Xenoliths and Xenocrysts from the Renard Kimberlites, Quebec: A Comprehensive Study of Mantle Samples to Determine the Evolution of the Superior Craton

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Introduction

The Superior Province in Eastern Canada is one of the world's largest Archean cratons. The Renard kimberlites are located within its eastern portion, in the northern Otish Mountains of Quebec. Nine kimberlite pipes have been discovered within a $2km^2$ area, named Renard 1 to 10, with Renard 5 and 6 joining at depth and being combined as Renard 65. The kimberlites erupted through Archean basement gneiss which had been metamorphosed to upper amphibolite to lower granulite facies (Birkett, et al. 2004).

Radiometric dating of hypabyssal Renard 1 kimberlite indicates Neoproterozoic emplacement, with a $^{206}Pb/^{238}U$ model age of 631.6±3.5 Ma (2σ) (Birkett et al., 2004). A later study on the main phases in Renard 2 and 3 gave a similar emplacement of 640.5±2.8Ma (Fitzgerald, et al. 2008). This makes this kimberlite district one of the oldest in Canada, similar in eruption age to the Wemindji kimberlites (629±29Ma: Letendre, et al. 2003). Kimberlite emplacement is broadly coeval with the conversion from subduction magmatism to rifting in northern Laurentia.

Samples

Xenoliths and xenocrysts provide a means to directly study the Earth's upper mantle. In the case of kimberlite hosted samples they provide direct insights into the origin and evolution of the subcratonic lithospheric mantle keels. To better constrain the diamond sources beneath Renard, 116 microxenoliths and xenocrysts were collected, ranging in weight from 1.2 to 2159 mg. The microxenoliths were typically bimineralic. The dominant assemblage was peridotitic, composed mainly of purple garnet and emerald green clinopyroxene with less abundant olivine and orthopyroxene, and a few pink and red garnets. A minor eclogitic assemblage consists predominantly of orange garnets with lesser amounts of clinopyroxene.

Major Elements Concentrations of the Xenoliths and Xenocrysts

The major element composition of mantle minerals was determined at the University of Alberta by wavelength-dispersive spectrometry (WDS) on a JEOL JXA-8900 Superprobe using silicate, oxide and metal standards.

Based on their Cr_2O_3 and Al_2O_3 concentrations, all but three of 54 clinopyroxenes fall into the on-craton garnet peridotite field of Ramsay (1992). Applying the single mineral thermometer of Nimis and Taylor (2000), the clinopyroxene xenocrysts indicate that a cold Slave-type paleo-geotherm was present at the time of kimberlite eruption. The majority of the samples fall on the low-pressure side of the diamond graphite-diamond transition although a single deep sample derives from a depth of 180km. Data collected by Stornoway Diamond Corp. plot further along an identical geothermal gradient down to 190 km, i.e. approaching the lithosphereasthenosphere boundary where the determined geotherm crosses the mantle adiabat. The difference may reflect a sampling bias, with deeper material being absent in the coarse sieve size collected for this research.

Analysis of the garnet grains shows that the majority plots in the on craton lherzolite field (G9A) of Grütter et al. (2004). A smaller harzburgitic (G10) and eclogite population is also present. Applying the P_{38} barometer of Grütter et al. (2006) minimum (presence of spinel not established) pressures of up to 60 kbar are derived. This is similar to the maximum depth determined from the clinopyroxene samples.

Trace Elements Concentrations of the Xenoliths and Xenocrysts

Trace element analyses were obtained by laser ablation ICP-MS, using a New Wave Research Nd:YAG UP213 laser system coupled to a Perkin Elmer Elan 6000 Quadrupole ICP-MS. The NIST 612 glass was used for primary standardization, with Ca, determined previously by electron microprobe analysis, being used as internal standard.

Ni contents of the garnets were analysed and the single-phase garnet thermometer of Canil (1999) applied. Projecting the garnet temperatures onto the established geotherm shows consistency in depth with the clinopyroxene samples. The majority of grains are derived from a restricted depth range within the graphite stability field (95-140km).

Considerable variability in the chondrite normalized trace element patterns of the peridotitic garnets is observed. Three main patterns have been identified: (1) sinusoidal; (2) humped; and (3) sloped. Sinusoidal patterns have steep positive slopes in the $LREE_N$, peaking at Nd, followed by negative slopes through the $MREE_N$ to minima at Ho or Er and positive slopes in the $HREE_N$ to Lu. Humped patterns have steep positive slopes through the $LREE_N$ from La to Sm, flat patterns from Sm to Gd with a negative slope down to Tb, followed by flat to slightly positive slopes from Tb to Lu. Sloped patterns have steeply positive slopes from La to Ho, with negative slopes from Ho to Lu.

Using data from the Kaapvaal craton, Griffin et al. (1995) developed an Y vs. Zr discrimination plot to distinguish metasomatic styles. Two trends were observed: (1) A low temperature phlogopite (fluid) metasomatism trend, with minor increase in Y compared to Zr; and (2) a more “conventional” melt metasomatism trend, with simultaneously increasing Y and Zr. The sinusoidal patterns follow the fluid metasomatism trend; the humped patterns follow the melt trend; the sloped patterns fall along a third trend not observed in Kaapvaal samples (Griffin et al., (1995)). The samples plot along a slope of increasing Y with little to no increase in associated Zr.

It is possible to determine the composition of the metasomatising fluid or melt from the garnet trace element pattern. For these model calculations the partition coefficients of Zack et al. (1997) were applied. The REE_N pattern of the calculated metasomatising agent of the garnets with sinusoidal patterns is extremely fractionated, with very high $LREE_N/HREE_N$. Such patterns are not observed in mantle melts, the likely agent, therefore, is thus a highly fractionated fluid.

The metasomatic agent associated with the garnets with sloped patterns is much less fractionated, similar to typical mantle melts such as kimberlites. The melt pattern associated with the garnets with humped patterns is similar, although the $LREE_N$ are more enriched and the heaviest REE_N more depleted (i.e. the $LREE_N/HREE_N$ is higher). Such trace element patterns may originate through interaction of an evolving melt with garnet. Similar to findings elsewhere (e.g. Malkovets, et al. 2007), it may have been the interaction of these enrichment events with more depleted regions in the subcratonic lithospheric mantle that promoted diamond formation.

Clinopyroxene Pb-Pb dating

A new protocol of In-situ Pb isotopic analyses was developed by A. Simonetti at the University of Alberta, using a Nd:YAG UP213 nm laser system (New Wave Research) coupled to a NuPlasma MC-ICP-MS instrument. A detailed description of the collector configuration array, laser and ICP-MS instrument configurations is described in Simonetti et al. (2005).

The results indicate an age of ~2.7 Ga for the subcratonic lithospheric mantle beneath Renard. This date is significant, coinciding with a major phase of continental crust generation. Also at 2.7 Ga, Kenorland (including the Superior Province) was formed by accretion of granitoid-greenstone terranes at convergent margins (Barley, et al. 2005).

Conclusions

The lithospheric mantle beneath Renard was formed no later than 2.7Ga, possibly in relation to the formation of Kenorland. Since its formation it has undergone a number of metasomatic events of different styles. The lithospheric mantle beneath Renard is composed predominantly of lherzolite, although more depleted harzburgitic portions are present, as well as eclogitic domains. Geothermobarometry indicates a cold Slave type geotherm with a large diamond window. The Renard kimberlites sampled to the base of the lithosphere at ~200km depth.

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