Double Flood Basalts and Plume Head Separation at the 660-Kilometer Discontinuity

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Several of the world's flood basalt provinces display two distinct times of major eruptions separated by between 20 million and 90 million years. These double flood basalts may occur because a starting mantle plume head can separate from its trailing conduit upon passing the interface between the upper mantle and the lower mantle. This detached plume head eventually triggers the first flood basalt event. The remaining conduit forms a new plume head, which causes the second eruptive event. The second plume head is predicted to arrive at the lithosphere at least 10 million years after the first plume head, in general agreement with observations regarding double flood basalts.

One hundred and twenty million years ago, much of the Ontong Java Plateau was formed in a cataclysmic event involving the ejection of tens of millions of cubic kilometers of basalt (*1*, *2*). Similar (yet smaller) flood basalt events led to the formation of, for example, the Deccan Traps, the Karoo basalts, the Madagascar province, and the Kerguelen Plateau. Flood basalts have been attributed to the arrival of starting mantle plume heads at the base of the lithosphere (*3–6*). After forming at a heated boundary (for example, the core-mantle boundary), these plume heads ascend through the mantle, possibly followed by a narrow conduit of plume material (*7*). In view of mantle temperatures and material properties, plume heads are likely to have sufficient volume such that upon melting at the base of the lithosphere, they can supply the magma necessary for a flood basalt event (*4*, *6*). Within a given province, most of the eruptive activity is thought to occur within a few million years.

However, this basic model does not explain recent evidence in several flood basalt provinces of two distinct episodes of major eruptions, separated by between 20 million and 40 million years, which suggests the existence of double flood basalt events. For example, ^{40}Ar-^{39}Ar dating of basement lavas from the Ontong Java Plateau (Fig. 1) has revealed two distinct age groupings, one at 120 to 122 Ma (million years ago) and another at 88 to 90 Ma; samples and dates are as yet too few to permit estimates of the relative volumes involved, but the two groups of basalts are nearly identical isotopically and chemically (*1*, *8*). Recent ^{40}Ar-^{39}Ar measurements for drilled and dredged lavas from the early products of the Kerguelen hot spot in the southeastern Indian Ocean yielded ages of 110 to 112 Ma for sites on the southern Kerguelen Plateau and 85 to 88 Ma for sites on the central Kerguelen Plateau and originally contiguous Broken Ridge (*9*). The emplacement age of the Shatsky Rise in the North Pacific has been estimated at 138 to 145 Ma (*10*); after a period of much reduced magmatic activity, the bulk of the Hess Rise to the east was probably formed by the same hot spot around 100 to 110 Ma (*11*, *12*). The Paraná basalts of Brazil, formed above the early Tristan hot spot, were erupted at 127 to 137 Ma (*13*); subsequent activity produced the long Walvis Ridge seamount chain on the African Plate over an extended period of time down to the present; however, a second large plateau, the western Rio Grande Rise, was formed by the Tristan hot spot on the South American Plate around 80 to 90 Ma (*14*). Morgan (*3*) and others have suggested that the Marion hot spot produced both the Karoo flood basalts in southern Africa, which erupted at 182 to 185 Ma (*15*), and the Madagascar province (including the submarine Northern Madagascar Ridge, the originally contiguous Conrad Rise, and the extensive lavas and dikes on Madagascar), which formed at 86 ± 2 Ma (*16*). If this interpretation is true, the Karoo-Madagascar pair could constitute yet another double flood basalt event, although the time between eruptive episodes is considerably longer than that separating other likely double flood basalts.

