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Four-phase geothermobarometry on mantle xenoliths from West Greenland: assessment of P/T-formulations and implications for diamond potential

Karina K. Sand[1,2], Tod Waight[3], Troels F.D. Nielsen[2], D. Graham Pearson[4], Emil Makovicky[3] and Mark T. Hutchison[2]

[1] Nano-Science Center, Department of Chemistry, University of Copenhagen, Universitetsparken 5, 2100 Copenhagen Ø, Denmark (karina.sand@gmail.com).
[2] Geological Survey of Denmark and Greenland, Copenhagen, Denmark.
[3] Institute for Geography and Geology, University of Copenhagen, Denmark.
[4] Northern Centre for Isotopic and Elemental Tracing, Department of Earth Sciences, Durham University, UK

In recent years the number of diamond finds from kimberlitic rocks (*senso lato*) (Nielsen and Sand, in press) in West Greenland has increased, resulting in a greater interest for the diamond potential of the region. Commercial size diamonds have so far only been found within ~20 km of the undeformed Archean craton boundary as defined by crustal exposures and geophysics (Van Gool et al. 2002). Detailed studies of the mantle beneath this region have been lacking. Here we assess the diamond potential of the southern West Greenland lithospheric mantle using geothermobarometry applied to 4-phase mantle peridotitic xenoliths (garnet, olivine, clinopyroxene, orthopyroxene) from ~600 Ma kimberlitic (*senso lato*) dikes and sills (Secher et al. 2008). The xenolith-bearing occurrences (Fig. 1) are located in three different settings relative to the margin of the undeformed North Atlantic Archean Craton. The Kangerlussuaq area is within the Nagssugtoqian Mobile belt, the Sarfartoq area just outside the deformation zone and the Maniitsoq area is entirely within the craton. The aim of this investigation was to estimate the depth of lithosphere, as sampled by mantle xenoliths and hence the diamond potential of West Greenland and to identify any variations in diamond potential between the three sub areas. A complementary study (Wittig et al. 2008), focused on evaluating the age of the lithospheric mantle beneath the region studied here.

In this study, we focus on garnet lherzolites (cpx, opx, ol) as this rock type provides a better evaluation of chemical equilibrium than other mantle rock types present in the kimberlitic host rock such as garnet harzburgites (ol, opx), garnet wehrlites (ol, cpx) or garnet dunites (ol). The more depleted harzburgites and dunites dominate the xenolith assemblage and hence a number of these other rocks have been also studied to allow a crude estimation of mantle stratigraphy (Sand, 2007, Sand et al., in preparation). The results presented here are from garnet lherzolites only. The PT estimates are calculated iteratively using well-known formulations (Table 1) based on major elements. The mineral compositions used to calculate P and T are means of replicate analyses (~10 analyses for garnets) from between three to five grains. Minerals were analyzed using a JEOL 8200 electron microprobe at the Institute of Geography and Geology, Copenhagen, Denmark. The acceleration voltage was set to 15 kV and the beam current to 50 nA and a beam diameter of 5µm was used.

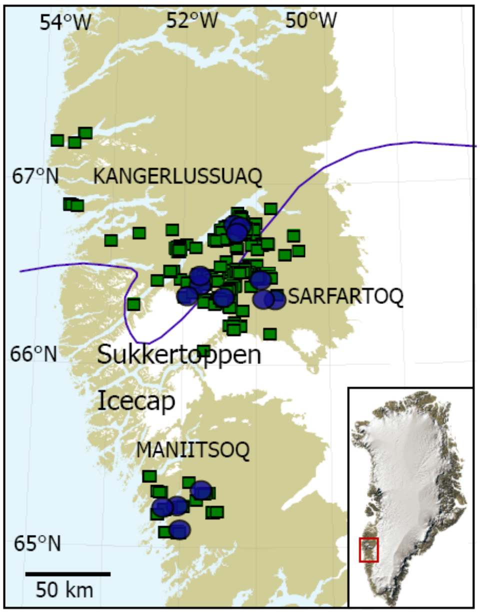

Figure 1: Map of in-situ kimberlitic *(senso lato)* occurrences (green squares) in the study area. The xenolith-bearing occurrences included in this study are indicated with blue. The blue line represents the boundary to the undeformed Archaean craton to the south.

