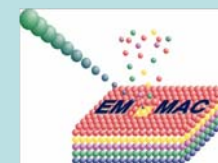




# Diamond Formation in association with Deep Mantle Dehydration Zones

Ben Harte

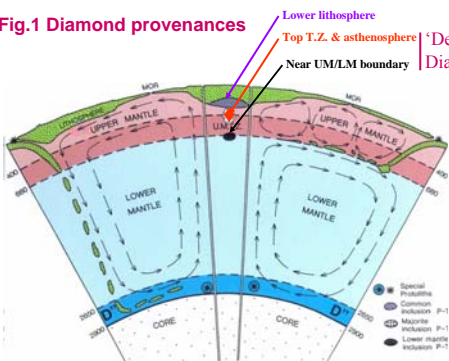
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## Diamonds and their Inclusions

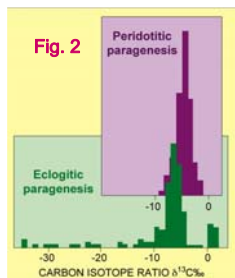
The great majority of silicate minerals found as inclusions in diamonds are typical of those expected, and known to occur, in ultrabasic and basic rocks forming deep continental lithosphere (up to depths of ca 210 kms and bordering on the asthenosphere). Typically they fall into two major groups with minerals similar to those seen in peridotite rocks (ultrabasic) and in eclogite rocks (basic) recovered as xenoliths from mantle lithosphere. The 'deep mantle' silicate inclusions under discussion here are rare and have new phases and new phase compositions compared with those of the lithosphere but the phases may again be referred to basic rock compositions of ultrabasic and basic character, and for simplicity the deep mantle equivalent of these two rock groups are referred to as *meta-peridotites* and *meta-basites*. Overall the diamonds with inclusions from below the lithosphere will be shown to come from two principal deep mantle regions as shown in Fig. 1.

Fig.1 Diamond provenances



### General features of natural diamonds.

- 1) On the basis of morphology and internal growth structures, natural diamonds are believed to normally crystallise in the mantle from fluids rather than in the solid state. These fluids might vary from C-O-H rich to carbonatitic and silicate-rich melts. Since diamond stability commonly demands formation at pressures in excess of 4.5 to 5 GPa (~150 kms depth), fluids of these compositions will show considerable miscibility with one another (Kawamoto, 2006).
- 2) The syngenetic mineral inclusions trapped in diamonds often show evidence of an imposed morphology with crystal surfaces parallel to diamond crystal faces, and this is believed to indicate simultaneous growth of the inclusion and the diamond. Thus the conditions of formation of inclusion and host diamond are the same.
- 3) Once trapped inside diamond the inclusions are protected from the medium surrounding the diamond, and are therefore believed to maintain constant chemical composition. However, changes in temperature and pressure may cause instability of included minerals and replacement by other phases even though the bulk chemistry remains constant. This is the common case for deep mantle perovskite inclusions.
- 4) Considering all natural diamonds, those with inclusions of peridotitic paragenesis show normal mantle  $\delta^{13}C$  values clustering around -6‰, whilst eclogitic diamonds show a long tail of values <-10‰ (Fig. 2). These features are also found in diamonds with deep mantle parageneses, but with the exception that nearly all diamonds of meta-basic (eclogitic) paragenesis have  $\delta^{13}C$  of <-20‰. Such low  $\delta^{13}C$  values are associated with living tissues, and are now widely viewed as indicating an initial crustal protolith.



## The Nature and Provenances of Deep Diamond Inclusions

Many experimental studies have been carried out on meta-peridotite compositions (often pyrolyte) and meta-basite bulk compositions to ascertain their mineralogy at depth. The diagrams below reproduce syntheses of these investigations down to 1000 kms: Fig. 3 - meta-peridotite diagram from Stixrude & Lithgow-Bertelloni, 2007, EPSL 263: 45-55; Fig. 4 - metabasite diagram from Perrillat et al., 2006, PEPI 157:139-149.

