

Diamond Accumulation in the Upper Mantle

THE present high gradient of density in the upper mantle provides neutral buoyancy zones in which certain minerals may have been accumulated in the past or to which they may still be migrating. The necessary condition for progressive accumulation in such a zone is that the mineral concerned has opportunities of rising or sinking relative to its surroundings with a velocity which, averaged over long periods, is great enough to overcome the bulk convective drift if such occurs. Frank¹ has pointed out the high heat transfer capability of a small volume fraction of melt fluid percolating through the bulk, compared with bulk convection. With percolation active, it is likely that a fluctuating distribution of migration and local concentration of fluid has been the dominating pattern of events in the mantle, at least down to 500 km, during a large fraction of the Earth's history. Hence it is unlikely that any portion of the mantle above this level has escaped epochs during which fluid has percolated through it. If during such an epoch of involvement in local fluidity the fluid fraction becomes sufficient to lower the effective viscosity to within an order of magnitude of that of a normal homogeneous melt, then insoluble crystals suspended in the partial melt, rising or falling under buoyancy forces, could well attain velocities a million-fold greater than any plausible bulk convection velocity of the mantle in which the localized partial melt is embedded.

Table 1. DIAMONDS IN THE UPPER MANTLE

(i) Depth (km)	(ii) Pressure (kbar)	(iii) Mantle density ρ_M (g cm ⁻³)	(iv) Diamond density less mantle density $\rho_D - \rho_M$ (g cm ⁻³)	(v) Viscosity velocity product ηv (dyne cm ⁻¹)
100	33	3.32	0.18	2.2
200	65	3.35	0.16	2.0
300	98	3.44	0.08	1.0
400	130	3.62	-0.09	-1.1
500	170	3.89	-0.34	-4.3
600	210	4.14	-0.57	-7.2

Consider diamond, for if migration towards a neutral buoyancy zone has acted to concentrate any mineral at all, then it would be expected to have operated on this species. Diamond is the physically stable form of carbon from a depth of about 100 km down to 1,200 km or more^{2,3} and its neutral buoyancy level, as shown by Table 1, is at about 350 km depth. In Table 1, columns (ii) and (iii) give the pressure and mean mantle density at the depth stated in column (i) according to Solution II of Birch⁴ which is close to Bullen's $A(i)$ model⁵. Column (iv), which lists the difference between the density of diamond (ρ_D) and mantle (ρ_M), makes use of Berman's calculations of the density of diamond at zero pressure and elevated temperature² together with the value 1.75×10^{-4} kbar⁻¹ as the compressibility of diamond. The variation of temperature with depth adopted is the mean of the "oceanic" and "continental shield" distributions of Tozer⁶; it suggests about 1,900 K at the neutral buoyancy depth of 350 km. The final column (v) is based on special assumptions. It takes a typical diamond to be one having a volume of 0.1 cm³, or a mass of 0.35 g ($1\frac{1}{2}$ carats), and to be of octahedral shape. The distance from centre to corner of the octahedron is used as the effective particle radius in the Stokes formula for drift velocity v cm s⁻¹ through a medium of viscosity η poise.

It will be seen that velocities of drift towards the 350 km level exceed 1 km yr⁻¹ at distances greater than 50 km above or below this level when the viscosity is 300 poise or less. If a diamond of the size assumed becomes but once in every 10⁶ yr incorporated for a brief period in a local accumulation of partial melt extending vertically through a depth of order 1 km, then the aggregate of possible vertical drifts would be sufficient to produce, say, a descent from 100 km to 250 km in about 10⁸ yr.

Does any evidence point to the existence of a diamond reservoir at a depth of 350 km? Very long storage at about 1,900 K would probably provide good conditions for developing the distribution of nitrogen impurity platelet precipitate commonly observed in diamond, but much shorter exposures to high temperature (such as would be experienced in a rapidly rising and expanding melt) might be sufficient^{7,8}. Rather, perhaps, one should enquire where does the Earth's store of carbon reside? In meteorites and in the Earth's lithosphere there is about one carbon atom to every 300 silicon atoms⁹. But the majority of meteorites seem to have been derived from small bodies in which negligible internal pressures due to gravity would have been developed, and much carbon may have escaped as volatiles. In bodies the size of the Moon and greater, interior pressures rise well into the diamond-stable region of the carbon phase diagram, making possible the retention of carbon as dense and unreactive diamond. Allowing the Earth's mantle no greater abundance of carbon than has been retained by meteorites, and assuming such carbon to be principally in the form of diamond, then if most of the diamond has migrated to within 100 km of its neutral buoyancy level, diamond concentrations in this zone might exceed one per cent.

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³ Bundy, F. P., *J. Chem. Phys.*, **41**, 3809 (1964).

⁴ Birch, F., *J. Geophys. Res.*, **69**, 4377 (1964).

⁵ Bullen, K. E., *An Introduction to the Theory of Seismology*, third ed. (Cambridge Univ. Press, 1963).

⁶ Tozer, D. C., in *The Earth's Mantle* (edit. by Gaskell, T. F.) (Academic Press, London and New York, 1967).

⁷ Frank, F. C., *Proc. Intern. Industrial Diamond Conf., Oxford, 1966* (Industrial Diamond Information Bureau, London, 1967).

⁸ Frank, F. C., in *The Application of Modern Physics to the Earth and Planetary Interiors* (edit. by Runcoorn, S. K.), 247 (Wiley-Interscience, London and New York, 1969).

⁹ Goldschmidt, V. M., *Geochemistry* (edit. by Muir, A.), 74 (Clarendon Press, Oxford, 1954).

Fitting, Fretting and Imprisoned Boulders

THE occurrence on rocky coasts of what Shelley¹ aptly calls "fitting boulders" is, as he says, not mentioned in standard works on shore processes; but the late Professor J. A. Bartrum discussed such boulders with me in 1934 and used the term "fretting" in relation to the development of common interfaces between adjacent boulders. Baker² described an example near Cape Paterson in Victoria (Australia) using the term "imprisoned rocks", and indeed they are not uncommon on the Victorian coast. I have observed them at Beaumaris among blocks of soft red Tertiary sandstone derived from collapses of the cliff face, also at Sorrento in Pleistocene calcareous aeolianite, and again around Lorne and Cape Paterson where the rocks are Mesozoic arkoses. They occur also at St David's (South Wales). Shelley's descriptions afford a basis for comparison.

Among the New Zealand examples one type comprises agglomerations of boulders piled together and fitting closely, the other being large isolated boulders which fit against the bedrock base. This is also true in Victoria. In both areas fitting boulders lie about or above mean sea level, but certainly in Victoria in a zone which is at present subject to wave action if only during storms. Shore platforms, on which the boulders occur as large isolated blocks