Event history and down-pressure re-equilibration of highly chromian, garnet-rich peridotite xenoliths from South Africa

T.J. Ivanic (1, 2), B. Harte (2) and J.J. Gurney (3)
(1) Geological Survey of Western Australia, Mineral House, 100 Plain St., East Perth WA 6004, Australia, (2) Grant Institute of Earth Sciences, School of GeoScience, University of Edinburgh, King's Buildings, West Mains Road, Edinburgh, EH9 3JW, U.K., (3) Mineral Services South Africa (Pty) Ltd, Block B, Technosquare, 42 Morningside Road, N'Dabeni, Cape Town, South Africa (tim.ivanic@doir.wa.gov.au)

Abstract

Evidence for a multi-stage history of uplift and metasomatism is preserved in a suite of highly chromian, garnet-rich peridotites found as xenoliths in Newlands and Bobbejaan kimberlites, South Africa. A high proportion of the garnets and chromites in these rocks plot in the diamond facies fields on Cr_2O_3-CaO and Cr_2O_3-MgO wt. % plots respectively. Petrographic evidence suggests that the earliest known mineralogy is a garnet-olivine rich rock with granuloblastic texture. A down-P-T event caused exsolution of spinel and pyroxenes in garnet and these inclusion textures have subsequently been partially annealed in most samples. Harzburgitic samples have garnets with inclusions of serpentine ± chromite and in lherzolitic samples, cpx is also present. Most of the garnets have strongly developed, diffusion-controlled, major element zonation patterns which are a result of: (1) External re-equilibration where diffusion is towards the matrix. (2) Internal re-equilibration where diffusion is towards inclusions. (3) Metasomatic zonation between garnet core and its metasomatic rim. The compositional trajectories associated with (1) and (2) may be closely modelled by means of sliding, garnet-spinel transition reactions involving differing bulk pyroxene Ca compositions and they conform to a decompression event. The diffusing cations for P-T re-equilibration show a decrease in Cr/Al in the vast majority of samples. Diffusion timescales for re-equilibration zonation are generally 0.3-2 Ma with the shorter timescales belonging to internal and the longer timescales belonging to external re-equilibration zonations. Few samples, however, display evidence for relatively long lived (5-10 Ma) diffusion involving primarily an increase in Ca/Mg and Ti towards the garnet rim, which is attributed to metasomatic fluid that percolated though the matrix. Modal reconstructions reveal that the pre-exsolution bulk compositions are garnets which plot as extensions of the zonation trends at higher Cr. Therefore a substantial change in P-T (involving approx. 10kb decompression) is proposed as an explanation for exsolution and the P-T re-equilibration zonations. Based on the extent and duration of this event, we have recognised a possible correlation with Archaean crustal events identified along the Colesberg magnetic lineament at 2.7-2.9 Ga.

Introduction

Peridotitic diamond inclusions indicate a dominant and distinct diamond-garnet-chromite-harzburgite paragenesis, but there are only a few polymineralic mantle xenoliths that conform to this rock type. The garnets and chromites found in diamond inclusions are known to be highly chromian with Cr/(Cr+Al) often > 0.2 for garnets and 0.8 for chromites.

Previous studies of zoned garnets from diamond- and chromite-free peridotite xenoliths show a range of compositional trajectories (e.g. Smith and Boyd, 1992; Burgess and Harte, 1999; Griffin et al., 1999b). Burgess and Harte (1999) attribute a variety of zonation trends to metasomatism and some of the zonation types found in the present garnet-chromite peridotite xenoliths are similar to the metasomatic zonations of Burgess and Harte (1999). However, the majority of samples described here show zonation patterns and exsolution effects that conform predominantly to P-T re-equilibration, and provide evidence of a multi-stage history of uplift in chromite-bearing, garnet-rich peridotites.

Klemme (2004) shows that in the MCrS system both garnet and spinel are stable up to 70 kb on a continental geotherm as the knorringite and magnesiochromite end members. Simultaneously the high-Cr content of the high-pressure garnets means that they will tend to re-equilibrate on decompression and thus a history of decompression may preserved in exsolution and zonation features. The exceptional xenoliths described here preserve such a record and indicate a major decompression event of around 10 kb, which signifies a metamorphic history similar to crustal orogenic rocks.

