Origin of Cr-diopside in peridotite xenoliths: Recent metasomatic addition revealed by a micro-sampling, trace element and Sr isotopic study of on-craton and off-craton peridotites

Jacqueline Malarkey[1], D. Graham Pearson[1], Jon Davidson[1], Nadine Wittig[1]
[1] *Department of Earth Sciences, Durham University*

The modal abundance of clinopyroxene (cpx) in mantle peridotite is one of the dominant factors controlling the lithophile trace element budget of the lithospheric mantle, especially Sr and the LREE. In addition, the abundance of this phase, along with garnet, strongly influences physical properties such as density and hence seismic velocity. It is therefore critical to understand the origin and timing of cpx formation within mantle samples if we are to understand the potential temporal controls on the chemical and physical evolution of the continental lithosphere. Traditionally, in most mantle peridotites, cpx has been assumed to be a residual phase following melt extraction. However, recent work indicates that cpx and garnet may have a very recent metasomatic origin (e.g., Simon et al. 2003). This is best illustrated from plots of modal cpx versus indices of depletion, such as olivine Fo contents. Melting experiments indicate that above approximately Fo92, cpx should be exhausted from the melting assemblage (Walter 1998). However, cratonic peridotite xenoliths with average Fo content of 92.8 contain widely varying cpx contents. This is incompatible with the level of melt depletion and supports the hypothesis that the cpx is a later addition. Further evidence of a lack of trace element and isotope equilibrium between cpx and garnet indicates that the cpx addition is likely to have occurred late in the history of the peridotite (Simon, et al. 2003).

Method

We have investigated the possible origins of cpx within mantle xenoliths from both cratonic and non-cratonic settings via detailed in-situ Sr isotope studies (Micromill and TIMS) coupled with major and trace element measurements (Charlier et al. 2006). The cpx crystals are milled from a 100μm thick petrographic section so that the textural setting can be considered and cracks avoided. The sample is dissolved, with a 10% aliquot taken out for trace element analysis, put through Sr columns and then the Sr isotope ratios are analysed by TIMS. This method therefore allows both trace element and isotope rations to be analysed for the same drilled sample. Individual picked cpx chips from the xenoliths selected for drilling have also been analysed in this way. The results are consistent with the drilling technique.

We present results from three localities - spinel lherzolites erupted in an alkali basalt in the Middle Atlas of Morocco plus kimberlite-hosted peridotites from the southern margin of the N. Atlantic craton, S.W. Greenland and from Kimberley in the Kaapvaal craton.

Off-Craton Peridotites

1) Middle Atlas, Morrocco

The samples from the Middle Atlas represent ‘normal’ off-craton mantle. Over thirty cpx crystals from two xenoliths have been analysed showing consistent LREE-enriched

REE patterns similar to previous bulk cpx analyses (Wittig, this volume). Although the trace ratios are similar there is a considerable range in concentrations, with Sr, for example, varying from 134ppm to over 300ppm, showing no spatial or textural correlation within the thin section. Despite the range in trace element concentrations there is a limited range in $^{87}Sr/^{86}Sr$ values from 0.703417 (±19 2SE) to 0.703681 (±12 2SE), the variation being only twice the analytical uncertainty. There is a sufficient range in $^{87}Rb/^{86}Sr$ to conclude that there is no isochronous relationship.

On-Craton Peridotites

1) West Greenland, North Atlantic Craton

The garnet lherzolite xenoliths from Greenland represent on-craton lithospheric mantle that has experienced less modal metasomatism than other cratonic peridotites, e.g., those from the Kaapvaal craton (Bernstein et al 2006; Wittig et al, this volume). The cpx drilled from these samples have very similar Sr isotope compositions and a similarly restricted range to those from the Middle Atlas, (0.703264 (±21 2SE) and 0.703985 (±08 2SE)), again with no isochronous relationship. The trace element concentrations vary, with Sr concentrations varying between 245ppm and 136ppm. The REE are LREE-enriched with similar trace element ratios.

2) Kimberley, Kaapvaal Craton

Peridotites from the Kimberley dumps, on the Kaapvaal craton, in contrast to the other locations studied, are more strongly metasomatised. A coarse garnet lherzolite sample, with less than 1% hydrous metasomatic minerals such as phlogopite, was studied in detail. The cpx analysed from this xenolith shows large variations in trace element concentrations with the REE being LREE-enriched. However the cpx from this sample is considerably more radiogenic than those from the Greenland or Middle Atlas locations, with a large range in $^{87}Sr/^{86}Sr$ (0.703390 (±19 2SE) to 0.705860 (±26 2SE)). Despite this large range in Sr isotopes there is no relationship with $^{87}Rb/^{86}Sr$.

Garnet has also been analysed from this sample, initially by crushing and picking, but also by cutting small sections, containing only one garnet, from a polished block. This small section could then be crushed and picked retaining some degree of spatial resolution, such as proximity to cpx. Initial results show that the garnet is significantly more radiogenic in Sr than the cpx. However there is some overlap between the most radiogenic cpx and the least radiogenic garnet.

Discussion

The major element chemistry of cratonic xenoliths is consistent with cpx having a metasomatic origin. This is supported by LREE-enrichment and high Sr concentrations in the cpx. If cpx was a residual phase then the LREE, being more incompatible, would be depleted relative to the HREE. This is not observed in the majority of cratonic lherzolite suites. These results are consistent with the modelling of REE in cpx where Ionov (2002) concluded that that LREE-enriched patterns observed in the majority of cpx can be explained by reactive porous flow of a metasomatic melt, probably in a single, recent event.

The Sr isotope composition of the samples from the Middle Atlas are within the range observed for typical ocean island basalt. The values are therefore inconsistent with either long-term depletion or enrichment. The isotopically homogenous nature of the cpx within the individual peridotites from these localities supports the cpx being added during a single, recent melt infiltration event. However previous events with similar melt cannot be ruled out by this data. This melt, probably originating in the convecting mantle, dominates the Sr isotopic composition of the new cpx crystallising within a depleted harzburgite. A global compilation of cpx Sr isotope data shows that the majority of off craton cpx would be compatible with such an origin.

Cpx from cratonic peridotites show a considerably larger range in Sr than those from off-craton peridotites, with a mode closer to $^{87}Sr/^{86}Sr$ ~0.705. This mode is consistent with the Sr compositions of multiple cpx analysed from one Kimberley xenolith. These compositions can be explained if a melt derived from the convecting mantle interacts with a more radiogenic component, possibly originating from a more ancient metasomatic event, in the lithosphere, before crystallizing cpx. Alternatively, the cpx may have formed directly from a melt, such as a Group II kimberlite. This latter possibility might be more suitable for the garnets as they are more radiogenic than the cpx.

The textural, trace element and isotopic relations between these two minerals are complex indicating that different locations have experienced different scenarios. In some cases garnet and cpx crystallised together, very close to the kimberlite eruption, but in other examples they crystallised separately and have not diffusively equilibrated prior to kimberlite eruption.

The recent addition of cpx and garnet to the lithospheric mantle has at least two major implications. The first is that new mineral growth could have a significant effect on the density structure of the lithosphere. In cratonic settings this could potentially affect the stability of the craton. The second important implication is that apparent fertility of some peridotites indicated by the presence of cpx and garnet may be a much more recent feature, superimposed on top of much more depleted ancient protoliths (Simon et al., 2007; Pearson & Wittig in press).

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