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The Yellowstone "hot spot" track results from migrating basin-range extension

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ABSTRACT

Whether the volcanism of the Columbia River Plateau, eastern Snake River Plain, and Yellowstone (western U.S.) is related to a mantle plume or to plate tectonic processes is a long-standing controversy. There are many geological mismatches with the basic plume model as well as logical flaws, such as citing data postulated to require a deep-mantle origin in support of an "upper-mantle plume" model. USArray has recently yielded abundant new seismological results, but despite this, seismic analyses have still not resolved the disparity of opinion. This suggests that seismology may be unable to resolve the plume question for Yellowstone, and perhaps elsewhere. USArray data have inspired many new models that relate western U.S. volcanism to shallow mantle convection associated with subduction zone processes. Many of these models assume that the principal requirement for surface volcanism is melt in the mantle and that the lithosphere is essentially passive. In this paper we propose a pure plate model in which melt is commonplace in the mantle, and its inherent buoyancy is not what causes surface eruptions. Instead, it is extension of the lithosphere that permits melt to escape to the surface and eruptions to occur—the mere presence of underlying melt is not a sufficient condition. The time-progressive chain of rhyolitic calderas in the eastern Snake River Plain–Yellowstone zone that has formed since basin-range extension began at ca. 17 Ma results from laterally migrating lithospheric extension and thinning that has permitted basaltic magma to rise from the upper mantle and melt the lower crust. We propose that this migration formed part of the systematic eastward migration of the axis of most intense basin-range extension. The bimodal rhyolite-basalt volcanism followed migration of the locus of most rapid extension, not vice versa. This model does not depend on seismology to test it but instead on surface geological observations.

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INTRODUCTION

Explaining how melt can exist in the mantle is not sufficient to explain surface volcanism. Melt is widespread in the shallow mantle and erupts where lithospheric extension permits it to do so. In the plate model, the lithosphere is the active agent that allows volcanism to occur. The lithosphere is not a passive, uninvolved interface between the mantle and the atmosphere through which melt passes transparently, as light passes through a sheet of glass. The mantle is not devoid of melt beneath regions where surface volcanism is absent. It is not required that melt formation and eruption to go hand-in-hand on the same time scale. In fact, the volumes and eruption rates in flood basalts preclude this (Cordery et al., 1997; Silver et al., 2006).

It is unlikely that a mantle-plume origin would ever have been suggested for the eastern Snake River Plain–Yellowstone (ESRP-Y) zone (western U.S.) were it not for the time-progressive chain of large rhyolitic caldera volcanoes there. The existence of such volcanic chains, and in particular their perceived fixity relative to the Hawaiian chain, was the cornerstone of the original plume hypothesis (Morgan, 1971). This hypothesis attributes apparent relative fixity of volcanic loci on different plates to their sources being in the deep mantle, below the rapidly convecting shallow mantle associated with plate movements. This was required by the model because sources in rapidly convecting mantle were expected to move relative to one another. In the deep mantle, the only viable candidate source region for thermal plumes is the core-mantle thermal boundary layer.

Correcting the time progression of the ESRP-Y rhyolitic volcanoes for the effect of basin-range lithospheric extension found that the relative fixity of the volcanic locus with respect to Hawaii was improved still further over uncorrected estimates (Rodgers et al., 1990). This has been taken to provide additional supporting evidence for a plume model for Yellowstone. Nevertheless, numerous seismological studies spanning nearly half a century essentially all agree that the seismic anomaly beneath the ESRP-Y zone is rooted in the shallow mantle (e.g., Burdick et al., 2012; Christiansen et al., 2002; Courtillot et al., 2003; Iyer et al., 1981a; James et al., 2011; Montelli et al., 2004a, 2004b, 2006; Ritsema and Allen, 2003; Schmandt and Humphreys, 2010; Tian et al., 2009; Xue and Allen, 2010). Estimates for the bottoming depth range from 200 km to a maximum of 1000 km. These studies include numerous sophisticated recent studies conducted by multiple research groups using data from USArray. This array comprises a 2000-station network spanning the entire contiguous 48 states, and has an areal extent of ~8000 × 2250 km. The data it returned are unprecedented in quality, quantity, and breadth of the monitoring area, and are unlikely to be surpassed in the near future.

A shallow provenance for mantle processes associated with ESRP-Y volcanism immediately weakens the argument that the time-progressive volcanic chain supports a mantle-plume interpretation. The fundamental premise of the hypothesis was that deep origins, below the shallow, rapidly convecting layer, were required to explain relative fixity of the volcanic loci. The plume hypothesis cannot explain relative fixity of volcanic loci fed from the shallow mantle, in particular in structurally and dynamically complex parts of the mantle such as that beneath the western U.S. It is not clear why a long-lived, thermally buoyant upwelling fixed relative to Hawaii should spontaneously arise in the upper mantle, nor how it could be sustained. A second argument frequently cited as conclusive evidence for a plume—the observation of high $^3He/^4He$ isotope ratios—is, as a consequence, also suspect. This is because the theory that such isotope ratios indicate plumes rests on arguments that only the core-mantle boundary region has sufficiently high $^3He/^4He$ to be the source.

These observations imply that the time progression of rhyolitic volcanism and its associated upper-mantle magmatism in the ESRP-Y zone are not induced by a plume arising from the base of the mantle. If this is so, some other process must be responsible. The Janus twin of the ESRP-Y zone, the mirror-image, east-to-west–migrating High Lava Plains time-progressive volcanic chain (the "Newberry trend"), which extends from the old end of the ESRP-Y zone to the active Newberry volcano in Oregon, has been attributed to interaction of the lithosphere and evolving shallow mantle convection associated with the subduction zone to the west. If such processes can explain the time progression of the Newberry trend, it follows that they might also explain that of the ESRP-Y zone.

This paper summarizes briefly some of the now extensive body of seismological information on the mantle beneath the western U.S. in the neighborhood of the ESRP and Yellowstone. Current plume- and plate-related models are reviewed. We propose a new, pure plate model for the ESRP-Y zone. In this model, volcanism is permitted by an evolving, migrating pattern of lithospheric deformation. We do not assume that the planform of surface volcanism merely reflects melt existence in the mantle, with little influence from a passive lithosphere. Our model for ESRP-Y volcanism is based on surface observations. It does not appeal to non-unique interpretations of remotely sensed mantle seismic structure. Instead, it is suitable for testing using surface geological observations.

FRAMEWORK

The basalts of the Columbia River Plateau (the Columbia River basalts, CRB) and the ESRP-Y volcanic provinces together (Fig. 1) are regarded by many as the products of the type-example continental mantle plume. It has been argued that these provinces are consistent with an initial plume head forming a flood basalt, followed by a time-progressive volcanic trail leading to a currently active volcanic locus. This comprises one of only three cases in the world where time-progressive volcanism is spatially associated with a flood basalt of the appropriate age (Courtillot et al., 2003).

Despite this, many aspects of the region do not fit this model (e.g., Christiansen, 2001; Christiansen et al., 2002):

1. The uplift claimed to have heralded plume-head arrival is based on ambiguous observations that could equally well

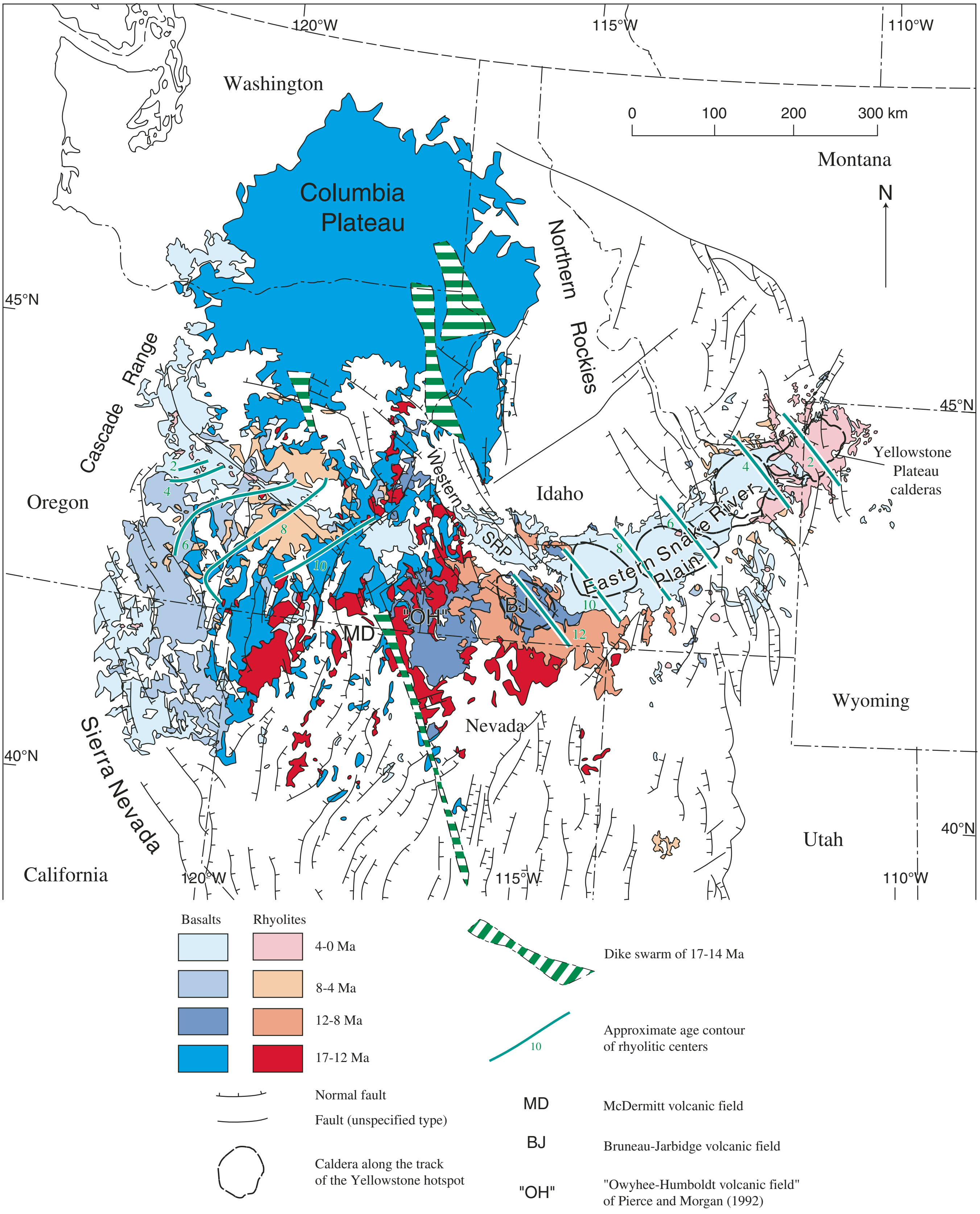


Figure 1. Map of the northwestern United States showing basin-range faults, and basalts and rhyolites of 17 Ma and younger (from Christiansen et al., 2002). Approximate age contours of rhyolitic volcanic centers (ca. 12, 10, 8, 6, 4, and 2 Ma) across the northeast-trending eastern Snake River Plain (SRP) are shown. A contemporaneous trend of oppositely propagating rhyolitic volcanism that trends northwest across central Oregon is indicated by similar contours. Locations of calderas are from Pierce and Morgan (1992) and Christiansen (2001).

be interpreted as indicating climate change (Bull, 1991; Foulger, 2010, p. 50; Hooper et al., 2007). Any uplift was local. Regional vertical motions were studied by Hales et al. (2005) who reconstructed the presumed initially flat topography of individual lava flows. This work found that regional subsidence, not uplift, preceded CRB eruption (Hales et al., 2005; Humphreys et al., 2000; Sheth, 2007).