Summary of xenolith petrology

The samples comprise xenoliths less than 2 cm in diameter, derived from coarse kimberlite concentrate from the Newlands and Bobbejaan kimberlites, South Africa. They are garnet-rich xenoliths of both harzburgitic and lherzolitic affinity where garnet is often > 50% modal abundance. Polygranular samples often exhibit a granuloblastic texture. All samples appear to be of peridotitic affinity on the basis of the presence of serpentine and/or their high Cr composition. The matrix may be of harzburgitic or lherzolitic affinity where the mineralogy of their inclusions corresponds to the matrix mineralogy. Opx and olivine in the samples are completely altered to serpentine by secondary alteration.

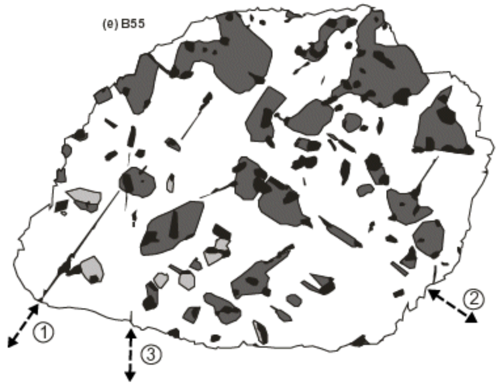

Figure 1: Digitised representation of sample surface for B55 (15mm length), a monogranular garnet sample with euhedral inclusions of Cpx (d. grey), Chr (black), srp (l. grey) in host garnet (white). Note the occurrence of at least three orientations of platey Chr and some tabular Cpx inclusions, conforming to the cubic garnet crystallography indicative of exsolution.

Internally, garnets nearly always contain inclusions of Srp ± Chr (i.e. harzburgitic affinity) or Cpx ± Srp ± Chr (i.e. lherzolitic affinity). The inclusions exhibit a range of textures from rounded and equant to subhedral and tabular to euhedral with both platy and tabular crystals. This is indicative of a product of exsolution annealed to varying degrees with B55 showing an example of a close to pristine exsolution texture (Fig. 1). Therefore the inclusions appear to be products of re-equilibration of garnet at different P-T rather than being generated by the overgrowth of garnet around pyroxene and chromite in the matrix.

Garnet Zonation Trends

The series of EMP analyses in a single garnet representing re-equilibration trends may either be ones of *external zonation, running* from the garnet core to its rim in contact with matrix, or of *internal zonation, running* from the interior of the garnet to a contact with an inclusion. The external zonation may be towards a harzburgitic (Srp ± Chr) or lherzolitic (Cpx ± Chr ± Srp) matrix and the internal zonation may be towards harzburgitic (Srp ± Chr) or lherzolitic inclusions (Cpx ± Chr ± Srp). The harzburgitic samples, with lower-Ca garnets, have steep to negatively sloping trends in Fig. 2a and the lherzolitic/wehrlitic samples, with higher-Ca garnets, have steep to moderate positive slopes Across the Cr-Ca range a continuum of zonation trajectories is present, which change gradually according to Ca concentration in garnet. This gradual change continues from the harburgitic (G10) field to the lherzolitic (G9) field. External and internal zonation show the same range of trajectories throughout the samples and, when both are present in one sample, the trends overlap each other. Metasomatic trends, form either sub-horizontal trends or ones parallel to the lherzolite line.

