

Diamonds and lithospheric mantle properties in the Neoproterozoic igneous province of southern West Greenland

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The search for diamonds in Greenland has resulted in the discovery of many new dykes of kimberlite and ultramafic lamprophyre and, most importantly, in the acquisition of a wealth of chemical data on rocks and minerals representing mantle material entrained by the dyke magmas. The discovery of a diamondiferous sheet at Garnet Lake in southern West Greenland stimulated the research (Hutchison 2005). Over the past five to ten years, the Geological Survey of Denmark and Greenland together with the Bureau of Minerals and Petroleum in Greenland and international research groups have acquired, processed and interpreted data with the objective of identifying diamond-favourable regimes within the lithospheric mantle below the Archaean craton in West Greenland. Here we present mineral data

from drift samples that allow us to identify where mantle conditions in terms of lithology and depth may be favourable for the occurrence of diamonds. Magma emplacement was concentrated in the Sarfartoq and Maniitsoq regions (Fig. 1), and took place from *c.* 600 Ma to *c.* 555 Ma (Secher *et al.* in press). The first period of magmatism appears to be confined to the Sarfartoq region while later magma pulses affected the entire region (Fig. 1). A 568 ± 11 Ma age of the Garnet Lake sheet (Hutchison & Heaman 2008) places this intrusion in the younger part of the period. Ultramafic dykes (some of which are diamondiferous) of the same age in Labrador, Canada (Tappe *et al.* 2006) show that the magmatism extended into the western part of Laurentia, the then contiguous continent comprising North America and Greenland. The magmatism is thought to have been triggered by incipient continental rifting. At about the same time, more pro-

Neoproterozoic igneous province

The province comprises the Sarfartoq carbonatite complex and abundant dykes and sills of carbonate-rich ultramafic silicate rocks (ultramafic lamprophyre and kimberlite) that have been emplaced in late Neoproterozoic time into Archaean rocks of southern West Greenland between 65°N and 67°30'N (Larsen & Rex 1992; Nielsen *et al.* in

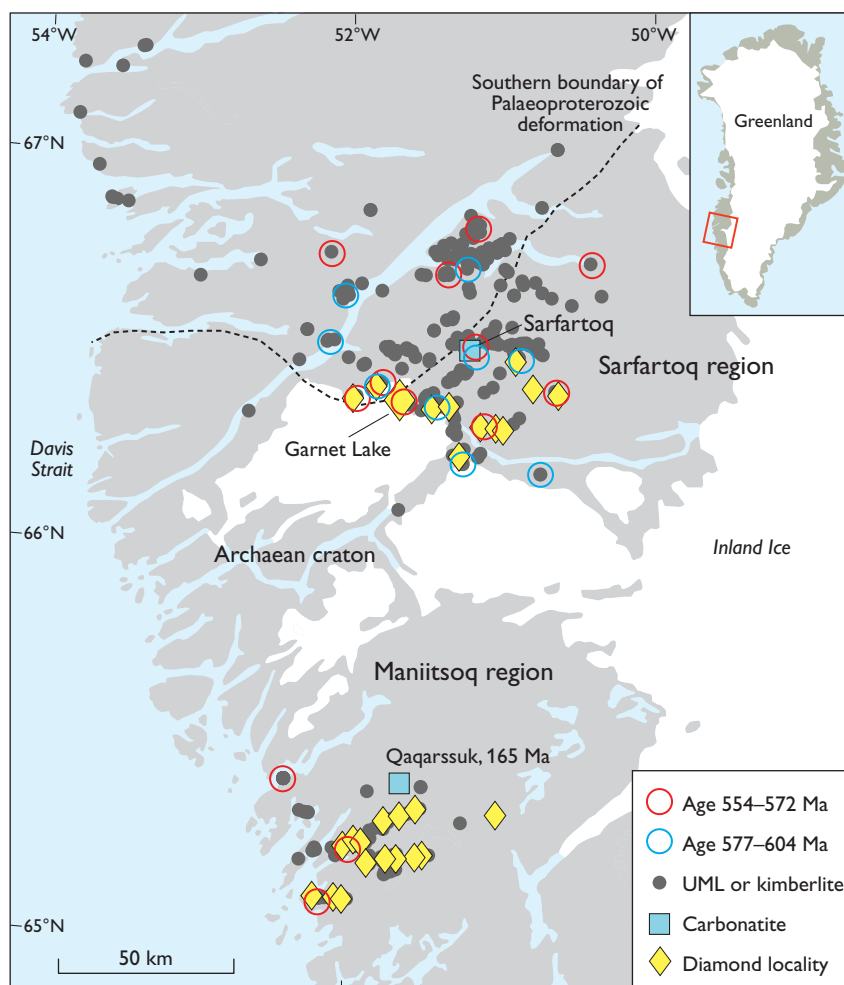


Fig. 1. Neoproterozoic igneous province and localities for rocks tested positive for diamonds (Jensen *et al.* 2004, with later updates from Intex Resources ASA, www.intex-resources.com). The large diamond symbol marks the Garnet Lake commercial diamond operation. The Sarfartoq carbonatite complex and dykes of kimberlite and ultramafic lamprophyre (UML) are emplaced into the Archaean craton, which suffered deformation in the northern part during a Palaeoproterozoic collision.

