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Beneath Yellowstone: Evaluating Plume and Nonplume Models Using Teleseismic Images of the Upper Mantle

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ABSTRACT

The Yellowstone hotspot commonly is thought to result from a stationary mantle plume rooted in the lower mantle over which North America moves. Yet Yellowstone's initiation and its association with the "backward" propagating Newberry hotspot across eastern Oregon pose difficult questions to those explaining Yellowstone as a simple consequence of a deep-seated plume. Teleseismic investigations across the Yellowstone topographic swell reveal: (1) the swell is held up by buoyant mantle of two types—partially molten mantle (of low seismic velocity) beneath the hotspot track and basalt-depleted mantle (of high velocity) beneath the rest of the swell; (2) an upwarped 660 km discontinuity beneath the Yellowstone hotspot track, as expected for relatively hot mantle at that depth, and an upwarped 410 km discontinuity, indicative of relatively cool mantle at this depth; and (3) anisotropic mantle with a preferred northeast orientation of olivine *a* axis, consistent with the strain expected for both plate motion and hotspot asthenosphere flow. Imaged mantle velocities can be reconciled with a plume hypothesis only if melt buoyancy within the hotspot asthenosphere drives convection, with melt segregating from the mantle beneath Yellowstone and residuum being deposited adjacent to the upwelling. Once such convection is admitted, an alternative, nonplume explanation for Yellowstone is possible, which has propagating convective rolls organized by the sense of shear across the asthenosphere. This explanation has the appeal that expected asthenospheric shear beneath the northwest United States predicts both the Yellowstone and Newberry hotspots with a single (upper mantle) process.

INTRODUCTION

Recent teleseismic studies of the upper mantle beneath the Yellowstone swell provide insight on the origin of hotspots. The upper mantle beneath this swell now is one of the most seismically resolved regions on Earth, and the physical state of the upper mantle is accordingly well understood. However, interpretation of our findings in terms of hotspot processes remains ambiguous. Where once a plume origin seemed natural, we now consider a nonplume explanation to be at least as attractive. Studies currently collecting teleseismic data in the greater Yellowstone area should answer most questions currently deemed important about this hotspot.

Hotspots are defined by their anomalous surface manifestations, in particular, the time-transgressive propagation of volcanism over hundreds of kilometers, often