Fig. 3 Mineralogy of meta-peridotite

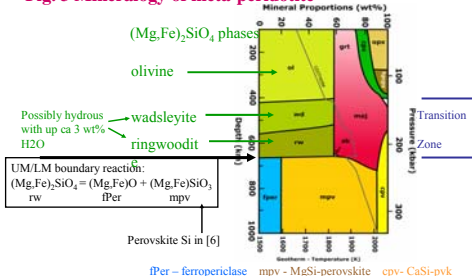
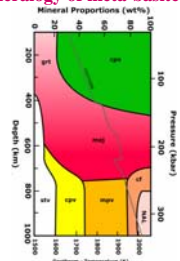


Fig. 4 Mineralogy of meta-basite



The inclusions found in natural diamonds of sub-lithospheric nature match closely the above experimental results and where several inclusions are associated in a single diamond they also indicate assemblages that fit with experimental studies. There is one exception to this – in associations from 600-800 kms majoritic garnets (maj) are usually absent and instead a phase is found with the composition of a pyrope-rich, almandine-pyrope, garnet solid solution but with a distinct crystallographic structure (Harris et al., 1997, Nature 387: 486-488). This phase is given the acronym TAPP (tetragonal almandine-pyrope phase); it is possibly stabilised by having a high ferric iron content. In Tables 1 and 2 below, the experimental mineralogies are listed in broad depth zones or facies and the inclusions found in diamonds are listed alongside the experimental depth zones.

Table 1 for Meta-peridotites	
Depth Zone / Facies	Inclusions
Grt peridotite	ol, opx, grt, (cpx, chr)
Maj peridotite	maj?
Maj 'wd-peridotite'	?
Maj 'rw-peridotite'	?
Upper/Lower Mantle Boundary	Mg <sub>2</sub> SiO <sub>4</sub> , fPer, maj/TAPP, mpv, cpv
Mpv(Al-poor) with fPer + cpv	mpv(Al-poor), fPer, maj/tapp, cpv
Mpv(Al-rich) with fPer + cpv	mpv(Al-rich), fPer, cpv, crn

Table 2 for Meta-basites ('eclogitic')	
Depth Zone / Facies	Inclusions
Eclogite	grt, cpx
Cpx-majorite	maj, cpx
majorite	Majorite (maj)
Cpv-majorite	?
Upper/Lower Mantle Boundary	maj(Na-opx), maj/TAPP, cpv
Mpv(Al-poor) with Cpv	mpv(Al-poor), cpv, maj/tapp, stv
Mpv(Al-rich) with Cpv	mpv(Al-rich), cpv, stv

### NOTE THE SELECTIVE DISTRIBUTION OF THE INCLUSIONS

Excluding the highest zone where inclusions have mineralogies matching the mantle lithosphere, two depth zones predominate in providing deep mantle inclusions:

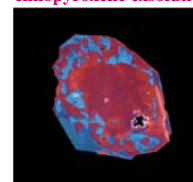
- (1) The uppermost Transition Zone and the overlying asthenosphere, where the inclusions are majoritic garnets of meta-basite affinity; and their host diamonds often show very low  $\delta^{13}C$  suggesting an initial crustal origin.
- (2) The lowermost Transition Zone and the uppermost part of the Lower Mantle, where the inclusion associations often include fPer and are dominantly of meta-peridotite affinity; this suite of inclusions may all come from a depth range of ca 600 to 800kms.

Minerals with meta-peridotitic chemical characteristics are missing for nearly the whole of the asthenosphere and Transition Zone. In contrast there are relatively common inclusions which appear to target the Upper/Lower Mantle Boundary, by having Mg<sub>2</sub>SiO<sub>4</sub> in combination with fPer &/or mpv.

For the most part, the asthenosphere and Transition Zone are represented alone by majoritic garnet inclusions, which may show clinopyroxene as well as garnet. Detailed studies (Harte & Cayzer, 2007, Phys Chem Mins: 34, 647-656) reveal that the cpx in these inclusions is the product of exsolution from an initially more Si-rich majorite (Fig. 5)

This implies that many majoritic inclusions may have similar depths of origin close to the top of the Transition Zone.

