitude, but most likely different from those of kimberlite and gabbroic intrusion. They both exhibit weak magnetic amplitudes. Kaolin deposit produces negative anomalies in both normal and reversed cases, whereas impact structure has a negative magnetic anomaly in the case of normal, and positive in the case of reversed polarity of the NRM.

4. Acknowledgements

We thank Olli Sarapää, Petri Peltonen, Matti Tyni and Seppo Elo (all at Geological Survey of Finland) for helpful discussions. The research was supported by VMY, Partek Oy, and the Estonian Science Foundation (grant #5500).

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Figure 1 – 4:

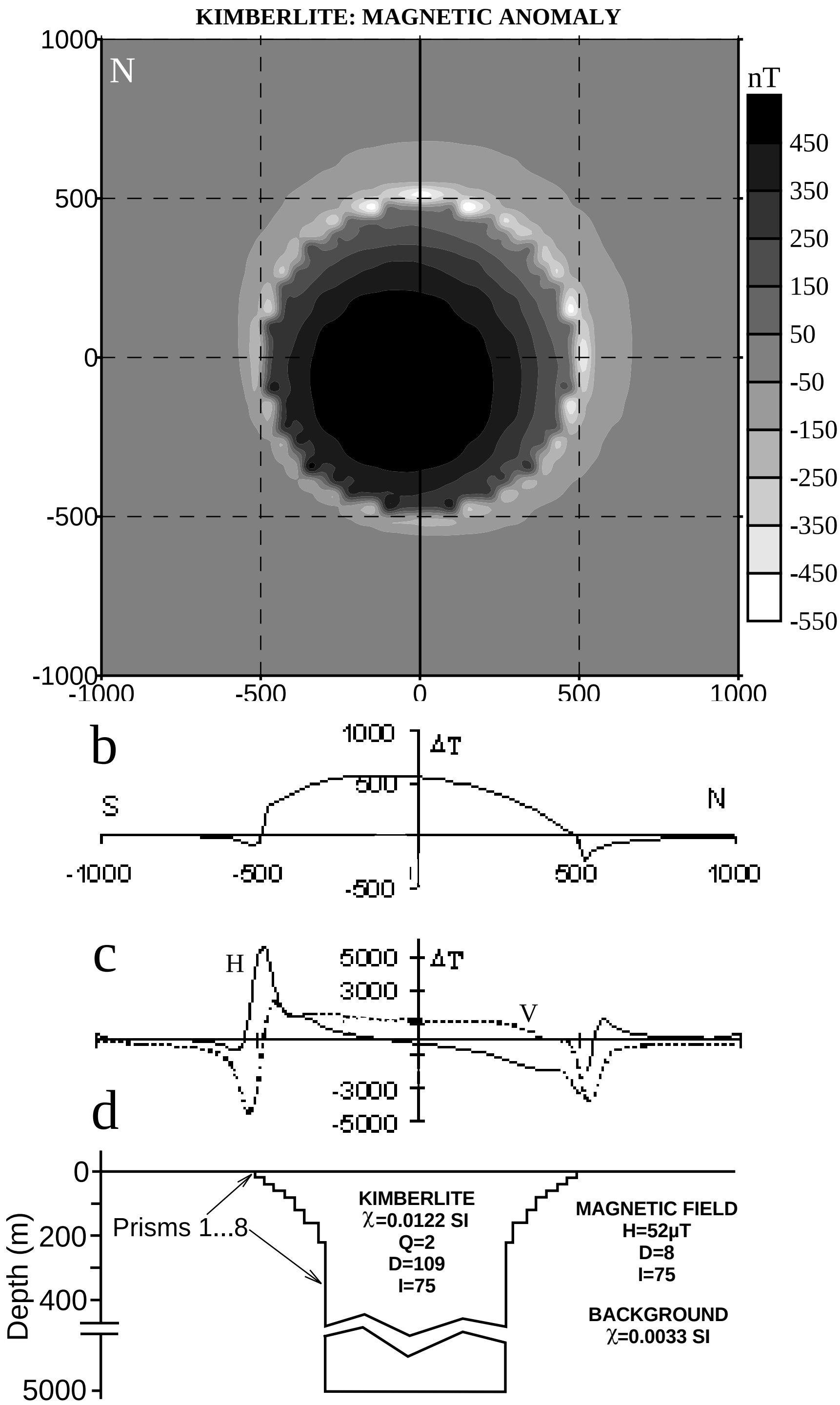

Figure 1. *(a) plan view of the magnetic anomaly (total intensity, nT) of kimberlite pipe at the normal magnetization (N). (b) S-N profile of the magnetic anomaly (nT) across the model. (c) South-north profile of the first vertical (V) and horizontal (H) gradient (nT/km) of the magnetic anomaly of kimberlite at the normal magnetization. (d) The geophysical model of kimberlite producing the calculated map (a) and profiles (b and c). Model consists of 8 polygonal vertical prisms with different thickness but homogeneous magnetic properties (χ = magnetic susceptibility; Q = Koenigsberger ratio; D = declination; I = inclination; H = magnetic field).*

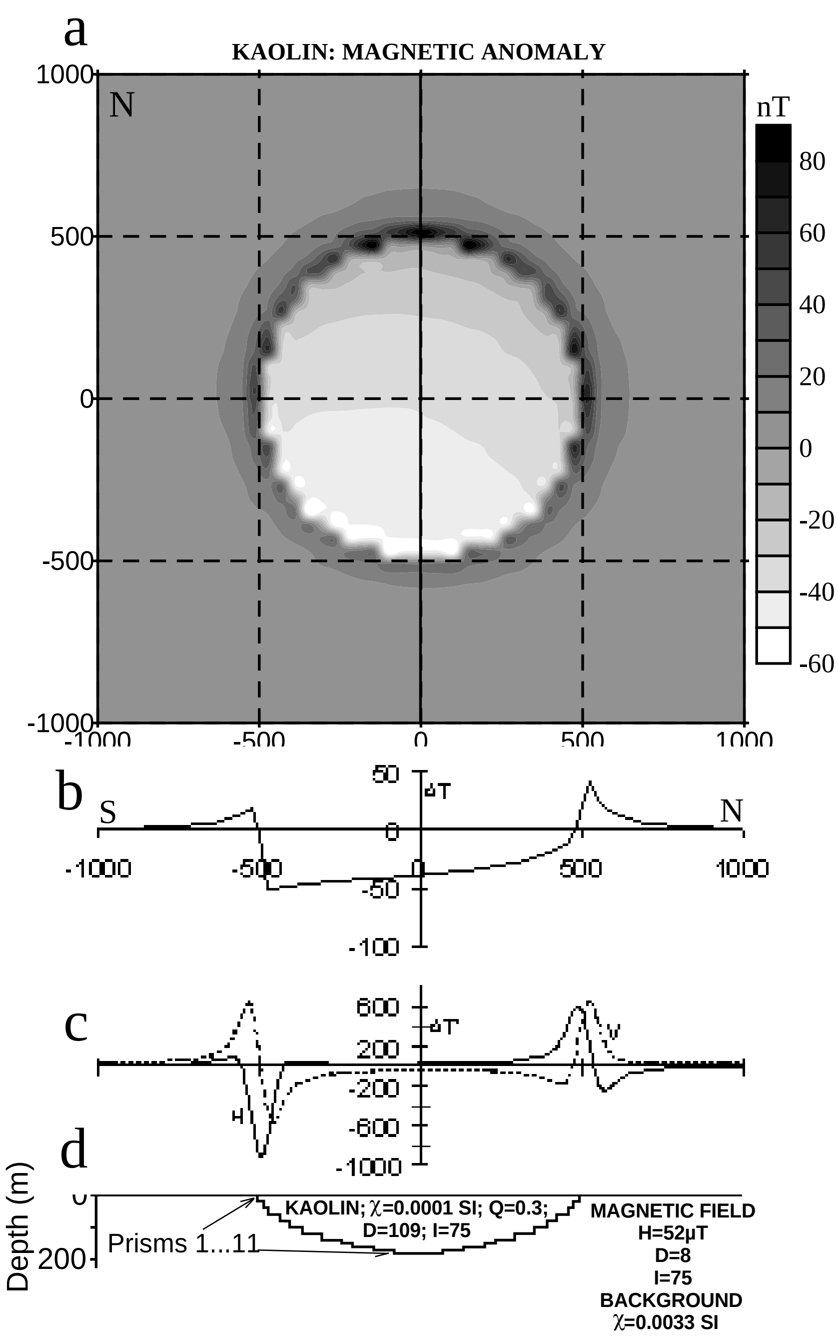

Figure 2. *(a) plan view of the magnetic anomaly (total intensity, nT) of kaolin deposit at the normal magnetization (N). (b) S-N profile of the magnetic anomaly (nT) across the model. (c) South-north profile of the first vertical (V) and horizontal (H) gradient (nT/km) of the magnetic anomaly of kaolin at the normal magnetization. (d) The geophysical model of kaolin producing the calculated map (a) and profiles (b and c). Model consists of 8 polygonal vertical prisms with different thickness but homogeneous magnetic properties (χ = magnetic susceptibility; Q = Koenigsberger ratio; D = declination; I = inclination; H = magnetic field).*