Beneath Yellowstone *continued on p. 2*

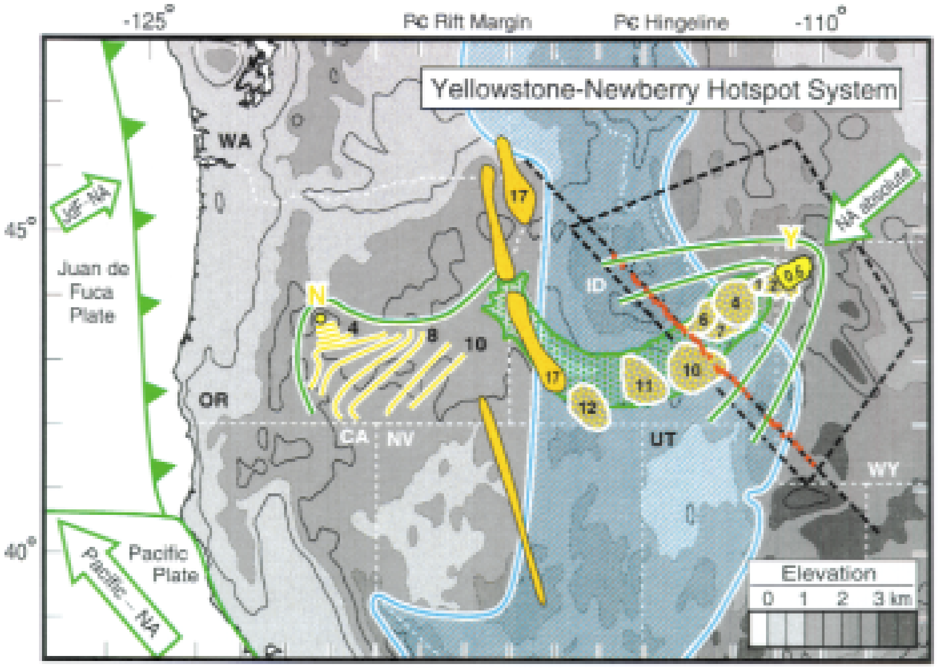

Figure 1. Volcanic-tectonic setting of Yellowstone-Newberry hotspot system. Volcanic elements are shown in gold and yellow (current locations of Yellowstone [Y] and Newberry [N] calderas in yellow), and tectonic elements are shown in blue (for older features) and green (younger features). Arrows indicate North America (NA) absolute motion and oceanic plate relative motions. Transform (solid) and subduction (toothed) plate boundaries are shown near western coastline. This hotspot system initiated 17 Ma from central Nevada rift–Steens Mountains–Columbia River flood basalt fissures (solid gold areas, from Christiansen and Yeats, 1992) located near the latest Precambrian rift margin of North America (western blue line, from Burchfiel et al., 1992). After ~5 m.y. delay, magmatism propagated west-northwest to Newberry (gold lines show initial rhyolitic volcanism in 1 m.y. increments, from MacLeod et al., 1976), constructing the High Lava Plains (north and west margins shown with green line in Oregon), and east-northeast to Yellowstone (major rhyolitic caldera centers shown in gold pattern with ages in m.y.; from Pierce and Morgan, 1992). Yellowstone propagation was rapid across Paleozoic passive margin (blue ruled area), and stalled near Precambrian hingeline (eastern blue line, from Burchfiel et al., 1992). Yellowstone swell occupies Anders et al.'s (1989) "tectonic parabola" (shown with parabolic-shaped green lines) and depressed Snake River Plain (green pattern). Red dots show seismometer locations. Black dashed lines indicate cross section and map area shown in Figure 3.

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In Memoriam

Frank C. Canney
Lakewood, Colorado
October 7, 2000

William W. Craig
New Orleans, Louisiana
September 25, 2000

Edward Barrett
Valrico, Florida
October 3, 2000

Albert Ray Jennings
Abilene, Texas
November 14, 1999

Robert U. King
Wheat Ridge, Colorado
January 14, 2000

Travis J. Parker
Bryan, Texas
September 25, 2000

Please contact the GSA Foundation for information on contributing to the Memorial Fund.

Beneath Yellowstone *continued from p. 1*

with geochemically distinct lavas. Because of their inferred association with Earth's "stable interior," hotspots have played an important role in plate tectonic theory (e.g., Morgan, 1971). Also, their presumed role as the actively ascending part of mantle convection (e.g., Davies, 1993), arising from a lowermost mantle thermal boundary layer (e.g., the core-mantle boundary or a boundary in the lower mantle [Kellogg et al., 1999]), gives hotspots special geodynamic significance.

A mantle plume origin of hotspots is widely accepted, on the basis of the relative fixedness of hotspots, the need for an anomalous heat source, and elevated ^{3}He/^{4}He values thought to represent long-isolated "primordial" mantle (e.g., Kellogg and Wasserburg, 1990). These observations combine to support the simple and elegant model well known to earth scientists: Conduits rooted deep in the stable lower mantle supply relatively undepleted mantle that feeds the surface expressions of hotspots. In this model, hotspot magmatic activity begins with the impact of a large plume-fed head of hotspot mantle, to which many flood basalts are attributed (Duncan and Richards, 1991), and is followed by supply from the conduit, which constructs a hotspot track leading away from the site of basalt flooding with plate motion. However, the actual deep structure of hotspots, and therefore the actual processes underlying their behavior, are not well understood. Furthermore, an apparent absence of uplift prior to head

Dialogue

Sara Foland, CEO


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A Year of Accomplishment and Learning

> *"I personally measure success in terms of the contributions an individual makes to her or his fellow human beings."*
>
> Margaret Mead

My first full year as CEO of GSA has been filled with success and learning—for myself, for GSA Headquarters staff members, and for our elected Councilors and Officers. I want to review what we've accomplished this year, share results of goals set forth in my December 1999 Dialogue column, and share some new goals and expectations for the next 12 months and beyond.

New Business Processes

GSA headquarters continues to evolve toward being a function-based organization, where the form of the organization follows the function of the projects we do for GSA members and the broader geoscience community. Staff efforts are focused in three key areas: providing programs, providing services, and creating products. Efforts in these areas are shaped by goals set forth in GSA's strategic plan.

The focal point of all programs, services, and products is *science.* That's why the chief science officer (CSO), whose role is to provide integration of these areas, shares leadership with the chief executive officer, whose role is to ensure that fiscal and human resources are available to accomplish the GSA vision.