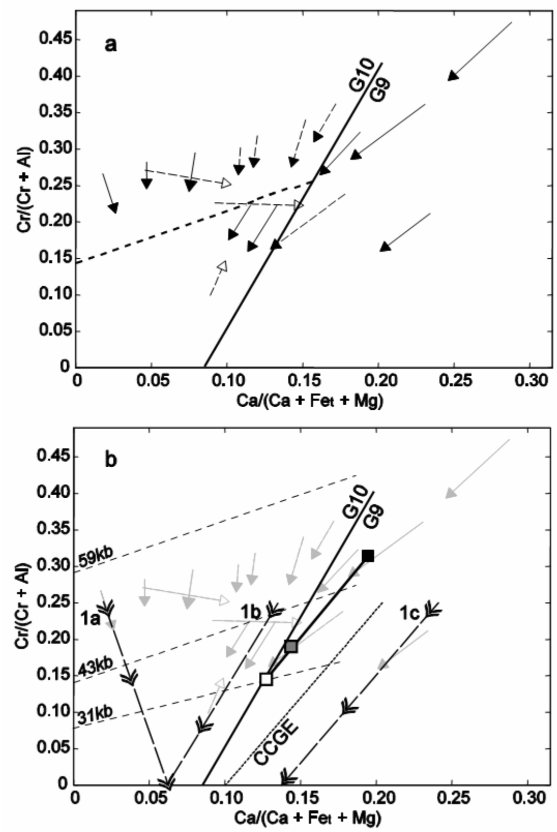

Figure 2: Garnet Cr-Ca zonation and exsolution relationships. (a) Garnet Cr-Ca zonation trends in Newlands and Bobbejaan samples in a Ca/(Ca +Fe_t + Mg) vs. Cr/(Cr + Al) atomic proportions plot. Black-tipped arrows are for re-equilibration trends and white-tipped arrows are for metasomatic trends. Dashed lines are for external zonations and solid lines are for internal zonations. Dotted lines with double barbed arrows indicate the resultant trajectories of formulations 1a, b and c. The equivalent positions of the lherzolite line (solid bold black line, Gurney, 1984) and diamond-graphite constraint (short-dashed bold black line, Grütter et al., 2004) are shown for reference. (b) as for (a), with garnet zonation trends shown in grey and with the reconstructed bulk xenolith garnet composition for B55 (black square symbol) shown in relation to the compositions of the garnet interior and garnet adjacent to inclusions (grey and white square symbols respectively). Note the continuity of the three compositions joined by a bold, long-dashed line. CCGE line (Kopylova, 2000). Three isobars are shown from Grütter et al. (2006).

The nature of the zonation patterns indicates interaction between garnet and the other phases present namely: Cr-spinel, olivine and opx (typically represented by serpentine) and with or without cpx; in all cases Cr-garnet (preserved in the cores of garnets) appears to be replaced assemblages with Cr-spinel. Thus an appropriate reaction equation of the re-equilibration process appears to have the form:

Cr-garnet + olivine $\rightarrow$ Cr-spinel + opx ± cpx

This will be a sliding or divariant reaction in which Cr-garnet components are partially converted to Cr-spinel and other phases, leaving a residual Cr-poorer garnet.

The external and internal zonation trajectories in $Ca/(Ca + Fe_t + Mg)$ and $Cr/(Cr + Al)$ in Figs. 3 and 5 clearly vary as a function of $Ca/(Ca+Fe_t+Mg)$, changing from slopes with steep negative to steep positive to moderate positive orientation. In considering the above reaction the obvious variable besides garnet compositions which must correlated with Ca content is the ratio of opx to cpx involved in each reaction

Three simple formulations of the above equation, calculated for differing Ca abundance, are used below to illustrate how the Cr-bearing garnet compositions will be affected during re-equilibration to produce Cr-spinel and variable amounts of opx and cpx. For simplicity we illustrate the end product garnet as being Cr-free, produce a reactant spinel with 50% magnesio-chromite molecule and we use ideal compositions with all Mg+Fe represented as Mg.

$2(Ca_{0.1}Mg_{2.9})[Cr_{0.5}Al_{1.5}]Si_3O_{12} + Mg_2SiO_4$ **(1a)**
$= (Ca_{0.2}Mg_{2.8})[Al_2]Si_3O_{12} + (Mg)[CrAl]O_4 + 4MgSiO_3$

$4(Ca_{0.4}Mg_{2.6})[Cr_{r0.5}Al_{1.5}]Si_3O_{12} + 2Mg_2SiO_4$ **(1b)**
$= 2(Ca_{0.2}Mg_{2.8})[Al_2\}Si_3O_{12} + 2(Mg)[CrAl]O_4 +$
$1.2CaMgSi_2O_6 + 5.6MgSiO_3$