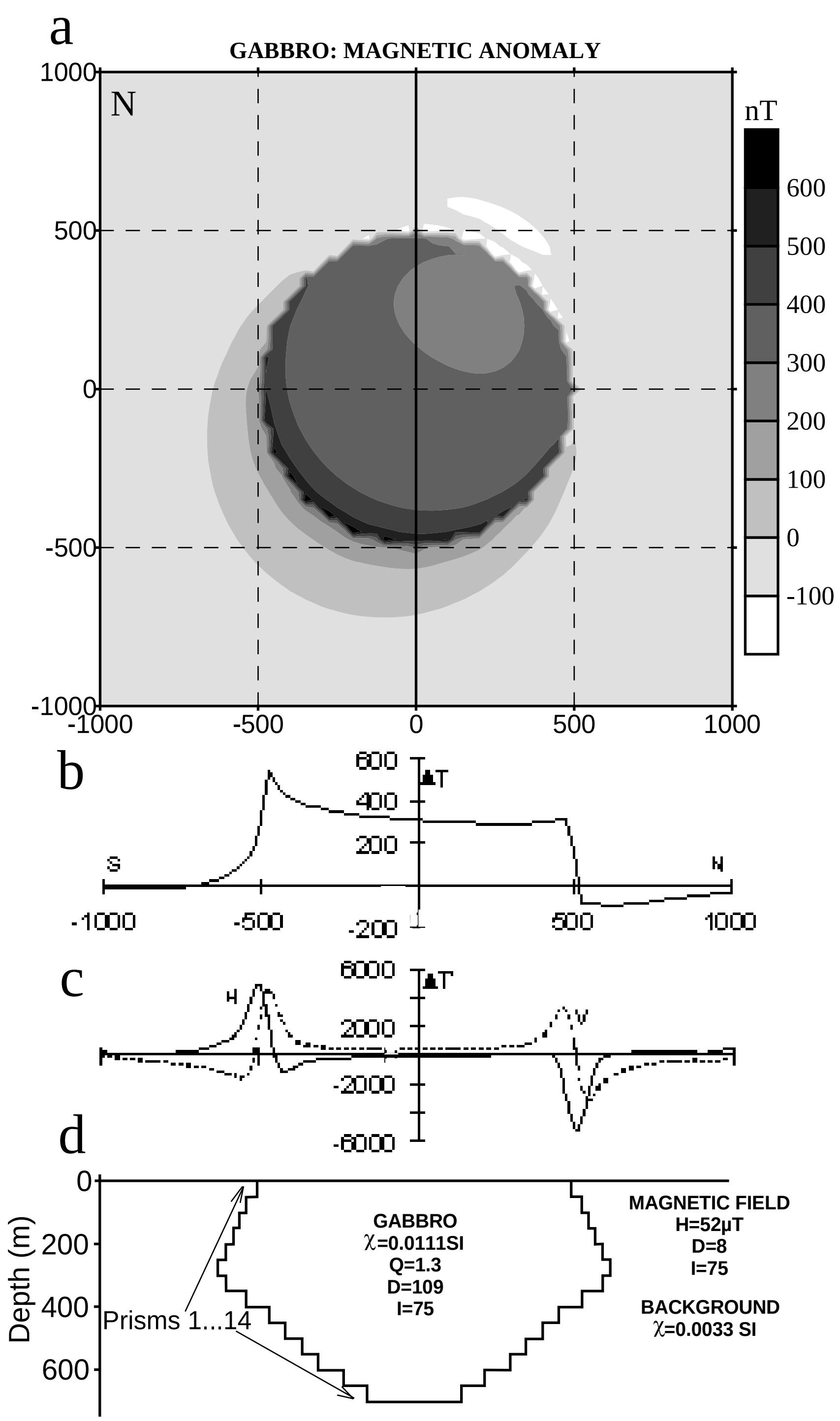

Figure 3. *(a) plan view of the magnetic anomaly (total intensity, nT) of gabbro at the normal magnetization (N). (b) S-N profile of the magnetic anomaly (nT) across the model. (c) South-north profile of the first vertical (V) and horizontal (H) gradient (nT/km) of the magnetic anomaly of gabbro at the normal magnetization. (d) The geophysical model of gabbro producing the calculated map (a) and profiles (b and c). Model consists of 14 polygonal vertical prisms with thickness of 50 m each but homogeneous magnetic properties (χ = magnetic susceptibility; Q = Koenigsberger ratio; D = declination; I = inclination; H = magnetic field).*

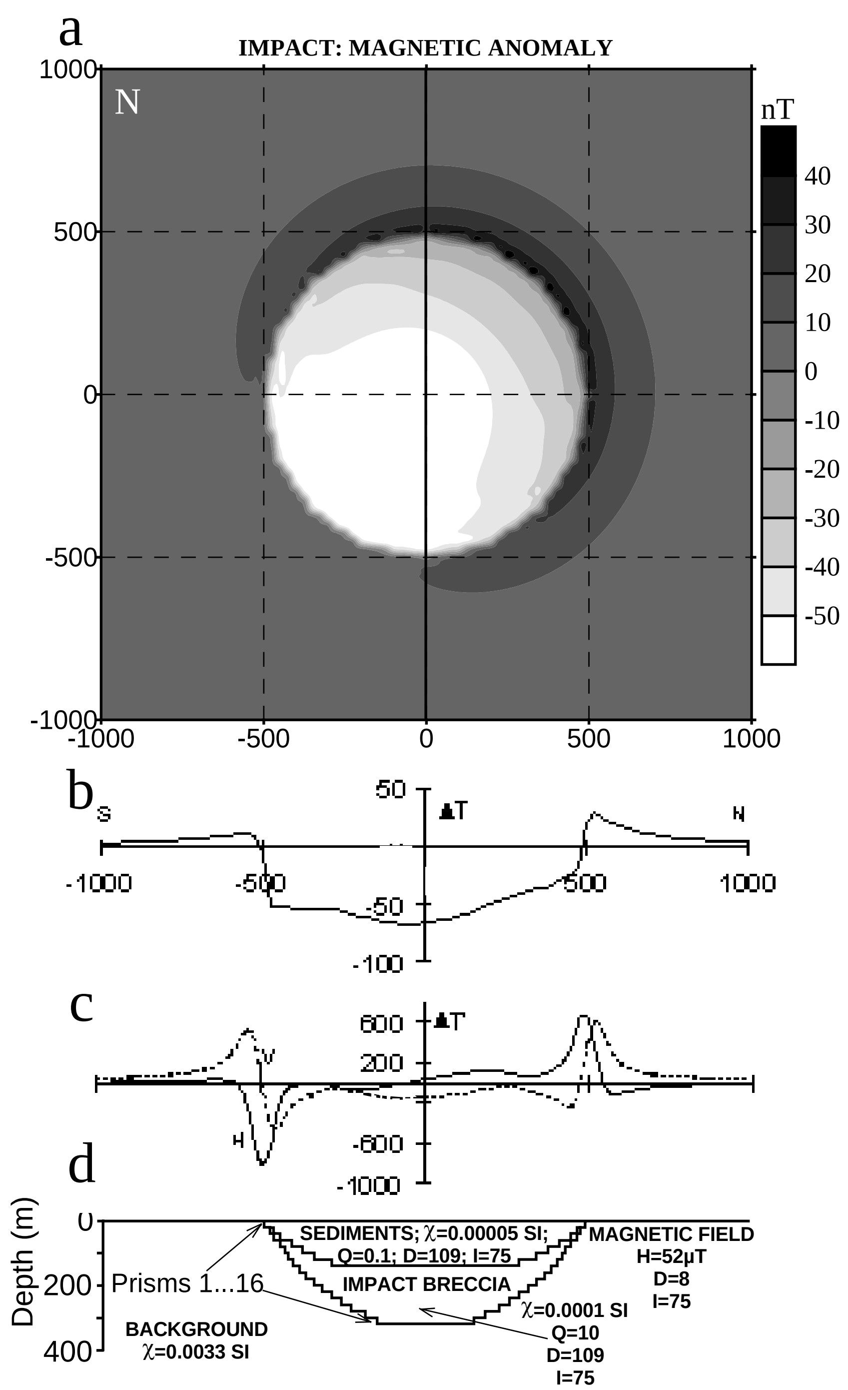

Figure 4. *(a) plan view of the magnetic anomaly (total intensity, nT) of impact structure at the normal magnetization (N). (b) S-N profile of the magnetic anomaly (nT) across the model. (c) South-north profile of the first vertical (V) and horizontal (H) gradient (nT/km) of the magnetic anomaly of the impact structure at the normal magnetization. (d) The geophysical model of the structure producing the calculated map (a) and profiles (b and c). Model consists of 7 polygonal vertical prisms of sediments and 16 prisms for breccias with thickness of 20 m each (χ = magnetic susceptibility; Q = Koenigsberger ratio; D = declination; I = inclination; H = magnetic field).*

Application of geophysical methods to diamond exploration in Greenland – experiences and data review

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Introduction

Geophysics has been an integral part of the methods used in the search for kimberlites in Greenland. The geophysical data are valuable both with respect to the general understanding of gross structures of the lithosphere and with respect to the direct search for and mapping of kimberlites.

