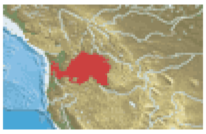
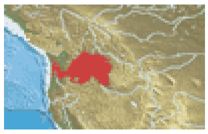


The Columbia River Basalts & Yellowstone Hot Spot: A Mantle Plume?



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Introduction

According to what Marcia McNutt labels "the standard model", the Yellowstone hot spot first manifested itself beneath what is now south-eastern Oregon at 16.6 Ma. The hot spot was then over-ridden by the North American plate travelling in a westerly direction, leaving its trace in sequential volcanic outbursts across southern Idaho, along the eastern Snake River Plain (ESRP) to reach its present position beneath the Yellowstone caldera. The track of the hot spot, or rather the track of the North American plate across the stationary hot spot in the mantle, is based on independently derived plate motions (*Engebretson et al.*, 1985; *Pierce & Morgan*, 1992).

There are four immediately apparent problems with this model as many workers have pointed out. **First**, the eastern Snake River Plain reflects a much more ancient tectonic boundary and it seems coincidental that the hot spot track should follow this structural discontinuity so exactly. **Second**, that while magmatism can be traced sequentially along this track from southern Oregon to Yellowstone Park, that magmatism is primarily silicic, not the basaltic magmatism expected from a mantle plume. **Third**, the huge outpourings of tholeiitic magma of the lower Steens Mountain and the *Columbia River Basalt Group (CRBG)* that are regarded as representing the original plume head, initially move north rather than east with time, with the great majority of the CRBG erupting in northeast Oregon and southeast Washington, rather than in southeast Oregon; that is, the main flood basalt eruptions occur well off the main track of the supposed plume. **Fourth**, there is the problem of apparently mirror-image, primarily silicic volcanism along the Brothers Fault Zone to the west.

To a degree some of these problems may be explained by the exact position of eruption and the type of magmatism being controlled by the tectonic regime in the overlying lithosphere (*Thompson & Gibson*, 1991; *Geist & Richards*, 1993; *Camp*, 1995; *Hooper et al.*, 2002).

So what is the evidence in support of a mantle plume as the standard model for the origin of the CRBG flood basalts?

1. First, there is the exceptionally large volume of tholeiitic magma of the Steens-CRBG province erupted in an extremely short time. If we accept the recent evidence that the lower Steens basalt is the first part of the whole CRBG flood

basalt event (*Hooper et al.*, 2002; *Camp et al.*, 2003) then this series of eruptions produced 234,000 km^3 of tholeiitic basalt, almost all erupted between 16.6 and 15.0 Ma (*Camp et al.*, 2003). This exceptional volume and eruption rate is reflected in other continental flood basalt provinces. The Deccan eruptions created approximately ten times the volume seen on the Columbia Plateau in less than one million years (*Hofmann et al.*, 2000). The Parana, Karoo and Siberian Traps erupted equivalent volumes of tholeiitic magma to the Deccan in similarly short periods of time. How much less than 1 m.y. will remain unclear until isotopic age-dating techniques get still more precise. Such huge volumes and high eruption rates are unique to continental flood basalt provinces. As such they appear to require a unique tectonic/magmatic event. A mantle plume appears to fit that requirement. From the prospective of flood basalt provinces, then, no other model appears to provide for the unique volumes and eruption rates of these large magmatic provinces.

2. Second, these huge eruptions frequently can be shown to occur at the beginning of a long trail of lesser eruptions which end at a currently active volcanic center. The Deccan is by far the best example of this correlation with the traditional hot spot/plume model, but the CRBG fits adequately with the Yellowstone hot spot model, albeit with the problems and plausible solutions noted above. The Parana flood basalt province also seems to conform. On the other hand evidence of such hot spot tracks is much less clear for the Karoo and the Siberian Traps.

3. The third line of evidence in support of the mantle plume - hot spot model for the origin of continental flood basalt provinces lies in the composition of the magmas. Here, again, the evidence is not unambiguous and certainly does not prove the existence of mantle plumes. But it does fit the mantle plume model and can be used to provide appropriate explanations for the lack of primitive upper mantle magmas. As with the Deccan, some of the earlier CRBG eruptions contain those elevated helium isotope ratios that are equated with an origin deep in the mantle (*Dodson et al.*, 1997). Assertions that such helium isotope ratios can be formed elsewhere requires substantiation beyond rhetoric or the circular argument that, because Yellowstone is not a product of a hot spot then elevated helium isotope ratios must be produced in the upper mantle. Are there, for example, clear examples of tholeiitic volcanic rocks not plausibly connected with hot spots which carry such elevated helium isotope ratios?

The CRBG lacks any primary magma that could have been in equilibrium with a normal peridoditic upper mantle and is dominated by relatively low Mg tholeiites and basaltic andesites, typified by the Grande Ronde Basalt Formation with 52-58% SiO_2 and an Mg number ($Mg/Mg+Fe^{+2}$) less than 55. Attempts to explain this by gabbro fractionation fail because the incompatible elements are no more evolved in the Grande Ronde basalts than those of the more mafic Imnaha Basalt flows and there is no evidence of large volumes of gabbro cumulate at depth below the main feeder dikes. Virtually all CRBG magmas have undergone gabbro fractionation within the crust, probably in large reservoirs at depths close to the mantle/crust boundary, but fractionation appears to have started from magma in equilibrium with a source composition more evolved and more iron-rich than typical upper mantle. A more iron-rich source has long been advocated by Tom Wright and his co-workers and supported by experimental evidence (*Wright et al.*, 1988; *Takahahashi et al.*, 1998; *Yaxley*, 2000). An eclogite-bearing mantle plume source derived from subducted ocean basalts recycled through the deep mantle appears to satisfy this requirement (*Cordrey et al.*, 1997) and to satisfy the trace element concentrations.