2. Almost all of the 234,000 km^3, 1.8-km-thick CRB erupted very quickly, over ~1.6 m.y. (Pierce and Morgan, 2009). This is much faster than the 10–20 m.y. predicted by numerical modeling of arriving plume heads (Farnetani and Richards, 1994).
3. The flood basalt lavas erupted from parts of a relatively narrow ~900-km-long zone of fissures that lie along the late Precambrian rift margin of North America (Fig. 1). This is more consistent with a linear source than a point source. The ~300 × 600 km, roughly oval flood basalt does not reflect the geometry of the magma source, but the topography of the land at the time of eruption (Christiansen et al., 2002).
4. The geochemistry of the CRB corresponds to shallow adiabatic decompression melting of mantle lithosphere, and the depths and temperatures of melting correspond to ~100 km and normal mantle temperatures near the base of the crust (e.g., Long et al., 2012). The composition of the CRB is different from basalts of the ESRP-Y zone, most notably in TiO_2, P_2O_5, SiO_2, and alkalis. There is, thus, no geochemical evidence that they come from the same source.
5. The oldest end of the ESRP-Y zone, the McDermitt caldera, lies south of the Steens Mountain and other main CRB eruptive fissures, and 400 km south of the largest eruptive centers (Camp, 2013; Pierce et al., 2002). This is not consistent with ESRP volcanism being fed by a CRB "plume tail", which would necessitate a migration rate up to 6.2 cm/yr from 17 to 10 Ma, much faster than the 2.5 cm/yr that occurred between later volcanoes (Anders, 1994).
6. The volcanism that began at ca. 16.1 Ma with formation of the McDermitt caldera was not an isolated event but part of major tectonic reorganization throughout much of a region 2000 km wide that included the newly forming, volcanically productive, basin-range region (Christiansen and Lipman, 1972; Christiansen and McKee, 1978). This onset of northeastward-propagating volcanism occurred at the western edge of the Archean North American craton (Hoffman, 1989).
7. McQuarrie and Rodgers (1998) reported that more than half of the total subsidence of the ESRP occurred before eruption of a 6.6 Ma ignimbrite from the major caldera center just west of Yellowstone. This indicates that downwarping preceded this portion of the time-progressive rhyolitic volcanism, the opposite of what is expected for "plume tail" volcanism.
8. The ESRP-Y volcanic zone existed in some form prior to the arrival of major caldera-forming eruptions. For example, smaller silicic eruptions occurred as early as ca. 10 Ma a few tens of kilometers south of Yellowstone and elsewhere in the northern Basin and Range province, well before major caldera-forming volcanism (Christiansen and McKee, 1978; Christiansen and Yeats, 1992; Love, 1956; Love et al., 1973).
9. The distribution of ESRP rhyolitic volcanism between 10.2 and 2 Ma was not a simple linear time progression. Rather, volcanism developed large caldera systems that evolved in place, gradually dwindled, then initiated in a new location in stepwise progression (Christiansen, 2001; Pierce and Morgan, 2009).
10. The calderas are blanketed and buried by post-caldera tholeiitic basalt which erupted continuously for hundreds of kilometers along the ESRP without spatial migration. This basaltic volcanism, which has been continuous to the present, is not predicted by the plume hypothesis (Campbell, 2007).
11. There is no evidence in the form of high-temperature petrology, e.g., picrite glass or komatiite-like magmas, for the high melt-source temperatures expected for a mantle plume which are 200–300 °C hotter than the regional mantle (Davies, 1999; Foulger, 2010, chapter 6; Foulger, 2012).
12. Simultaneous with northeastward migration of volcanism along the ESRP-Y zone, volcanism also migrated northwestward across the High Lava Plains (the Newberry trend) (MacLeod et al., 1976). These mirror-image volcanic chains do not lie at random places but run along the northern margin of the region of basin-range extension.
13. To the south of the ESRP-Y zone, the Basin and Range province has widened by ~250 km since volcanism began at ca. 17 Ma (Wernicke and Snow, 1998). To the immediate north however, extension has been no more than a few tens of kilometers, dwindling within a few tens of kilometers farther northward to essentially zero (Christiansen and McKee, 1978; Christiansen and Yeats, 1992; Lawrence, 1976).
14. The ESRP-Y zone, functioning essentially as a transfer zone between regions of differential extension (Christiansen and McKee, 1978; Christiansen and Yeats, 1992; Payne et al., 2008), lies at a profound change in lithospheric structure between thin, hot, extending lithosphere to the south and thick, cold lithosphere underlying the North American craton to the north. This zone is also marked by a regional aeromagnetic anomaly that runs along the axis of the ESRP from Nevada northeastward through Montana and on to Canada (Eaton et al., 1975; Mabey et al., 1978).
15. Numerous Precambrian geologic and geophysical alignments that parallel the ESRP-Y zone suggest deep-seated

lithospheric structural control. O'Neill and Lopez (1985) identified a complex broad zone of diverse northeast-trending features, the Great Falls tectonic zone. This zone is at least 250 km wide and 600 km long and lies north of the ESRP-Y, crossing younger Rocky Mountains structural trends. Thomas et al. (1987) and Hoffman (1989) regarded it as the expression of a Paleoproterozoic suture between the Archean Wyoming and Hearne provinces, though Boerner et al. (1998) considered it an intracontinental shear zone. The Madison mylonite zone (Erslev, 1983) lies along its southeastern exposed margin. Deep-seated structures detected by seismic and potential-field surveys demonstrate the lithospheric scale of both the Great Falls tectonic zone and the Archean Wyoming province (Lemieux et al., 2000).

16. Other magmatic zones in the Basin and Range province are also oriented parallel to the ESRP-Y zone, in particular, the Valles and the St. George zones (Smith and Luedke, 1984). These zones also parallel regional lithospheric structures of Precambrian origin (Ander et al., 1984; Dueker et al., 2001; Humphreys and Dueker, 1994; Karlstrom et al., 2002). They too have erupted both rhyolite and basalt over the same time period as the ESRP-Y zone although their volcanism is not time progressive. Nevertheless, the seismic structure beneath them is similar to that of the ESRP-Y province. Beneath the Valles zone, low velocities in the mantle extend to even greater depths than beneath the ESRP-Y zone (see the Continental-Scale Tomography Using USArray Data subsection) (Burdick et al., 2012).

As a consequence of the above observations, opinion regarding the origin of CRB-ESRP-Y volcanism varies widely. Since USArray data have become available, many studies have attempted to resolve the question, and the ESRP-Y region has become the most intensively studied melting anomaly in the world. These studies have returned varied results but have not produced reliable, repeatable evidence for a plume. Nevertheless, opinion still remains divided (e.g., Christiansen et al., 2002; Tian and Zhao, 2012). Briefly reviewing some of these seismological studies is the task of the next section of this paper.

In light of many new seismic tomography images, a wide range of new models has been proposed for CRB-ESRP-Y volcanism. Any successful model in addition has to explain in particular the north-south–oriented, 900-km-long array of CRB and other contemporaneous eruptive fissures, the two oppositely propagating time-progressive chains of rhyolitic central volcanoes, and the widespread basaltic volcanism and basin-range extension throughout an ~800-km-wide province. Models proposed previously fall into three broad classes:

1. A mantle plume;
2. Upper-mantle convection related to subduction-zone evolution (assuming the lithosphere to be passive); and
3. Upper-mantle convection combined with lithospheric extension, assuming the lithosphere to influence the site of volcanism but not the fundamental fact that it occurs.

None of these are pure "plate" models that view the lithosphere as the active element (Foulger, 2010). The plate hypothesis proposes that volcanism results from lithospheric extension, driven by plate-tectonic processes, that permits the escape of melt to the surface. The volume erupted is dependent on the amount available in the mantle which is, in turn, dependent on many processes, including convection. However, the mere presence of melt in the mantle per se is not a sufficient explanation for surface eruptions.

In this paper we thus propose a fourth class, a pure plate model, for the ESRP-Y zone:

4. Lithospheric extension driven by plate-boundary processes that allows pre-existing melt to erupt.

SEISMIC STRUCTURE OF THE MANTLE

Of all major melting anomalies on Earth, the ESRP-Y region is the best placed for study using seismology because of its position within the North American continent. Consequently it is the most comprehensively studied. It has been the target of several ambitious seismometer deployments, and the full suite of seismic methods has been applied, including diverse tomography approaches and study of the transition zone (TZ) using receiver functions. Seismic tomography (a term first proposed by Anderson and Dziewonski [1984]) has been conducted on local, regional, and whole-mantle scales and, most recently, on a continental scale using data from the ~2000-station USArray network that covered the entire country over the period 2004–present (http://www.usarray.org).

Caveats on Seismic Tomography

The results of tomographic experiments can vary considerably according to the data-inversion and plotting strategies used (Foulger et al., 2013). The values chosen for factors such as damping may be fairly arbitrary, within bounds, but can have a major effect. A strongly damped inversion will produce relatively simple models with broad, weak anomalies, whereas a weakly damped inversion will produce more complex models with smaller, stronger anomalies. There is no fully objective method for choosing the correct damping factor, and in general, amplitudes of anomalies are probably underestimated by a factor of several (Sun and Helmberger, 2011). The effect of structure outside the study volume on the approach directions of rays is ignored in many inversion methods. This means that the seismic rays used do not necessarily travel along the paths assumed. This will have an unknown corrupting effect on the results.

A particular problem for the ESRP-Y region is that of inhomogeneous ray coverage. Because the dominant source of recorded earthquakes is the circum-Pacific belt, a large majority of rays approach at angles of ~20°–30° to the vertical, from northwest or southeast azimuths. This will produce preferred smearing of anomalies along those incoming ray directions. Such smearing is visible in all teleseismic tomography images of the region.

Despite widespread assumptions, teleseismic tomography does not yield the three-dimensional structure of the study volume but only lateral variations in structure in each independent layer (Foulger et al., 2013, their section 2.3). Apparent continuity of imaged anomalies between the layers is controlled by the assumed "normal" background seismic velocity for each layer. Neglect of anisotropy will work to create low-velocity artifacts in regions where melt lamellae exist (Anderson, 2011). Checkerboard tests do not have the power to determine which, if any, parts of a study volume have been imaged reliably because they do not test resolving power for the real structure present. A nontechnical summary of these problems is presented by Foulger et al. (2013).

In addition to these challenges, there is a wide choice of approaches to displaying the results, including choice of color scale, use of smoothing and interpolation to produce images that look "natural", and selection of lines of section that yield images that fit best the preferred model. Assessment of the results may be out of reach for non-seismologists as a practical matter because errors are rarely published in a way that is straightforward to deal with, models may not be available on the internet, and plotting tools provided may be challenging to use and the outputs nonuniform in appearance (Pavlis et al., 2012).

Most problematic, perhaps, is the fact that interpretation of anomalies is ambiguous. The effects of lithology, melt content, and temperature cannot be unambiguously separated out. Seismology cannot be used as a thermometer, and seismic velocity anomalies cannot be interpreted solely as temperature variations. Even if the different effects could be known, because amplitudes cannot be reliably determined, strengths of the anomalies cannot be reliably interpreted.

Given these issues, it is an unsurprising if inconvenient fact that there is limited repeatability among the many tomographic results available, including those recently produced using USArray data (see Continental-Scale Tomography Using USArray Data subsection). Furthermore, there is a diverse range of interpretations.

Early Studies—Teleseismic Tomography

Teleseismic tomography to study the mantle beneath Yellowstone was pioneered in the 1970s by Iyer et al. (1981b) who deployed a 57-station network of vertical short-period seismometers over an area of 430 × 250 km. That experiment detected a low compressional wave-speed (low-V_P) anomaly in the upper crust, decreasing in strength in the lower crust and upper mantle. Christiansen et al. (2002) reprocessed the data, finding strengths of typically –4% to –5% throughout the main low-V_P body (Fig. 2). They confirmed the results of Iyer et al. (1981b) that the anomaly terminates at ~200 km depth, ruling out deeper bodies with V_P anomalies stronger than about –1% and dimensions comparable to the shallower anomaly. At greater depth, immediately beneath Yellowstone, high V_P was imaged at 300–400 km.

Additional weak anomalies, both high- and low-V_P, tilting at ~20°–30° to the vertical to both the northwest and southeast, were also imaged by Christiansen et al. (2002). These anomalies extend down to ~400 km. Doubt was cast on their veracity because they are weak and parallel to bundles of incoming rays. They were critically examined using resolution analysis, and it was concluded that they are artifacts resulting from smearing of the strong, shallow body along the ray bundles. Christiansen et al. (2002) concluded that the strong, shallow low-V_P body does not extend deeper than the sub-lithospheric low-velocity zone, which has its base at ~200 km depth. The strong, shallow low-V_P body is continuous to the west-southwest beneath the ESRP in the depth interval ~50–200 km, but not elsewhere.

Later work using networks of modern, digital, three-component seismometers yielded similar results. Yuan and Dueker (2005) imaged a strong low-V_P anomaly in the upper ~250 km beneath the ESRP-Y zone and high-V_P anomalies at greater depth beneath Yellowstone (Fig. 3). They found the strength of most of the low-V_P anomaly to be ~1.5%, reaching a maximum of ~3.2%. Like Christiansen et al. (2002), they also imaged deeper anomalies, both high- and low-V_P, tilting down and away from Yellowstone (Fig. 3G).

