

Compositional variability of the Roberts Victor eclogites: evidence for mantle metasomatism involving diamond dissolution

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The origin of eclogite xenoliths in kimberlites has long been a controversial subject but models favoring subduction of ancient oceanic crust are now generally accepted, based primarily on stable isotope evidence (e.g. Jacob, 2004). However, textural, petrological and compositional features which earlier studies cited as evidence of mantle processes are still not explained adequately from the crustal protolith standpoint. Published garnet and clinopyroxene compositions in mantle eclogites show extreme variability, indicating the influence of mantle differentiation, in addition to that created by protolith heterogeneity. The mineral assemblages of most eclogite xenoliths are generally biminerale (clinopyroxene and garnet), whereas more complex assemblages should be expected for metamorphosed crustal processes. The combined evidence suggests that high-pressure intra-mantle processes may have substantially altered the compositions of the original metamorphic products.

In order to identify the processes creating the huge compositional variability within “eclogites”, an extensive xenolith suite from the Roberts Victor Mine, South Africa was re-examined, devoting particular attention to compositional heterogeneities preserved at the individual nodule scale. The typically large size of Roberts Victor eclogites allows a through examination of the scale-length of compositional heterogeneity. We investigated the major elements variability of constituent garnet and clinopyroxene from 74 samples [56 new samples and 18 specimens previously examined in Hatton (1978)] and combined this with data for 212 samples from previous studies (Bishop *et al.*, 1978; Caporuscio and Smyth, 1990; Carswell *et al.*, 1981; Chinner and Cornell, 1974; Harte and Kirkley, 1999; Hatton, 1978; Kushiro and Aoki, 1968; Lappin, 1978; Lappin and Dawson, 1975; MacGregor and Manton, 1986; O'Reilly and Griffin, 1995; Reid *et al.*, 1976; Sautter and Harte, 1988; Schulze *et al.*, 2000; Schulze *et al.*, 1996; Sobolev, 1977).

Eclogite classification

It has been widely accepted that mantle eclogites can be classified into two groups (I and II) based on their textural and compositional characteristics (MacGregor and Carter, 1970; McCandless and Gurney, 1989). Group I eclogites have subhedral or rounded garnet in a ‘matrix’ of interstitial clinopyroxene, whereas in Group

II xenoliths garnet and clinopyroxene have straight grain boundaries and an interlocking fabric. Group I eclogites can be distinguished from Group II eclogites by their higher Na₂O in garnet (≥ 0.09 wt%) and K₂O in clinopyroxene (≥ 0.08 wt%). Although this classification scheme has been established specifically for Roberts Victor samples, there are a significant number of samples (~10%) that are difficult to categorize unambiguously. For example, Hatton (1978) reported mineral compositions for 21 orthopyroxene-bearing eclogites (websterites) and placed only 3 samples into Group I based on textural appearance. However, 5 of his Group II websterites contain high-Na garnet or high-K clinopyroxene. McCandless and Gurney (1989) suggested that all kyanite-bearing eclogites at Roberts Victor are of Group I, but low-Na garnet and low-K clinopyroxene coexist with kyanite in 4 of 21 samples. We therefore relied mainly on the above chemical criteria and assigned 62 of 286 samples to Group II.

As shown in Fig. 1A, Group II eclogites may be differentiated into two subgroups based on the almandine component of their garnet [IIA: Fe/(Ca+Mg+Fe) <0.3, IIB: Fe/(Ca+Mg+Fe) >0.3]. IIB eclogites generally show typical Group II textures and minimal compositional heterogeneity within single specimen. Accessory quartz and rutile are relatively common. Note that all reported eclogites showing $\delta^{18}\text{O}$ -values <5‰ belong to this group (MacGregor and Manton, 1986; Ongley *et al.*, 1987).