$2(Ca_{0.8}Mg_{2.2})[Cr_{0.5}Al_{1.5}]Si_3O_{12} + Mg_2SiO_4$ **(1c)**
$= 2(Ca_{0.4}Mg_{2.6})[Al_2]Si_3O_{12} + (Mg)[CrAl]O_4 +$
$1.2CaMgSi_2O_6 + 1.6MgSiO_3$

The trajectories of change of garnet composition for these idealised reactions are compared with the actual zonation trajectories in Fig. 2. It may be seen that reaction 1a, without cpx, has a trajectory similar to the zonation patterns found in the most Ca-poor garnet compositions. Reaction 1b, with cpx present but subordinate to opx, yields slopes similar garnet compositions near the G10/G9 boundary (and the harzburgite-lherzolite transition line). Whilst the reaction with the most Ca-rich garnet and involving fairly equal amounts of cpx and opx has the shallowest positive slope, matching the zonation trend in the most Ca-rich natural garnets. Fig. 2b also shows the trend of compositions found in xenolith B55 which has the most obvious exsolution reaction texture And the trend of re-equilibration compositions in the zoned garnet forms a continuation of the change in composition which resulted from exsolution.

The modelled diffusion profiles generated error function curves from which time estimates could be made using the diffusion coefficient data of Carlson (2006). These timescales, like the diffusion distances are relatively consistent for each type of zonation. Internal zonation estimates average ~ 0.5 Ma, external zonation averages ~ 1-2 Ma and metasomatic zonation ~ 5-10 Ma.

Discussion

The complete event history is as follows:

1. The earliest known mineralogy is that of a high-Cr garnet ± olivine rock type with predominantly granuloblastic texture.
2. The start of the main down P-T event leads to the exsolution of inclusions of spinel and pyroxenes in garnet which are evident in most samples but spectacularly preserved in sample B55.
3. Annealing of original straight-sided exsolution inclusions to more rounded shapes. Annealing appears to have been T-dependent with higher T samples possessing progressively more rounded inclusions.
4. Metasomatism has affected a small volume of the xenoliths and it conforms to the percolation of a Ca-Ti metasomatic fluid, followed by diffusion over approximately a 7 Ma timescale.
5. The later part of the history involves P-T re-equilibration between garnet and minerals in its matrix and its inclusions. These have relatively short timescales of approximately 1 and 0.5 Ma, respectively. For B55 the internal re-equilibration is approximately 3 kb, which are the final P-T estimates at internal garnet-cpx boundaries.
6. An unknown time period during which the samples were below their diffusion closure temperature then occurred prior to kimberlite eruption.

The implications for the sequence of events are a significant down P-T re-equilibration history. On the basis of summing internal, external and metasomatic zonation timescales, this decompression event must have lasted at least 10 Ma, but was clearly of longer duration since the time for exsolution preceded this. Using phase equilibria modelling of high-Cr bulk rock compositions (Klemme et al., in prep) the overall changes in garnet composition indicate a total decompression of 10 kb, i.e. 30 km uplift, which is equivalent to an average of 3 mm/y for 10 Ma.

These figures signify major orogenic compressional and extensional events of lithospheric thickening and thinning which must have affected the crust as well as lithospheric mantle. Such events might be linked in southern African crustal history with the proposed coming together of the Kimberley and Witwatersrand cratonic blocks in the vicinity of the Colesberg lineament at ca 2.9 to 2.8 Ga (De Wit and Tinker, 2004; Carlson and Moore, 2004; Schmitz et al., 2004). Seismic profiles and associated data do provide evidence of major tectonic imbrication and stacking of Kimberley block crustal slices or panels on the Witwatersrand block at ca 2.9 to 2.76 Ga and preceding a period of extension during Ventersdorp volcano-tectonic rifting at ca 2.7 Ga (De Wit and Tinker, 2004). Thus there is evidence of substantial crustal thickening and thinning within a 2.9 to 2.7 Ga time period, which would correspond well with the estimated duration of decompression for the Cr-rich mantle xenoliths described herein. This would also offer a possible explanation for the long-lived metasomatic event affecting some of the rocks at this time. This correspondence would imply a firm linkage of crust and mantle lithosphere at this time. The coupling of crust and mantle is supported by the similarity of Os/Re model ages for peridotite xenoliths from Newlands, Kimberley and Monastery to those of U/Pb zircon ages for nearby crustal rocks in the Kimberley block (De Wit and Tinker, 2004; Eglinton and Armstrong, 2004; Carlson and Moore, 2004).

