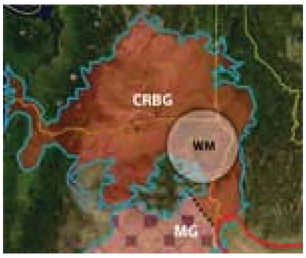

Delamination Origin for Columbia River Flood Basalts and Wallowa Mountains Uplift

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Read more about this topic in a recent publication in the journal Nature (*Hales et al.*, 2005).

Introduction

The mechanism driving flood basalt volcanism (*i.e.*, hot spot initiation) is undoubtedly an issue of great contention in many geologic circles, and rightly so. These enormous events represent large scale melting and, as many have argued, may result from deep-reaching convective currents that transport hot, fertile mantle to the surface (*Morgan*, 1972; *Crough*, 1983; *Hill et al.*, 1992; *van Keken*, 1997). However, our recent investigations show that a plume-like mantle upwelling is not the principle cause of Columbia River Basalt Group (CRBG) volcanism in northeast Oregon, southwest Washington, and western Idaho. The pattern of uplift observed in the region is inconsistent with that expected from the impingement of a rising plume head (*e.g.*, *Ribe & Christensen*, 1994; *Farnetani & Richards*, 1994), but the upper mantle seismic structure is consistent with it being the source region for CRBG melts. Here we not only provide evidence supporting our proposed model, but also hope to stimulate further work on this important problem.

The northwestern United States provides an ideal locale for the study of large igneous provinces (Figure 1) because it is home to the most recent flood basalt event on Earth, the effects remain relatively unaltered by subsequent tectonic, volcanic or erosional events, and an approximately plate-motion-parallel progression of volcanism can easily be traced from southeast Oregon across the Snake River Plain to Yellowstone. The effects in northeastern Oregon include the eruption of ~175,000 km^3 of dominantly tholeiitic basalt (*Tolan et al.*, 1989), 300 m of syn- and post-eruptive uplift over a broad region, and persistent uplift of ~2 km in the Wallowa Mountains. It should be noted that recent revisions to the classification of flood basalt volcanism in the region have been made bringing the total volume to ~234,000 km^3 (*Camp & Ross*, 2004); the Columbia River flood basalt province now includes not only the CRBG but also the Steens and Malheur Gorge basalts of southeastern Oregon. Though it is likely they are closely related, our study focuses on the source of volcanism and uplift in northeastern Oregon rather than the entire province.

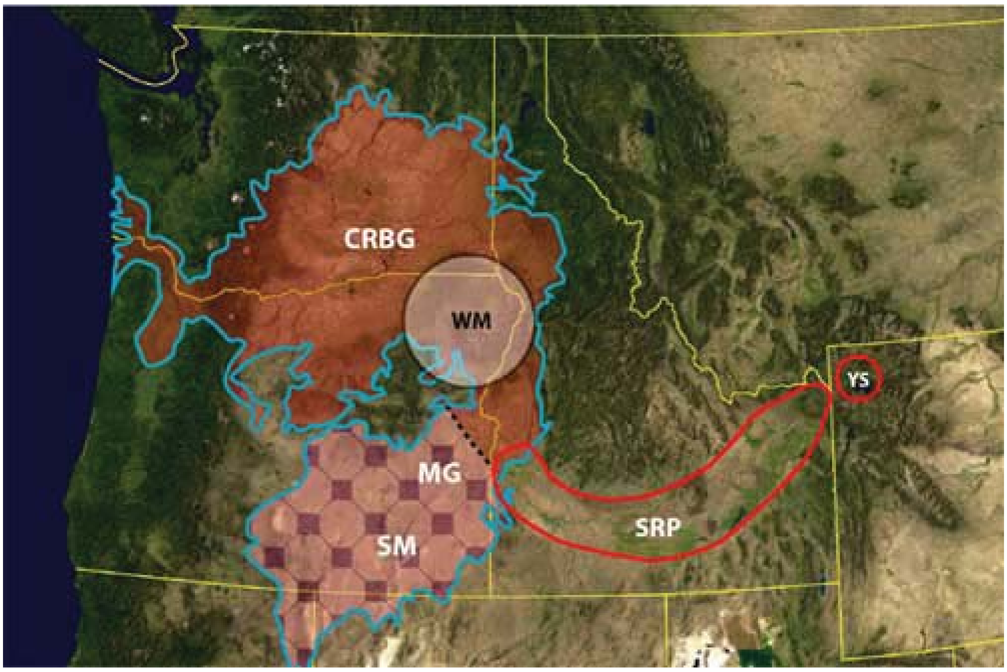

Figure 1. Map showing the distribution of the mid-Miocene Columbia River flood basalts (CRBs). The white circle denotes the region of uplift described in Figure 2. We separate the CRBs into the CRBG and Steens/Malheur Gorge basalts because of their distinct source regions. MG = Malheur Gorge, SM = Steens Mountain, SRP = Snake River Plain, WM = Wallowa Mountains, YS = Yellowstone.