Double flood basalts may have several possible causes. For example, they may be triggered by tectonic events (that is, plate reorganizations). In fact, it has been hypothesized that continental flood basalts are due not to starting plume heads but to rifting above large plume tops that have accumulated gradually beneath slowly moving continental lithosphere (*5*, *17*). The Madagascar basalts, for example, were erupted at about the same time that Madagascar and Greater India rifted apart (*16*). The oceanic plateaus in the Pacific have also been linked to the effects of major changes in plate motion (*11*). Indeed, the dates for the Ontong Java Plateau correlate fairly closely with proposed major reorganizations in the motion of the Pacific Plate (*11*, *18*). Moreover, the roughly similar ages (80 to 90 Ma) of several of the secondary flood basalts (in particular, those associated with the second Ontong Java event, Broken Ridge and the central Kerguelen Plateau, the Madagascar province, and the Rio Grande Rise) suggest a global, possibly tectonic, origin.

Plate motion changes alone, however, appear insufficient to cause flood basalt volcanism above a hot spot; for example, the large change in Pacific Plate direction around 43 Ma was not accompanied by flood basalt volcanism above the Hawaiian (or any other Pacific) hot spot. Similarly, several examples exist wherein rifting above a hot spot did not by itself create anomalously high volumes of magma, as, for instance, in the passage of the Central Indian Ridge above the Réunion hot spot around

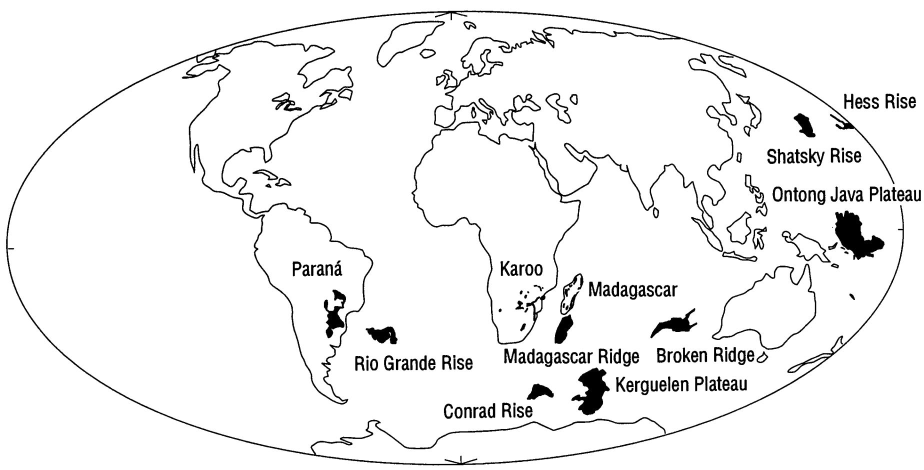

Fig. 1. World map showing the locations of apparent double flood basalt provinces mentioned in the text. Modified from (*2*).

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40 Ma (6). Other arguments against the tectonic origin of flood basalts are summarized elsewhere (4).

Alternatively, double flood basalt events may be a signature of basic mantle-plume dynamics. Experimental and theoretical models suggest that rising diapirs simply spread and collapse after arriving at the lithosphere (19) and thus predict no more than one flood basalt event. Additional trailing diapirs from a plume tilt instability (20) or plume solitary waves (21) could induce extra eruptive events, although these mechanisms are more likely to cause multiple events, not just two. In this report we offer a simple theory for the formation of double flood basalts. We propose that because the upper mantle is likely to be less viscous than the lower mantle (22), a starting plume head will accelerate and separate from its trailing conduit (23) after it passes the interface between the upper mantle and the lower mantle (Fig. 2). The abandoned conduit subsequently forms another plume head above this interface. The staggered arrival of the two plume heads at the base of the lithosphere would then trigger a double flood basalt event.