These appear to be the principal reasons why virtually all workers on flood basalt provinces subscribe to the mantle plume model. Other, such as plate margin, models do not appear capable of accounting for either the huge volumes of magma, the high magma eruption rates, nor the restricted eruptive centers required of flood basalt provinces. Nor do these models account for their compositional peculiarities. In addition many CFBs can be shown to lie at the starting end of typical hot spot tracks which would surely be coincidental in any plate margin model.

I am not persuaded by the arguments outlined by *Christiansen et al.* (2002) that their five geologic constraints are inconsistent with the mantle plume model or that their own or any other model explains these geologic factors any better. I do concede that the supposed track of the hot spot coincides with an older major tectonic structure: this is a coincidence that has long troubled me. Yet that it is a coincidence cannot be denied: the entirely independently derived reconstruction of the plate motions determined by *Engebretson et al.* (1985) places the hot spot beneath southeast Oregon below the massive lower Steens Basalt eruption at 16.5 Ma. We now know that the Steens Basalt was the first episode in the CRBG sequence of flood basalt eruptions. Given the older structure along the eastern Snake River Plain (ESRP), this is a coincidence whatever model is adopted to explain the magmatism. The Brothers Fault Zone, which is a mirror image of the ESRP, is also an older structure, almost certainly involving originally right-lateral motion separating an area of greater east-west extension to the south from an area of less extension to the north (*Lawrence*, 1976; *Hooper & Conrey*, 1989; *Hooper et al.*, in press). Given that the other parallel WNW-ESE trending fault zones recognised by Lawrence are not followed by silicic or bimodal magmatism, it seems plausible that the magmatism along this older structure was due to the expanding mantle plume beneath SE Oregon, as suggested by others.

The argument that CRBG volcanism is caused by the Basin & Range extension makes no sense from the view of the Columbia River basalt eruption. First, it is surely now widely accepted that east-west extension has been going on from the Eocene to the present (of many papers one could quote, there is the work of Gains and others to the south and *Hawkesworth et al.*, 1995, and many to the north including, for example, *Janecke*, 1992; *Hooper et al.*, 1995; *Morris & Hooper*, 1997, *Morris et al.*, 2000 and, the most recent, *Breitsprecher et al.*, 2003). Certainly from north of the Canadian border to Nevada Eocene extension is well established. The Pasco Basin in central Washington State, for example, is a NS rift which has been actively extending from before the Eocene, throughout the Miocene CRBG eruptions, and apparently continues developing today.

The magmatism associated with Eocene and subsequent east-west extension from British Columbia to Nevada is of small volume and of calc-alkaline to alkaline affinity. This volcanic activity is physically and chemically distinct from the huge burst of tholeiitic activity that was superimposed on the extension magmatism for a brief period in the Miocene (16.6 to 15.3 Ma in east central Oregon). The details of this relationship have been recently documented and need not be repeated here (*Hooper et al.*, 2002, *Camp et al.*, 2003, and references therein). It is logical that the superimposition of the hot spot, plume or otherwise, on the stretching lithosphere in the eastern Oregon area, would have softened the lithosphere and accelerated extension immediately following the CRBG-Steens eruption. Thus, although significant extension and associated volcanism had preceded the Steens eruptions, the large and conspicuous Oregon-Idaho graben lying between the Oregon-Idaho border and Steens Mountain began to form immediately after the hot spot magmatism ceased.

An equivalent example of rapid extension following the main CFB eruptions is also well documented on the western side of the Deccan (*Hooper*, 1990; *Sethna*, 2003). Thus, the most recent field and geochemical studies in eastern Oregon do not support the argument that the Yellowstone magmatism coincidentally began as the extension started. Again, to view the concept of lithospheric structures controlling the funnelling of hot spot generated magmas to the surface as a “difficult to explain coincidence” seems unrealistic. Rather it might be viewed as inevitable that such structural control would play a part in the final eruptions on to the surface. In brief I find neither the geologic constraints nor the

$^3He/^4He$ arguments against a mantle plume model at all convincing.

Summary

The bottom line to this contributor is the huge volume, exceptional rate of eruption, and restricted area of continental flood basalt eruptions in general and the CRBG in particular. None of the non-plume models appear to recognize, far less explain, these very basic facts. Until they do flood basalt workers are likely to retain their belief in a mantle plume model as the best explanation available for the origin of continental flood basalts, despite the model's poor constraints.

Having said all that, this worker would be the first to concede that the mantle plume model is poorly constrained and in need of more rigorous investigations. Current programs with this in mind are to be greatly welcomed. The evidence against the mantle plume model appears to be almost entirely geophysical, not geological. As a basalt petrologist I can have no adequate answer to the geophysical problems, but cannot but note that such techniques as seismic tomography are relatively new and, as we have so often found of exciting new techniques in the past, may not yet be fully understood. To that extent and to a non geophysicist its results appear susceptible to misinterpretation.

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