Regional Uplift (Mid-Miocene to Present)

CRBG lavas erupted onto a low relief surface of Mesozoic accreted oceanic terranes stitched together by Jurassic plutons, of which the Wallowa pluton is the largest (*Goles*, 1986). After initial Imnaha flows filled valleys, subsequent Grande Ronde (GR) eruptions deposited thin, flat-lying sheets. The well-mapped, large, continuous areal extent of these early CRBG flows allows for detailed flow interface analysis to accurately measure deformation (Figure 2a). We correct elevation maps of the GR magnetostratigraphic units (*Walker*, 1979; *Hooper et al.*, 1992; *Reidel et al.*, 1995) for the effects of erosional unloading (*Lambeck*, 1988; *Anderson*, 1994) to obtain markers of post-eruptive deformation. Imnaha basalts ponded in incipient basins, indicating possible pre-eruptive subsidence (*Camp*, 1981). Basin development continued during GR eruptions, causing local ponding and thickening of flows, while syn-eruptive uplift created locally thinned units. Post-GR deformation is evidenced by the contrasting distributions of GR and later CRBG Wanapum (15-14 Ma) and Saddle Mountains (14-6 Ma) flows, which show distinctive, well-developed channelization and ponding in response to emerging topographic relief (*Tolan et al.*, 1989). The uplift and downwarp of these flows closely conform to current topography, with up to 2 km of uplift focused on the Wallowa pluton (Figure 2b) and more subdued uplift centred on the lesser plutons in the area. This structural evidence leads us to conclude that most Wallowa Mountains uplift occurred after the majority of CRBG eruptions and over a period of <10 m.y, and we find the volume of uplift relative to the hinge-line in Figure 2b is ~7300 km^3.

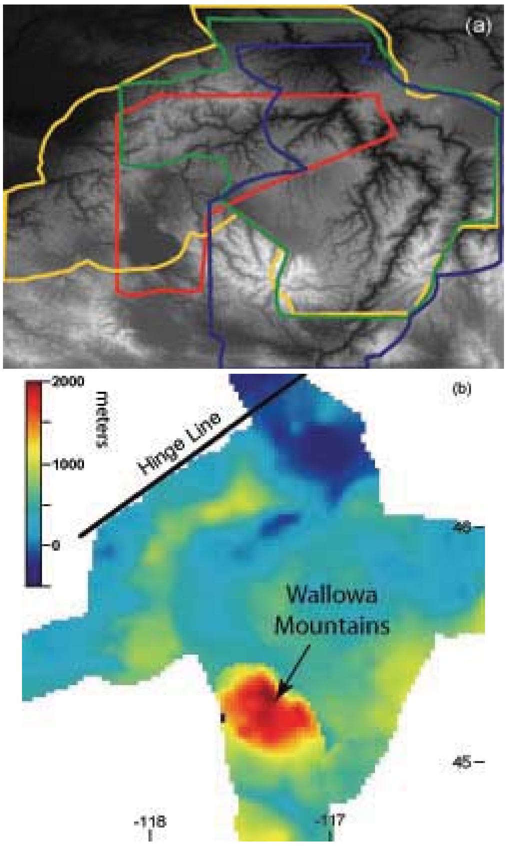

Figure 2. Post-eruptive uplift. (a) Digital elevation map showing the overlapping distribution of exposed GR magnetostratigraphic interfaces: Imnaha-R1 (blue), R1-N1 (green), N1-R2 (gold) and R2-N2 (red). (b) Composite surface for GR uplift. This surface was made by vertically shifting the individual interfaces using published flow thicknesses (Camp, 1981), smoothing the resulting surface with a mild low-pass filter, and removing the effects of erosional unloading by deconvolving the point load response of an elastic plate (Lambeck, 1988; Anderson, 1994), assuming total coverage by the GR lavas and an elastic thickness of 5 km, similar to other estimates from this area (Lowry & Smith, 1995). The absolute elevation is referenced to a hinge line (black line) that separates the uplifted Blue Mountains from the down-dropped Pasco Basin immediately NW of the Blue Mountains.