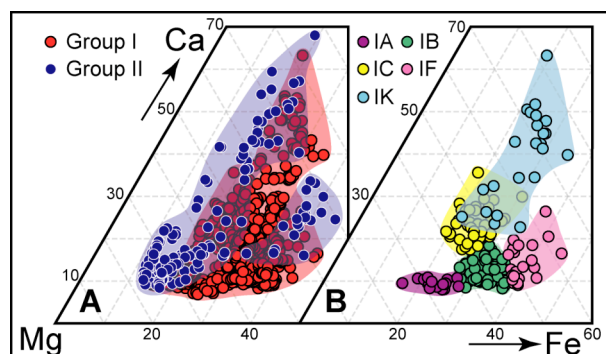


Fig. 1. Garnet compositions for Roberts Victor eclogites on Ca-Mg-Fe ternary diagrams, displaying differences between Group I and II (A), or variations within homogeneous Group I (B; see text for detail). Most plots represent averaged compositions within single samples, except for heterogeneous samples where all analyzed compositions are plotted.

On the other hand, most IIA eclogites display varied compositional heterogeneities manifested by garnet exsolution from precursor CaTs-rich clinopyroxene (e.g. Sautter and Harte, 1988) and Cr-enrichments across the modal layering (Hatton, 1978). Primary spinel, orthopyroxene and corundum can be found as accessory minerals in this group, showing some affinity with the Kaalvallei Group II eclogites (Viljoen *et al.*, 2005).

Hereafter, we focus on Group I eclogites because diamonds are confined to Group I, and the majority of eclogites investigated belong to Group I (224 of 286 samples). This proportion is consistent with the other estimations of the occurrence of Group I eclogites at Roberts Victor (~75%: Hatton, 1978; 79%: Schulze *et al.*, 2000). Most group I eclogites show minimal compositional heterogeneity (184 of 224 samples) and can be classified here as “homogeneous” in that their garnets occupy characteristic fields in a conventional Ca-Mg-Fe ternary diagram (Fig. 1B). These homogeneous eclogites can be further subdivided into a Mg-rich Group (IA: 19 samples), a transitional main Group (IB: 73 samples), a Ca-rich Group (IC: 43 samples), an Fe-rich Group (IF: 25 samples) and a kyanite-bearing Group (IK: 24 samples). Apart from the IK Group, accessory silicate minerals are absent in the vast majority of these eclogites. However, orthopyroxene is relatively common in IA (8 samples) and coesite occasionally occurs in Groups IC and IK (9 and 7 samples, respectively). Schulze *et al.* (2000) reported rare occurrences of coesite in other sub-groups (IA: 1 sample, IB: 2 samples, IF: 4 samples).

In contrast to these “endmember” sub-groups, the remaining Group I eclogites possess cm-scale compositional heterogeneity, and most of them display layer-by-layer variations in garnet compositions that tend to lie between the fields of Groups IA, IC, IF and IK thorough to those of IB main Group (Fig. 2A). In contrast, garnet compositions in two heterogeneous diamondiferous eclogites lie between Group IA and IC. The origin of this trend is discussed in Ishikawa *et al.* (This volume).

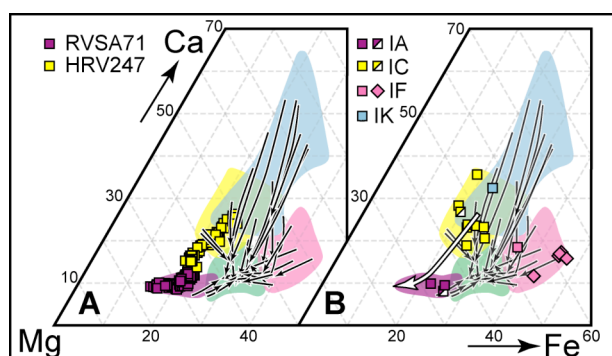


Fig. 2. (A) Garnet compositional trends for Group I heterogeneous eclogites shown by arrows, which represent the extents of variation within single xenoliths. Squares show all analyzed compositions of garnet in heterogeneous diamondiferous eclogites. (B) Garnet compositions (averaged) for diamondiferous eclogites (squares), graphite eclogites (half-open squares) and E-type diamond inclusions (diamonds). Black arrows may represent trends related to diamond dissolution, whereas the white arrow shows the compositional trend that may be related to diamond precipitation.

