New constraints on the origin of Roberts Victor eclogites: geochemical evidence for a subducted arc or back-arc basalt protolith

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Introduction

Two scenarios of formation are prevalent in the debate over the origin of deep mantle eclogites. The first proposes that the eclogite protoliths were Proterozoic and Archean oceanic basalts and gabbroic cumulates that were subducted and accreted to the peridotitic bases of the cratons (e.g. MacGregor and Manton, 1986). Alternatively it has been suggested that eclogite is formed beneath cratons in a process that occurs at pressures in excess of 3GPa. This involves accumulation from deep-mantle melts of an anomalous, hyperaluminous pyroxene, followed by exsolution of kyanite, garnet and sometimes silica due to decreasing in temperature (O'Hara and Yoder, 1967).

Much of the above debate has centred around the Roberts Victor eclogite suite due to the large size and abundance of eclogites formerly available from this mine. A subduction origin for eclogites from this location has become the favoured hypothesis due to convincing arguments based on δO^{18} data, REE patterns, and Eu anomalies (e.g. Jagoutz *et al.*, 1984; Schulze *et al.*, 2000; and Jacob *et al.*, 2003). Jacob *et al.* (2003) invoked oceanic gabbroic cumulate protoliths for the coesite-bearing eclogites from Roberts Victor. Here we present new trace element and Re-Os isotope data for a suite of eclogites from this kimberlite with the aim of further evaluating their origin, specifically attempting to identify the likely protoliths.

Samples and regional geology

The Roberts Victor kimberlite is situated in the centre of the Kaapvaal craton and lies on the Colesberg magnetic lineament. This lineament is thought to represent a collisional suture between the Kimberley and Witwatersrand blocks, which converged approximately 2.9 billion years ago. Suturing was accommodated by subduction and terrane collision (Schmitz *et al.* 2004).

A suite of 12 bimineralic eclogites, classified as Group I and II were analysed for whole-rock major and trace elements by ICP-OES and ICP-MS. In seven of the xenoliths, garnets and clinopyroxenes were analysed for REE by Laser Ablation-ICP-MS. 'Reconstructed bulk-rock' trace element concentrations were produced by combining modal mineral proportions with LA-ICP-MS data generated on garnet and clinopyroxene. Re-Os isotopes were measured for nine of the samples, by negative-TIMS.

Elemental geochemistry

All 12 eclogites analysed have 1 atmosphere CIPW normative assemblages containing considerable amounts of plagioclase (~30 – 60 wt %) and between approximately 17 and 38 wt % olivine. None of the samples have normative quartz. Five of the xenoliths (RV-IM-09, -10, -12, -13 and -17) are nepheline normative and thus can be classified as having protoliths of alkali basaltic compositions. The remaining seven xenoliths contain normative hypersthene, thus, chemically they resemble olivine tholeiites. Interestingly, samples with olivine tholeiite normative compositions are classed as Group I eclogites, while those with alkalic normative assemblages fall within Group II.

Whole-rock MgO contents range from 10.06 – 14.84 wt%, with Group I xenoliths being generally more MgO-rich. In comparison, published MgO data for potential protoliths are as follows: oceanic gabbros, ~4 – 12 wt%; komatiites and basaltic komatiites, > ~10 wt%; MORB, ~5 – 10 wt%; and Archean picrites and komatiites, ~17.5 – 25 wt% (Wilson, 1989).

Element (wt %)	Mean Roberts Victor Eclogites	Mean Grenada Picrites
SiO_2	44.71	46.02
Al_2O_3	16.60	13.78
Fe_2O_3	12.73	10.24
MgO	12.70	14.06
CaO	9.00	11.65
Na_2O	1.88	1.99
K_2O	0.52	0.63
TiO_2	0.40	0.94
MnO	0.25	0.17
P_2O_5	0.05	0.20
Total	98.83	99.63

Table 1. Mean major element composition of Roberts Victor eclogites (this study) and Grenada arc picrites (Woodland *et al.*, 2002).