The existence of the strong, shallow low-V_P anomaly is not in dispute. However, it is on the significance and interpretation of the weaker, deeper low-V_P anomalies that the debate rests regarding the depth of origin of ESRP-Y volcanism. In the images presented by Yuan and Dueker (2005), one of these deep anomalies, tilting to the northwest, is continuous with the shallow anomaly and extends to ~500 km depth (Fig. 3G). This deeper anomaly has a strength of ~0.5% throughout most of its volume, reaching a maximum of ~0.9%. Yuan and Dueker (2005) interpreted it as a plume tail. The same feature, detected by Christiansen et al. (2002) (Fig. 2), was considered to be discontinuous, and an artifact due to smearing along an incoming ray bundle.

The amplitudes of the anomalies imaged in the two inversions differ significantly. Christiansen et al. (2002) reported strengths of up to –4% to –5% and a compact body, and Yuan and Dueker (2005) strengths of up to –3.5% and a more distributed body.

Whole-Mantle Tomography

The minimum size of bodies that can be resolved by whole-mantle tomography is at the level of hundreds of kilometers where station coverage is good and teleseismic earthquakes plentifully recorded. This increases to a thousand kilometers or more where conditions are poor, which is insufficient to detect bodies only a few tens of kilometers in diameter (Hwang et al., 2011). Nevertheless, a review would not be complete without brief mention of these results.

No hint of a mantle plume beneath Yellowstone has been found in whole-mantle tomography or waveform tomography (Fig. 4) (e.g., Montelli et al., 2004a, 2004b, 2006; Ritsema et al.,

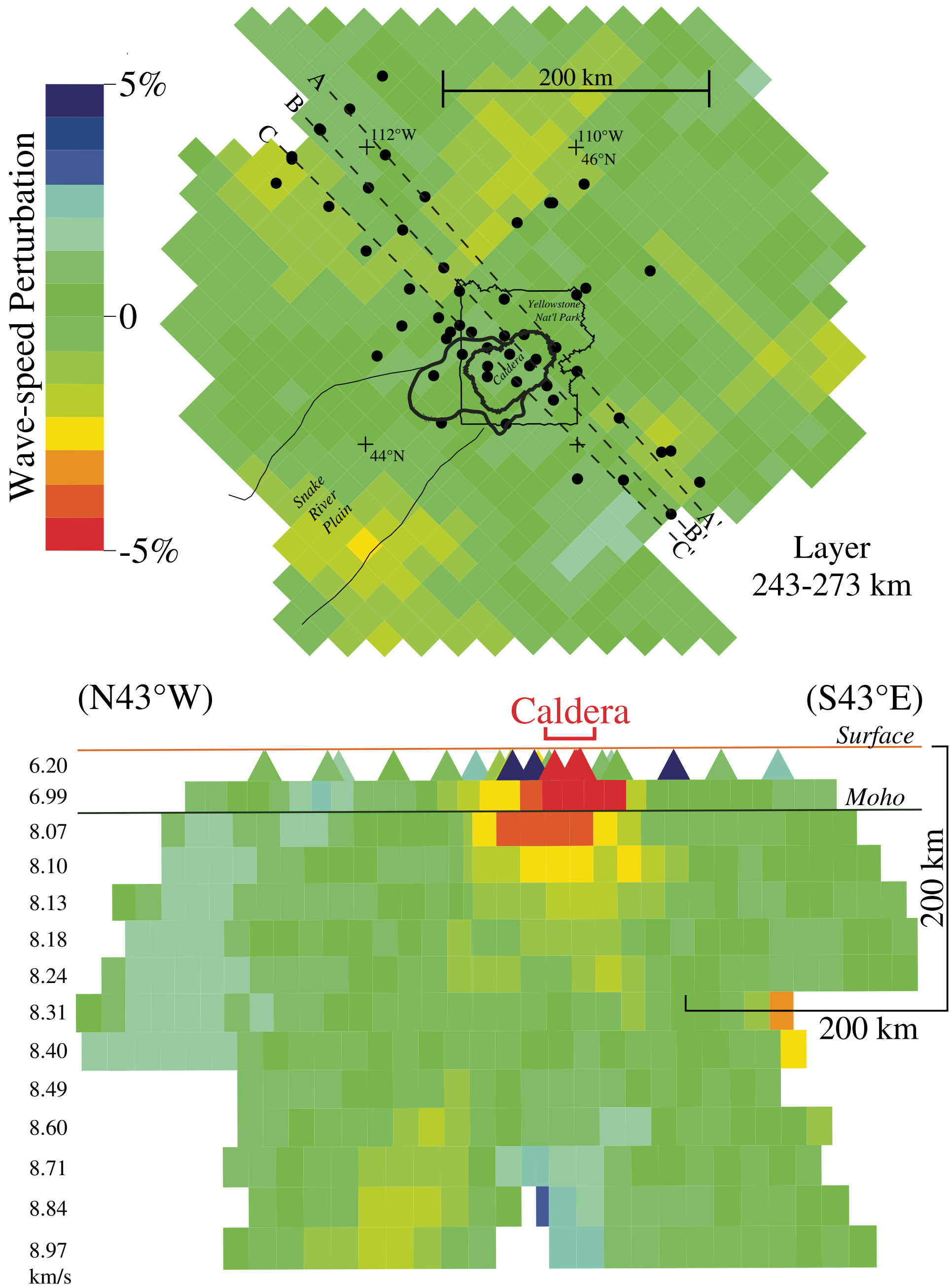


Figure 2. Teleseismic tomographic compressional-wave (V_P) structure beneath Yellowstone (from Christiansen et al., 2002). Top panel: Dots show the seismic stations used, the boundary of Yellowstone National Park, the calderas of the Yellowstone Plateau volcanic field, the edges of the eastern Snake River Plain, and the line of cross section B-B′ shown in lower panel. Colors indicate wave-speed variations in the depth interval 243–273 km, where a deep plume-like structure would be imaged if one exists. Values along left side are the initial-model velocities. Bottom panel: Cross section through the model in the northeast of the caldera.

1999; B. Romanowicz, personal commun., 2015). Whole-mantle images do, however, serve well to emphasize the profundity of the lithospheric structural change at Yellowstone. There, low seismic velocities beneath the Basin and Range province to the southwest are juxtaposed against the high-velocity, thick lithosphere of the North American craton to the northeast. Despite the difference in scale of bodies resolvable, the structure observed in the whole-mantle cross section shown in Figure 4 corresponds in some detail to what is observed using teleseismic tomography, with high velocities being detected beneath the low velocities in the shallow mantle beneath Yellowstone (Fig. 2).

Continental-Scale Tomography Using USArray Data

Since inception of the USArray project in 2004, a vast database of seismic recordings has accumulated which has been used by numerous research groups to study the structure of the mantle beneath the contiguous 48 states (Burdick et al., 2012; James et al., 2011; Obrebski et al., 2010; Schmandt and Humphreys, 2010; Tian et al., 2009; Tian and Zhao, 2012; Xue and Allen, 2010). Beginning with the installation of ~400 stations in a swath covering Washington, Oregon, and California, USArray migrated progressively east and has at the time of writing almost completed

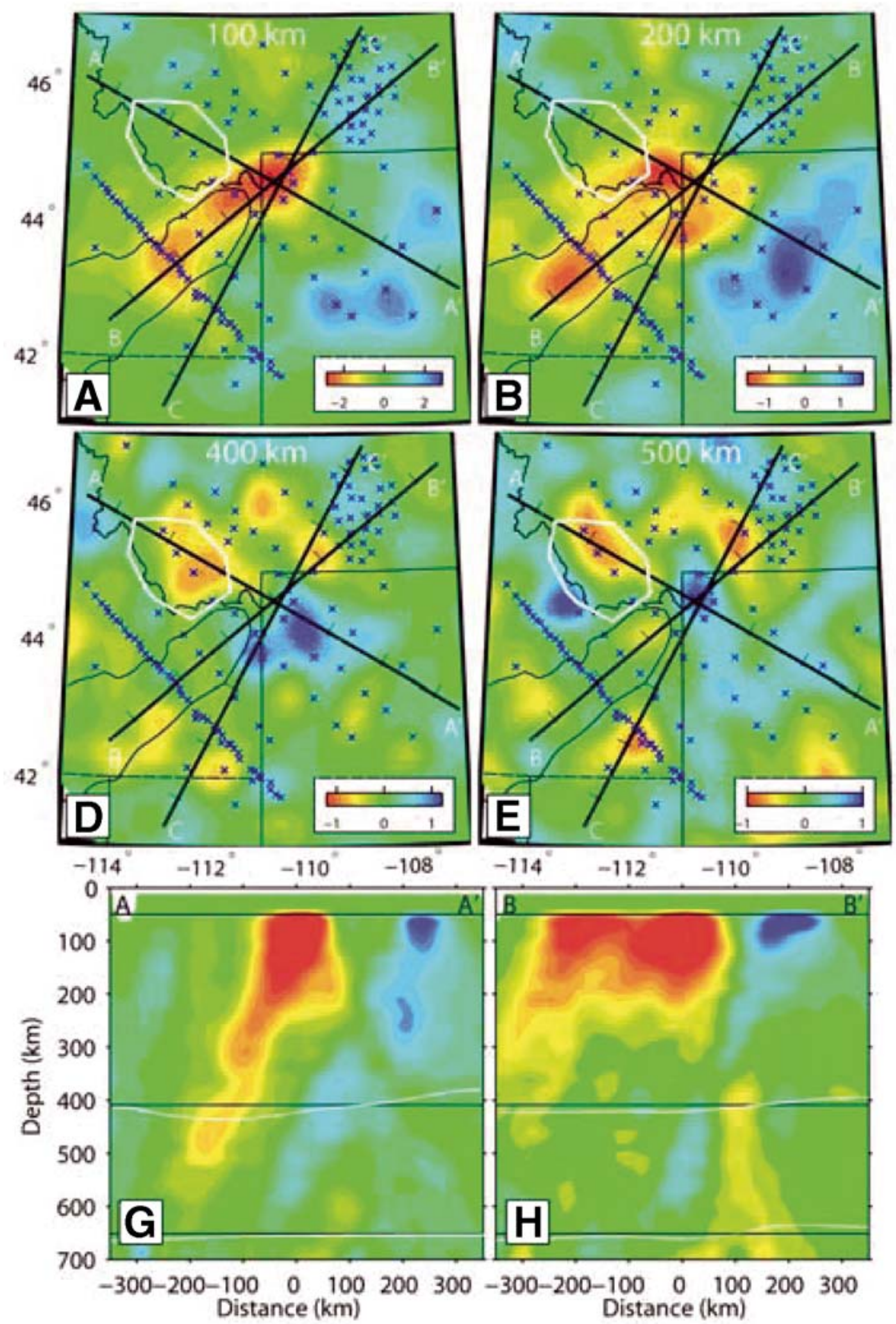


Figure 3. Teleseismic tomography compressional-wave speed (V_p) structure beneath Yellowstone (from Yuan and Dueker, 2005). White rings on the horizontal sections indicate where the 410 km discontinuity is depressed. Units of the color scales are percent variation in wave speed. × symbols indicate seismic stations. In the cross sections in G and H, the 410 and 650 km discontinuities are shown by white lines, and their average depths by black lines (from Fee and Dueker, 2004).

its sweep across the continent. The unprecedented size of the area covered has yielded tomographic images with higher resolution to greater depths in the mantle than has been achieved before.