The mineral chemistry of the West Greenlandic garnet lherzolites generally resembles that of the Slave and Kaapvaal cratons (Sand, 2007). However, elevated TiO_2 contents in clinopyroxenes and garnets are a feature of the West Greenland minerals and further analyses with lower detection limits are required to determine the significance of this feature. For whole rock bulk compositional data the reader is referred to Wittig et al. 2008.

Several geothermobarometers were applied to the data set (Table 1). Consistent results between these formulations based on various mineral and element exchanges are taken as an expression of well-equilibrated samples.

Table 1: PT formulations used for West Greenland peridotites

Method	Minerals	Equilibria	Comments	Accuracy[a]
Barometers				
PMC	gt-opx	Al exchange	MAS	± 0.6 GPa
PNG	gt-opx	Al exchange	SMACCr	± 0.9 GPa
PBKN	gt-opx	Al exchange	CMAS (SMACCr)	±0.5 GPa
PNimis	cpx	Cr exchange	SMACCr	±0.5 GPa
Thermometers				
THarley	gt-opx	Fe-Mg exchange	Sensitive to Fe^{3+}	92°C
TO´Neill	gt-ol	Fe-Mg exchange	Sensitive to Fe^{3+}	180°C
TCa-in-opx	opx	Ca exchange	in equilibrium with opx	60°C
TBKN	opx-cpx	Ca-Mg exchange	4-phase formulation	60°C
TNimis	cpx	Ca exchange	Equilibrium with gt	62°C

[a]Accuracies are from the literature and represent a 2σ confidence level based on the ability to reproduce experimental data. Gt=garnet, opx=orthopyroxene, ol=olivine, cpx=clinopyroxene. PMC from McGregor (1974), PNG from Nickel and Green (1985), P/TBKN from Brey and Köhler (1990), P/TNimis from Nimis and Taylor (2000), THarley from Harley (1984), TO´Neill from (O´Neill and Wood (1979), and TCa-in-opx from Brey and Köhler (1990).

Despite consistency in temperature estimates using a variety of thermometers, equilibration pressures varied with the choice of barometer (Sand, 2007). In Figure 2 the P/T estimates using PBKN/TBKN are shown with reference to the diamond stability field of (Kennedy and Kennedy, 1976), the model geotherms of (Chapman and Pollack, 1977) and a mantle adiabat (Rudnick and Nyblade, 1999). The general trend of the West Greenland lherzolite data scatters between geotherms of 40 and 42 mW/m^2. Only 3 data points appear to be derived from depths shallower than the diamond stability field. Included in Fig. 2 (blue dots) are equilibrium pressure and temperature conditions calculated for xenoliths from the diamondiferous Garnet Lake main sheet (Hutchison and Frei, *this volume*), demonstrating that this material is sourced from amongst the greatest depths sampled by West Greenland kimberlitic rocks.

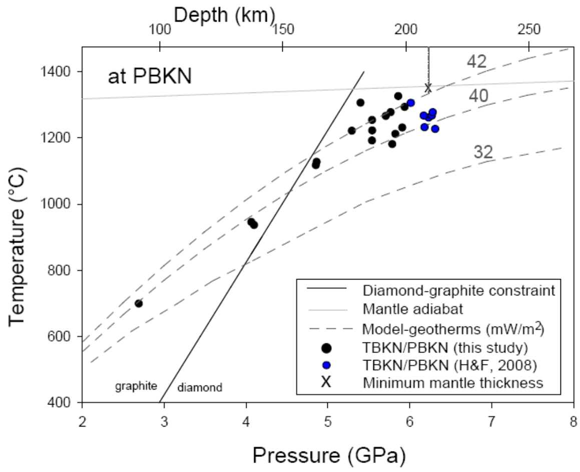

Figure 2: PBKN vs. TBKN. See text for discussion.