In summary, magnetic data are found to be most valuable, whereas detailed electromagnetic data have so far not proved very useful in the search for kimberlites in Greenland. This presentation focus on the magnetic data.

Available data

Regional airborne magnetic surveys
Regional magnetic survey data covers the entire ice-free part of South and Central West Greenland. The regional magnetic data set (Figure 1) is produced by merging the data from different regional aeromagnetic surveys collected in the Airborne Geophysical Survey programme during the years 1992–2001 financed jointly by the Geological Survey of Denmark and Greenland (GEUS) and the Bureau of Minerals and Petroleum the (BMP). The line spacing for these surveys is 500 m and the nominal sensor altitude above ground is 300 m.

Detailed airborne magnetic and electromagnetic surveys
Most of the detailed airborne surveys include combined electromagnetic and magnetic measurements. The electromagnetic measurements have mainly been carried out with the frequency domain Dighem V system, but one of the larger surveys was done with the transient electromagnetic GEOTEM system.

The coverage with detailed aeromagnetic survey data is shown by the black polygons in Figure 1. The survey data originate from the AEM Greenland 1995 & 1996 projects financed by the Bureau of Minerals and Petroleum (BMP) and from projects carried out by prospecting companies. The data from the surveys carried out by the prospecting companies have been delivered to the BMP as part of the mandatory reporting by licensees. The data are made publicly available after termination of the license agreement within which the data were collected. Note that the surveys displayed in Figure 1 were only partly carried out in relation to prospecting for kimberlites. Typical line spacing of the detailed surveys is 200 m and nominal sensor altitude above ground is 45 m.

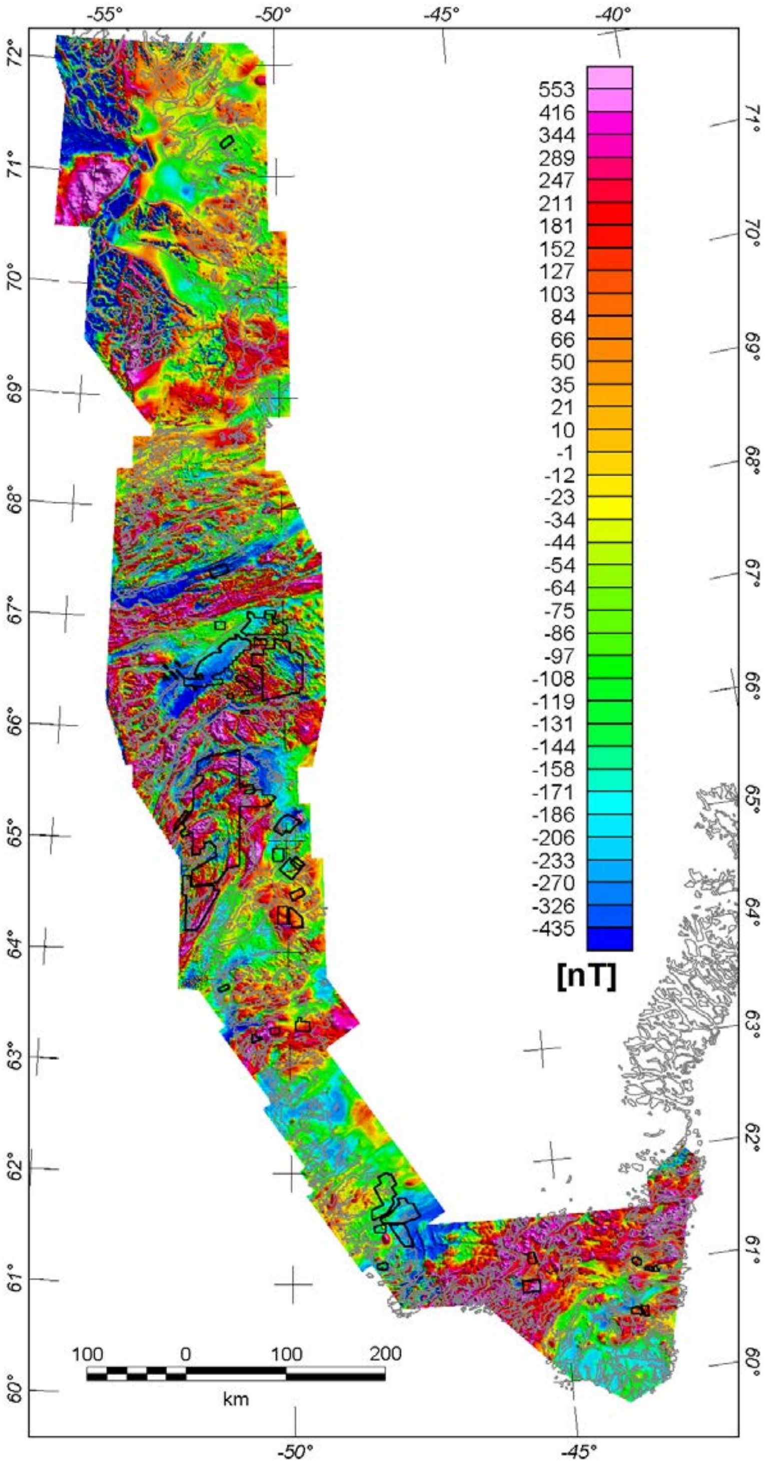

Figure 1. *The coverage of regional magnetic field data is shown by the measured total field anomaly. Areas covered by detailed surveys are outlines by the black polygons.*

Ground magnetic surveys

Ground magnetic profiling has been carried out by GEUS at selected sites during field campaigns in 2002, 2003 and 2004. The magnetic profiles were made by using a GSM858 caesium-vapour magnetic gradiometer manufactured by Geometrics Inc. that measures the magnetic field intensity with two sensors. A GSM856 proton magnetometer was used for recordings of diurnal magnetic variations at a base station placed within distances of a few km from the profiles. The vertical gradient option for the GSM858 instrument with a top and bottom sensor mounted on a vertical rod was used during the measurements. Recordings of the magnetic field are made with a sampling frequency of 10 Hz while walking along the profiles. A 10 Hz sampling corresponds approximately to 10 cm sampling distance. The bottom and top sensors were approximately 0.5 m and 1.5 above the ground respectively.

Prospecting companies have also carried out ground profiling or made grid surveys with measurements of the total field, although with a lower resolution than the GSM858 surveys.

Results from data processing and interpretations

Crustal domains and large-scale lineaments from regional and detailed aeromagnetic data

Large-scale lineaments have been proposed as a guide to kimberlite emplacement. The magnetic field data from Greenland contain numerous large-scale features of which some can be traced for several hundreds of kilometres. Some of the larger linear features are shown in Figure 2. Most of the linear features defined by magnetic lows are most likely associated with faults or shear zones, where magnetite has been destroyed by oxidation. Valleys associated with fracture zones often contribute significantly to the anomalous field and the topographic effects are in some cases very significant. Dykes, mainly dolerites, often cause the linear features defined by positive anomalies. The lineaments can be viewed as elongated anomalies that are superimposed on the background of regional anomalies. In most cases, it is evident from the shape of the background magnetic anomalies that only minor lateral displacements are associated with the supposed fault and shear zones.

Some coincidence between major linear features in the magnetic field and kimberlite occurrences is seen, but no clear correlation is evident. The kimberlite dykes located south of Maniitsoq Ice Cap are in most cases oriented N80°E, but this direction is only observed for two of the larger lineaments (marked a-A and b-B in Figure 2), and for numerous dolerite dykes that crosses the boundary of the Inland Ice between latitudes 65°15’ and 65°45’. It is noticeable that the kimberlite dykes south of Maniitsoq Ice Cap are located in an area with closely spaced lineaments. A clear correlation between lineaments and kimberlite occurrences is seen in the area around Sarfartoq. Figure 3 shows an example of linear magnetic anomalies from the area around W–E oriented Sarfartoq valley. The topographic low is associated with a low in the magnetic field, but superimposed on that is a positive anomaly that extends minimum 16 km in the valley. The positive anomaly is caused by a dyke of ultramafic composition.

