Mantle Composition, Age and Geotherm beneath the Darby Kimberlite field, West Central Rae Craton

Garrett A. Harris[1], D. Graham Pearson[1], Jingao Liu[2], Matthew F. Hardman[1] and David Kelsch[3]

[1] University of Alberta, Edmonton, Canada, gaharris@ualberta.ca, gdpearso@ualberta.ca, mhardman@ualberta.ca

[2] China University of Geosciences, Beijing, China, jingao@cugb.edu.cn

[3] Bluestone Resources Inc., Vancouver, Canada, dkelsch@telusplanet.net

Introduction

The Rae craton in Canada's North contains several kimberlite fields and has been the subject of episodic diamond exploration, with proven diamond-bearing deposits. However, relatively little is known about the deep mantle lithosphere that underpins the architecturally complex crust of this craton. The Darby Kimberlite field, located ~ 200 km southwest of the community of Kugaaruk, Nunavut, provides an opportunity to study the mantle beneath the western portion of the central Rae craton via erupted mantle xenoliths. The Darby kimberlite field contains nine bodies, of which at least eight are kimberlitic. The bodies erupted at circa 540 Ma (Rb-Sr phlogopite). Five of the kimberlites have proven to be diamondiferous including the 12 hectare 'Iceberg' kimberlite (Counts 2008).

Samples

Mantle xenoliths were collected from kimberlite float above proven kimberlite targets across the property. Most of the surface kimberlite is highly altered and hence the peridotite xenoliths they contain are generally serpentinized or deeply-weathered. A total of 33 mantle xenoliths exceeding one cm in maximum dimension (14 peridotites and 19 "eclogites") were selected for mineral chemistry and bulk analysis. After the xenoliths were removed from the kimberlite, the remaining kimberlite was crushed for kimberlite indicator mineral separation to allow for a larger suite of kimberlite indicator minerals (KIMs) to be analyzed. Because of the small numbers of mantle xenoliths recovered the KIM suite permits a more statistically valid determination of the mantle mineralogy and lithological variation beneath the Darby kimberlite field.

Results

Peridotites: Fresh olivine within the peridotite xenoliths is scarce. Olivine in 11 peridotitic samples have a median Mg# of 92.5, indistinguishable from the median value of 92.6 that is typical of cratonic peridotites world-wide (Pearson and Wittig 2014). Four of the 14 peridotitic xenoliths contain fresh garnet. Of these, garnet in one sample is classified as harzburgitic (G10), giving a minimum pressure of 4.7 GPa using the P_{38} geobarometer (38 mW/m^2 model geothermal gradient), while garnets from three peridotites are classified as lherzolitic (G9) using the Grütter et al. (2004) classification scheme. Of the garnets picked from the kimberlite concentrate, 52 grains (18 %) are peridotitic. Of these, 98 % are lherzolitic, in two distinct groups (31% "on-craton" i.e., lower Ca/Cr, 67 % "off-craton" i.e., higher Ca/Cr) and 2 % wehrlite (G12). Two of the garnet-bearing peridotites display "sinusoidal" garnet rare earth element patterns which are often associated with rocks that have interacted with a diamond forming fluid (Stachel and Harris 2008), and of these the harzburgitic (G10) garnet has the strongest "sinusoidal" pattern. The other two garnet peridotites have garnets that are light rare earth element depleted with La < C1 chondrite and heavy rare earth element enriched (~ 10 x C1 chondrite), typical of lherzolitic garnets from cratonic peridotites (Stachel and Harris 2008).

Eclogites: The garnets from 19 "eclogite" samples are relatively Ca-poor and range from pyrope to almandine on a Mg-Ca-Fe ternary. From these eclogite xenoliths 53 % are classified as pyroxenitic (G4) and 47% eclogitic (G3). The majority of the garnet concentrate (239 grains or 82 %) contained less than 1 wt. % Cr_2O_3, and of these 5 % fall into the unclassified (G0) field, 32 % in the pyroxenitic (G4) field, and 63 % in the eclogitic (G3) field. Garnets from the eclogitic xenoliths have low TiO_2 and low Na_2O, plotting away from the eclogitic diamond inclusion field of Gurney and Zweistra (1995). Therefore, these eclogites are most likely from shallow depths outside the diamond stability field. Traditionally, to classify these eclogitic garnets as having a mantle or crustal origin, the approach of Schulze (2003) has been employed, which utilizes Ca# and Mg# as variables. This approach classified all of our xenoliths as being mantle-derived, and assigns 82 % of our eclogitic concentrate as mantle-derived. The majority of the eclogites are primarily bimineralic with respect to garnet and clinopyroxene (~ 60:40 modal abundance, respectively, ± trace rutile); however, one sample was identified petrographically as a plagioclase-bearing garnet-pyroxenite. This petrographic assessment classified this xenolith as crustal in origin, in conflict with the Schulze (2003) classification. The Hardman et al. (submitted) graphical classification scheme reduces the failure rate of crustal garnets by employing log-normalised Pearce element ratios of Ti. The method correctly classifies the plagioclase pyroxenite in our dataset as crustal and reduces the number of classified "mantle-derived" xenoliths from 100 to 47 %, and "mantle-derived" concentrate garnets from 82 % to 19 %. The Hardman et al. (submitted) graphical method defines fields where 66 % and 95 % of the scheme training data fail or are misclassified. Most of our xenolith garnet data falls within the 66 % failure envelope suggesting that crust or mantle classifications of such data are less certain. It is inferred that they are derived from very close to the crust-mantle boundary. Of 11 "eclogitic" xenoliths with fresh clinopyroxene, nine are classified as garnet-pyroxenites containing low jadeite clinopyroxene, thus most of the "eclogites" studied at Darby should be referred to as pyroxenitic.