Upper Mantle Seismic Structure

We have also conducted the first tomographic study of the upper mantle in northeast Oregon using a six-station array (Figure 3a). Lateral resolution at shallow depth is low due to large station spacing (75-150 km), but the broad aperture of the network allows for reasonable imaging to depths of 250 km. There exists a high-velocity region between ~70 km and ~150 km depth centered beneath the Wallowas and other granite-cored mountains in the region (Figure 3b). “Squeezing” tests indicate no need for significant anomalies below ~175 km. Other less-well-resolved structures include two separate high-velocity bodies: (1) beneath station IDA in western Idaho at shallow depth and (2) deeper structure beneath the western Snake River Plain. The remaining upper mantle imaged indicates slower than normal (relative to IASPI91) seismic velocities. Maximum deviations in V_p are ±4%.

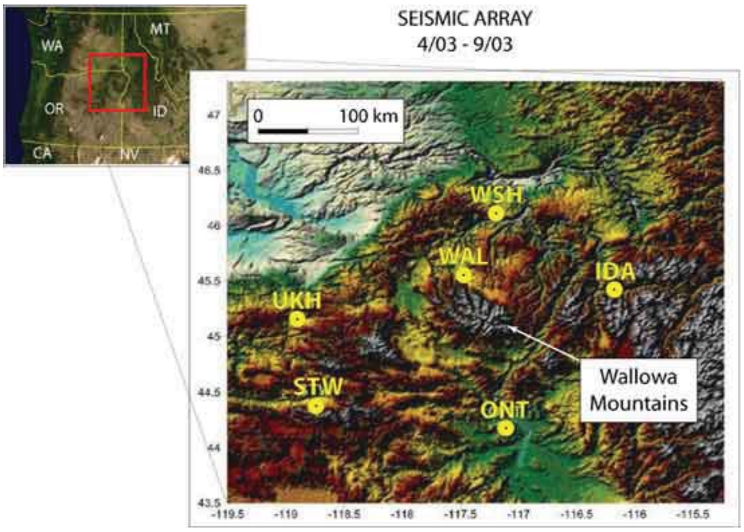

Figure 3a

Figure 3. (a) Study area and seismic array utilized for the tomographic inversion. Sensors were all Guralp CMG40-T broadband seismometers from PASSCAL. (b) Upper mantle seismic structure from ~600 teleseismic rays. The largest and best-resolved structure is the high-velocity anomaly centered beneath station WAL and the Wallowa Mountains. The rough dimensions of this body are 80 km thick, 125 km N-S, and 200 km E-W. The shallow structure beneath IDA is at sub-crustal depth, and if real, could represent residuum in the spinel-peridotite stability field where an increase in seismic velocity is expected (Schutt & Lesher, 2005) without a significant density decrease. The high-velocity anomaly southeast of ONT may be related to volcanism in the western SRP or MG/SM basalts. Without a broader array, the extent of these features remains ambiguous. The remaining low-velocity mantle is likely a result of excess heat or partial melt from the flood basalt event.