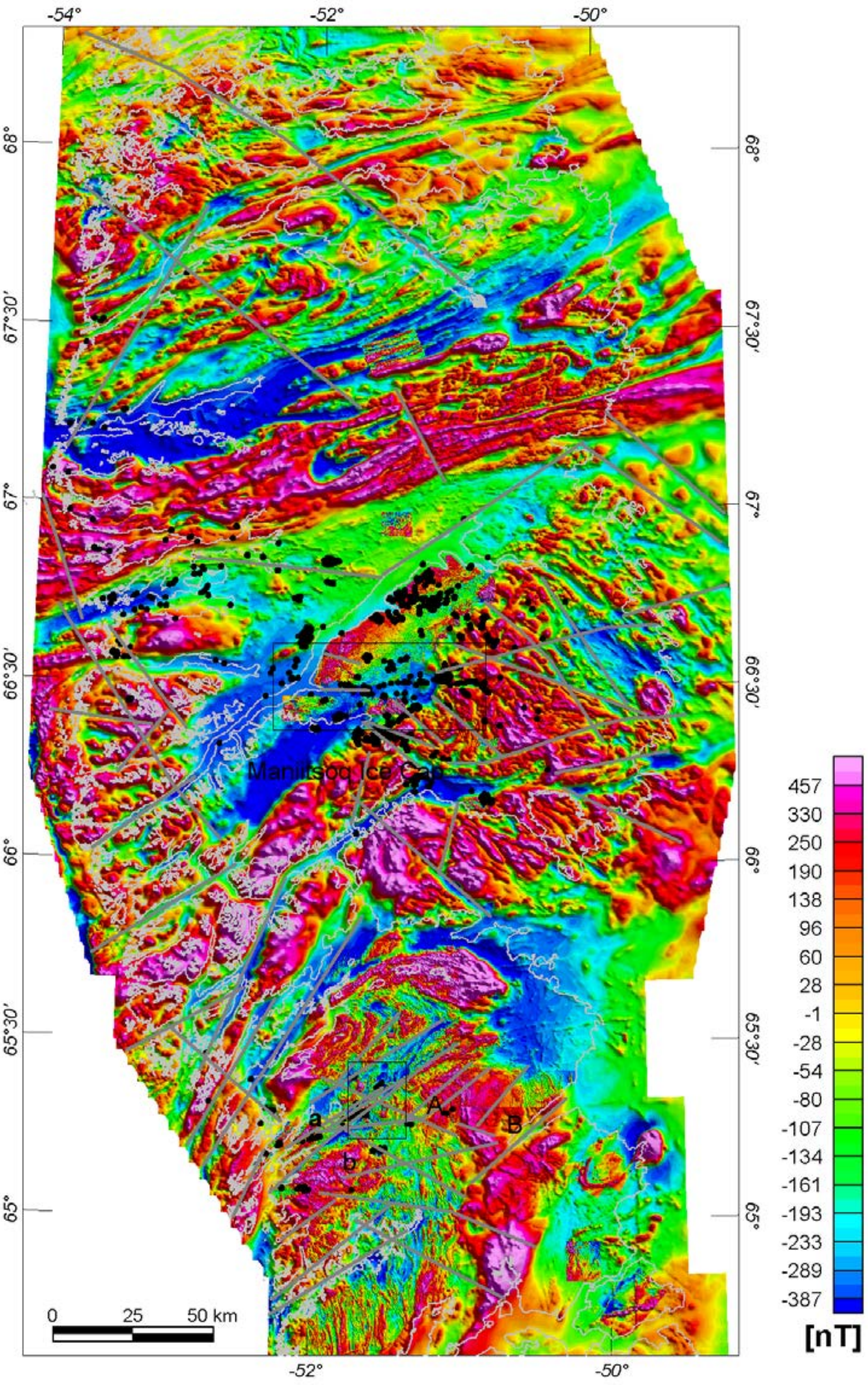

Figure 2. *Magnetic total field anomaly with some of the major linear features (grey lines). Kimberlite occurrences are marked by black dots. The magnetic total field data are from both regional and detailed surveys. The rectangles in black colour outlines the areas shown in Figures 3 and 4.*

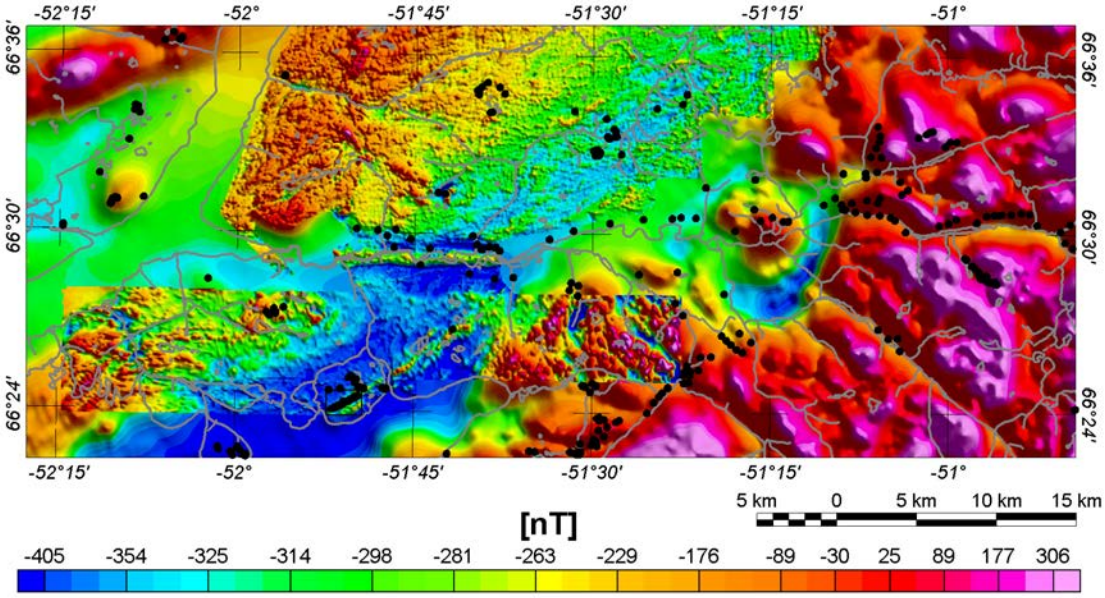

Figure 3. *Magnetic total field anomaly in the area around the Sarfartoq Valley. Black dots marks kimberlite occurrences. The magnetic data are from regional and detailed airborne surveys. The rectangle in black colour outlines the area shown in Figures 5 and 6.*

Small-scale lineaments detailed magnetic data

In addition to the large-scale structures discussed above, the detailed magnetic survey data contain significant amounts of structural information on a smaller scale. An automatic procedure has been developed that extracts linear features based on flight line data. The procedure identifies local minima and maxima in the flight line data, and evaluates the similarity of the field variation across flight lines along line segments defined by locations of extremum values on adjacent flight lines. Thus, the term *lines segment* describes here a connection between points on two adjacent *flight lines*. A standard root mean square (RMS) function is used as a measure for the deviation between the field along the line segments. The line segments are concatenated into lineaments by mean of RMS values in conjunction with criteria for maximising the number of points on a lineament and minimising the angle difference between connecting line segments. The procedure provides an objective determination of lineaments and is not subjected to the artefacts that often are produced from levelling, interpolation and gridding. However, the result depends on the flight line directions, because magnetic anomalies elongated along a flight line direction will not have well-defined extremum values. Threshold values for both anomaly amplitude and width are used in the selection of extremum points.

Figure 4 shows an example for an area south of Maniitsoq Ice Cap (the rectangle shown in Figure 2 outlines the area) Locations of minima and maxima are shown by dot in light blue and red colour respectively. Corresponding lineaments that fulfil the selection criteria are shown as lines in blue and cyan colour. Kimberlite occurrences are shown by green dots. A system of kimberlite dykes with mean orientation N°80E is located at latitude 65°18'. The thickness of the kimberlite dykes is of the order of 1 m, which is insufficient to produce a detectable anomaly in the airborne data measured at an altitude of 45 m above ground. The same orientation as for the kimberlite dykes can be seen in the preferred orientations of the magnetic anomalies. Another prominent orientation of the magnetic anomalies are along N°45E and some lineaments are oriented approximately N-S. The results indicate that the intrusion of the kimberlite dykes was controlled by a system of N°80E structures that are seen in the entire area.