Many images and several models of the mantle beneath the western U.S. have now been published, some on the internet, and several with particular focus on the ESRP-Y region. Many of the same issues affect these results as confuse the results of teleseismic tomography (see Caveats on Seismic Tomography subsection above). These include damping-related variations in the complexity of the results, in particular the anomaly strengths between models (Becker, 2012). Other problems include inhomogeneous ray distribution, variations in background model used, variations in model parameterization and inversion techniques, and likely corruption of results from unmodeled structure outside the study region. Checkerboard tests are routinely used to claim significance for imaged features despite the fact that the same features may not be seen in other models that are supported by other checkerboard tests. Repeatability is achieved only for the largest, strongest, first-order features. For second-order, small-scale and weak features, including the

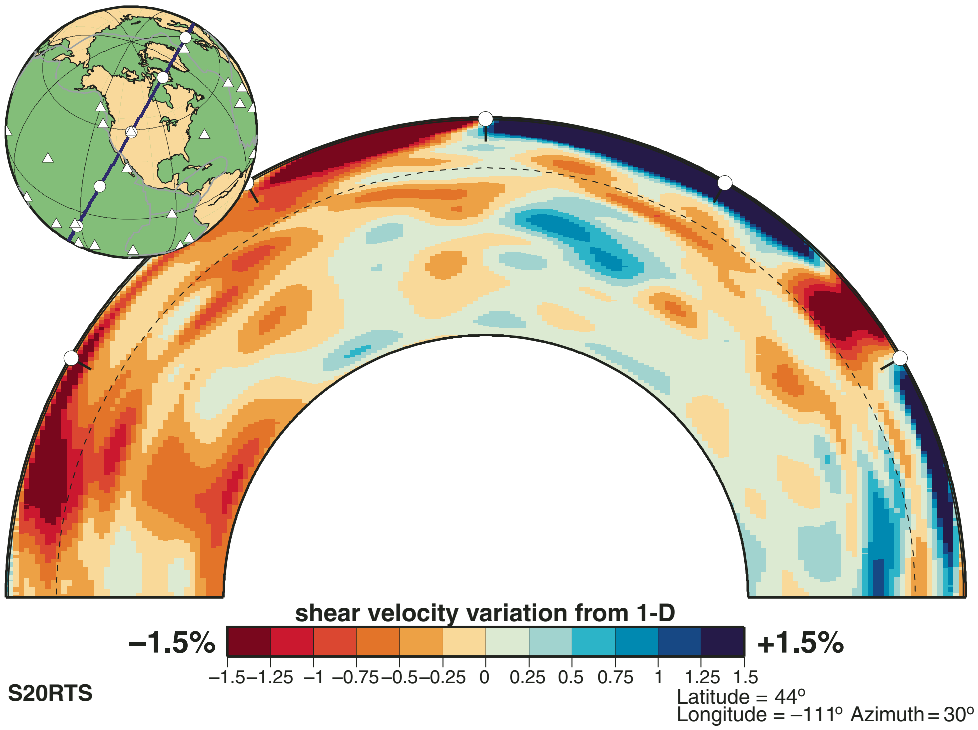


Figure 4. Northeast-southwest cross section through the Yellowstone caldera, showing the mantle tomography model of Ritsema et al. (1999). White triangles: seismic stations; white circles: corresponding points on map and cross section.

detailed shape and strength of the larger features, repeatability is low.

A useful contribution to understanding the bewildering suite of results was made by Pavlis et al. (2012). They compared 12 mantle models produced using USArray data, including nine body-wave tomography models, one surface-wave tomography model, one model obtained using both surface and body waves, and one three-dimensional wavefield image. This involved resampling the data and rendering them to a standard format so that each could be visualized using a single open-source visualization software package. The data were made available by the original authors in different formats. Some had not been published along with the original papers. Assembling these data for comparison purposes was a significant task and illustrates the practical difficulties that face cross-disciplinary researchers wishing to use the seismic-tomography results obtained by others.

Some of the main features revealed by studies using USArray data include:

1. Relative to the region east of the Rocky Mountains, the western U.S. is associated with widespread low velocities that are strongest in the upper ~300 km. These low velocities are particularly prominent beneath the California coastal ranges, the Sierra Nevada, the Basin and Range province, Arizona, and New Mexico, with tongues of low velocity underlying the ESRP-Y zone, the Valles zone, and the St. George zone (Fig. 5). At greater depth, velocities are lowest beneath Arizona. Anomalies weaken at TZ depths.
2. The subducting Farallon slab bottoms at TZ depths or a little below under the western U.S. It is fragmented and has a gap or tear beneath eastern Oregon (Pavlis et al., 2012). It is unclear where the ~5000 km of oceanic lithosphere subducted since the Cretaceous lies (Schmandt and Humphreys, 2010; Tian et al., 2009).
3. The ESRP-Y region is underlain by shallow, ultra-low seismic velocities in the upper 200 km. This anomaly is one of the strongest low-velocity features observed anywhere in the continental lithosphere.
4. Velocity anomalies at depths >200 km beneath Yellowstone have received particular attention. All studies find them to be weak, and among studies there is considerable variation in detail. Xue and Allen (2010) reported a low-velocity anomaly that dips to the northwest, bottoms at 500 km depth, and is seen in V_P but not shear wave-speed (V_S). They ruled out a deeper body wider than 50 km and stronger than –1.5% in V_S and –0.75% in V_P. In a paper published just nine days later, the same group reported an inversion showing a continuous, corkscrew-shaped "whole-mantle plume" bottoming at 900 km depth in both V_P and V_S (Obrebski et al., 2010). They reported good recovery of structure down to 1200 km depth. Tian and Zhao (2012) imaged low velocities under Yellowstone extending to at least 1000 km. Schmandt and

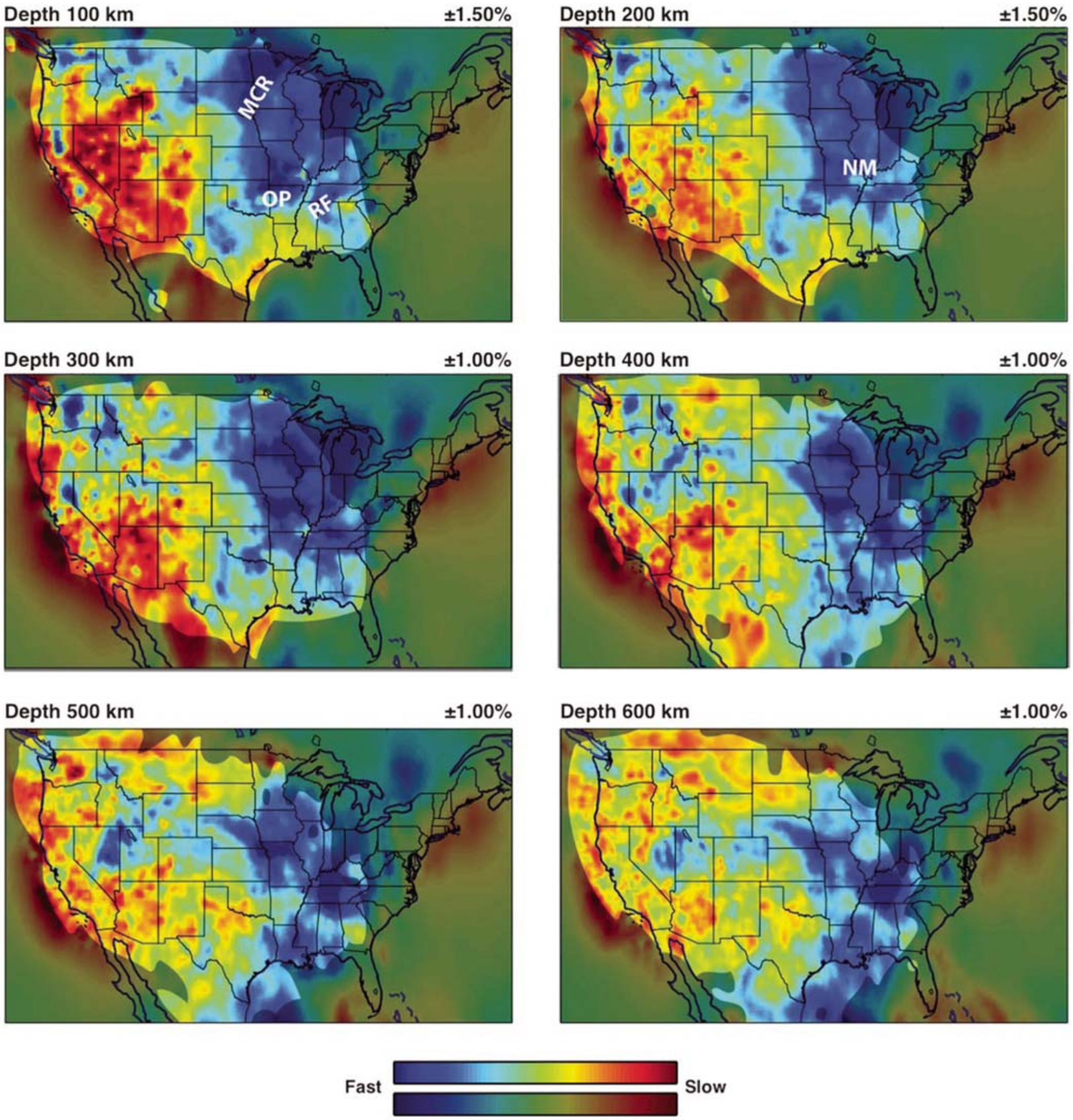


Figure 5. Lateral variations in compressional-wave velocity (V_P) according to model MITP_USA_2013JAN (see Burdick et al., 2014, for details) at 100, 200, 300, 400, 500, and 600 km depth in the mantle beneath North America (from Burdick et al., 2014). Note that the 100 and 200 km depth slices are saturated at ±1.5% velocity anomaly, and the other depths at ±1%. MCR—Midcontinent rift; OP—Ozark Plateau; RF—Reelfoot rift; NM—New Madrid seismic zone. In the slice at 100 km depth, the three tongues of low velocity that trend northeast under the western U.S. and underlie, from north to south, the eastern Snake River Plain–Yellowstone, St. George, and Valles volcanic zones, are particularly clear.

Humphreys (2010) reported discontinuous low-velocity anomalies and find no evidence that they extend into the lower mantle. James et al. (2011) imaged a convoluted subvertical sheet of low-velocity material extending the entire length of the ESRP-Y zone. Adams and Humphreys (2010) inverted for upper mantle attenuation and interpreted the results jointly with velocity tomography. They concluded that the strong anomaly in the top ~200 km is less attenuative than the adjacent mantle, a counterintuitive result. Tian et al. (2009) reported an imbricated, discontinuous pair of low-velocity bodies, one terminating at 500 km depth and the other extending to 1000 km depth.

5. Most studies reported high velocities in the TZ beneath the Yellowstone region (Becker, 2012; Pavlis et al., 2012).

Figure 6 shows cross sections through nine of the models studied by Pavlis et al. (2012). The sections run from Cape Mendocino (California), through the northwest Basin and Range province, along the ESRP, and on into the North American craton. The repeatable features and variations between models are