The results using the PMC and TCa-in-opx formulations are shown in Figure 3. This apparent geotherm displays a more linear trend that transects the model-geotherms of Pollack and Chapman, (1977) and shows a kink at pressures between 5.1 and 5.7 GPa, dividing the xenoliths into a low-T and a high-T suite.

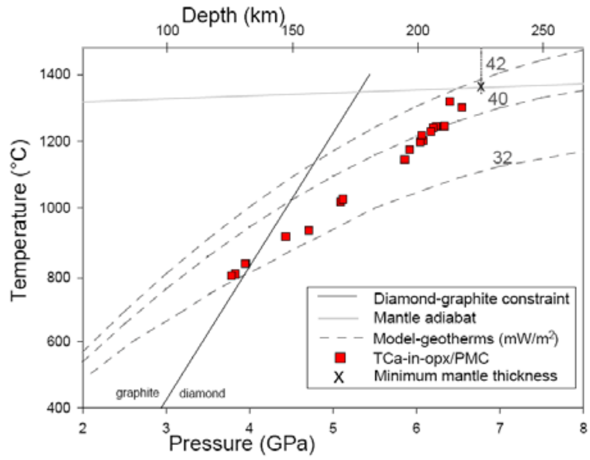

Figure 3: TCa-in-opx vs. PMC. See text for discussion.

Comparing Figure 2 and 3 it is evident that the combination PMC/TCa-in-opx formulation yields greater pressures compared to the PBKN/TBKN formulation. To exclude artifacts of the thermometers, pressure estimates using PMC and PBKN were calculated at a fixed T (Fig. 4). Here the PMC estimates are consistently 0.5 ± 0.5 (2σ) GPa higher than PBKN. This relative deviation to lower pressures using the PBKN formulation is also observed when compared to the PNG and PNimis barometers. The latter two barometers show, in general, pressures that are consistent with the PMC formulation. These observations are not further discussed here but for these reasons we prefer pressure estimates using the PMC barometer rather than PBKN formulation.

The inconsistency between the barometers and the implication for mantle evolution models are discussed in Sand (2007) and Sand et al. (in preparation).

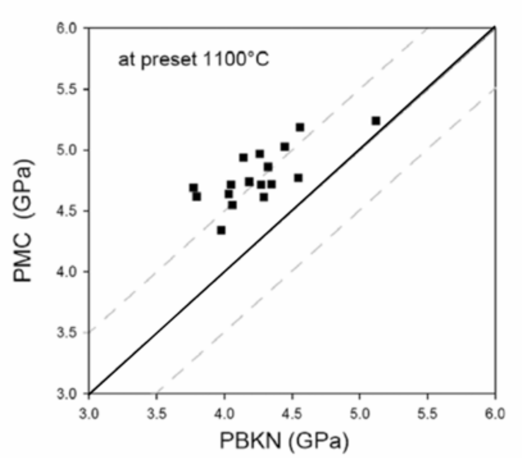

Figure 4: PBKN vs. PMC at 1100 °C. See text for discussion.

The transition from apparent xenolith-based geotherms to the convective heat transfer of the asthenosphere, shown by the mantle adiabat, yields the minimum thickness of the lithospheric mantle (Rudnick and Nyblade, 1999). The base of the lithospheric mantle ~600 mya ago is here suggested to have been at a minimum of ca. 210-220 km (Fig. 2 and 3). The potentially thicker mantle section and the higher pressures obtained using the PMC formulations yield a greater diamond potential compared to the PBKN formulation. However, most P/T estimates from the PBKN/TBKN formulation (Fig. 2) are also within the diamond stability field defined by Kennedy & Kennedy (1976).

When comparing the P/T results between the three regions no lateral variation in P/T estimates or heat flows at mantle depths are defined by our data, despite variable crustal histories. We recognize that the spatial coverage of P/T estimates from lherzolites is not comprehensive and a more extensive study may be warranted. However, from the available data it is clear that a significant portion of the West Greenland lithosphere was within the "diamond window" at the time of kimberlite eruption ~550-600 mya ago, and hence the whole region has considerable diamond potential.

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