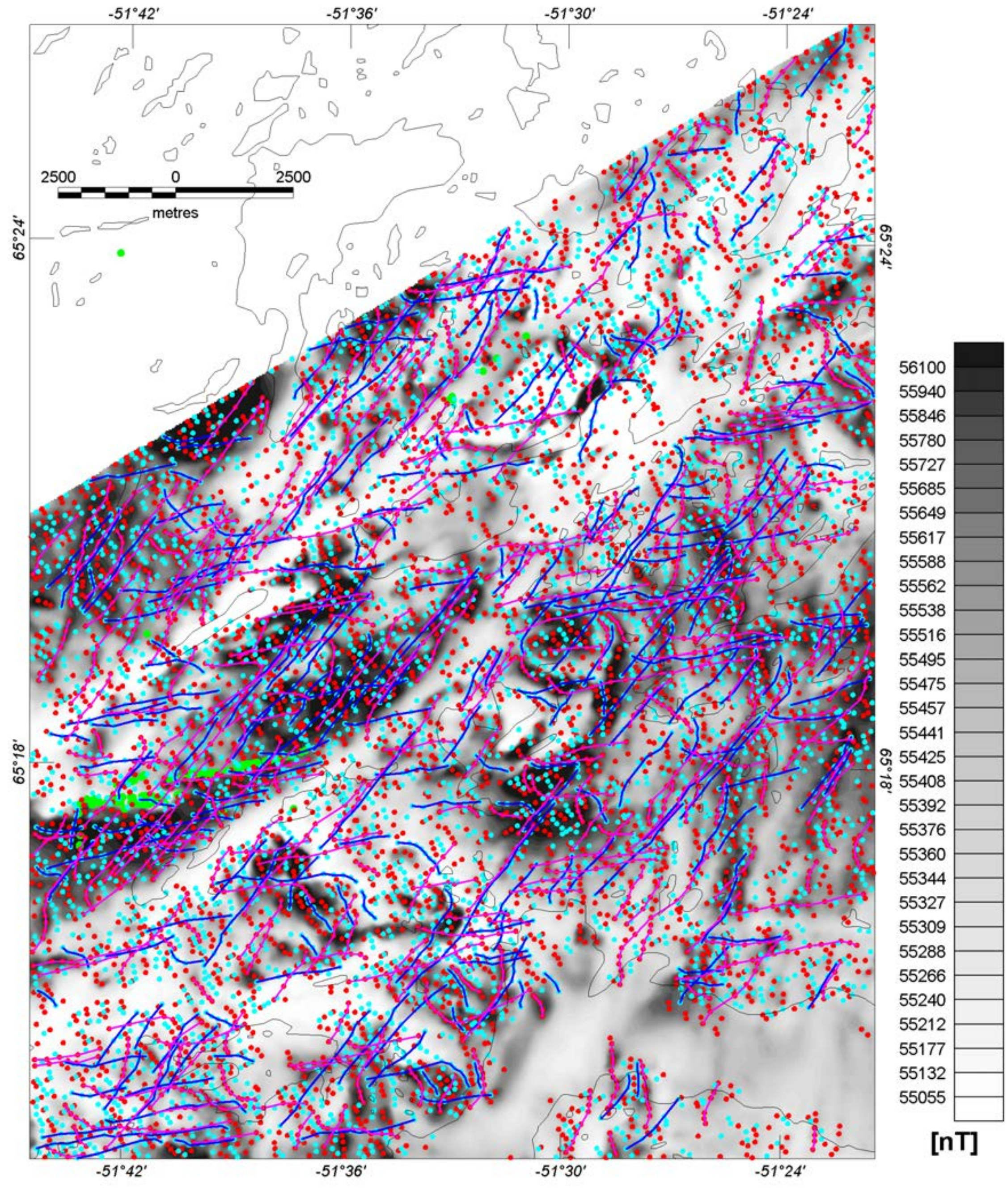

Figure 4. *Minima (red dots) and maxima (light blue dots) of magnetic field data from an area south of Maniitsoq Ice Cap outlined by the black rectangle in Figure 2. The lineaments obtained from the minima are shown by lines in blue colour and lineaments obtained from the maxima are shown by lines in cyan colour. Kimberlite occurrences are shown by green dots. The magnetic total field is shown as background colour. The extremum points for the analysis are limited by applying a selection criteria based on anomaly width (25 m<width<500m) and field strength.*

Ground magnetic surveys

The high spatial resolution provided by the GSM858 magnetometer results in data that are very useful in an attempt to understand magnetic response from kimberlites and the host rocks. The small width of most known kimberlite dykes requires a very dense sampling in order to map the occurrences. Figures 5 and 6 illustrates typical responses from kimberlites but they also illustrate some of the difficulties in distinguishing between responses caused by variations in magnetisation of the host rocks. Figure 5 shows results of 20 magnetic profiles marked 1-20 that crosses mapped kimberlite dykes (black lines). Magnetic field data from airborne data are also shown. Figure 6 shows the responses measured along profile 3. Along profile 3, two large magnetic peaks are observed. The southernmost anomaly is caused by a narrow zone of high magnetic susceptibility of the host rock (see also Figure 3), whereas the northernmost anomaly is caused by a kimberlite dyke. Adjacent to the large anomaly caused by a kimberlite dyke is a peak caused by a thin kimberlite. There is no possibility to discriminate between the causes for the observed anomalies solely from the magnetic data. Profile 7-12 cross an area covered by boulders where visual mapping of kimberlites where difficult. The profile data from these profiles were useful by excluding the existence of significant kimberlite occurrences in the surveyed area.

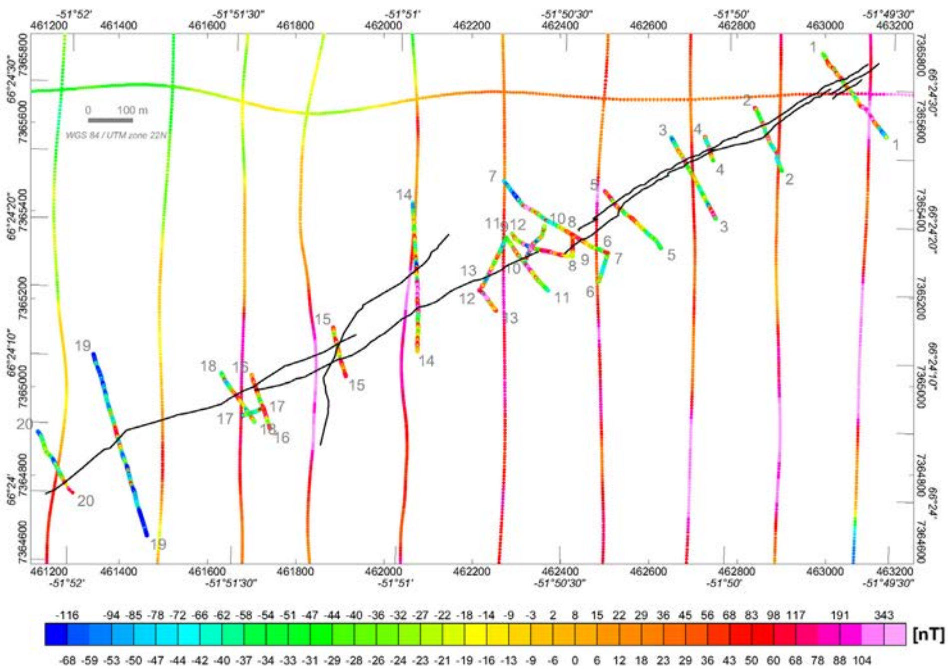

Figure 5. *Magnetic total field anomaly measured at the top-sensor (large coloured dots) along the ground profiles numbered 1–20 and magnetic total field anomaly from the airborne survey (small coloured dots). The class limit annotations above the legend bar are for the ground survey data and the annotations below are for the airborne survey data. Black lines mark the trace of the kimberlitic dykes.*

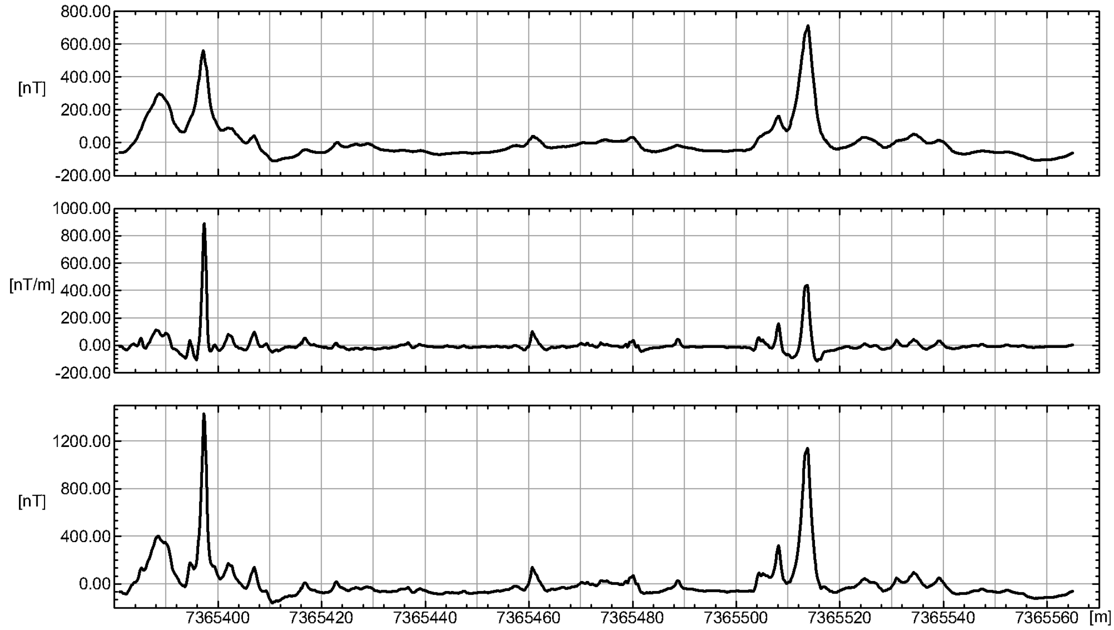

Figure 6. *Magnetic total field anomaly at the top sensor (upper panel), vertical gradient (middle panel) and total field anomaly at bottom sensor (lower panel) along profile 3. The horizontal axis is the north co-ordinate in zone UTM22. The kimberlitic dykes are at co-ordinates 7365508 m and 7365513 m. The peaks around co-ordinate 7365397 m are caused by gneiss with high magnetic susceptibilities*

Conclusion

The experience obtained from both airborne and ground surveying in Greenland is that magnetic data can be used in a direct search for kimberlites provided the resolution is high and that the data contains very valuable information about structures in general. The structural information may be useful for interpreting kimberlite emplacement patterns.

