



## Origin of high-Mg bimineralic eclogite xenoliths in kimberlite: A comment on a paper by Aulbach and Arndt (2019)



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Most mantle eclogites sampled by kimberlite through cratons are essentially bimineralic, consisting of garnet and omphacite, with rare accessory rutile (Jacob, 2004). Despite this simple lithology, many hypotheses have been proposed for the origin of bimineralic eclogite, and the excellent reviews provided by Jacob (2004) and Smit et al. (2014) cover four possibilities. These are: 1) remnants of subducted oceanic crust, 2) high pressure cumulates of mantle melts, 3) residues after melting of subducted oceanic crust and, 4) melt-rock reaction products. To these I will add a fifth hypothesis.

The first hypothesis, that bimineralic eclogite xenoliths are remnants of subducted oceanic crust, seems reasonable because it is widely recognized that the basalt-eclogite transformation is a major driving force in subduction zones. Aulbach and Arndt (2019) have assumed this hypothesis to be true, and state: “Some high-Mg eclogite xenoliths (i.e., bimineralic eclogite) ... have elemental and isotopic compositions indicative of protoliths that formed as little-differentiated melts erupted in ancient ocean floors”. If this is correct, then it is possible to infer the thermal conditions of the mantle at which these “primary magmas” formed (i.e., mantle potential temperature  $T_p$ ) using petrological methods. Furthermore, as many bimineralic eclogite xenoliths have Archean ages, these rocks may offer a new way to constrain the thermal history of the Earth. However, these inferences will be erroneous if high-Mg bimineralic eclogite xenoliths are not remnants of subducted oceanic crust.

The compositions of Archean high Mg bimineralic eclogites used in the Aulbach–Arndt study are shown in Fig. 1a, a projection from Diopside into the Ol–CATS–Qz plane. These include all samples, filtered and unfiltered, and they have been reconstructed

from clinopyroxene and garnet compositions. They all project close to the Garnet–Pyroxene plane, as expected for bimineralic eclogites. Moreover, the rules of stoichiometry require that they project exactly within the Garnet–Pyroxene plane, so the variability in Fig. 1a is likely an artifact of analytical uncertainties, and the neglect of  $\text{Cr}_2\text{O}_3$  and  $\text{Fe}_2\text{O}_3$ . Addition of minor rutile would shift their projected compositions slightly to the silica-rich side of the plane.

Included in Fig. 1a are modern MORB glasses, their PRIMELT3 primary magma (Herzberg and Asimow, 2015), and a MELTS liquid line of descent LLD (Gualda et al., 2012). I also include a database for Archean non-arc basalts, a representative primary magma composition (Herzberg et al., 2010) and a MELTS LLD (Gualda et al., 2012). Primary magmas never erupt because they readily transform to derivative magmas owing to heat loss and fractional crystallization in the crust, a well-known process that results the diversity of igneous rocks. This is illustrated by the liquid lines of descent & lava compositions shown in Fig. 1a, and they are a good guide to modern and Archean oceanic crust diversity. If these basalts were subducted to sufficient depths, they are predicted to recrystallize to mostly coesite eclogite (Gt+Cpx+Cs). Furthermore, it can also be shown that cumulate troctolite and olivine gabbro sections of subducted oceanic crust have compositions that also project to the silica-rich side of the Garnet–Pyroxene plane, and they must also recrystallize to coesite eclogite (Gt+Cpx+Cs) if subducted and recrystallized to sufficient depths. Yet, according to Jacob (2004), bimineralic eclogite (Gt+Cpx) xenoliths are the most common type of eclogite in kimberlite; coesite eclogite does exist, but it is comparatively rare. So, where is all the expected subducted oceanic crust in kimberlite preserved as coesite eclogite xenoliths (Fig. 1a)? And why were the unexpected primary magmas preserved instead? The assumption that some bimineralic eclogites represent protoliths that formed as little-differentiated melts in ancient ocean floors (Aulbach and Arndt, 2019) is perplexing and difficult to understand.