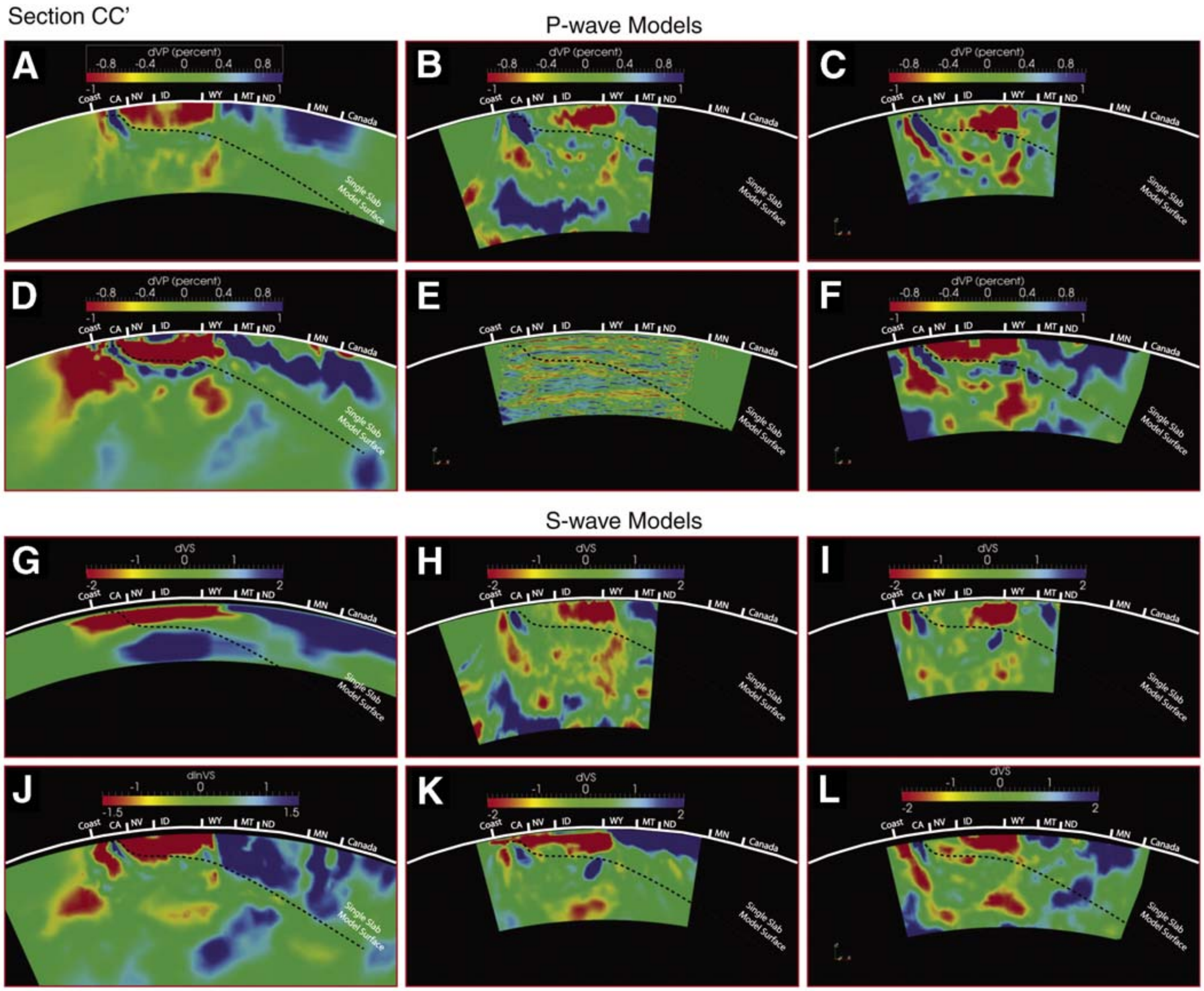


Figure 6. Cross sections through the western U.S. running from Cape Mendocino (California) to the Minnesota-Canada border. Sections are viewed from the southeast and slice the same section of each volume. The white line on each section is Earth's surface with geographic boundaries marked by radial, white colored ticks. State abbreviations: CA—California; NV—Nevada; ID—Idaho; WY—Wyoming; MT—Montana; ND—North Dakota; MN—Minnesota. Tomography models A–D and F–L show high velocities as blue and low velocities as red with the scale shown on each section. The scattered wave image result (shown in E) shows positive P- to S-wave conversion scattering potential in red and negative conversion as blue. Compressional-wave velocity (V_P) tomography results and the scattered wave image result shown in (E) are as follows (see Pavlis et al. [2012] for details): (A) MIT11; (B) NWUS11-P; (C) DNA09P; (D) SIG11; (E) PWMIG11; (F) UOP. Shear-wave velocity (V_S) tomography results are as follows: (G) NA07; (H) NWUS11-S; (I) DNA09S; (J) TIA10; (K) DNA10; (L) UO10S. See Pavlis et al. (2012) for further details. Color scales are percent change in wave speed, dVS.

immediately clear. Only the largest, strongest, first-order features are common to most images. These are, from west to east, the subducting, high-velocity Farallon slab, the strong low-velocity anomaly underlying the entire length of the ESRP down to a depth of ~200 km, and the high-velocity North American craton in the east. Both high- and low-velocity anomalies become less repeatable between models with increasing depth. Low-velocity anomalies at depths >200 km beneath the Yellowstone region are weaker than the shallower anomalies, with poor repeatability between models (Foulger et al., 1995, 2013).

The Transition Zone

The TZ discontinuities at 410 and 660 km are thought to result largely from mineral-phase transitions in the peridotite mantle. Their exact depths are affected by pressure, temperature, and composition, including water. High temperatures, dry conditions, and high-Mg content are thought to deepen the 410 km discontinuity and shallow the 660 km discontinuity, thus thinning the TZ (Bina and Helffrich, 1994; Ghosh et al., 2013; Katsura et al., 2004; Presnall, 1995; Wood, 1995). The behavior of the two discontinuities is expected to be anticorrelated because of the opposite signs of the Clapeyron slopes of their respective olivine mineral-phase changes. Multiple phase changes occur at ~660 km depth, and this complication renders the behavior of that discontinuity less certain (Vacher et al., 1998).

TZ discontinuity topography has been measured using the receiver-function technique. Early work assumed simplistically that three-dimensional velocity variations could be neglected and that topography was controlled only by temperature. The method was therefore commonly used as a thermometer. It was extensively applied in purported plume localities where the task at hand was commonly to identify the place where the TZ appeared to be thinnest and to propose this as the TZ-crossing place of the assumed hot plume. Offsets from the surface location of most intense volcanism were explained as tilting plumes (e.g., Shen et al., 2002), mantle wind (e.g., Steinberger et al., 2004), or disruption of the assumed plume conduit by upper-mantle structural complications (e.g., Fee and Dueker, 2004).

The receiver-function technique has been used in the Yellowstone region in several studies, which have yielded varied results. Dueker and Sheehan (1997) and Fee and Dueker (2004) used pre-USArray data from several experiments and found uncorrelated TZ discontinuity topography on the 410 and 660 km discontinuities of ±35–40 km. They found a depression in the 410 km discontinuity of ~18 km centered ~130 km north-northwest of Yellowstone, with a flat 660 km discontinuity beneath. This locality coincided with the weak, downward extension of the shallow low-V_p body reported by Yuan and Dueker (2005). Fee and Dueker (2004) concluded that the region of deepened 410 km discontinuity corresponds to a ~200 °C temperature anomaly, with no temperature anomaly at 660 km. They also found a ~20 km shallowing of the 660 km discontinuity ~400 km northeast of Yellowstone, where the 410 km discontinuity also shallows by ~15 km. Interpreted in the same way, this would suggest a temperature anomaly of ~+200 °C at 660 km depth and –200 °C at 410 km depth. Neither discontinuity was reported to be significantly perturbed under an adjacent area where V_p is high. The uncorrelated ±35–40 km topography on the discontinuities would require ~400 °C variations in temperature anomalies, apparently uncorrelated with surface features. Such interpretations are implausible.

Beucler et al. (1999) reanalyzed the same data using different techniques and obtained very different results. They found the 410 km discontinuity to have a fragmented aspect that precluded accurate mapping of TZ thickness, and the 660 km discontinuity to be strongly deflected. They concluded that the TZ was complicated by Farallon slab fragments and that no evidence could be found in support of a TZ-penetrating hot body as suggested by Dueker and Sheehan (1997) and Fee and Dueker (2004). Beucler et al. (1999) further suggested that, in addition to temperature, composition, and volatile content, TZ-discontinuity depths can also be affected by the kinetic effects of actively subducting slabs.

Later work reported still different results. Schmandt et al. (2012) utilized USArray data to study the TZ and found it to be ~4 km thicker than the global average throughout the entire western U.S. This finding is inconsistent with temperature-related interpretations of TZ thickness in view of the magmatically active nature of the region. In the Yellowstone region they found very different results from those of Fee and Dueker (2004). They reported that the 660 km discontinuity is 12–18 km shallower than normal (with a 2σ error of 16.6 km) beneath a large area centered 75 km northeast of Yellowstone, but that the 410 km discontinuity was at normal depth everywhere in the vicinity. They interpreted their results to propose a TZ-crossing hot plume that is disrupted by mantle structural heterogeneity above 660 km. Implausibly high estimated temperatures of ~700 °C led them to attribute some of the topography of the 660 km discontinuity to non-thermal effects such as anhydrous mineralogy.

Most recently Gao and Liu (2013) introduced a new method to deal with the problem of tradeoffs between the discontinuity depths and velocity heterogeneity above. They used both converted and multiply reflected phases, and P-wave to S-wave converted phases, to simultaneously determine the discontinuity depths and velocity anomalies. They applied the method to a north-south swath 780 km long and 336 km wide centered on Yellowstone. Low velocities, but no significant topography on either the 410 or the 660 km discontinuities, were detected.

Interpretation of the Seismic Results

What can be concluded from these results regarding Yellowstone? It is a robust result that ultra-low seismic velocities underlie the ESRP-Y in the upper 200 km along its entire length. The nature of low-velocity anomalies at greater depth is controversial, however. No coherent low-velocity anomaly is repeatably imaged that extends continuously from the surface down into the lower mantle. High-velocity bodies littering the TZ under the

ESRP-Y zone, interpreted as fragments of the Farallon slab, make a throughgoing plume more implausible. Figure 6 serves well to illustrate the variability between models. Below 200 km depth, low-velocity regions imaged vary from large, rounded blobs several hundred kilometers in diameter, to weak, fragmented, vertically elongated features. Equally strong low-velocity anomalies are widespread beneath other regions (Fig. 5).

The weak, low-velocity anomalies that are imaged below ~200 km have been interpreted both as artifacts of smearing of the shallow anomaly along incoming ray bundles and as a real and continuous extension of the shallow anomaly. Neither interpretation suggests a deep-mantle plume. Thermal interpretations are non-unique and find little support in the suite of studies of TZ discontinuity topography which, like seismic tomography, yields poor repeatability.

Under these circumstances, interpretations may be influenced by authors' model preferences. Several authors interpret low-velocity bodies as hot plumes, including both downward-continuous and fragmented types and ones confined to the upper mantle. Xue and Allen (2010) based their interpretation on the assumption that the gap in the Farallon slab must have been caused by an arriving Yellowstone plume head. Despite not imaging an anomaly in the lower mantle, they cite the time-progressive chain of rhyolitic volcanoes on the ESRP, high-$^3He/^4He$, and a CRB magma source containing recycled oceanic crust as evidence in support of a plume. They attribute the time-progressive Newberry volcanic chain to upper-mantle processes. Obrebski et al. (2010) interpreted the low-velocity anomaly beneath the ESRP as part of a plume head, whereas Tian and Zhao (2012) attributed it to hydrated minerals. Obrebski et al. (2010) suggested that a Yellowstone plume rose opportunistically through a pre-existing tear in the downgoing Farallon slab. James et al. (2011) interpreted the sheet-like low-velocity body they imaged as evidence that CRB and ESRP-Y volcanism arose from poloidal and toroidal upwellings around the edges of a fragmented subducted Farallon plate. Adams and Humphreys (2010) attributed to dehydration their finding that the strong anomaly in the top ~200 km under Yellowstone is less attenuative than the adjacent mantle. They estimated a temperature anomaly of 30–50 °C for the deeper part of the anomaly, with higher temperatures at shallower depth.

MODELS FOR EASTERN SNAKE RIVER PLAIN–YELLOWSTONE VOLCANISM

All continental-scale seismic tomography images for the western U.S. show a complex mantle. Interpretations have associated these complexities with the collage of major tectonic features that make up the western U.S. including the fragmented, subducted Farallon slab, the delaminated Sierra Nevada, the basin-range region, the ESRP-Y, the Valles zone, and the St. George zone. Many models seek to account for western U.S. volcanism by explaining how melt can form in the mantle beneath. Others consider the fragmented state of the Farallon slab to be pivotal. A minority of models interpreted the observations essentially solely in terms of a simple subducting slab disrupting an independent deep-mantle plume.

Explanations for western U.S. magmatism linked to retreat of the subduction hinge and lithospheric extension were suggested as far back as the 1970s (e.g., Cross and Pilger, 1978). Ford et al. (2012) attributed the age-progressive Newberry trend to mantle upwelling in response to slab rollback. This does not, however, explain why the age-progressive volcanism should comprise a narrow zone and not a broad region, nor does it explain the decoupling between the rhyolitic and basaltic volcanism along that trend.

Faccenna et al. (2010) suggested that small-scale convection brought about by Farallon slab dynamics and return flow results in focused upwellings in which melt forms via decompression. They envisaged upper-mantle upwellings occurring in general in areas that are floored by subducted slab in the TZ, with melt formed near its end and edges, in the back-arc area, and in response to slab retreat and tearing. Changes in relative trench motion and subduction velocity can introduce further complexities. They argued that such upwellings would produce temperature anomalies at the surface and transport H_2O which would encourage melting, and that the petrology predicted is supported by observations. They drew a comparison with European volcanism, which occurs behind the Mediterranean subduction zone. In common with other models, Faccenna et al. (2010) sought to explain surface volcanism solely by the formation of melt in the mantle, with the lithosphere viewed as an essentially non-participative interface separating the mantle and the atmosphere.

Liu and Stegman (2012) attributed the CRB to an episode of tearing in the Farallon slab that permitted upwelling of sub-slab asthenosphere, decompression, and melting. The rupture was proposed to have started under eastern Oregon at ca. 17 Ma and to have propagated north and south to attain a length of 900 km and to extend north into Washington and south across most of Nevada (Fig. 7). This matches the spatial and temporal pattern observed for dike formation and flood basalt eruption. Liu and Stegman (2012) suggested that melting beginning with subducted oceanic lithosphere and grading upward into oceanic crust can explain the petrology of the CRB. Hales et al. (2005) attributed the CRB to lithospheric delamination on the grounds that the region subsided prior to eruption.