References

Burgess, S. R. and Harte, B., 1999. Tracing lithosphere evolution through the analysis of heterogeneous G9/G10 garnets in peridotite xenoliths, I: Major element chemistry, in: Gurney, J.J., Gurney, J.L., Pascoe, M.D., Richardson, S.H., (Eds.), Proceedings of the VIIth International Kimberlite Conference, Cape Town, Red Roof Designs, 66-80.

Carlson, R.W., Moore, R.O., 2004. Age of the eastern Kaapvaal mantle: Re-Os isotope data for peridotitic xenoliths from the Monastery kimberlite, in: De Wit, M.J., Richardson, S.H., Ashwal, L.D. (Eds.), Kaapvaal craton, South African Journal of geology. Special Volume 107, 81-90.

Carlson, W. D., 2006. Rates of Fe, Mg, Mn and Ca diffusion in garnet. American Mineralogist, 91, 1-11.

De Wit, M.J., Tinker, J., 2004. Crustal structures across the central Kaapvaal Craton from deep-seismic reflection data, in: De Wit, M.J., Richardson, S.H., Ashwal, L.D. (Eds.), Kaapvaal craton, South African Journal of Geology Special Volume 107, 185-206.

Eglinton, B.M., Armstrong, R.A., 2004. The Kaapvaal Craton and adjacent orogens, southern Africa: a geochronological database and overview of the geological development of the craton, in: De Wit, M.J., Richardson, S.H., Ashwal, L.D. (Eds.), Kaapvaal craton, South African Journal of Geology Special Volume 107, 13-32

Grütter, H. S., Gurney, J. J., Menzies, A. H. and Winter, F., 2004. An updated classification scheme for mantle-derived garnet, for use by diamond explorers. Lithos, 77, 841-857.

Grütter, H. S., Lattu, D., Menzies, A. H., 2006. Cr-saturation arrays in concentrate garnet compositions from kimberlite and their uses in mantle barometry. Journal of Petrology, 47. 801-820.

Gurney, J. J., 1984. A correlation between garnets and diamonds in kimberlites, in: Glover, J.E., Harris, P. G. (Eds.), Kimberlites: Occurrence and origin: A basis for conceptual models in exploration. University of Western Australia, Extension Services, 8, 143-166.

Ivanic, T. J., 2007. The chromite garnet peridotite assemblages and their role in the evolution of the mantle lithosphere. Unpublished PhD thesis, Univ. Edinburgh.

Klemme, S., 2004. The influence of Cr on the garnet-spinel transition in the Earth's mantle: experiments in the system MgO-Cr2O3-SiO2 and thermodynamic modelling, in: Mitchell, R.H., Grütter, H.S., Heaman, L.M., Scott Smith, B.H., Stachel, T., (Eds.), 8th International Kimberlite Conference Selected Papers. The J. Barry Hawthorne Vol. (2). Lithos, 77, 639-646.

Klemme, S., Ivanic, T. J. and Harte, B., Thermodynamic modelling of Cr-bearing garnet-spinel peridotite with reference to a suite of highly chromian, garnet-rich xenoliths from South Africa. In prep.

Kopylova, M.G., Russel, J.K., Stanley, C., Cookenboo, H., 2000. Garnet from Cr- and Ca-saturated mantle: implications for diamond exploration. Journal of Geochemical Exploration, 68, 183-199.

Schmitz, M.D., Bowring, S.A., De Wit, M.J., Gartz, V., 2004. Subduction and terrane collision stabilize the western Kaapvaal craton tectosphere 2.9 billion years ago. Earth Planetary Science Letters, 222, 363-376.

Smith, D. and Boyd, F. R., 1992. Compositional zonation in garnets in peridotite xenoliths. Contributions to Mineralogy and Petrology, 112, 134-147.