SiO_2 contents of the eclogite suite are low (40.19 – 48.42 wt %) relative to MORB and oceanic gabbros, but fall within the range of komatiites and basaltic komatiites. All of the xenoliths are relatively rich in Al_2O_3 (11.21 – 20.62 wt %), while, TiO_2 concentrations are low (0.22 – 0.50 wt %). Over all, the whole-rock major element compositions of this suite of eclogites strongly resemble those of a suite of picrites from Grenada, in the Lesser Antilles arc (Table 1) (Woodland *et al.*, 2002), presuming no mantle-based modification of major element chemistry has taken place.

The Roberts Victor eclogites have flat reconstructed bulk-rock HREE patterns with relative depletion in the LREEs (mean La/YbN = 0.361). Positive Eu anomalies in the reconstructed eclogite trace element compositions (Figure 1) indicate that the protoliths of these eclogites have, at some time, experienced plagioclase fractionation in a low pressure environment (< 0.6 GPa).

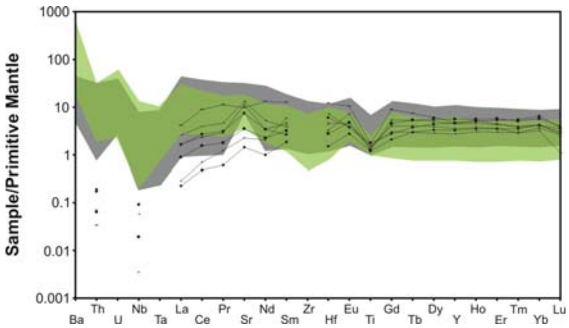

Figure 1. Trace element patterns for RV reconstructed bulk eclogite, normalised to primitive mantle (Sun and McDonough, 1989). Green shaded area = measured bulk-rock for RV suite, grey shaded area = New Britain Arc bulk-rock (Woodhead *et al.*, 1998).

Mantle normalised multi-element plots of both measured and reconstructed bulk-rock data show strong negative anomalies in Ta, Nb, and Ti (mean Nb/LaN = 0.024; mean Ti/Ti*= 0.132) and consistently positive anomalies for Sr. Similar Sr anomalies can be seen in other eclogite suites, however Ta, Nb, and Ti anomalies of such extreme magnitude are abnormal (Figure 1). The same pattern is seen in reconstructed bulk-rock data for rutile-bearing Roberts Victor coesite-eclogites (Jacob *et al.*, 2003). In this case the authors state that the Nb, Ta and Ti anomalies are "artificially low" since rutile was not used for the reconstructions where as in samples that were reconstructed allowing for rutile, positive Nb, Ta and Ti anomalies are observed. However, in the case of the bimineralic eclogites of this study, Nb, Ta and Ti depletion is also observed in measured bulk-rock, as mentioned above, though it is less pronounced. It is possible that the difference in concentration of these elements between measured and reconstructed bulk-rock is due to the (unconfirmed) presence of very minor amounts of rutile; alternatively it may be a product of contamination with Ti-bearing phlogopite by the host kimberlite (Jacob *et al.*, 2005), since phlogopite is observed along fractures and around the margins of these xenoliths, or a combination of both.

The eclogite trace element patterns are strikingly similar to those observed for basalts in modern arc (Woodhead *et al.*, 1998; Woodland *et al.*, 2002) and back-arc environments (e.g. Pearce *et al.*, 1995), not only in shape but also in the range of normalised concentrations displayed (Figure 1).

Re-Os isotopes and abundances

Re contents of the Roberts Victor eclogites span approximately the same range as Alpine gabbroic eclogites (~100 – 1000 ppt; Dale *et al.*, 2007). However, Os concentrations are relatively high (Os, 48 – 702 ppt) and exceed Alpine eclogite values (Figure 2) such that Roberts Victor eclogite Re/Os ratios are lower. Grenada picrites are very low in Re but their Os contents overlap with those of the Roberts Victor samples (Woodland *et al.*, 2002). Re concentrations in komatiites from Alexo, Ontario fall within the range of the Roberts Victor samples and their Os contents also overlap the Roberts Victor range (Gangopadhyay and Walker, 2003). However, Commondale komatiitic lavas from the Southern Kaapvaal Craton have lower Re and higher Os than the eclogites (Wilson *et al.*, 2003), and consequently lower Re/Os ratios (Figure 2).