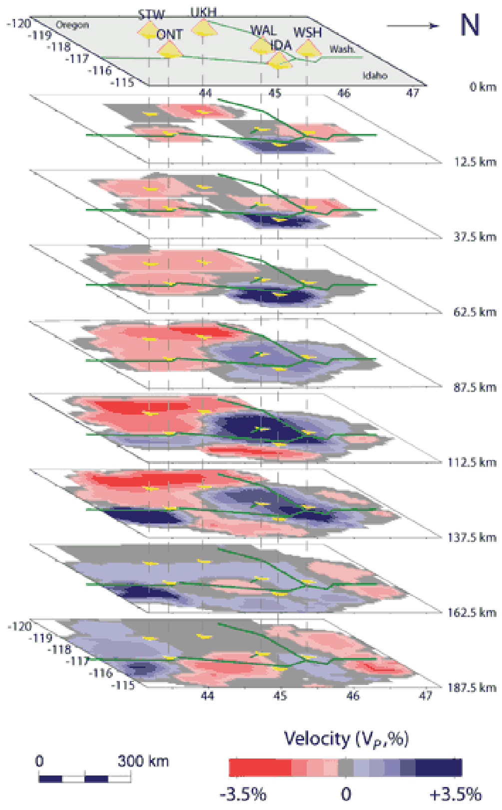

Figure 3b

Discussion

Schutt and *Lesher* (2005) investigated the effects of partial melting on mantle peridotite residuum density and seismic velocity. Though they find a density decrease of 0.65% per 10% partial melting in the garnet stability field (*i.e*., below 70 km), no significant perturbations in V_p , V_s, or V_p/V_s are observed. Thus, if our imaged body is residuum from the CRBG, a different mechanism for increasing seismic velocity is needed. The occurrence of basaltic volcanism in the recent past and the major uplift in the Wallowa Mountains are inconsistent with the high-velocity mantle being relatively cool. We argue that a reasonable alternative is that melt content has been reduced (and possibly eliminated) by eruption of the CRBG to the extent that seismic velocity is increased. The hypothesis that this anomaly is in fact the source region for the CRBG is strengthened by the spatial correlation between the upper mantle high-velocity volume and the location of flood basalt dikes. Also, high pressure melting experiments on a member of the GR basalts (GR make up 85% of the CRBG) indicate a melting depth of ~70 km (*Takahashi et al.*, 1998), coincident with the upper limit of the imaged high-velocity body.

If we assume that all melt produced here was erupted (*i.e.*, the volume of the CRBG) [**1.75×10^5 km^3**] and conservatively estimate the volume of mantle source region (our high-velocity body) [**2×10^6 km^3**], then we can find an approximation for the amount of partial melting needed to produce the CRBG [**6.84%**]. Using this percentage, an estimate of positive mantle buoyancy [**2.64×10^3 kg**] is possible, and we can compare this with the volume of uplifted crust [**7.3×10^3 km^3**] and its negative buoyancy [**2×10^3 kg**]. These simple (very rough) calculations demonstrate that the high-velocity volume of mantle imaged is a very good candidate for the source of the CRBG as well as the isostatic support for the syn- and post-eruptive uplift in the region.

Several plume-related theories have been proposed for the origin of the CRBG. For example, northward deflection of a plume by the subducting Juan de Fuca slab (*Geist & Richards*, 1993), sub-lithospheric melting beneath southeast Oregon with melt then transported laterally through the crust some 400 km north (*Takahashi et al.*, 1998, see their figure 8), and radiating volcanic migrations from a plume in southeast Oregon (*Camp & Ross*, 2004; Ed: see also Radiating Volcanic Migrations & Columbia River Basalts & Yellowstone pages). However, none are able to account for the combined pattern of uplift and seismic structure.

The formation of Rayleigh-Taylor instabilities and subsequent mechanical detachment of sections of the lithosphere has been suggested as the cause for the Siberian flood basalts (*Elkins-Tanton & Hager*, 2000). Delamination of lithospheric material allows for the rapid upwelling of hot (and likely fertile) asthenosphere to unusually shallow depths where it can then readily melt through decompression. The catalyst in their model is the intrusion of relatively small amounts of dense adiabatic melts into the lower lithosphere causing it to weaken and mechanically decouple from the upper lithosphere. Unlike the Pacific Northwest, Siberia does not show evidence for significant uplift following the rapid eruption of flood basalts, but it is likely that lithospheric structure plays a role in determining the pattern of uplift in a different provinces (*Burov & Guillou-Frottier*, 2005). The extensive volcanic and tectonic history of the accreted terranes in northeastern Oregon must certainly have had an effect here; possibly by (1) creating a weak layer within the lithosphere that would later facilitate a delamination event and (2) forming a density structure conducive to uplift after delamination (*e.g.*, buoyant plutons with dense roots). Prior to the physical separation of the lower lithosphere, uplift forces, either from a thermal anomaly or buoyant residuum, would have been counteracted by the downward pull of detaching material. Following delamination, extensive upwelling and melting formed the GR basalts, and the buoyant residuum that today supports the regional uplift was emplaced.

Summary

With our new tomographic images and uplift analysis, we believe that delamination of dense mantle lithosphere in northeast Oregon ultimately produced the CRBG and subsequent uplift of the region. It remains unclear, however, what controlled the timing and location of this event. Did the pre-existing lithospheric structure coincidentally fail at the same time as the impingement of a plume head 400 km to the south? Did delamination occur (*e.g.*, *Elkins-Tanton & Hager*, 2000), triggered by melt intrusion from a plume head spreading north from southeast Oregon? Did the Precambrian margin to the east play a role in creating flow from beneath the older, thicker lithosphere up to the accreted Mesozoic terranes without the help of a plume (*e.g., King & Anderson*, 1998)? These are only a few of the questions that remain unanswered, but with this and future, higher-resolution tomographic studies we have a new means of addressing and resolving the origin of the CRBs and possibly other flood basalt eruptions.

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