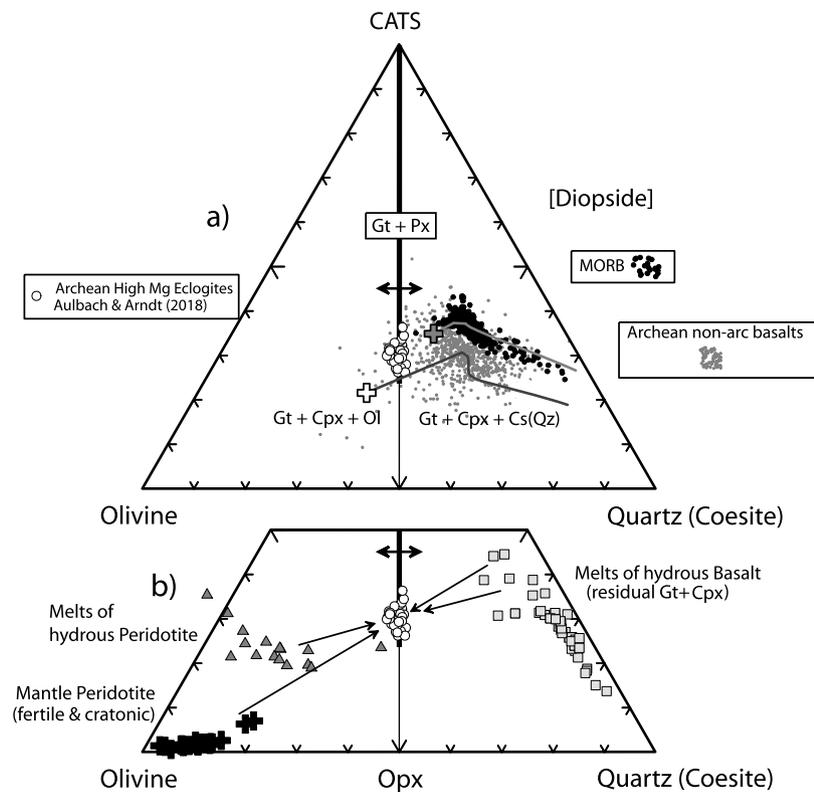
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**Fig. 1.** A mole% projection of rock and glass compositions from or towards Diopside into the plane Olivine–Quartz–Calcium Tschermak's (CATS). Panel a): white filled circles are high Mg bimineralic eclogite compositions from Aulbach and Arndt (2019); black filled circles are MORB glasses from the East Pacific Rise ([www.earthchem.org/petdb](http://www.earthchem.org/petdb)); gray filled circles are Archean non-arc basalts (Herzberg et al., 2010); gray cross and gray line are a primary magma composition for MORB and its liquid line of descent; white cross and gray line are a primary magma composition for a representative Archean non-arc basalt and its liquid line of descent. Panel b): black filled crosses are fertile and cratonic mantle peridotite compositions (Herzberg et al., 2010); gray filled squares are experimental melt compositions of hydrous basalt with residual Gt+Cpx compiled by Jean-François Moyen (personal communication, 2014); gray filled triangles are experimental melt compositions of hydrous peridotite (Tenner et al., 2012); divergent arrows depict the Garnet–Pyroxene plane as a thermal divide which prohibits the mixing of melts on the low- and high-SiO<sub>2</sub> sides of it; convergent arrows depict the formation of high Mg bimineralic eclogite by melt–rock reaction and melt–melt intermingling and crystallization (text). The mole % projection is derived from the code given in O'Hara (1968): Olivine (OL) = 0.5(Al<sub>2</sub>O<sub>3</sub> + Cr<sub>2</sub>O<sub>3</sub> + FeO + MnO + NiO + MgO) – 0.5(CaO + Na<sub>2</sub>O + K<sub>2</sub>O) + 1.75P<sub>2</sub>O<sub>5</sub>. CATS = TiO<sub>2</sub> + Al<sub>2</sub>O<sub>3</sub> + Cr<sub>2</sub>O<sub>3</sub> + Na<sub>2</sub>O + K<sub>2</sub>O. Quartz (QZ) = SiO<sub>2</sub> + TiO<sub>2</sub> + 0.5(Al<sub>2</sub>O<sub>3</sub> + Cr<sub>2</sub>O<sub>3</sub>) – 0.5(FeO + MnO + MgO + NiO) – 1.5CaO – 4.5(Na<sub>2</sub>O + K<sub>2</sub>O) + 5.25P<sub>2</sub>O<sub>5</sub>.