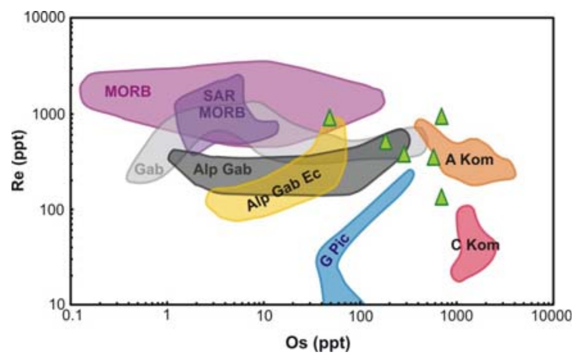

Figure 2. Os vs. Re for six Roberts Victor eclogites. Fields as follows: Purple, MORB (Schiano *et al.*,1997); dark purple, MORB glasses, South Atlantic Ridge (Escrig *et al.*, 2005); light grey, Gabbros – ODP Site 735B (Blusztajn *et al.*, 2000); dark grey, Alpine gabbros; yellow, Alpine gabbroic eclogites (Dale *et al*,. 2007); orange, komatiites from Alexo, Ontario (Gangopadhyay and Walker, 2003); red, Commondale komatiitic lavas (Wilson *et al.*, 2003); and blue, Grenada picrites (Woodland *et al.*, 2002).

$^{187}Os/^{188}Os$ and $^{187}Re/^{188}Os$ ratios (ranging between 0.33 – 1.03 and 0.96 – 95.3 respectively) match the patterns of other non-diamondiferous eclogites from the Kaapvaal Craton (Shirey *et al.*, 2001). The relatively unradiogenic Os isotope ratios found in eclogites from Roberts Victor and in eclogites from the Kaapvaal craton in general contrast with the considerably more radiogenic ratios and requisite higher time-integrated Re/Os ratios displayed by Siberian eclogites (Pearson *et al.*, 1995).

Re-Os model ages scatter widely, suggesting some disturbance of the Re-Os system has occurred. The eclogite suite as a whole does not form an isochron but scatters across a wide range of $^{187}Re/^{188}Os$ values. One sample has highly elevated $^{187}Re/^{188}Os$, suggestive of recent Re gain. However, samples with lower $^{187}Re/^{188}Os$ have a well correlated range of $^{187}Os/^{188}Os$ values that scatter around an 'isochron' of approximately 3Ga with an elevated initial ratio. Eclogite samples that show the most coherent Re-Os isotope variation belong to the group I classification, which is more commonly diamondiferous. This supports the general observation made by Shirey *et al.* (2001) that diamondiferous or Group I eclogites from a variety of locations show the least disturbed Re-Os isotope systematics.

Discussion and genetic model

The geochemical signatures of the Roberts Victor eclogites appear to have a strong crustal signature and both major element and trace element compositions match various rock suites associated with modern-day subduction zones, particularly those from island arcs. Examples of subducting back-arc basins are numerous in SE Asia today and subduction of arc rocks has been observed in modern collision zones (Macpherson *et al.*, 2003). It has been postulated that genesis of the peridotitic root of the Kaapvaal craton took place via subduction in an arc environment (Parman *et al.*, 2004; Simon *et al.*, 2007; Pearson & Wittig, 2008) Given this subduction association we believe it is reasonable to assume that arc rocks may also have been subducted in Archean collision zones.

It should be noted that we do not discount the low δO^{18} data presented by authors such as Jagoutz *et al.* (1984), Schulze *et al.* (2000) and Jacob *et al.* (2003) as strong evidence of hydrothermally altered gabbroic protoliths for mantle eclogites. However, subducted Archean oceanic crust is isotopically heterogeneous (as noted by Jacob *et al.*, 2005), and, like modern oceanic crust, generated in a variety of tectonic environments, giving rise to diverse compositional variation. Hence we propose that the Roberts Victor bimineralic eclogites analysed in this study were formed from picritic basalts crystallised in an arc or back-arc environment. Subsequent subduction and terrane collision processes at ~2.9 Ga forced the Ta, Nb and Ti depleted protoliths from their crustal environment to the base of the craton. Later extensive silicate metasomatism of the type described by Ishikawa *et al.* (this volume) acted to disturb Re-Os and other isotope systematics in many eclogites while the Group I eclogites appear to have mostly evaded this modification.

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