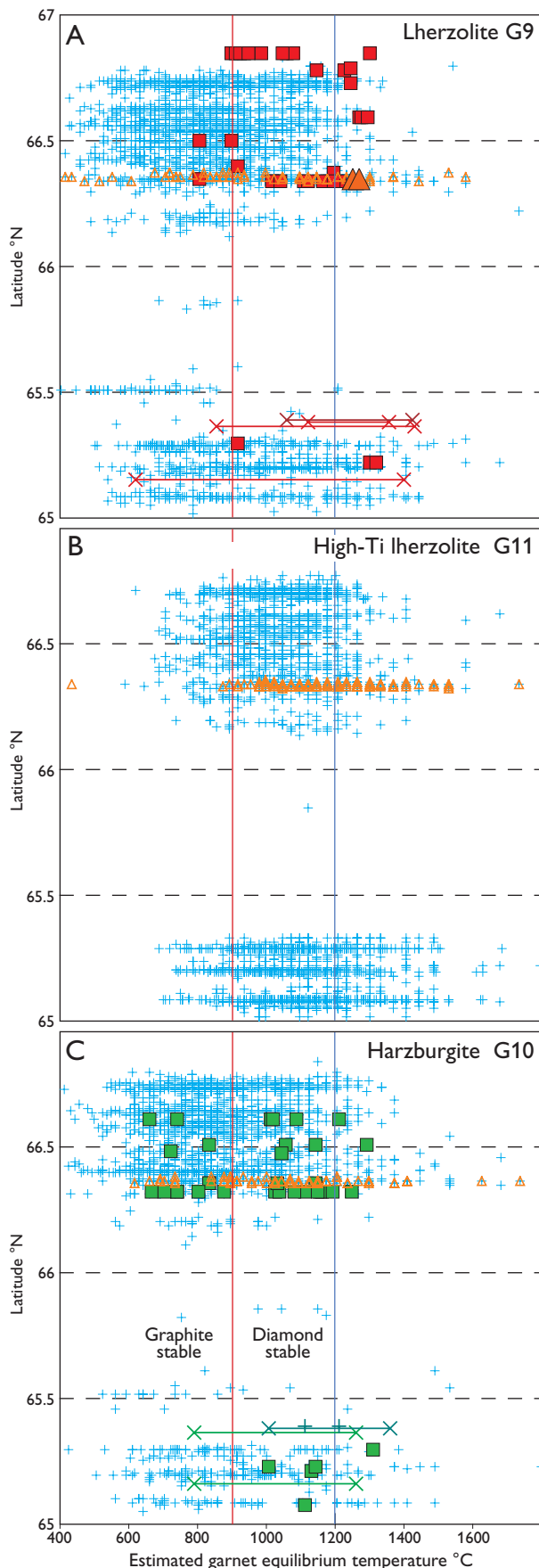


Fig. 2. Estimated temperatures of three classes (A: G9, B: G11 and C: G10) of mantle-derived garnet grains picked from the non-magnetic, heavy mineral fraction of drift samples (mainly till). Northern latitudes on vertical scale: upper group Sarfartoq region (north of 66°N), lower group Maniitsoq region. Orange, open triangles are grains from the Garnet Lake area. Red, vertical line marks the temperature of graphite-diamond phase transition (900°C). Blue line (1200°C, c. 180 km depth) marks the cut-off value for deeply derived grains plotted in Fig. 3. Squares represent lithologically sorted temperature estimates based on mantle xenoliths (Larsen & Rønso 1993; Garrit 2000; Bizzarro & Stevenson 2003; Jensen *et al.* 2004; Sand *et al.* in press); lines between x-symbols are ranges in Ni-in-garnet temperatures of grains in garnet concentrates (data from Garrit 2000). Large, filled, red triangles are temperatures determined on xenoliths from Garnet Lake (Hutchison & Heaman 2008).

nounced rifting took place at the northern margin of Laurentia and resulted in the intrusion of a prominent basaltic dyke swarm in North-West Greenland and northern Baffin Land (Dawes 2006).