Fig. 5. Majorite with clinopyroxene exsolution



## The Origin of Deep Diamonds

Given the formation of natural diamonds in C-O-H bearing fluids/melts, one may ask where such fluids/melts may be present in the sub-lithospheric mantle, and if the distribution of fluids/melts may correlate with the provenances of the deep inclusions. The occurrence of such fluids/melts will be greatly dependent on the stability of hydrous fluid phases. In terms of the normally expected mantle phases, wadsleyite and ringwoodite are the two main potentially hydrous phases (e.g. Smyth, 1987, Am.Min. 72: 1051-1055; Inoue et al., 1995, Geophys. Res. Letts 22: 117-120; Kawamoto, 2006, Revs. Min. & Geochem. vol. 62) and in upward convection one might expect the liberation of free H<sub>2</sub>O at the top of the Transition Zone where hydrous wadsleyite is replaced by olivine. Thus Bercovici and Karato (2003, Nature, 425, 39-44) have proposed the widespread occurrence of a melt zone at the top of the Transition Zone (see Fig. 7, at bottom).

In terms of release of fluid from hydrous silicates in downward transport, attention focuses on the DHMS (dense hydrous magnesium silicates) which may carry H<sub>2</sub>O down in subducting slabs (e.g. Kawamoto, 2006, op cit; Komabayashi, 2006, AGU monograph 168: 29-43). In a recently derived petrogenetic grid for the reaction relations in model peridotite compositions, Komabayashi (2006, op.cit.) recognises several situations where dehydration reactions may occur in subducting slabs depending on the temperature. Several of these dehydration situations, which may correlate with the formation of diamonds and their inclusions, are shown in Fig. 6. The prominent possibilities are summarised in Figs. 6 & 7. Where a subducting slab remains relatively cold, dehydration may not occur until reaching uppermost Lower Mantle conditions (reaction locations 9 and 10 in Figs 6 & 7). If, on the other hand a cool slab starts to warm &/or stagnate in the lower part of the Upper Mantle, reaction location 5 to 8 in Figs. 6 & 7 may apply.

Fig. 6. Phase relations and P-T paths in subducting hydrous meta-peridotite

(after Komabayashi, 2006, the numbers in oval boxes are estimated water contents held in hydrous silicates.)

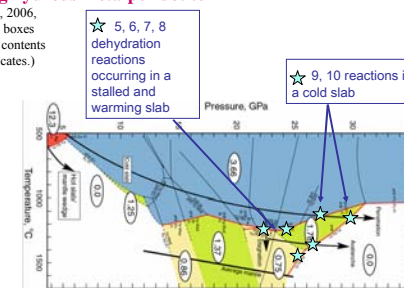
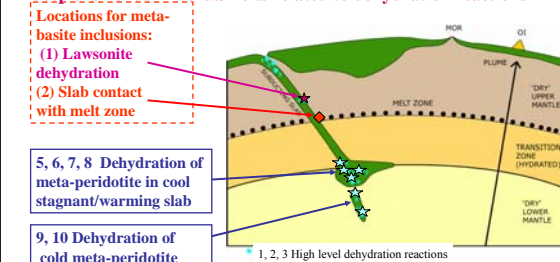


Fig. 7. Schematic representation of locations of formation of deep diamonds in fluids/melts related to dehydration reactions



**CONCLUSIONS:** The locations of peridotitic dehydration reactions in Figs 6 & 7 fit well with the distribution of meta-peridotitic diamond inclusions in Table 1, and thus provide an explanation of the distribution found. For the formation of the meta-basic majoritic inclusions an ideal location is represented by the intersection of the upper surface of the slab with the melt zone of Bercovici & Karato (op cit.). The location of lawsonite dehydration in the meta-basalts of the slab may also give rise to diamonds with meta-basic majoritic inclusions.