Long et al. (2012) favored a model whereby trench rollback starting at ca. 20 Ma induced asthenosphere upwelling, and back-arc extension provided eruptive pathways. Their view differs significantly from that of Liu and Stegman (2012) and Faccenna et al. (2010) who considered the lithosphere as passive. Long et al. (2012) considered that ongoing trench migration enables continued magmatism. They point out that the Juan de Fuca trench is currently retreating at ~35 mm/yr, a period of rapid rollback that started at ca. 20 Ma. They conducted idealized laboratory experiments using glucose and a rigid fiberglass "plate" to study flow in the upper mantle and emphasized the spatio-temporal complexity in mantle flow, a view that contrasts with more common simplistic models. Pavlis et al. (2012), for example, suggested

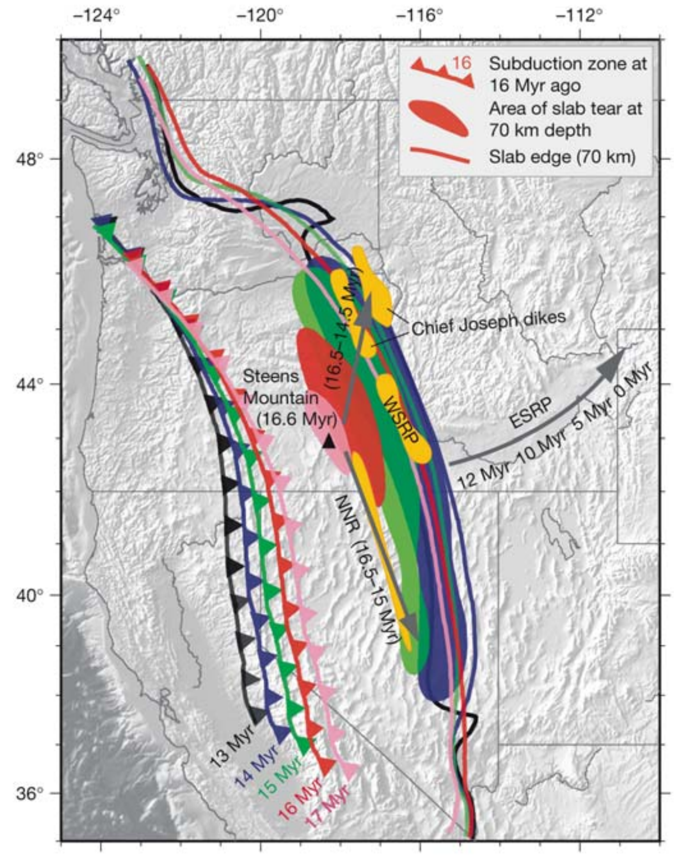


Figure 7. Development of the Farallon slab rupture beneath the western U.S. showing geometry of Farallon subduction at different times. Both the slab edge (solid lines) and slab gap (filled area, color matched to associated slab edge and subduction zone locations) are shown at a depth of 70 km. Major volcanic dike swarms are shown in yellow. WSRP—western Snake River Plain; ESRP—eastern Snake River Plain; NNR—northern Nevada rift zone (from Liu and Stegman, 2012).

that the Farallon slab is in reality continuous, but the absence of high velocities interpreted as a slab tear are, instead, a region where the slab seismic signature has been neutralized by thermal effects. There is still no obvious explanation in the model of Long et al. (2012) for the narrowness of the Newberry trend, and an ad hoc upwelling has to be invoked to explain ESRP-Y volcanism.

HELIUM

There is a growing body of evidence that high $^3He/^4He$ in surface lavas derives from mantle lithosphere, not from the deep mantle, and the case for the ESRP-Y zone is particularly strong. Historically, $^3He/^4He$ in ESRP-Y volcanics and thermal springs higher than mid-ocean-ridge basalt (MORB) values has been widely cited to support a plume model (Craig et al., 1978; Kennedy et al., 1985; Welhan, 1981). The rationale attributes high $^3He/^4He$ to a near-primordial region of the mantle. This region is postulated to have been uninvolved in mantle convection over the 4.5-billion-year lifetime of Earth and, thus, to have experienced little loss of primordial ^3He. As a result of the high concentration of ^3He, the value of $^3He/^4He$ was reduced only slowly by ^4He ingrowth compared with regions of the mantle that lost most of their ^3He through degassing. Because of the perceived need to place the postulated near-primordial region beyond involvement in shallow-mantle convection, its location is assumed, in that model, to be the core-mantle boundary. Such a model requires the postulated Yellowstone plume to be rooted in the deep mantle.

$^3He/^4He$ ratios higher than those of MORB nevertheless do not provide direct evidence for depth. Instead, they indicate a source that has experienced unusually slow reduction in the original value of ~200 R/Ra ($^3He/^4He$ normalized to the atmospheric value) of the young Earth. Simply put, they indicate an old source, not necessarily one that resided in the deep lower mantle.

There are difficulties with the deep model. A high concentration of ^3He in the deep mantle is inconsistent with high-temperature planetary accretion, which strongly degassed Earth in volatile elements and reduced the amount of He by many orders of magnitude. Also, if high $^3He/^4He$ were associated with an undegassed mantle region, then rocks with high $^3He/^4He$ would be rich in He. In fact, the opposite is observed (Anderson et al., 2006; Moreira and Sarda, 2000; Ozima and Igarashi, 2000).

A slower-than-average reduction in $^3He/^4He$ over time could occur as a result of unusually slow ^4He ingrowth. This could occur, for example, via storage in a low–U + Th environment (Anderson, 1998a, 1998b; Meibom et al., 2003, 2005). Low–U + Th hosts include the residuum left after basalt melt is extracted from mantle peridotite (e.g., Brooker et al., 2003), recycled oceanic lithosphere, and olivine-rich cumulates (Natland, 2003). Individual olivine crystals, which are essentially devoid of U + Th, encapsulate gas bubbles that are largely CO_2 but also contain He. ^4He atoms generated by U + Th decay in surrounding minerals are not sufficiently energetic to penetrate the crystals and therefore do not lower $^3He/^4He$ in the bubbles. In addition, the diffusion of ^4He from surrounding materials into olivine crystals is hindered by differences in chemical potential. Helium is volatile but highly soluble in trapped CO_2-rich bubbles in olivine, and essentially insoluble in olivine itself. Thus, it will tend to be retained in bubbles in olivine crystals. This suggests a model whereby noble gases are trapped in olivine and pyroxene in cumulate olivine-gabbroic layers in the lowermost oceanic crust. Such a model could explain the high $^3He/^4He$ in volcanics that contain a component of recycled oceanic crust.

Recently, new evidence has been presented for an origin for high $^3He/^4He$ in the continental lithospheric mantle (Huang et al., 2014). $^3He/^4He$ values in the range ~5–22 R/Ra from a suite of postulated plume localities are anticorrelated with unradiogenic $^{206}Pb/^{204}Pb$ and correlated with unradiogenic $^{207}Pb/^{204}Pb$. The most internally consistent model to explain this is ancient sequestration of both He and Pb in unradiogenic sulfide melts that were co-precipitated with mafic cumulates (pyroxenites) during major melting episodes at the time of continental crust formation. The lack of U + Th in these cumulates, which do not partition into sulfides, would ensure preservation of ancient, high $^3He/^4He$ isotope ratios. The cumulates are stored in the deep continental lithosphere, or have been delaminated over time and dispersed throughout the asthenosphere and upper mantle.

Recent work by Lowenstern et al. (2014) demonstrated that the copious ^4He degassed at Yellowstone must have its source in the Archean lithosphere. It thus seems likely that ^3He too could have been stored in the lithospheric mantle to be liberated during the voluminous Quaternary volcanism. A model whereby the high $^3He/^4He$ derives from basement geology and not a deep, primordial reservoir fits well the He-Pb systematics of the High Lava Plains and the ESRP-Y zone. This agrees with the strong seismic evidence that the source of ESRP-Y volcanics is the shallow mantle.

A PURE PLATE MODEL

There is a tendency to assume that the main factor needed to explain surface volcanism is melt in the mantle, and that involvement of the lithosphere is relatively unimportant. Lithosphere involvement is invoked only where spatial relations do not fit, and then phenomena such as "upside down drainage", "thin spots", "ridge capture", or "ridge escape" may be invoked (Keller et al., 2000; Mittelstaedt et al., 2011; Sleep, 1997). This amounts to suggesting that sub-lithospheric topography guides the lateral flow of rising melt—the lithosphere is still not viewed as controlling whether or not eruption occurs.

Here, we propose a pure plate model for CRB-ESRP-Y volcanism. Surface volcanism is attributed to extension of the lithosphere permitting the rise of pre-existing melt. Melt is viewed as being commonplace in the mantle, and its tendency to rise is not considered to be the primary cause of surface eruptions.

At 17 Ma, as the subduction zone to the west shortened with northward migration of the Mendocino triple junction leaving a slab window in the Farallon plate farther south, the CRB erupted in response to back-arc extension behind the downgoing plate from fissures parallel to the margin of the adjacent cratonic plate interior. The source of the melt may have been decompression upwelling of asthenosphere flooding through a slab tear, or a reservoir of melt pre-existing at the lithosphere-asthenosphere boundary (Silver et al., 2006). Simultaneously, the basin-range region began to extend. Extension has not been distributed uniformly throughout the province, however, but is mostly taken up along two dominant, subparallel axes (e.g., Thatcher et al., 1999). We propose that the time-progressive chain of rhyolitic calderas in the ESRP-Y zone formed in response to the eastward migration of the easternmost of these axes of intense basin-range extension (Fig. 8).

Throughout most of the Basin and Range province, extension is accompanied by relatively minor, commonly rhyolite-basalt volcanism (Christiansen and Lipman, 1972). The ESRP-Y zone lies at a major lithospheric boundary where thin basin-range lithosphere is juxtaposed against thick lithosphere of the northern Rocky Mountains and Idaho batholith. Across this zone, the rate of extension decreases abruptly over a distance of only 100 km. We propose that because of this the style of extension changes from "dry" (normal faulting) in the Great Basin region to "wet" (magmatic) in the ESRP-Y zone (cf. Parsons et al., 1998).

Rodgers et al. (1990) and Anders (1994) showed that migration of silicic volcanism on the ESRP-Y zone has gone hand-in-hand with accelerated normal-fault motion on large, range-bounding normal faults (Fig. 9). Pierce and Morgan (2009) described Cenozoic faulting south of the three youngest rhyolitic calderas of the ESRP-Y and also found that belts of fault activity have migrated northeast in conjunction with the adjacent rhyolitic volcanism. These findings are reflected in current deformation studied using GPS surveying. At present, the most intense zones of extension accompany Holocene faults and lie near the western and eastern boundaries of the province. Little extension occurs across the central 500 km of the province (Thatcher et al., 1999). Our model proposes that rhyolitic volcanism along the ESRP-Y zone followed migration of the locus of most rapid extension, not vice versa. Importantly, the ESRP-Y zone existed in some form prior to the arrival of the axis of extreme extension. Its present-day manifestation formed along a pre-existing extensional zone—it did not form in initially inactive lithosphere.

GPS data have been collected locally in the ESRP-Y zone since 1990 (Chadwick et al., 2007; Puskas and Smith, 2009; Puskas et al., 2007; Rodgers et al., 2005). Assessing long-term-averaged rates of motion is difficult because deformation is highly episodic. Major, time-varying deformations result from uplift and subsidence of the Yellowstone caldera and post-seismic viscoelastic deformation transients from large local earthquakes such as the A.D. 1959 M7.5 Hebgen Lake and the A.D. 1983 M7.3 Borah Peak earthquakes (Puskas et al., 2007). These motions cannot simply be subtracted from the long-term deformation field, however, because coseismic and post-seismic transient motions are intrinsic components of the time-averaged total motion (Foulger et al., 1992; Heki et al., 1993; Hofton and Foulger, 1996a, 1996b).

Despite these problems, assessing regional variations in time-averaged motion has been attempted (Fig. 10). The following is reported for the period A.D. 1987–2003 (Chadwick et al., 2007; Puskas and Smith, 2009; Puskas et al., 2007; Rodgers et al., 2005): (1) the Yellowstone plateau is extending at a rate of 2–5 mm/yr; (2) the ESRP displays little measurable internal deformation; and (3) the rate of motion immediately north of the ESRP (~2.0 mm/yr) is significantly lower than the rate just south of it (~3.4 mm/yr).