Rather than being recrystallized primary magmas of subducted oceanic crust, there are more probable ways of forming high-Mg bimineralic eclogite. Smit et al. (2014) provide an excellent summary of models for their interpretation of eclogite xenoliths in the Victor kimberlite in Canada. Of these, I draw attention to hypotheses 3 and 4, residues of slab melting and reaction products of slab melts and peridotite. There is yet another plausible model that I discuss below.

Bimineralic eclogites might be residues after melting of hydrated Archean basalts. For the production of Archean tonalite–trondhjemite–granodiorite many models require residual hornblende, plagioclase, rutile and quartz in addition to garnet and clinopyroxene (e.g., Palin et al., 2016). Residues of coesite eclogite and bimineralic eclogite could have formed during advanced melting beyond plagioclase and hornblende stability as the slab, drip or base of thick crust heated up on descent. Residual coesite eclogite may display properties similar to subducted oceanic crust (Fig. 1a). The wide range of Archean non-arc basalt compositions shown in Fig. 1a adds a layer of difficulty to mass balance evaluations, and more work is needed to test the residuum hypothesis. What is relevant to the present discussion is that mantle potential temperature  $T_P$  and melt fraction  $F$  can only be inferred from primary magmas, not from residues. A caveat may be residue compositions computed from primary magma compositions by mass balance; however this cross calibration is not practical at present owing to the unknown effects of water and temperature in the production of hydrated primary magmas in Archean subduction zones or drips.

The formation of bimineralic eclogite xenoliths by melt–rock reaction was suggested by Smit et al. (2014) and it has partial support from the experiments of Yaxley and Green (1998). Fig. 1b shows that high-Mg bimineralic eclogites might have formed by the reaction of a variety of peridotite compositions with melts of hydrous basalt. I include refractory harzburgite xenolith compositions in kimberlite that occupy cratonic lithospheric mantle (Herzberg et al., 2010). Hydrous partial melts of basalt range from dacitic to basaltic in composition with increasing extent of melting; bimineralic eclogites have compositions that are most consistent with peridotite reacting with basalt, not dacite (Fig. 1b). Reacting dacitic melts are expected to produce orthopyroxene, and this was reported by Yaxley and Green (1998) as an experimental simulation of melt–rock reaction in ascending mantle. We might imagine a different scenario for a subducted slab as it descended into the mantle. Initial TTG and dacitic melts would have been the first to form and drain upwards, perhaps forming rare Opx-bearing eclogite reaction products (Smit et al., 2014). More advanced and deeper melting yielded basalts that reacted on contact with cratonic mantle peridotite, forming bimineralic eclogite. This melt–rock reaction model might explain why xenoliths of cratonic harzburgite and bimineralic eclogite are a common association in kimberlite.

Melt–melt intermingling and crystallization is a variant of melt–rock reaction for making bimineralic eclogite. In the case of a subducted slab, hydrothermal alteration may have extended below the basaltic crust and into the underlying mantle peridotite. High pressure melts of hydrated peridotite project to the SiO<sub>2</sub>-poor

side of the Garnet–Pyroxene plane (Tenner et al., 2012), in contrast with hydrous melts of basalt (Fig. 1b). At pressures appropriate to eclogite stability, these melts cannot mix because the Garnet–Pyroxene plane is a thermal divide. Any intermingling of melts of hydrous peridotite and hydrous basalt will trigger crystallization of bimineraleclogite, not mixing. More work is needed to test this hypothesis because the experimental melts of Tenner et al. (2012) were sourced from hydrous fertile peridotite at 3.5 GPa rather than hydrous depleted cratonic peridotite at a wider range of possible pressures in nature.

Inferences about the thermal state of the mantle during melting can only be drawn from primary magmas, and residue compositions computed from primary magma compositions by mass balance as discussed above. In my opinion, the burden of proof is very heavy that bimineraleclogites were primary magmas as suggested by Aulbach and Arndt (2019), or even magmas at all (Fig. 1a). These rocks are more likely to have been residues, the crystalline products of melt–rock reaction, or melt–melt intermingling and crystallization (Fig. 1b). It is not possible at present to infer mantle potential temperature  $T_P$  and melt fraction  $F$  for bimineraleclogites formed in these ways, and the solutions obtained from software such as PRIMELT3 have no meaning. Therefore, inferences drawn by Aulbach and Arndt (2019) about the thermal state of the Archean ambient mantle from these rocks are non-unique and insecure.

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