Distribution of kimberlite indicator minerals in till within the Neoproterozoic Sarfartoq-Maniitsoq province of kimberlite and ultramafic lamprophyres, southern West Greenland

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Introduction

The recovery of kimberlite indicator minerals (KIM) from overburden material such as till, soil or stream sediment has been used widely as prospecting method for kimberlites, particularly in glaciated terrain. In Greenland, thousands of samples of till and stream sediment have been collected and processed by exploration companies, and abundant indicator minerals including garnet, chromite, ilmenite and clinopyroxene have been identified, particularly in the Sarfartoq-Maniitsoq (S-M) province of abyssal kimberlite and ultramafic lamprophyre. The compilation of all released company data by Jensen *et al.* (2004) enabled an overview of the KIM distribution in West Greenland. In the Sarfartoq-Maniitsoq province, the KIM distribution patterns have south-westerly trends and may be seen as trails subparallel to the general direction of ice movement. This leaves the possibility that the KIM – or at least a large proportion of the grains – are derived from unknown kimberlite bodies up-ice from the present location.

2004-05 investigation by GEUS-BMP

An investigation was undertaken in 2004 to 2005 by GEUS and BMP with the aim of finding the likely source for the KIM. Data have been acquired to compare the abundance and composition of KIM within known dykes and sills with those in the surrounding till and glaciofluvial deposits. In addition, samples have been collected with the aim of verifying previously obtained company data, because individual companies have used distinct methods and laboratories to process and analyse their samples.

Geology and topography of study areas

The Neoproterozoic (0.56–0.6 Ga) Sarfartoq and Maniitsoq kimberlite fields comprise numerous dykes and sills intruded into the Archaean craton of West Greenland. The craton is a part of the North Atlantic Craton that also comprises parts of Labrador to the west as well as parts of East Greenland and Scotland to the East. The southern Maniitsoq field lies entirely within the craton, whereas the Sarfartoq field straddles the craton's northern boundary towards the Palaeoproterozoic Nagssugtoqidian Orogen. The country rocks for both kimberlite fields are dominated by tonalitic to granodioritic orthogneisses, but also comprises

enclaves of supracrustal rocks of predominantly mafic volcanic origin, and a Palaeoproterozoic dolerite dyke swarm affects most of the Sarfartoq field.
Topographically, the study areas display large variations. In the Sarfartoq area gently rolling lowlands gradually rise in altitude from north (average about 500 m) to south (average about 1000 m). The Maniitsoq area presents a landscape dominated by steep SSW-trending ridges with peaks in the range of 500 to1200 m and a coastline characterised by deep fjords.

Quaternary geology
With the exception of a few very high mountain peaks, the entire West Greenland has been glaciated. The deposits of till resulting from the retrieval of the ice are irregularly distributed and generally thin except where the ice margin has been stationary over a period of time, and undulating ridges of terminal moraines have formed. Also the main valleys have large amounts of glacial deposits, both terminal moraines from valley glaciers and abundant glacio-fluvial material. Although ice and melt water movements have been generally towards the west, the late valley glaciers have caused transport in more varied directions from NW to SW, so that directions of transported overburden are not easily deduced at a local scale.

Sampling and sample treatment
Sampling was performed from 8 field camps supplied by helicopter-supported visits to selected localities. The distribution of sample sites was intended to cover some known kimberlite occurrences, previously sampled areas and background areas outside and up-ice from known kimberlite occurrences.

Rock samples were collected by hammer as representatively as possible to obtain c. 5 kg of material. They were treated at Overburden Drilling Ltd. where they were milled in stages to maximize 0.25 to 2 mm grain size fraction. KIM were picked from three fractions (0.25-0.5, 0.5 –1, and 1-2 mm) of non-ferromagnetic, heavy (d >3.2 g/cm^3) minerals.

Till samples (overburden samples)
A pit was dug with a common field spade at each sample site in the local overburden, most commonly till, but locally glaciofluvial material were present at the sampling site. Material from below the vegetation was loaded onto and passed through a 4-mesh (6.35 mm) screen fitted on top of a 20-l bucket. Both screen and bucket had been rinsed carefully with a brush, and further rinsed by the discarded first load of material from each new site. Then till material was passed through the screen and collected in the bucket until an amount of c. 20 kg was achieved. The resulting pit was typically 40 to 50 cm deep with a diameter of 30 to 40 cm. The surroundings of the site and the character of the sampled till (proportion of gravel, sand and silt, humidity) was noted. The samples were treated at Overburden Drilling Ltd. to produce three fractions (0.25-0.5, 0.5-1, 1-2 mm) of non-ferromagnetic heavy minerals (d >3.2 g/cm^3) from which kimberlite indicator minerals were picked.

A small sample *c.* 400 g was collected representatively (though avoiding stones larger than 1 cm) from the sides of each pit using a small plastic shovel and a paper sample bag. The sides of the pit were first scraped with the plastic shovel to avoid contamination from the metal of the spade. The samples were further dried at GEUS, then screened into a number of fractions to characterise the grain size composition of the till at the sampling sites. The <

0.1 mm fractions have been analysed chemically for major and trace elements (ICP-ES and ICP-MS upon dissolution of fused samples) at Activation Laboratories Ltd.

Mineral chemistry

About 7000 mineral grains have been analysed by microprobe at Geocenter Copenhagen. Preliminary results are presented by Jensen *et al.* (this volume).

Results

KIM were picked from all but one of the 27 rock samples submitted, and from 80 of the 131 till samples submitted.

	Garnet				
Rock	Peridotic	Eclogitic	Clinopyroxene	Ilmenite	Chromite
Max	21650	6125	47250	151700	5312
Min	0	0	0	0	0
Median	536	4	5	12272	50
Till					
Max	3205	71	75	31600	746
Min	0	0	0	0	0
Median	0	0	0	2	0

Table 1. *Total number of picked kimberlite indicator mineral grains in the 0.25 to 2 mm grain size fraction.*

Local dispersion

The abundance of KIM is high close to kimberlite dykes (sills) or among kimberlite boulders, but the number decreases significantly within a short range down-ice from the occurrence. Many new occurrences and boulders were found at the sampling sites, so that where KIM have been recorded previously in till samples, a local source were found present. In most of the sites where our samples were collected close to previous company samples, the order of magnitude of KIM was the same (Figure 1). KIM were not recorded in till samples from areas without kimberlite occurrences, including those up-ice from known occurrences. The chemistry of the fine fraction of till sustains that the till surrounding kimberlite occurrences contains kimberlite-derived material.

Regional variation

The till results mimics regional variations observed in rock samples, namely that peridotitic and eclogitic garnets are more abundant in the Maniitsoq than in the Sarfartoq region (Figure 2), and that chromite and clinopyroxene relative to peridotitic garnets are higher in the Sarfartoq region. Rock samples from a locality north of the boundary towards the Nagssugtoqidian orogen also contain KIM, like the till samples.