A mantle plume head can separate from its trailing conduit if its rise velocity U exceeds the maximum velocity of fluid in the conduit V_{max}. Once the plume head passes into the upper mantle, it rises at approximately the Stokes velocity

$$U = \frac{\Delta\rho g R^2}{3\mu_u} \quad (1)$$

where $\Delta\rho$ is the density contrast between plume fluid and surrounding mantle, g is gravitational acceleration, μ_u is the viscosity of the upper mantle, and R is the radius of the spherically shaped plume head upon crossing the 660-km discontinuity. If we assume Poiseuille flow in the trailing conduit, then

$$V_{max} = \sqrt{\frac{\Delta\rho g Q}{2\pi\mu_p}} \quad (2)$$

where μ_p is the viscosity of plume fluid and Q is the volumetric flux of material in the conduit. The radius R can be constrained from estimates of flood basalt volume and melt fractionation, and the volume flux can be approximated as

$$Q = \frac{4\pi\Delta\rho g}{15 D_\ell \mu_\ell} R^5 \quad (3)$$

where μ_ℓ is the lower mantle viscosity and D_ℓ is the thickness of the lower mantle (24, 25). The plume head therefore separates from the conduit if

$$\frac{U}{V_{max}} = \sqrt{\frac{5}{6}\frac{\mu_\ell\mu_p}{\mu_u^2}\frac{D_\ell}{R}} > 1 \quad (4)$$

Because this ratio decreases with increasing plume head size R, the most stringent test of the separation criterion will be for the plume head associated with the largest flood basalt province known, the Ontong Java Plateau. The Ontong Java Plateau is estimated to contain approximately 5×10^7 km^3 of basalt (1, 2) and, given a likely average degree of partial melting of 25% to make the basalts (1, 8), the total amount of plume head material involved in this plateau's formation had a volume of approximately 2×10^8 km^3. There are no current estimates of the respective volumes of the two flood basalts for Ontong Java; thus, we use the entire volume of plume-head material to make a conservative estimate of U/V_{max}. In this case, R = 363 km (though clearly the first plume head must have only a fraction of this radius), and given D_ℓ = 2200 km, separation occurs if $\mu_p/\mu_u > 1/5(\mu_u/\mu_\ell)$. Detachment of the plume head from its conduit is likely, given that most estimates of μ_p/μ_u are between 1/10 and 1/100 (24) and $1/100 \leq \mu_u/\mu_\ell \leq 1/30$ (22). Separation is much less likely to occur if, as has been suggested by some workers, $\mu_p/\mu_\ell << 1/1000$ (26) or if the upper and lower mantles have essentially equivalent viscosities (27).

The amount of time necessary for the plume head (which stops inflating once it begins separating from the conduit) to traverse the upper mantle is $D_u/U \approx 1$ million years (where D_u = 600 km is the thickness of the upper mantle to the base of the lithosphere, and for U we use $\Delta\rho$ = 40 kg/m^3, $\mu_u = 10^{21}$ Pa-s, and R = 363 km). After the starting plume head detaches, a second plume head forms at the tip of the abandoned conduit and rises to the base of the lithosphere in approximately 12 million years (28). This time is probably a lower limit (28, 29); thus, we conclude that the arrival of the first and second plume heads at the base of the lithosphere will be separated by at least 10 million years.

The volume of the second plume head upon reaching the base of the lithosphere is approximately 10^7 km^3 (28). That this is considerably smaller than the volume of the first plume head was demonstrated in the laboratory experiments (Fig. 2) and is to be expected, given the smaller thickness and lower viscosity of the upper mantle (28). Apart from the Hess Rise having a smaller area than the older Shatsky Rise (which supports our prediction, assuming that the crustal thicknesses are similar and that the statistics of a single case are meaningful), there are as yet no quantitative bounds on the volumes of individual flood basalts in double flood basalt systems.

The mechanism proposed here provides a simple explanation for the cause of double flood basalt events. Obviously, there is considerable uncertainty in our analysis, although we hope we have erred on the side of conservativeness (29). One of the most important field tests of our hypothesis is an estimate of the volumes of individual flood basalts within double flood basalt systems; however, this volume determination may not be readily acquired for continental flood basalts where erosion is advanced (such as the Karoo and Paraná).