CSO Cathleen May notes, "Headquarters' function is centered on supporting science and the value of science by and for GSA members. The changes in structure allow effective integration of functions within the system. On the staff side, the dedicated professionals at headquarters can work more directly and collaboratively on things that add meaning to their working lives."

Fiscal year 2000 was the first to utilize GSA's new budgeting process. It involves coordinated management of three separate budgets: an operating budget for core programs, services and products; a strategic budget for new initiatives derived from the strategic plan; and a capital budget for maintaining GSA facilities. This fiscal year, all three will come in at or under projected costs.

This new budgeting process allows for significant participation by GSA's elected leaders in reviewing and prioritizing projects in the strategic budget. The Programmatic Overview Committee (POC) reviewed nine business plans this year, ranging from electronic publishing to globalization. A total of $1.275 million is set aside for strategic spending over the next 18 months.

A change in GSA's fiscal year in 2001–2002 from a calendar year to a 12-month year that begins July 1 will concentrate revenue-generating activities in the first two quarters. Should we miss our projected revenues, we would then have two additional quarters to make adjustments.

Strategic Partnerships

Expanding our external focus, we initiated a partnership with The Geological Society (London). Our first joint activity, a global meeting in Edinburgh, Scotland, is scheduled for June 2001. The theme of this meeting is Earth System Processes, emphasizing the integrated nature of our science and the need for enhanced collaboration between geoscience disciplines and the related sciences we use to interpret earth system problems. Ian Fairchild and Ian Dalziel have set a unique technical program for this meeting, which you can see in the November issue of *GSA Today* or on the Web at www.geosociety.org.

In July we began discussions with the Geological Society of Australia on joint publications and a second global meeting in 2003.

GSA holds a unique position within the geoscience community. We have an imperative to expand our external focus and use our fiscal strength to pursue our collective vision for the geosciences. It has been a great year at GSA, with successful projects and new ventures. We couldn't have achieved these successes without the dedication, contribution, and sacrifice of GSA staff, and I thank each one of them. I'm looking forward to the year ahead, and wish you all a safe and prosperous new year.

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impact and the unusual circumstances under which hotspot magmatism often initiates (e.g., Anderson, 1999; Czamanske et al., 1998) are difficult to incorporate into a plume model. As a result, alternative hotspot hypotheses have been suggested with an upper mantle origin (e.g., Anderson, 1994) or a dominance of upper-mantle processes (Saltzer and Humphreys, 1997).

Of the hotspots investigated seismically, Iceland and Yellowstone are the two most thoroughly studied. A plume origin is argued for Iceland based on tomograms of the upper mantle (Wolfe et al., 1997) and imaged deflection of the temperature-sensitive 410 km and 660 km seismic discontinuities (Shen et al., 1998). However suggestive, an absence of seismic information from adjoining regions near Iceland provides little context in which to interpret the imaged structures. The Yellowstone hotspot offers the advantage of broad accessibility compared to oceanic hotspots, but teleseismic arrivals travel through the relatively complicated continental crust. The resulting tradeoff is that, compared with oceanic hotspots, the geometry of the ray set is superior for deep and regional imaging, but the data are degraded by greater amounts of crust-generated noise.

In most ways, Yellowstone is a typical hotspot. Figure 1 shows the Yellowstone-Newberry volcanic-tectonic system in the context of the western United States. Yellowstone is characterized by a magmatic track and a southwest-widening topographic swell left in the wake of the north-east-propagating (relative to North America) hotspot. The topographic swell is thought to result from plume flattening beneath the southwest-moving lithosphere (Anders and Sleep, 1992), as conceptualized in Figure 2. The swell's margins have been termed the "seismic parabola" (Anders et al., 1989) for their seismicity (see Fig. 3). The magmatic track is the eastern Snake River Plain, which trends near the symmetry axis of the swell; it is a topographic depression because basaltic intrusions have loaded the crust, causing subsidence (Anders and Sleep, 1992). For Yellowstone, as for some other hotspots, relatively high $^3He/^4He$ values (Hearn et al., 1990) are thought by

Beneath Yellowstone *continued on p. 4*

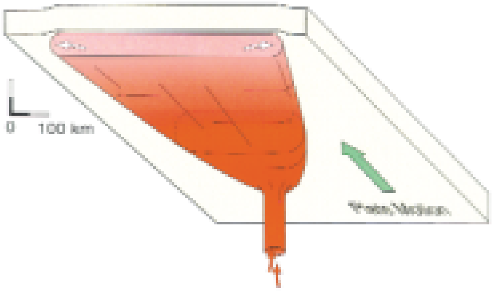

Figure 2. Simple hotspot model showing flattening plume beneath moving plate. Modeled after Ribe and Christensen, 1994.