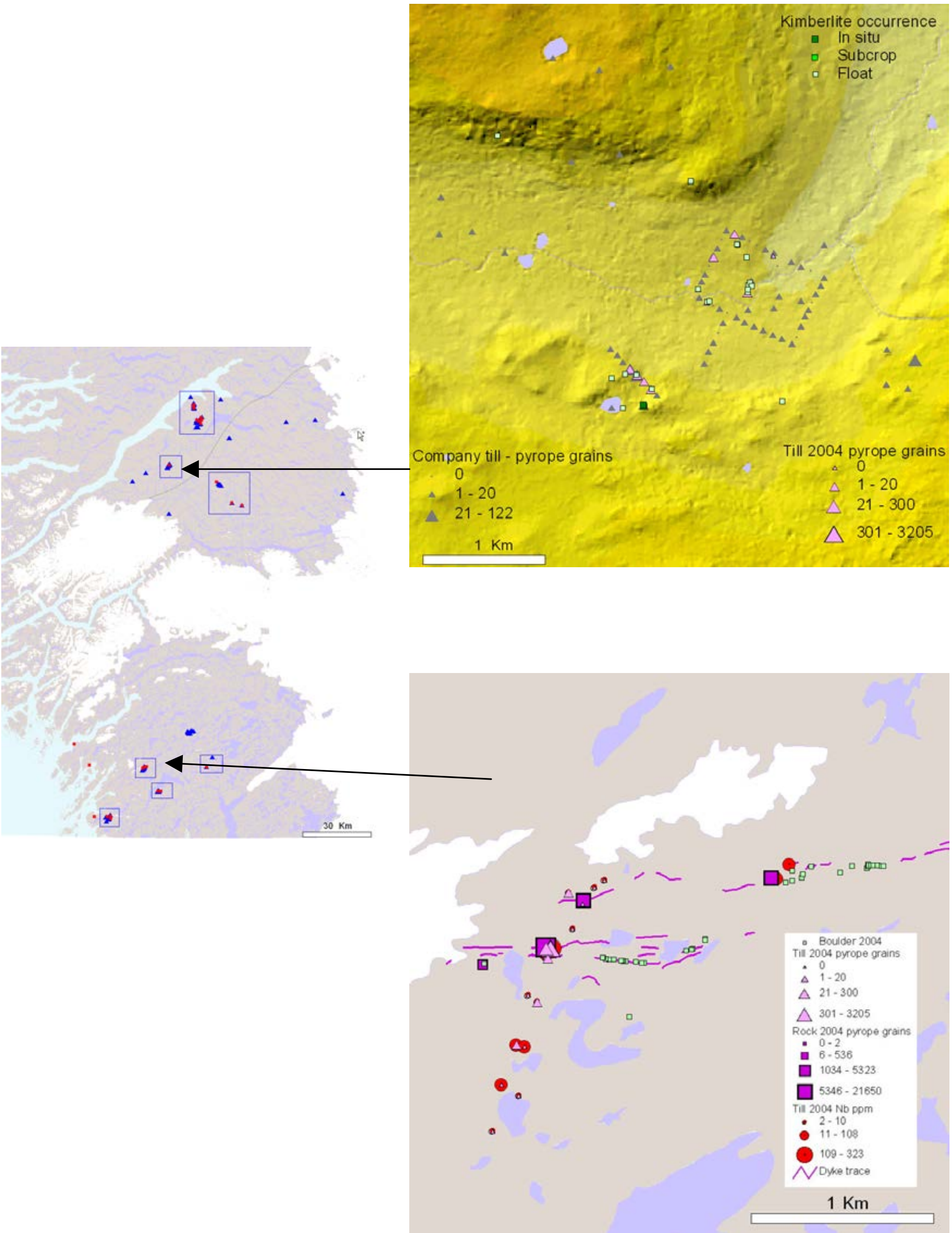

Figure 1. *Index map with sampling areas and two examples of local distribution of pyrope in rock and till samples.*

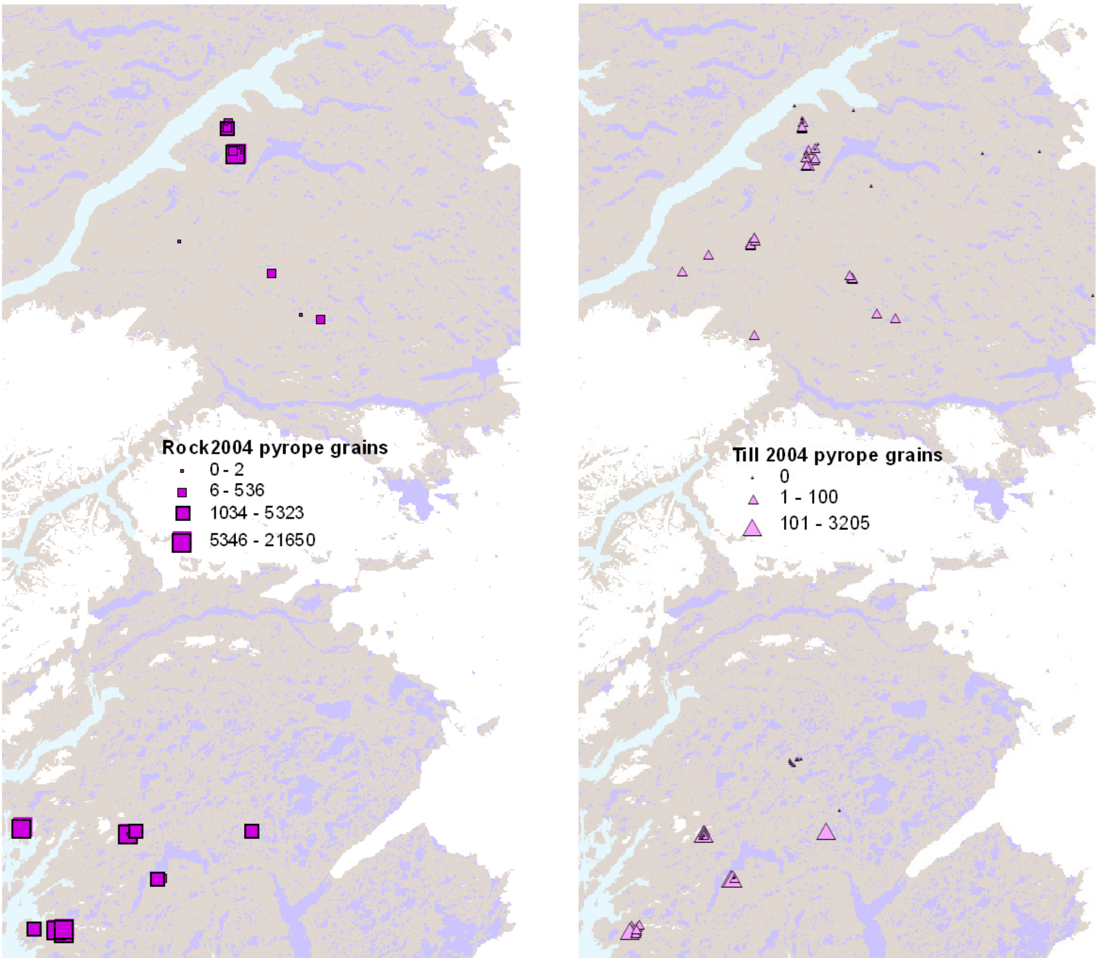

Figure 2. *Regional distribution of pyrope (peridotitic garnet) from rock samples (left) and till samples (right).*

Conclusion

The similarity in abundance and proportion between KIM from kimberlite rocks and the surrounding till, both locally and regionally, together with the absence of KIM in till in kimberlite barren areas are taken to indicate that the KIM in overburden have a local origin. The KIM in till samples north of the Nagssugtoqidian front are likewise probably sourced by local rocks. Jensen et al. (this volume) provides further evidence for our conclusion.

Testing the implication

The compilation of company KIM in till data (Jensen et al. 2004) shows a small cluster of picked garnet south-east of Nuuk. Neither lamprophyres nor kimberlites were known from that area until several ultramafic lamprophyre dykes and a carbonatite complex were discovered by GEUS during this summer's fieldwork (2005).

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Ultramafic Lamprophyres and carbonatites of Labrador and New Quebec: towards a genetic model for Neoproterozoic rift-related alkaline magmatism in the North Atlantic region

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Abstract

Late Neoproterozoic potassic to carbonatitic dyke rocks of deep origin occur throughout northern Labrador and New Quebec forming part of an alkaline province which encompasses the former Laurentian margin, West Greenland and the Scandinavian Peninsula. Characteristic rock types of this North Atlantic Alkaline Province (Doig, 1970; Tappe *et al.*, 2004) are ultramafic lamprophyres (UML) and associated carbonatites, but not kimberlites (Tappe *et al.*, 2005).

Our U-Pb perovskite results for the UML dykes from northern Labrador/New Quebec and from central Labrador (Aillik Bay) indicate similar emplacement ages ranging between 606-568 and 590-555 Ma, respectively. Reported ages for carbonate-rich ultramafic dykes from Sisimiut, Sarfartoq and Maniitsoq in West Greenland (~ 607-583 Ma; see Larsen & Rex, 1992) fall within the same time frame. This implies coeval and comparatively long lasting UML/carbonatite igneous activity at the borders of the present-day Labrador Sea during the Late Neoproterozoic.

The northern Labrador/New Quebec UML (aillikites and mela-aillikites) define an array in Sr-Nd and Nd-Hf isotope space that extents from fairly depleted compositions with positive ε_{Nd} (up to +1.8), positive ε_{Hf} (up to +3.5) and unradiogenic $^{87}Sr/^{86}Sr_{(582)}$ (< 0.7037) towards long-term enriched isotope compositions with negative ε_{Nd} (down to -3.3), negative $_{Hf}$ (as low as – 6.6) and moderately radiogenic $^{87}Sr/^{86}Sr_{(582)}$ (0.7039-0.7046). The carbonate-rich aillikites predominately fall on the depleted end of this “Torngat array”, whereas the carbonate-poorer mela-aillikites tend to be isotopically more enriched; however, there are gradations between rock types. The generally carbonate-richer aillikites (> 10 wt.% CO_2) from

Aillik Bay have more homogenous Sr-Nd-Hf isotope compositions than their northern Labrador/New Quebec analogues and fall close to the depleted end of the “Torngat array” (ε_{Nd} = 0.1-1.8; ε_{Hf} = -0.9 to 2.6; $^{87}Sr/^{86}Sr_{(582)}$ typically < 0.7040).