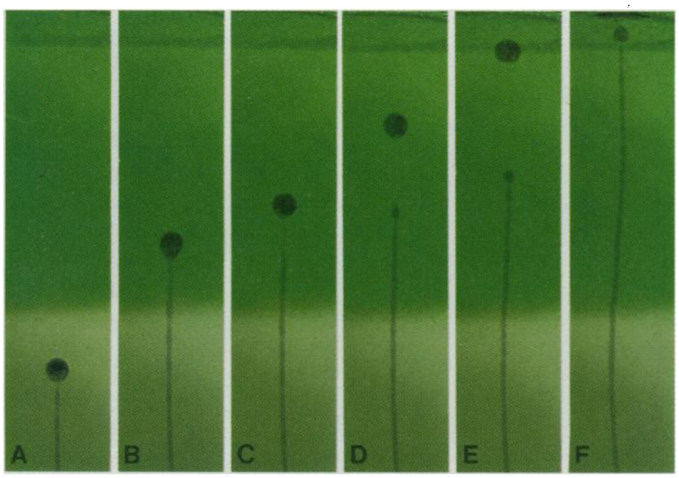

Fig. 2. A simple laboratory demonstration of the plume head separation mechanism. Chemically buoyant fluid composed of 65% (by volume) clear Karo corn syrup and 35% water [with a viscosity of 30 centipoise (cP; 10 P = 1 Pa-s) and dyed dark purple] was ejected from a pipe with an inner diameter of 0.7 cm at 0.014 cm^3 s^{-1} into the base of a tank with a 20-cm-thick layer of 100% clear corn syrup (viscosity 4400 cP) overlain by a 10-cm-thick layer of 95% syrup (viscosity 1400 cP and dyed green). The diapiric head that forms at the mouth of the pipe ascends through the lower layer while being trailed by a plume conduit (**A**). Upon passing into the less viscous upper layer, the plume head accelerates, causing the conduit to stretch and thin (**B** and **C**). The plume head eventually detaches from the conduit (23), which forms a new smaller plume head (**D** and **E**) that arrives at the surface some time after the first plume head (**F**).

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23. The laboratory experiments suggest that rather than immediately separating from the conduit, the accelerating plume head causes the conduit to be stretched into an extremely thin filament (Fig. 2). The fluid in the lower, unthinned portion of the conduit rises through this filament by forming an upward propagating bore; the head of the bore inflates until it is soon indistinguishable from another plume head. Typically, the filament diffuses away before the bore moves a large distance, causing the bore to become a genuine diapir. See also the numerical models of plumes interacting with a viscosity transitions [for example, L. H. Kellogg, *Geophys. Res. Lett.* **18**, 865 (1991); P. E. van Keken, D. A. Yuen, A. P. van den Berg, *Earth. Planet. Sci. Lett.* **112**, 179 (1992); *Geophys. Res. Lett.* **20**, 1927 (1993); M. Manga, H. A. Stone, R. J. O'Connell, *J. Geophys. Res.* **98**, 19979 (1993)].
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25. If the volume of the conduit is negligible, then the radius of the first plume head upon reaching the interface between the upper mantle and the lower mantle is

$$R = R_0(1 + 5D_\ell/R_0)^{1/5}$$

where

$$R_0 = \left(\frac{3\mu_\ell Q}{4\pi\Delta\rho g}\right)^{1/4}$$

is the radius of the plume head upon detachment from the D'' layer [see (*24*), equation 15]. Because we expect $D_\ell \gg R_0$, we can use the expression for R to approximate the volume flux in the conduit as

$$Q = \frac{4\pi\Delta\rho g}{15 D_\ell \mu_\ell} R^5$$

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28. For simplicity, we neglect the effects of the endothermic phase change at the 660-km discontinuity [see E. Ito and E. Takahashi, *J. Geophys. Res.* **94**, 10637 (1989); E. Ito, M. Akaogi, L. Topor, A. Navrotsky, *Science* **249**, 1275 (1990)]. In fact, this phase transition should impede penetration of the second plume head into the upper mantle [see M. Liu, D. A. Yuen, W. Zhao, S. Honda, *Science* **252**, 1836 (1991); T. Nakakuki, H. Sato, H. Fujimoto, *Earth Planet. Sci. Lett.* **121**, 369 (1994)]. Moreover, we again must use R = 363 km (that is, an R based on the volume of all the plume head material forming the Ontong Java Plateau), which leads to underestimates of the formation and transit times for the second plume head. The time necessary for the second plume head to inflate and begin ascent is

$$t_d = \left(\frac{4\pi\mu_u^3}{3Q\Delta\rho^3 g^3}\right)^{1/4} \approx 1.2 \text{ million years}$$