Beneath Yellowstone *continued from p. 3*

many to represent a lower mantle source.

The Yellowstone hotspot also is characterized by a strange initiation and a close association with another propagating continental hotspot, Newberry (Fig. 1). Yellowstone-Newberry magmatism began vigorously ca. 17 Ma with the eruptions of the central Nevada rift, Steens Mountains, and Columbia River flood basalts (Christiansen and Yeats, 1992). While often attributed to an impact of a plume head, there is no obvious indication of expected uplift preceding initial magmatism. Furthermore, these magmas erupted from a narrow set of fissures extending roughly north-south for ~700 km along the late Precambrian rift margin of North America (Fig. 1). Magmatic activity continued in this vicinity until ca. 12 Ma before propagating (irregularly) northeast toward Yellowstone and west-northwest toward Newberry. With a west-northwest direction of propagation, the Newberry hotspot cannot be connected to a stationary deep-seated plume

TELESEISMIC INVESTIGATION

In teleseismic seismology, the distortion of seismic waves is analyzed to infer the structure of the upper mantle and crust through which the waves propagated as they arrive from distant earthquakes to an array of seismometers. To address the structure beneath the Yellowstone swell, we deployed a seismic array occupying ~50 sites in a line trending across the width of the swell (Figs. 1 and 3). Our work follows that of Evans (1982), who imaged upper mantle P-wave velocity structure by making use of traveltime delays of the first arriving waves recorded on 1 Hz vertical-motion seismometers. Our three-component broadband seismometers enabled receiver function imaging for crust and upper mantle interfaces, S-wave splitting analysis for upper mantle anisotropy, and P- and S-wave tomographic imaging of upper mantle velocity variations—methods now routine in teleseismic seismology.

Receiver Function Imaging of Crustal and Mantle Interfaces

A P wave partially converts to an S wave as it travels across an interface. At Earth's surface, the time delay of the converted S wave relative to the (faster traveling) P wave is proportional to the depth of the interface, and the magnitude of the S wave depends on the seismic contrast of the interface. Using these principals, the receiver function technique was used to image crustal and upper mantle discontinuities beneath our array. Combined with previous reflection-refraction investigations (Sparlin et al., 1982), receiver function analysis allowed Peng and Humphreys (1998) to image the crustal structures shown in Fig. 3: (1) a mid-crustal basalt sill across the width of the Snake River Plain, (2) an ~5 km thick partially molten lowermost crust across the width of the plain, and (3) a Moho that is approximately flat across the width of the seismic parabola but which thickens rapidly southeast of the swell. P-wave velocities (from Sparlin et al., 1982) suggest that the basalt sill is about half basalt and half the granitic country rock that comprises the upper crust away from the eastern Snake River Plain. The ~10 km thickness of the basalt sill therefore implies ~5 km of basalt added to the upper crust across the width of the eastern plain, and the partially molten lower crust suggests an underplating of probably 5 or more km of gabbroic crust. This crustal inflation is not reflected by a greater Moho depth, suggesting that lower crust was squeezed from beneath the eastern Snake River Plain to adjoining regions.

Perhaps the most important result of crustal imaging is the information it provides to model crustal density structure, which allows us to calculate mantle buoyancy across the width of our array. Mantle buoyancy holds the swell about 1 km higher than would normal mantle (e.g., eastern U.S. seaboard mantle), whereas mantle southeast of the swell is of more normal density (Peng and Humphreys, 1998). The highly (and uniformly) buoyant mantle across the width of the swell and the isostatic balance of the crust above it are consistent with standard thoughts on hotspots (e.g., Fig. 2).