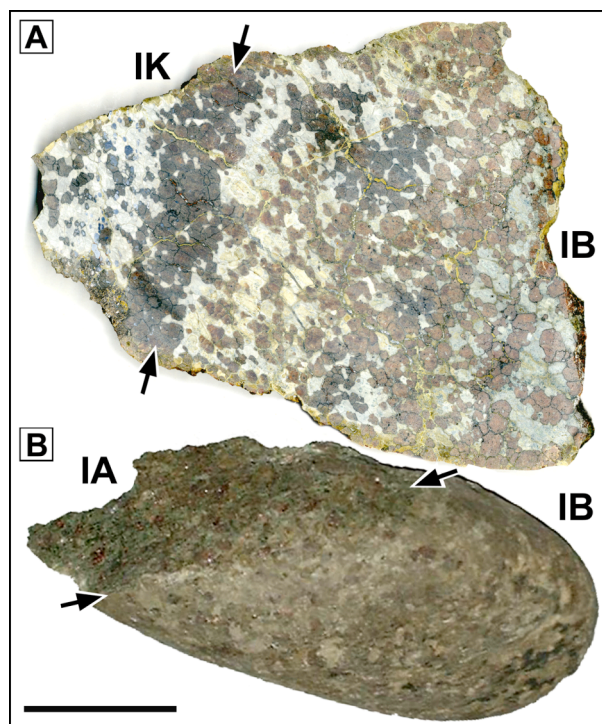


Fig. 3. Photographs of Group I heterogeneous eclogites divided into (A) kyanite-rutile bearing (left; IK) and bimineralic portions (right; IB), and (B) websterite (upper-left; IA) and bimineralic portions (lower-right; IB). Arrows indicate possible boundary defined by disappearance of accessory kyanite and orthopyroxene. Scale bar = 5 cm.

Origin of the compositional layering

The continuously variable chemistry of the heterogeneous samples is accompanied by petrological and textural variation that can be summarized as: (1) disappearance of kyanite, rutile, orthopyroxene and possibly coesite (Figs. 3A and 3B); (2) the prominence of “cumulate” textures characterized by rounded grains of garnet in an interstitial matrix of clinopyroxene (Figs. 3A and 4A); (2) the appearance of phlogopite (Fig. 3B) and poly-mineralic inclusions in garnet (Fig. 4B). These petrologic features of compositionally heterogeneous samples, can be explained by a model that invokes the metasomatism of Group I eclogite by infiltrating silicate melts, consuming and removing easily fusible components from the protoliths while generating refractory garnet, clinopyroxene and “secondary” phlogopite in the residue. This model indicates that the most abundant IB eclogites were more extensively disturbed than other subgroups.

Although the origin of the infiltrating magma (possibly related to the proto-kimberlite or a highly-evolved low-Cr megacryst magma) remain uncertain, this stage of infiltration metasomatism was most likely aggressive towards diamonds because none of the IB eclogites have been found to contain diamond. In contrast, the garnet and clinopyroxene compositions of previously reported diamondiferous eclogites and E-type diamond inclusions (Gurney *et al.*, 1984) are restricted to those of “endmember” IA, IC and IF compositions. This interpretation is consistent with the observation that the Re-Os isotopic system in diamondiferous eclogites is less disturbed than in non-diamondiferous eclogites

(Shirey *et al.*, 1999). Thus, detailed study utilizing trace element and isotopic analyses is aimed at providing further constraints on this metasomatic process.