(using, as a conservative estimate, $\mu_\ell = 3 \times 10^{22}$ Pa-s to determine Q) (*7*, *24*). See (*25*) on the determination of Q. The time for this second plume head to rise across the upper mantle is

$$t_r = \frac{4\pi R_1^3}{3Q}[(1 + 5fD_u/R_1)^{3/5} - 1]$$

where

$$R_1 = \left(\frac{3\mu_u Q}{4\pi\Delta\rho g}\right)^{1/4}$$

is the radius of the second plume head when it begins its ascent and f is the fraction of the upper mantle left for the second plume head to traverse. If μ_u/μ_ℓ is sufficiently small, then f is of order of magnitude 1 (that is, separation of the first plume head occurs quickly and near the 660-km boundary); however, f can be as low as 1/3 before it has an influence on t_r. The expression for t_r is slightly more general than that given by Olson (*24*) but follows from the same derivation. The volume of the second plume head upon reaching the base of the lithosphere is

$$\text{volume} = \frac{4\pi R_1^3}{3}(1 + 5D_u/R_1)^{3/5}$$

or

$$= Qt_r + \frac{4\pi}{3}R_1^3$$

29. Increasing μ_ℓ (for example, to 10^{23} Pa-s) or decreasing R (to reflect only a part of the net Ontong Java plume head volume) would enhance the likelihood that the first plume head separates from the conduit (U/V_{max} would increase) and would lengthen the time delay between eruptive events; these same adjustments would also diminish the volume of the second plume head. Perhaps more importantly, the addition of the endothermic phase change (*28*) would undoubtedly make separation of the first plume head more probable [see in particular Liu *et al.* in (*28*)], lengthen the delay time between arrival of the plume heads, and increase the volume of the second plume head. However, if the conduit flux Q is not sufficiently large, the phase change may preclude the penetration of the second plume head into the upper mantle altogether [see Liu *et al.* in (*28*)].
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Activation and Regeneration of Rhodopsin in the Insect Visual Cycle

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Light absorption by rhodopsin generates metarhodopsin, which activates heterotrimeric guanine nucleotide–binding proteins (G proteins) in photoreceptor cells of vertebrates and invertebrates. In contrast to vertebrate metarhodopsins, most invertebrate metarhodopsins are thermally stable and regenerate rhodopsin by absorption of a second photon. In experiments with Rh1 *Drosophila* rhodopsin, the thermal stability of metarhodopsin was found not to be an intrinsic property of the visual pigment but a consequence of its interaction with arrestin (49 kilodaltons). The stabilization of metarhodopsin resulted in a large decrease in the efficiency of G protein activation. Light absorption by thermally stable metarhodopsin initially regenerated an inactive rhodopsin-like intermediate, which was subsequently converted in the dark to active rhodopsin. The accumulation of inactive rhodopsin at higher light levels may represent a mechanism for gain regulation in the insect visual cycle.

In both vertebrates and invertebrates, light absorption by rhodopsin triggers activation of G proteins in the photoreceptor cell (*1*, *2*). In vertebrates, the intermediate (metarhodopsin II) that activates G proteins is thermally unstable and decays eventually into all-*trans* retinal and opsin (*3*). Rhodopsin is subsequently regenerated by the recombination of 11-*cis* retinal with opsin (*4*). In contrast, in most invertebrates, the intermediate (metarhodopsin) believed to activate photoreceptor G proteins is thermally stable (*5*, *6*). In invertebrates, rhodopsin is regenerated by illuminating metarhodopsin (*5*, *7*,

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