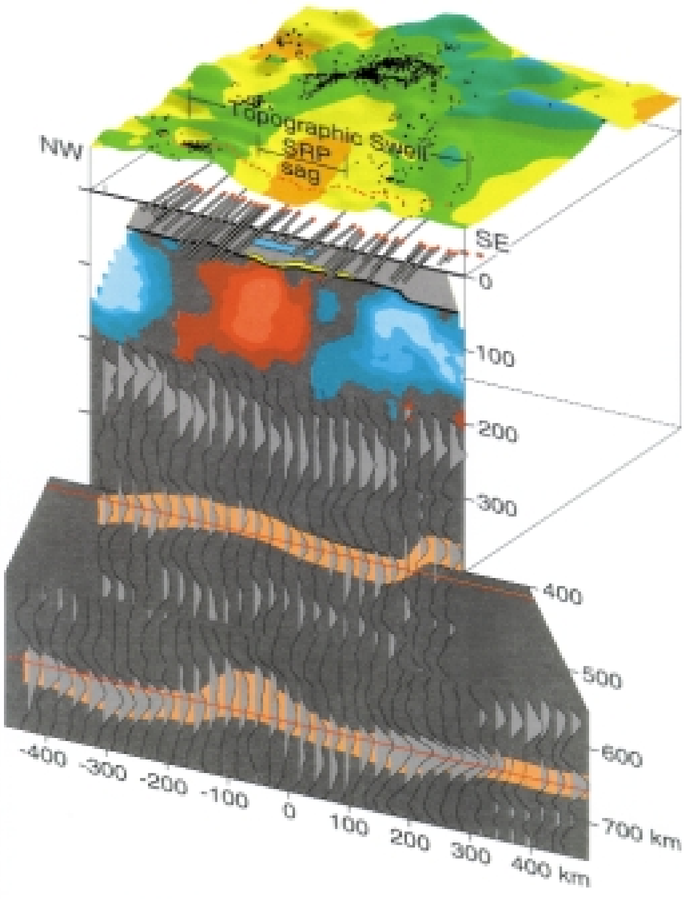

Figure 3. Seismic structure beneath Yellowstone swell. View is to north. High topography (green) correlates with local seismicity (black dots) and defines hotspot swell. Teleseismic studies derived from data collected by seismometers crossing swell (red dots) image: (1) crust that is not greatly thickened beneath Snake River Plain (SRP) (Moho shown with heavy line near 40 km depth), in spite of intrusion of high-velocity mid-crustal basalt sill (blue) and partially molten underplate (yellow); (2) high-velocity mantle (blue) beneath higher elevations and low-velocity mantle (red) beneath depressed SRP (contour level is 1% in P-wave velocity); (3) split SKS waves indicating anisotropic mantle with a fast-axis orientation oriented to the southwest (black and white bars show split times of 0.6–1.6 s; black bars show unsplit arrivals that were naturally polarized in the direction of the bar); and (4) undulatory 410 km and 660 km interfaces (highlighted in salmon color). These imply: (1) that mantle is approximately uniformly buoyant across entire swell; (2) upper 200 km of mantle is partially molten beneath SRP and depleted of basaltic component elsewhere beneath swell; (3) upper few hundred km of mantle has been simply sheared with a southwest-northeast finite extension direction; and (4) mantle beneath SRP is anomalously hot beneath SRP at 660 km, but appears to be cool at 410 km.