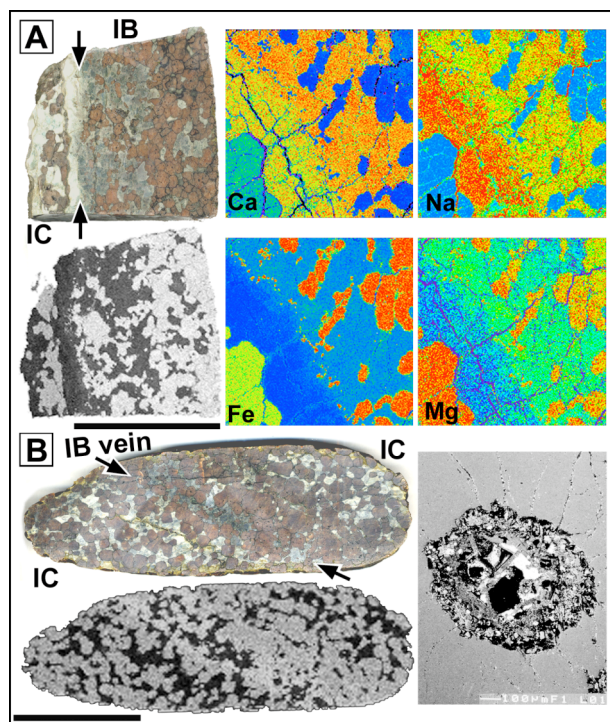


Fig. 4. Photographs of Group I heterogeneous (between IC and IB) bimineralic eclogite xenoliths. Greyscale images are Fe concentration maps made by scanning X-ray analytical microscope (SXAM), illustrating the occurrence of high-Fe garnet in IB portions. Scale bars = 5 cm. (A) Sample RVSA63 shows abrupt changes in clinopyroxene and garnet chemistry across the two zones as illustrated in elemental concentration maps of the boundary region (right coloured images; field of view = 1.8 cm). Note the fine-grained garnet nucleated in the IB side of the boundary. (B) Sample RVSA78 has thin-layer of IB "vein", whose garnet contains abundant polyminerallc inclusions (right BSE image) comprised of phlogopite, amphibole, chlorite, Al-spinel and diopside.

References:

- Bishop, F.C., Smith, J.V., Dawson, J.B., 1978. Na, K, P and Ti in garnet, pyroxene and olivine from peridotite and eclogite xenoliths from African kimberlites. *Lithos*, 11, 155-173.
- Caporuscio, F.A., Smyth, J.R., 1990. Trace element crystal chemistry of mantle eclogites. *Contributions to Mineralogy and Petrology*, 105, 550-561.
- Carswell, D.A., Dawson, J.B., Gibb, F.G.F., 1981. Equilibration temperatures of upper-mantle eclogites: implications for kyanite-bearing and diamondiferous varieties. *Mineralogical Magazine*, 44, 78-89.
- Chinner, G.A., Cornell, D.H., 1974. Evidence of kimberlite-grospydite reaction. *Contributions to Mineralogy and Petrology*, 45, 153-160.
- Gurney, J.J., Harris, J.W., Rickard, R.S., 1984. Minerals associated with diamonds from the Roberts Victor Mine. In: Kornprobst, J. (Ed.), *Kimberlites II: The Mantle and Crust-Mantle Relationships*. Elsevier, Amsterdam, 25-32.
- Harte, B., Kirkley, M.B., 1999. Partitioning of trace elements between clinopyroxene and garnet: data from mantle eclogites. *Chemical Geology*, 136, 1-24.
- Hatton, C.J., 1978. The geochemistry of xenoliths from the Roberts Victor Mine. Ph.D Thesis, University of Cape

Town, 179 pp.