Exploration and diamond discoveries

Exploration companies have used the so-called kimberlite indicator minerals in their search for host rocks for diamonds. Samples of overburden or drift (mainly till) have been collected systematically over the entire Archaean craton of southern West Greenland and processed to obtain the non-magnetic heavy mineral fraction, from which grains of mantle-derived minerals including peridotitic garnet (pyrope), eclogitic garnet, chromite (chrome-spinel), microilmenite and chrome-diopside have been picked under a microscope. Many grains were subsequently chemically analysed to verify the visual identification and allow chemical classification. Numerous samples with diamond-indicative, high-pressure mineral compositions indicate that the Neoproterozoic province has a high prospective potential, and subsequent diamond tests have confirmed that the carbonate-rich ultramafic magmas brought up diamondiferous mantle at several localities within the province (Fig. 1). The huge amount of mineral analyses were compiled and quality controlled by Jensen *et al.* (2004).

In 2004 Hudson Resources Inc., guided by drift samples with an abundance of garnets derived from the diamond-stable mantle, discovered a significant amount of diamonds hosted in carbonatite-rich ultramafic rocks at Garnet Lake (Fig. 1) in the Sarfartoq region (Hutchison 2005). Continued exploration has established the presence of a 4 m wide, shallow-dipping sheet of kimberlitic rock with a promising diamond grade and diamond crystals up to 4 carats (0.8 g; Hutchison & Heaman 2008; www.hudsonresources.ca).

The Neoproterozoic lithospheric mantle

Many mineralogical and chemical investigations of mantle xenoliths hosted by the kimberlites and ultramafic lamprophyres have demonstrated that the lithospheric mantle comprises an upper section of peridotitic rock types (lherzolite, harzburgite, dunite) depleted in elements such as Ca, Fe and Ti relative to asthenospheric mantle because of extraction of large portions of basalt. The section of depleted mantle is underlain by a section with a predominance of Fe-Ti-rich, so-called fertile garnet lherzolite (references in Fig. 2). It has also been demonstrated that some xenoliths from both regions have been derived from depths clearly within the high-pressure regime where diamond is stable (references in Fig. 2). The constraints for the Neoproterozoic geotherm have recently been improved to 38–41 mW/m², and the thickness of the Neoproterozoic lithosphere has been estimated to be at least 215 km over the entire province (Sand *et al.* in press).

Studies by Hutchison & Heaman (2008) indicate that the diamonds at Garnet Lake probably formed at great depths within the fertile lherzolite, i.e. at temperatures above 1200°C, and within a period of 50 million years before the transporting magma brought them to the surface. The deep lithospheric mantle provenance of the xenoliths is also stressed by Grütter & Tuer (in press), who found an unusually high proportion of high-*T* peridotitic garnets in drift samples from the immediate surroundings of Garnet Lake.

Garnets from deep lithospheric mantle

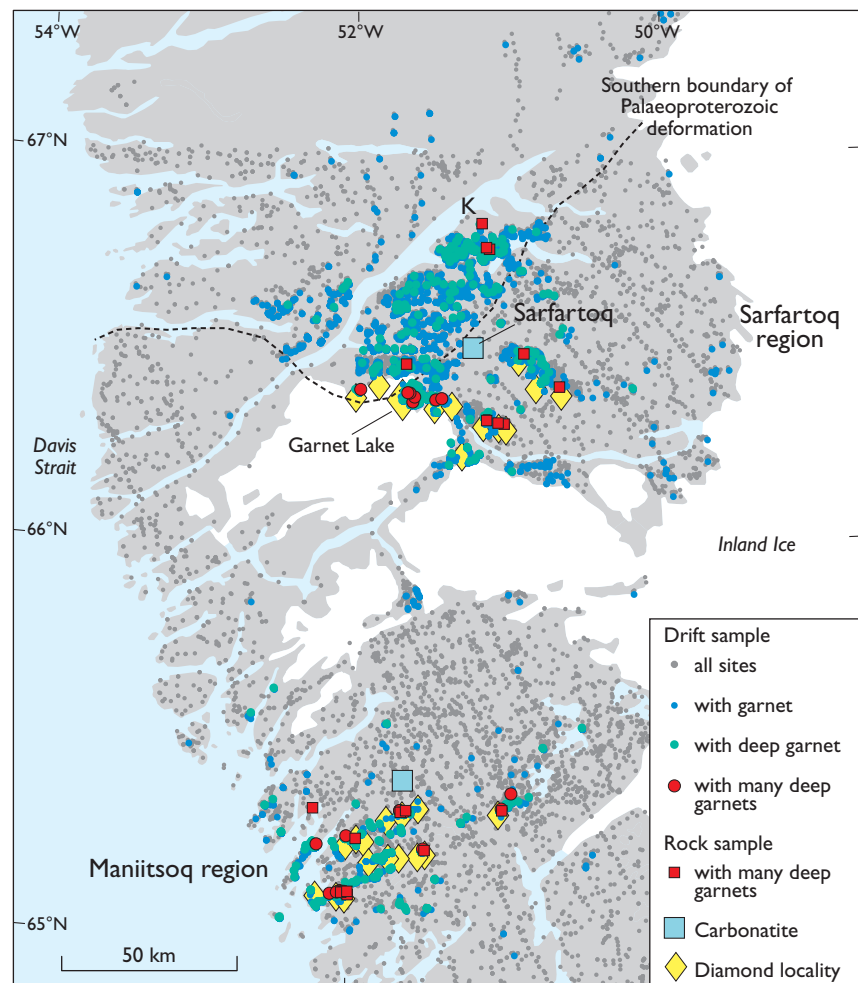
Garnet is the mineral that has been used most extensively in lithosphere studies and diamond exploration to reflect the temperature and pressure conditions as well as the lithology at the site where it equilibrated. The 15 000 available ana-