Geotherm: Darby peridotite xenoliths were too altered to preform multiphase thermobarometry. Instead, clinopyroxenes, selected based on compositional filters of Nimis and Taylor (2000) from kimberlite heavy mineral concentrate yield a 37-39 mW/m^2 preliminary geotherm for the West Central Rae lithosphere and indicate a lithospheric thickness of ~ 200 km. Using averaged Ni-in-garnet temperatures calculated from Griffin et al. (1989) and Canil (1999), four garnet peridotites and 49 peridotitic garnets from concentrate yield two distinct modes in mantle sampling depths. A cluster of samples from the higher Ca/Cr lherzolitic garnets equilibrated at 765 to 920 °C and a group of peridotitic garnets (50 % of xenoliths and 28 % of concentrate) from the lower Ca/Cr lherzolitic garnets (94 %) have anomalously high Ti concentrations and very high Ni, yielding unreasonable T_{Ni} values of >> 1400 °C. In addition, the aluminum-in-olivine thermometer of Bussweiler et al. (2017) was applied to olivine from concentrate and xenoliths based on applying the Al – V based "garnet facies" compositional filters outlined by Bussweiler et al. (2017). This yielded two distinct mantle sampling depths from 785 to 1005 °C, in broad agreement with the Ni-in-garnet sampling mode and 1140 to 1390 °C, suggesting deep mantle sampling of thermally disturbed lithosphere close to the lithosphere-asthenosphere boundary. The Ni-in-garnet and Al-in-olivine temperatures show that the Darby kimberlite field is sampling a large depth region across the geotherm.

Age of lithospheric mantle: Osmium isotope analyses of the Darby peridotites reveal that they are highly unradiogenic. Whole-rock Re-depletion ages range from Mesoarchean to Paleoproterozoic. The pyroxenite xenoliths have very radiogenic Os isotope compositions and provide the first age information from pyroxenites/"eclogites" beneath the Rae craton. Their resulting Archean whole rock T_{MA} ages are consistent with a Mesoarchean age of the western Central Rae lithosphere, older than the lithosphere beneath the Repulse Bay block in the East section of the Rae craton (Liu et al. 2016).

Conclusions

The highly depleted olivine compositions, thick cold lithosphere, and Archean ages of the Darby peridotite xenoliths clearly indicate the presence of thick cold cratonic lithospheric mantle beneath the western segment of the central Rae craton circa 540 Ma. The Archean model ages of most of the pyroxenites support this, notwithstanding the fact that some of these rocks could be sampling either crust or mantle lithologies very close to the crust-mantle boundary. The anomalously high abundance of pyroxenite in xenoliths and in garnet concentrate at Darby (58 % of xenoliths and 82 % of concentrate: every field location yielded such xenoliths) is at odds with the abundance of eclogite/pyroxenite thought to be present in cratonic lithospheric mantle from xenocryst studies (~ one to ~ five %; Schulze, 1989; Dawson and Stephens, 1975). However, a significant portion of these rocks could originate from the lower crust, or from a pyroxenite-enriched layer in the very shallow mantle, close to the Moho. If the amount of pyroxenite is an accurate reflection of the deeper crust or shallow lithosphere beneath Darby, the high abundance of these may be related to the proximity of the field to the proposed suture between the Committee Block and the Queen Maud Block to the far West of the Rae craton. In terms of diamond potential, the low pressure nature of the abundant pyroxenitic component sampled by Darby kimberlites is non-prospective. However, the recovery of a harzburgitic (G10) garnet-bearing xenolith in a small sample of mantle xenoliths is encouraging evidence of diamond-facies peridotitic mantle being sampled. Furthermore, garnet T_{Ni} and olivine T_{Al} suggest a fairly wide diamond window is being sampled. The presence of very high T_{Ni} in some peridotitic garnets and Al-in-olivine temps approaching 1400 °C, along with the abundant higher Ca/Cr lherzolitic garnets are indicative of late thermal disturbance of the lowermost lithosphere, close to kimberlite eruption. This heating event may have reduced the diamond tenor of the lithosphere. Further studies are on-going to better evaluate the diamond potential of the Darby cratonic mantle.

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