- Ishikawa, A., Pearson, D.G., Maruyama, S., Cartigny, P., Ketcham, R.A., Gurney, J.J., This volume. Compositional layering in a highly diamondiferous eclogite xenolith from the Roberts Victor kimberlite, South Africa and its implications for diamond genesis. Extended abstracts of the 9th International Kimberlite Conference, Frankfurt.
- Jacob, D.E., 2004. Nature and origin of eclogite xenoliths from kimberlites. *Lithos*, 77, 295-316.
- Kushiro, I., Aoki, K., 1968. Origin of some eclogite inclusions in kimberlite. *American Mineralogist*, 53, 1347-1367.
- Lappin, M.A., 1978. The evolution of a grospydite from the Roberts Victor Mine, South Africa. *Contributions to Mineralogy and Petrology*, 66, 229-241.
- Lappin, M.A., Dawson, J.B., 1975. Two Roberts Victor cumulate eclogites and their re-equilibration. *Physics and Chemistry of the Earth*, 9, 351-365.
- MacGregor, I.D., Carter, J.L., 1970. The chemistry of clinopyroxenes and garnets of eclogite and peridotite xenoliths from the Roberts Victor Mine, South Africa. *Physics of the Earth and Planetary Interiors*, 3, 391-397.
- MacGregor, I.D., Manton, S.E., 1986. Roberts Victor eclogites: ancient oceanic crust. *Journal of Geophysical Research*, 91, 14063-14079.
- McCandless, T.E., Gurney, J.J., 1989. Sodium in garnet and potassium in clinopyroxene: criteria for classifying mantle eclogites. In: Ross, J. (Ed.), *Kimberlites and Related Rocks. Vol. 2. Their Mantle/Crust Setting, Diamonds and Diamond Exploration*. Geological Society of Australia Special Publications, 14, 827-832.
- O'Reilly, S.Y., Griffin, W.L., 1995. Trace-element partitioning between garnet and clinopyroxene in mantle-derived pyroxenites and eclogites: P-T-X controls. *Chemical Geology*, 121, 105-130.
- Ongley, J.S., Basu, A.R., Kyser, T.K., 1987. Oxygen isotopes in coexisting garnets, clinopyroxenes and phlogopites from Roberts Victor eclogites: implications for petrogenesis and mantle metasomatism. *Earth and Planetary Science Letters*, 83, 80-84.
- Reid, A.M., Brown, R.W., Dawson, J.B., Whitfield, G.G., Siebert, J.C., 1976. Garnet and clinopyroxene compositions in some diamondiferous eclogites. *Contributions to Mineralogy and Petrology*, 58, 203-220.
- Sautter, V., Harte, B., 1988. Diffusion gradients in an eclogite xenolith from Roberts Victor kimberlite pipe: 1. Mechanism and evolution of garnet exsolution in Al_2O_3 -rich clinopyroxene. *Journal of Petrology*, 29, 1325-1352.
- Schulze, D.J., Valley, J.W., Spicuzza, M.J., 2000. Coesite eclogites from the Roberts Victor kimberlite, South Africa. *Lithos*, 54, 23-32.
- Schulze, D.J., Wiese, D., Steude, J., 1996. Abundance and distribution of diamonds in eclogite revealed by volume visualisation of CT X-ray scans. *Journal of Geology*, 104, 109-113.
- Shirey, S.B., Carlson, R.W., Gurney, J.J., Van Herden, J., 1999. Re-Os isotopic systematics of eclogites from Roberts Victor: implications for diamond growth and Archean tectonic processes. Extended abstracts of the 7th International Kimberlite Conference, Cape Town, 808-810.
- Sobolev, N.V., 1977. Deep seated inclusions in kimberlites and the problem of the composition of the upper mantle. American Geophysical Union, Washington D.C.
- Viljoen, K.S., Schulze, D.J., Quadling, A.G., 2005. Contrasting group I and group II eclogite xenolith petrogenesis: petrological, trace element and isotopic evidence from eclogite, garnet-websterite and alkremite xenoliths in the Kaalvallei kimberlite, South Africa. *Journal of Petrology*, 46, 2059-2090.