Net extension in the Yellowstone area is consistent with the existence of a volcanic center there. Although little surface deformation is reported for the ESRP, extension must occur in the long term because it lies between zones to the south and north that are both extending via normal faulting. Extension via basaltic diking parallel to basin-range trends (Fig. 11) has been discussed by Rodgers et al. (1990), Kuntz et al. (1992), and Parsons et al. (1998). Northwesterly oriented Holocene volcanic rift zones tra-

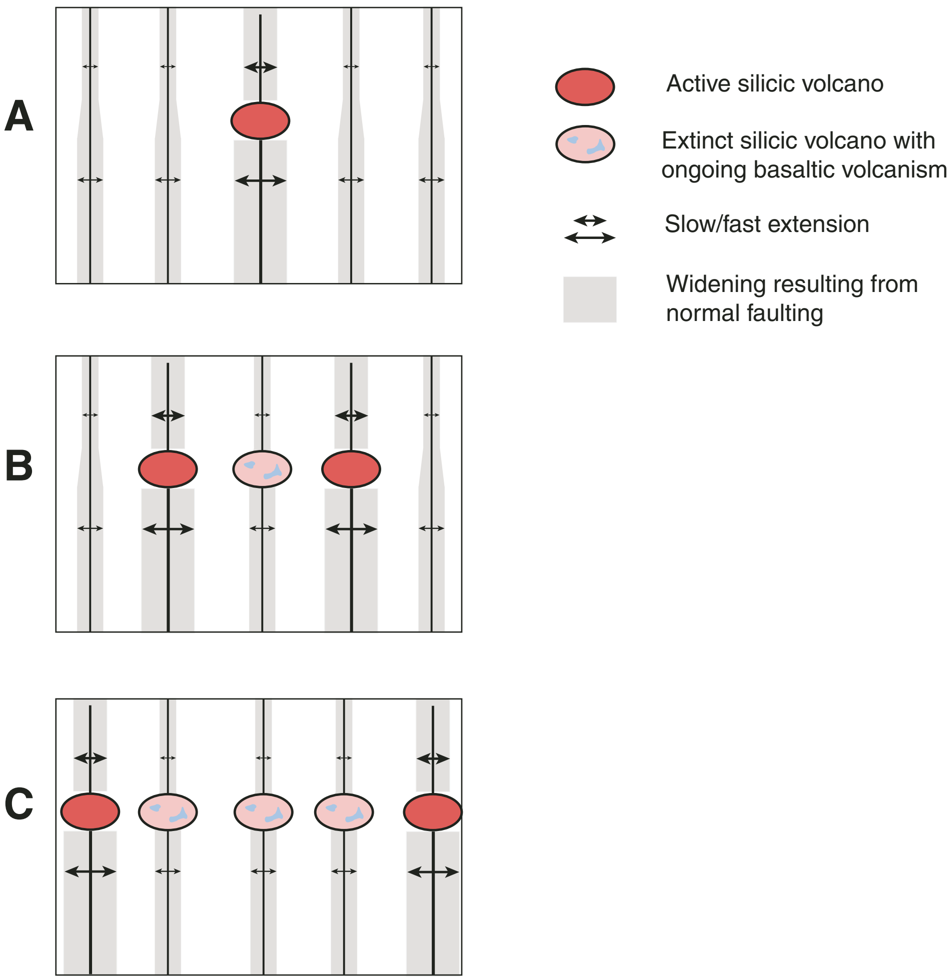


Figure 8. Schematic diagram illustrating a model whereby the time-progressive chain of rhyolitic calderas in the eastern Snake River Plain–Yellowstone zone (ongoing rhyolitic volcanism in red; extinct rhyolitic volcanism in pink) formed in response to the eastward migration of the axis of most intense basin-range extension. The complementary "Newberry trend" formed by westward migration. Time increases from A to C.

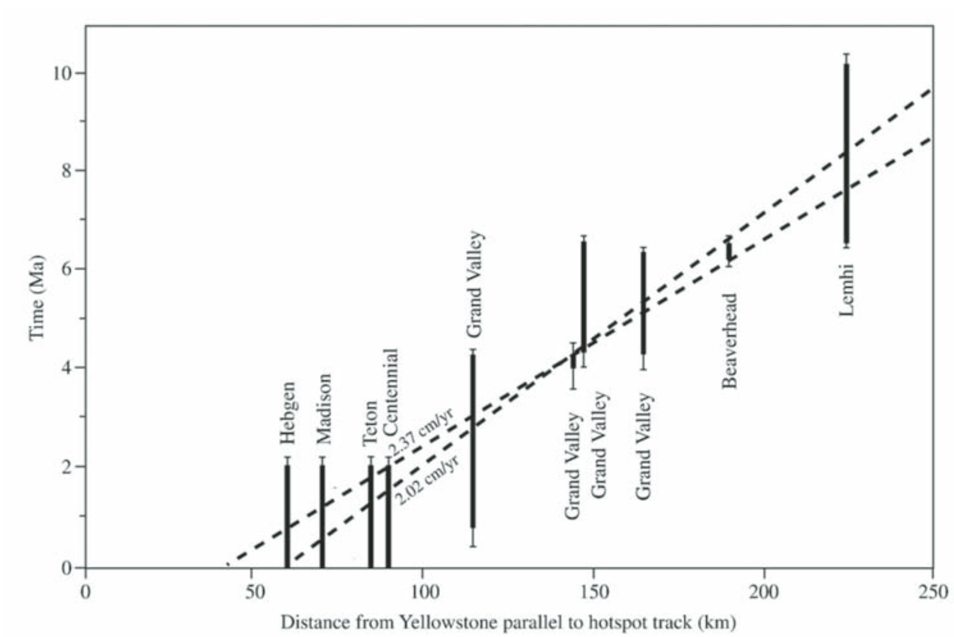


Figure 9. Migration of high fault displacements on large range-bounding normal faults in the vicinity of eastern Snake River Plain–Yellowstone (after Anders, 1994). The rate of migration of high fault activity is 2.02–2.37 km/m.y., similar to the migration rate of large caldera-forming volcanism from 10 to 2 Ma.

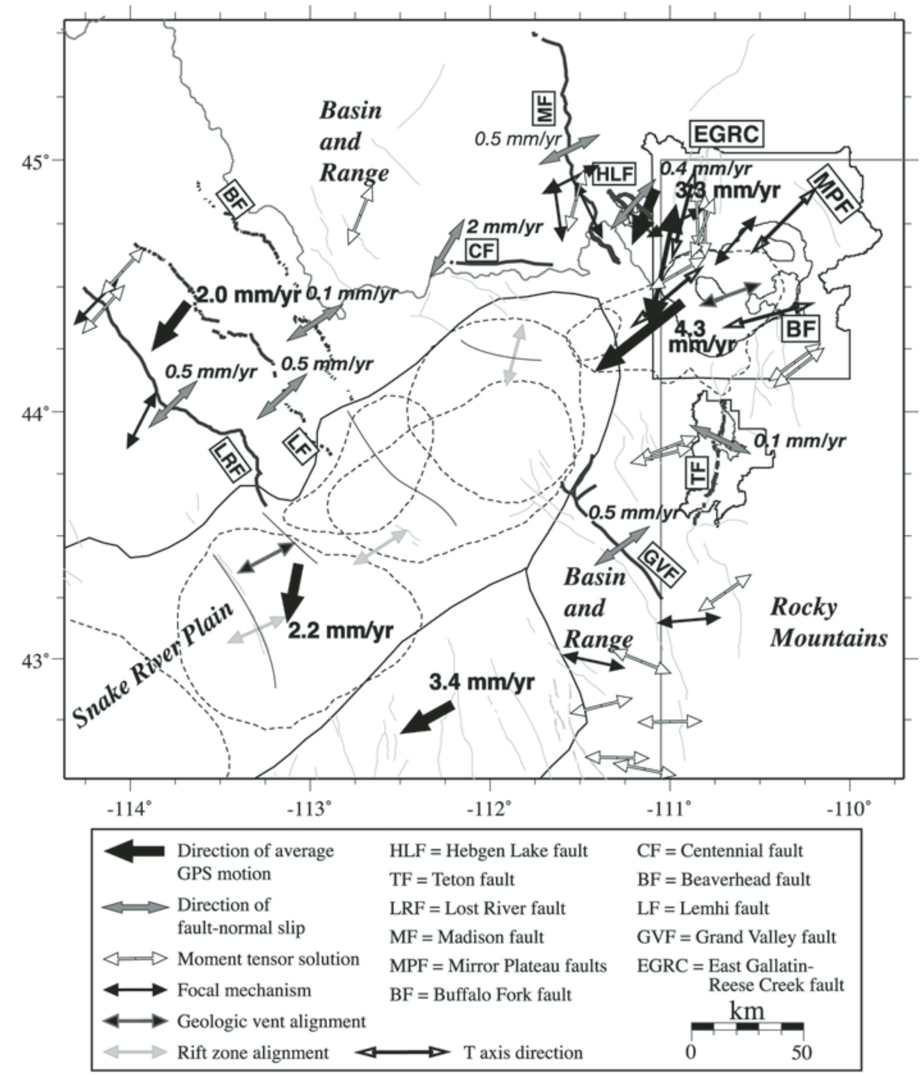
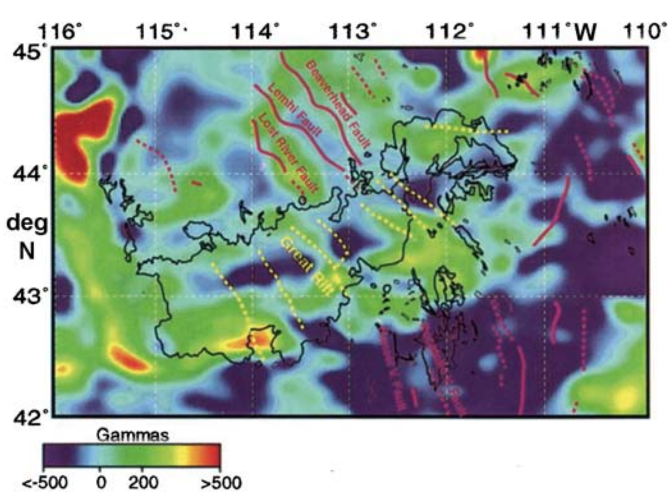


Figure 10. Summary map of GPS-measured deformation vectors for the eastern Snake River Plain and Yellowstone (from Puskas et al., 2007). Average GPS rates are labeled in large font and local values in small, italic font. For comparison, minimum principal stress indicators from other studies are also shown (double-headed arrows). For more details, see Puskas et al. (2007).



verse the ESRP and have erupted basalt flows—95% of the surface of the ESRP has been covered by basalt in the past 730,000 yr and ~13% within the last 15,000 yr (Kuntz et al., 1992). A time-averaged extension rate of a few millimeters per year would be sufficient, or ~10% of a slowly spreading plate boundary. Extension via diking is episodic, with brief periods of extension alternating with long periods of quiescence (e.g., Björnsson et al., 1977). It is thus unsurprising that deformation has not been

Figure 11. Aeromagnetic map of the eastern Snake River Plain and Yellowstone region (from Parsons et al., 1998). Black line outlines the area of young basalt flows. Yellow dashed lines indicate volcanic rift zones. Major faults with Quaternary (solid red) and Pleistocene (dashed red) offsets are shown.

captured in short-term GPS surveys conducted long after cessation of the most recent volcanic episode. If the ESRP has deformed in this style throughout its lifetime, the width of the entire set of dikes emplaced must amount to ~35 km. The rates of motion measured using GPS are in broad agreement with geological observations that suggest that the long-term extension rates for the last few million years are 2 mm/yr north of the ESRP and 5 mm/yr south of it (Anders, 1994; Christiansen et al., 2002; Rodgers et al., 2002).

Analogs for this situation occur elsewhere in the western U.S. The Coso Hot Springs is a nascent core complex that forms at a right-stepping en echelon offset in the dextral strike-slip system of the Owens Valley (California) (Monastero et al., 2005; Weaver and Hill, 1978). The resulting northwest-directed transtension gives rise to normal and strike-slip faulting in the upper few kilometers of crust and ductile stretching, permitting shallow igneous intrusions to rise, from deeper levels (Monastero et al., 2005).

A larger example is Long Valley caldera at the northern end of Owens Valley. This volcanic field is orders of magnitude more voluminous than other volcanic localities nearby. It has been active for the last ~3 m.y., culminating in a giant 600 km^3 caldera-forming rhyolitic eruption at 760 ka. This is ~25% of the volume of the massive 2500 km^3 Huckleberry Ridge Tuff that erupted from Yellowstone at 2.2 Ma. Like the ESRP-Y zone, Long Valley has erupted compositions ranging from rhyolite to basalt. Hill (2006) and Riley et al. (2012) presented a model whereby Long Valley caldera formed in an area of lithospheric dilation induced by regional fault movements. Specifically, block kinematics predict dilatation between the Sierra Nevada, Adobe, and Owens Valley blocks, inducing mantle to upwell (Riley et al., 2012).