Any petrogenetic scenario for UML magma generation at the borders of the Labrador Sea has to account for the presence of residual phlogopite in the melting assemblage, which places the magma source region in comparatively cold cratonic lithospheric mantle (< 1300°C). Furthermore, the unradiogenic Nd and Hf isotope compositions of some UML forming the long-term enriched end of the “Torngat array” indicate a contribution from isolated subcontinental lithospheric mantle (SCLM). However, the carbonate seems to be derived from convective upper mantle given the positive ε_{Nd} and ε_{Hf} values of the carbonate-richest UML. These observations are best interpreted by a large-scale upwelling of the asthenosphere beneath the present-day Labrador Sea area due to incipient continental rifting, thereby heating and successively converting the stretched base of the SCLM. Potassic to carbonatitic fluids/melts were injected into the cold base of the SCLM, where they solidified as a phlogopite + carbonate-dominated vein network shortly prior to UML magmatism (there was not enough time for Hf-Nd isotope decoupling; delta ε_{Hf} = -1.7 to -4.6). Remelting of the veins plus melting of the lithospheric wall-rock peridotite occurred because the asthenosphere-lithosphere boundary beneath the present-day Labrador Sea area moved further upward and sideward during rift propagation (from ~ 180 to 120 km). The fact that UML from the northernmost occurrences (i.e. Torngat UML) span a well developed isotope mixing array points to a significant contribution from older SCLM to those magmas. The carbonate-rich type aillikites, however, represent UML magmas with a much higher vein/SCLM wall rock ratio in the melting assemblage than their Torngat counterparts, which implies advanced lithospheric thinning in the southern part of the Labrador Sea rift zone at ~ 582 Ma. The presence of a long-term enriched SCLM reservoir deep underneath Aillik Bay is evident from the Nd-Hf-Sr-Pb isotope signature of recently discovered Mesoproterozoic lamproites (ε_{Nd} = -5.3 to -8.4; ε_{Hf} = -7.8 to -10; $^{87}Sr/^{86}Sr_{(1376)}$ typically > 0.7047; $^{206}Pb/^{204}Pb_{(1376)}$ = 14.2-14.8).

Taken together, enhanced UML and carbonatite igneous activity affected the cratonic assembly of the North Atlantic region as a consequence of large-scale plate reorganization (breakup of Rodinia) during the Late Neoproterozoic. Ascending potassic carbonate-rich asthenosphere-derived fluids/melts had been concentrated underneath stretched lithospheric blocks, where they solidified as veins. Subsequent high pressure re-melting (~ 4-6 GPa) of these carbonate-phlogopite dominated vein assemblages together with variable amounts of their host peridotites during the incipient rifting stages produced carbonate-rich UML magmas. These primary UML magmas intruded the rift margins as dyke swarms or central complexes, but low-pressure processes such as liquid immiscibility and filter pressing may have produced a variety of associated rock types including carbonatites.

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Detection of kimberlitic rocks using airborne hyper-spectral data from southern West Greenland

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High-resolution hyperspectral (HS) remote sensing data have been successfully used for the location of kimberlitic rocks, e.g. in Australia and Africa. However, its potential as a viable method for the mapping of kimberlite occurrences in arctic glaciated terrain with high relief was previously uncertain. In July - August 2002, GEUS conducted an airborne hyper-spectral survey in central West Greenland using the commercially available HyMap hyper-spectral scanner operated by HyVista Corporation, Australia (Fig.1). Data were processed in 2003, and in 2004 follow-up field work was carried out in the Kangerlussuaq region to test possible kimberlites indicated by the HS data. The project was financed by the Bureau of Minerals and Petroleum, Government of Greenland.

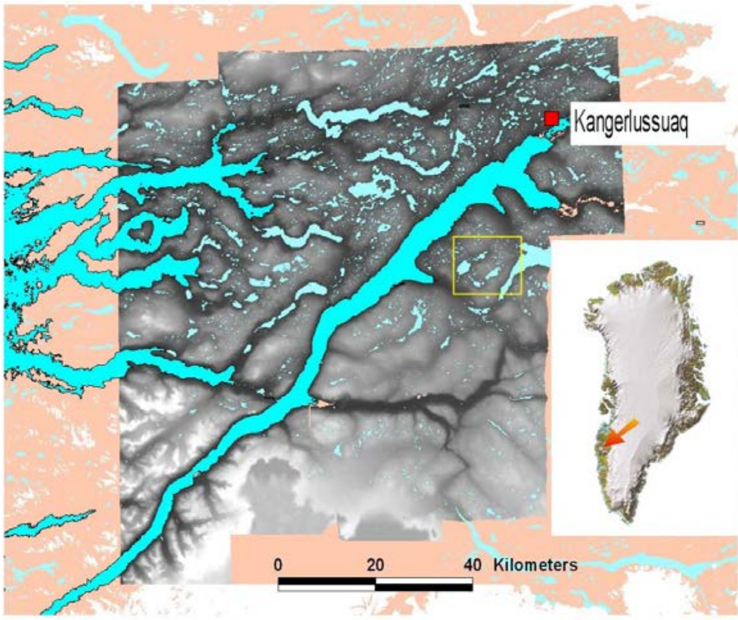

Figure 1. *Coverage of the HyperGreen2002 survey in West Greenland as indicated by a shaded topographic map.*

Kimberlites consist of predominantly ultramafic material that has crystallised *in situ*, and commonly host megacrysts formed in the upper mantle from the kimberlite magma and mantle derived xenoliths (dunite, lherzolite, wehrlite, harzburgite, eclogite and granulite) incorporated during magma transport. Common matrix minerals are olivine, phlogopite, perovskite, spinel, chromite, diopside, monticellite, apatite, calcite and Fe-rich serpentine. The most interesting minerals with respect to hyperspectral mapping are phlogopite, Fe-rich serpentine (antigorite) and calcite; these minerals have characteristic spectral responses in the Short Wave Infrared (SWIR) spectral region (2.0 – 2.5 μm).

To fully exploit the possibilities of hyperspectral image data delivered "at sensor radiance data", they must be converted to surface reflectance data. The small size of potential targets and the relatively subtle spectral characteristics as established by a ground truth survey included in the project, demonstrated that the rugged terrain conditions of West Greenland required the use of advanced atmospheric correction methods.

The conversion of the data to surface reflectance was done by producing a detailed digital elevation model and using this with the hyperspectral data in a commercially available software package, which take sensor viewing geometry and terrain information into consideration. Comparison of the HyMap spectrum of kimberlite to the spectra measured with a field instrument at the same locality shows a close match (Fig. 2) demonstrating the quality of the conversion to surface reflectance.

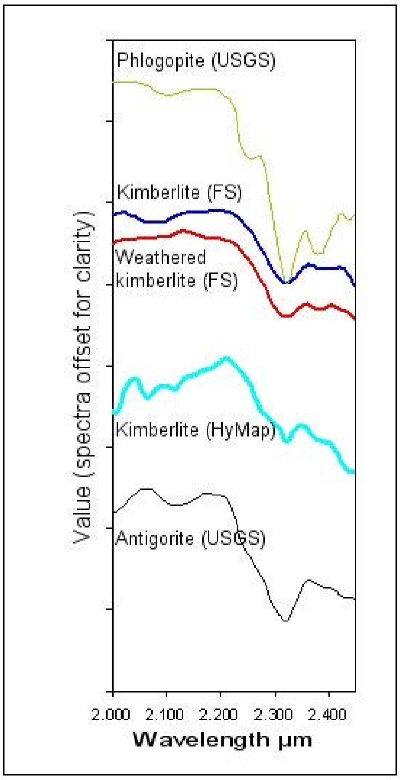

Figure 2. *Comparison of laboratory mineral spectra to the kimberlite spectra measured by field instruments (FS) and airborne HyMap hyperspectral scanner.*

The field measurements have shown that the spectral response from kimberlitic rocks within wavelengths of 2.0–2.5 μm is remarkably uniform. Thus the simplest way to locate the kimberlitic rocks is to use selected characteristic kimberlite field spectra as end members for the spectral processing. The Spectral Angle Mapper (SAM) was used in this project for comparing the HS image spectra to selected, characteristic kimberlite field spectra and mineral spectra such as phlogopite and antigorite.

The results were encouraging. The known occurrences could be seen in the hyperspectral data; new ones were also suggested and later proven during the fieldwork. Examples will be shown and some cases of similar anomalies originating from other types of rocks will be discussed.

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