lyses of garnet grains from the Neoproterozoic province therefore provide excellent material with which to locate dykes that have incorporated material with deep mantle provenance similar to that recorded at Garnet Lake.

Using a chemical discrimination system devised by Grütter *et al.* (2004) we have selected garnets derived from depleted lherzolite (G9; Fig. 2A), fertile lherzolite (G11, Fig. 2B) and harzburgite (G10, Fig. 2C), and determined their equilibration temperatures using MnO concentrations (Grütter *et al.* 1999). The results shown in Fig. 2 are plotted against the latitude of the sample sites in order to reveal any regional differences. Temperatures of Garnet Lake grains and published temperature estimates based on other minerals are shown for comparison.

The diagrams show that a majority of the garnet grains derive from depths where diamond is the stable carbon phase, i.e. where the temperature is above 900°C. It appears that G11 garnets (from fertile lherzolite) mainly come from greater depths and have large populations over the entire latitude interval. This enforces the validity of current models invoking the ubiquitous presence of fertile lherzolite in the

Fig. 3. Neoproterozoic igneous province with localities of drift samples and results of screening garnet grain analyses belonging to classes G9, G10 and G11. Deep garnets (green dots) have *T*-Mn above 1200°C. The red symbols marking samples (drift or rock) with more than 10 deep garnets in the picked populations of peridotitic garnet grains show spatial correlation with diamond occurrences.



lower lithospheric mantle section. A tendency for relatively more G11 grains above 1200°C in the Maniitsoq region is observed. Lherzolitic (G9) and harzburgitic garnets (G10) display origins in wider depth intervals, and very deep grains occur in both regions. The Garnet Lake garnets do stand out in reaching higher temperatures than many grains in the Sarfartoq region. However, grains from several localities in the Maniitsoq region have also yielded temperatures above 1400°C. It should be mentioned that the temperature is inversely correlated with MnO concentrations, so that temperature data above 1600°C are uncertain owing to low analytical precision at low concentrations.

The range in garnet *T*-Mn temperature estimates is in good agreement with estimates using other methods, and the advantage of having the many additional data to establish a more statistically reliable, regional picture of mantle provenance is obvious. In addition, the drift-derived garnets provide information from areas where dykes have not been located or sampled.

Distribution of sites with high diamond potential

Figure 3 shows the extensive coverage of drift sample sites and the clusters of garnet-bearing samples (any mantle-derived kind) where dykes are common (compare Fig. 1). The deep (high-*T*) garnets have a narrower distribution, yet they are abundant in both regions. In order to highlight localities with a high proportion of deep garnets, an arbitrary lower limit of ten grains has been applied. Rock-sample localities with a high proportion (more than ten grains) of deep garnets have been identified and are added as supplementary information. They outline additional localities with diamond potential in the Sarfartoq region.

The distribution of localities rich in deep garnet exhibits spatial correlation with that of diamond-bearing rocks and thus supports the observation made at Garnet Lake that an abundance of deep, lower lithospheric mantle material is characteristic of diamond-bearing dykes. However, the data also demonstrate that Garnet Lake is not unique in the province in this respect and the potential for making equally promising diamond discoveries elsewhere appears to remain. One small area near Kangerlussuaq (K in Fig. 3) has not yet proved positive for diamonds, but is considered a target for further exploration. Subsurface exploration methods would be needed in that area, though, because poor exposure impedes surface recognition of significant dykes.

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