The combination of rhyolitic caldera volcanoes and fissures erupting basaltic lava on the ESRP is reminiscent of the so-called "volcanic systems" of Iceland. Icelandic volcanic systems comprise fissure swarms, each containing a central volcano erupting both rhyolite and basalt. The spreading plate boundary crossing Iceland comprises en echelon arrays of such spreading centers. Along the ESRP-Y zone, voluminous rhyolitic caldera volcanoes and fissures erupting basalt lie side by side, forming a chain oriented parallel to the direction of lithospheric extension. This contrasts with the situation in Iceland, where the volcanic systems form en echelon chains oriented roughly perpendicular to the direction of extension (Fig. 12). The explanation for this may be that, whereas oceanic spreading plate boundaries form by propagation of rifts perpendicular to the direction of spreading, the ESRP has formed by propagation of basin-range extension parallel to the direction of extension. Thus, a volcanic zone has formed that comprises an array of systems analogous to Icelandic volcanic systems that lie side-by-side and not end-to-end.

An example of a laterally migrating Icelandic volcanic system is the Hengill-Grensdalur complex in the southwest. This area is a ridge-ridge-transform triple junction and lies at a locality where thin crust underlying the ridge branches meets thicker crust underlying the transform branch. Lateral migration of the locus of volcanism occurred at ca. 0.5 Ma, when the then-active Grensdalur volcanic system became extinct and the currently active Hengill volcanic system developed ~5 km further to the west (Fig. 12) (Foulger, 1988a, 1988b; Foulger and Toomey, 1989; Miller et al., 1998). It is interesting to note that Torfajökull, the Icelandic central volcano that produces by far the largest proportion of rhyolitic eruptives, lies in the most slowly extending part of the Icelandic rift system.

SYNTHESIS AND DISCUSSION

Plume Models for Yellowstone

Notwithstanding the most fortuitous location and the most sophisticated seismological experiment ever staged, seismic evidence in support of a Yellowstone plume is underwhelming. None of the many tomography models produced to date show repeatable evidence for a vertically extensive low-velocity body extending down into the lower mantle, accompanied by deflections on the TZ discontinuities (Fouch, 2012). This adds to the many geological details of CRB-ESRP-Y volcanism that do not fit a plume model without special pleading (see Framework section).

A mantle-plume origin for CRB-ESRP-Y volcanism is nevertheless still assumed by some workers. It is important to appreciate that the plume model cannot be disproven because it is so conveniently flexible. Any mismatch between prediction and observation of spatial or temporal variations in volcanism can be explained simply by distorting and pulsing in the mantle. Thus, for example, Camp and Ross (2004) suggested that the Newberry zone results from a backward-flowing arm of a plume beneath Yellowstone. The excessive rate of migration required by the postulated plume tail for the period 10–17 Ma has been attributed to westward deflection of a plume head by the Farallon slab (Pierce and Morgan, 2009), or the "snapping" to an upright position of a plume after escape from the Juan de Fuca plate (Geist and Richards, 1993). Such ad hoc models may be far removed from realistic mantle dynamics, and furthermore, any such model embellishments must be testable. The lithosphere-delamination model suggested by Hales et al. (2005) to explain observed precursory subsidence was countered by Pierce and Morgan (2009) who suggested that the delamination was triggered by an arriving plume head.

The original plume model of Morgan (1971, 1972a, 1972b) provided an elegant, testable hypothesis for apparently fixed, time-progressive volcanic chains, and it inspired much productive research on some of the most interesting geological provinces on Earth. This research quickly produced new observations that prompted the a posteriori addition of empirically based predictions of the original concept. These included laterally extensive flood basalts, rapid emplacement rates, ocean island–type geochemistry (Hanan and Schilling, 1997; Hart et al., 1992; Hofmann, 1997; Schilling, 1973), and high $^3He/^4He$ ratios (Craig and Lupton, 1981). There has, however, been insufficient skepticism of these postulated plume characteristics, and they have tended to give rise to circular reasoning. Thus, when such observations were made where a plume had been proposed, they were assumed to characterize plumes, and when discovered elsewhere, they were taken to demonstrate that a plume must be present there as well. For example, high $^3He/^4He$ ratios were originally observed at Hawaii and were proposed to be a plume characteristic (Craig and Lupton, 1981). When observed at Yellowstone, such ratios were then cited as conclusive evidence for a plume irrespective of evidence to the contrary.

In the case of the CRB, the huge area covered is frequently cited in support of a plume-head model (e.g., Faccenna et al., 2010). Indeed, "large igneous provinces", often assumed to represent plume-head volcanism, are defined by surface area, not by the total volume of magma emplaced (Coffin and Eldholm, 1994). Nevertheless, the area covered is a function of the topography at the time of eruption, not just of the volume erupted. The main eruptive phase of the CRB lasted ~1.6 m.y. and produced 234,000 km^3 of lava. Such rapid emplacements are frequently cited as evidence of plumes despite numerical modeling that shows that the generation of melt in a rising, decompressing plume head would take 10–20 m.y. (Farnetani and Richards, 1994).

Ocean island–type geochemistry is explained by the incorporation of fusible, subducted, near-surface materials in the source (Hofmann and White, 1982). High-pressure melting experiments on the most primitive rock compositions of the Grande Ronde Basalt suite of the CRB show that the entire compositional range of the melts can be explained by melting of up to 30%–50% of a MORB-like source at ~2 GPa (~70 km depth) at a normal mantle temperature of 1300–1350 °C (Takahahshi et al., 1998).

Tomography and Geochemistry

Despite many major seismic studies of the ESRP-Y region, researchers are still divided regarding whether or not a mantle plume underlies Yellowstone. Seismology has not resolved this perennial question. This suggests that seismic tomography, as conventionally practiced, cannot test the plume hypothesis. In the case of Yellowstone, the experimental conditions are the best likely to be achievable anywhere on Earth in the foreseeable future. The region is optimally located in the interior of a continent, surrounded on all sides by the most ambitious seismic network ever deployed and targeted by several local dense arrays. This contrasts with most melting anomalies which comprise small oceanic islands. Despite its optimal setting, seismic tomography images of Yellowstone are insufficiently repeatable to unite the scientific community on the question of the existence of a plume. Regardless of one's preferred model, evidence to support it can be found somewhere within the wide suite of results available.

Although seismology can yield much remarkable information about the interior of Earth, it alone probably is fundamentally unable to resolve the question of whether deep-mantle plumes exist. The absence of low velocities is typically not a possible finding because seismic tomography results are generally presented as deviations from the regional mean. Images of the results are thus constrained to show both high and low velocities in equal amounts (Foulger et al., 2013). Furthermore, there is always a lower limit in size and strength of anomalies that can

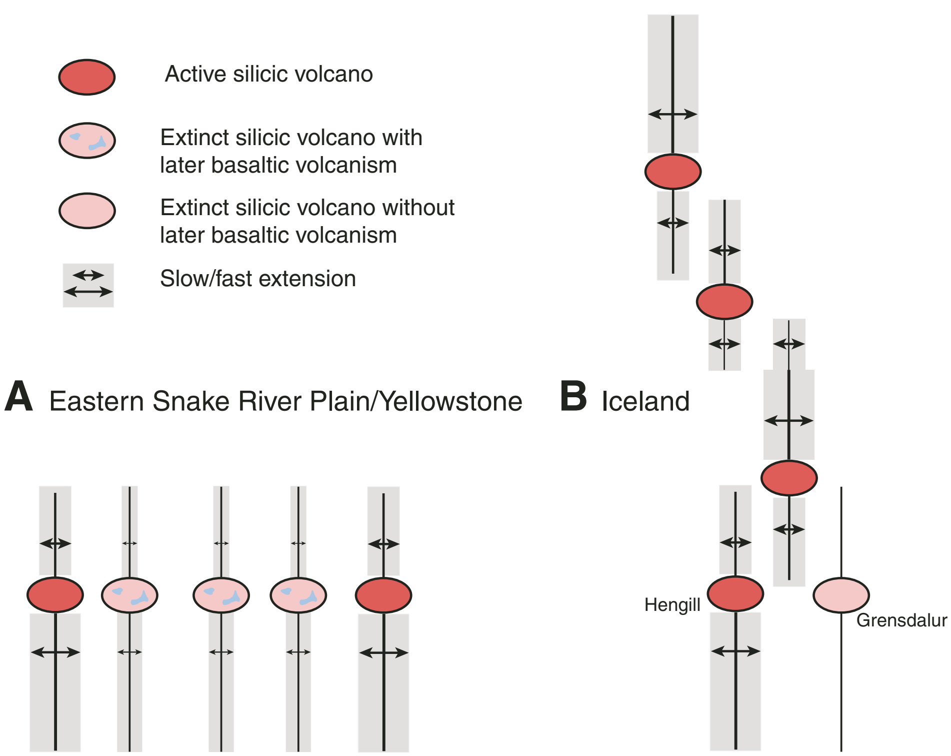


Figure 12. Schematic diagram comparing the eastern Snake River Plain and Yellowstone to the spreading plate boundary in Iceland, where the basaltic-rhyolitic volcanic systems typically form en echelon arrays oriented perpendicular to the direction of extension. (A) Eastern Snake River Plain–Yellowstone (same as panel C from Fig. 8). (B) Array of volcanic systems forming a volcanic zone in Iceland.

be resolved, and it will always be possible to propose plumes that are too weak or narrow to be detected.

The message from geochemistry is similar (Lustrino and Anderson, this volume). Geochemistry has essentially no power to resolve depth. Proposed geochemical associations with the deep mantle are based entirely on theories concerning the postulated locations of the sources of particular geochemical signatures. In the case of $^3He/^4He$, the assertion that high values indicate a plume is based on an initial empirical correlation with Hawaii, which was followed by a theory constructed to explain how it could arise from the core-mantle boundary (Craig and Lupton, 1981).

Final Remarks

Many plume models for Yellowstone are logically flawed. All models for mantle dynamics in the western U.S. call for substantial complexity in the mantle flow field. This is at odds with a plume explanation for the time-progressive chain of rhyolitic volcanoes. Ironically, what is considered the strongest evidence for a plume thus counts against the model (Fouch, 2012). Time progression, showing relative fixity to the Hawaiian volcanic locus, and high-$^3He/^4He$ are explained in the plume model only by a source at the core-mantle boundary. There is no reason why "upper-mantle plumes" (e.g., Xue and Allen, 2010), "TZ plumes" (e.g., Fee and Dueker, 2004), and the numerous variants proposed to be related to subducting-slab processes (e.g., Faccenna et al., 2010) should produce time-progressive volcanism fixed relative to Hawaii. A more reasonable explanation for the approximate relative fixity of the Hawaiian and Yellowstone melt loci for the last few million years is that both are fixed relative to the global plate-boundary system, as predicted by the plate hypothesis.

Referring to purported upper-mantle diapirs as "plumes" introduces confusion. Semantics are influential (Faccenna et al., 2010; Long et al., 2012). Constructive discussions require well-defined and uniformly understood terminology. The time-progressive Newberry trend is generally attributed to plate boundary–related processes. If plate-related processes can cause time progression in this volcanic chain, there is no reason why they cannot do the same for the ESRP-Y zone. The fact that its azimuth is parallel to the direction of plate motion is not proof of a deep-mantle plume.

Voluminous rhyolitic volcanism along the ESRP-Y zone followed migration of the locus of most rapid extension, not vice versa (Anders, 1994). Models that consider the volcanism to have initiated the large range-bounding faults in the neighborhood seek to separate out the effects of the purported plume from basin-range deformation. This would imply that these faults are independent of, and unrelated to, basin-range extension further south, which is unconvincing. The entire tectono-magmatic system that includes the CRB, the High Lava Plains, the ESRP-Y zone, and the widespread volcanism throughout the western U.S. calls for a holistic explanation involving the subducting Farallon slab, the complexities of plate-boundary evolution, and the development of the vast back-arc extensional region (Fouch, 2012). Models that involve separate and unrelated elements—*dei ex machina*—that occur as they do by coincidence, do not further geological understanding. The extreme seismic anomalies beneath the ESRP-Y zone may have developed from the top down, growing downward and outward, in response to extraction of melt and volatiles at the surface inducing replacement by compensating upwelling of melt and volatiles from below. Small-scale analogies are the depletion zones in exploited geothermal or hydrocarbon reservoirs, which grow downward and outward from the fluid-extraction loci (Gunasekera et al., 2003). Future advances are unlikely to come from the results of any one single technique, but in the application of sound scientific logic to the multidisciplinary observations, and testing of clearly defined, competing hypotheses.

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