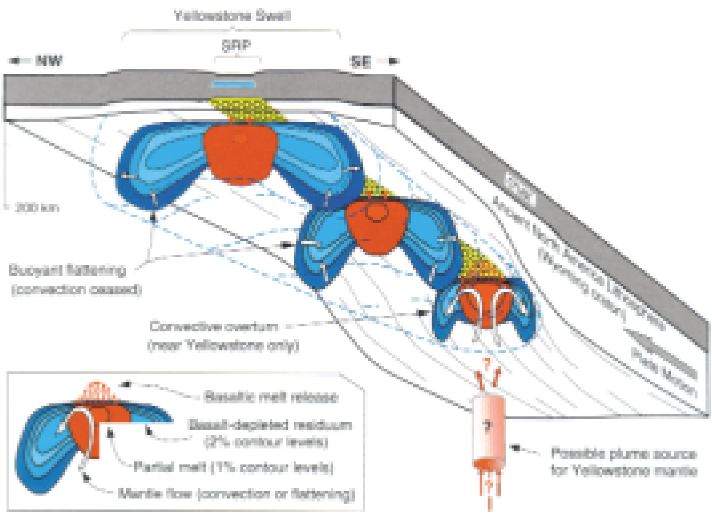

Figure 4. Schematic of mantle processes active within asthenosphere beneath Yellowstone swell. Buoyant and fertile mantle ascends beneath area of active hotspot magmatism, possibly supplied by mantle plume (see Fig. 5 for alternative model). Melt buoyancy drives convection in this mantle (large white arrows). Melt is expelled at top of convective roll (wavy red lines) and depleted residuum (blue areas) is pushed to sides, where it accumulates. When residuum buoyancy equals melt buoyancy, convective overturn ceases, leaving partially molten core (red areas). Buoyant mass then flattens (small white arrows) as it is carried southwest by North America plate motion. Effects of hotspot on North America are (1) magmatic modification of Snake River Plain (SRP) (basaltic underplating of crust, shown in yellow, and intrusion of basalt into midcrust, shown with blue tabular body), which loads and depresses SRP crust, and (2) uplift of region underlain by buoyant mantle (within the blue envelope), creating Yellowstone swell. With plate motion, Yellowstone encounters increasingly thick lithosphere of Wyoming craton.

Dueker and Sheehan (1997) used P-to-S conversions from the 410 km and 660 km seismic discontinuities to assess if locally hot mantle (e.g., plume-affected mantle) deflects these interfaces. Making use of the fact that interface deflection is of opposite sign on these interfaces for a given temperature anomaly (Bina and Helffrich, 1994), the observed thinning of the intervening layer by ~20 km (Fig. 3) beneath the Snake River Plain suggests a thermal anomaly there of 150–200 °C. This result, however, is entirely a consequence of the upwarp in the 660 km discontinuity; the upwarped 410 km discontinuity implies cooler temperatures at this depth beneath the plain.

S-wave Splitting and Upper Mantle Anisotropy

Upper mantle strain via olivine dislocation creep tends to align the olivine *a* axis in the finite elongation direction, and even moderate strains (one or more) can create a significant fabric in this orientation (Ribe, 1992). Much like light traveling through a crystal, an S wave passing through anisotropic upper mantle will split into two orthogonally polarized waves, with the faster traveling wave vibrating parallel to the direction of the *a* axis. The polarization of SKS waves in a known direction makes them ideal for anisotropy studies. Figure 3 shows the results of split SKS waves recorded by our array (from Schutt et al., 1998). The fast-wave polarizations trend approximately N65E, which is nearly aligned with the hotspot track and North America absolute plate motion. Waves that were naturally polarized with this orientation are not split, indicating that anisotropy of a different orientation does not exist at greater depth. The region of nearly uniform anisotropy orientation ends near the southeast margin of the swell, and most of the western United States has orientations not aligned with North America absolute plate motion (Savage and Sheehan, 2000). Thus the asthenosphere beneath the Yellowstone swell defines a coherent, simple, and distinctive upper mantle anisotropy domain.

There are two reasonable ways to interpret the observed upper mantle anisotropy. In the first, buoyant mantle beneath the swell is simply sheared by North America as it moves over a more stable interior (causing the *a* axis of olivine to align preferentially in the direction of plate transport. Another possibility is that a plume supplies buoyant mantle at a high rate, and this buoyant mantle flows to the southwest accommodated by deformation in the previously deposited low-viscosity hotspot asthenosphere (see Fig. 2). In this model, the southwest orientation of the finite elongation direction results from mantle flow driven by the local pressure gradient, and not by passive shear driven by plate motion. The similarity of results from different processes highlights the difficulties in understanding the mechanisms responsible for the mantle structure.

Tomographic Imaging of the Upper Mantle Velocity Variations

Figure 3 shows an image of the upper mantle P-wave velocity structure (Saltzer and Humphreys, 1997). Red and blue areas represent areas where waves propagate relatively slowly (red) and quickly (blue). The blue areas have a seismic velocity that is about average for mantle beneath continents. The low-velocity anomaly is about as wide as the Snake River Plain, and is much narrower than the swell. The prominence of the relatively high-velocity mantle beneath the high-standing swell seems at odds with simple plume models, which have buoyant mantle distributed beneath the entire swell (as in Fig. 2). A nearly universal relation is that seismically fast rock is dense, yet the mantle is highly buoyant across the width of the swell (as discussed in the "Receiver Function" section). The only reasonable explanation for mantle that is both buoyant and relatively fast is that it is significantly depleted in basaltic components. Such depletion decreases density while increasing seismic velocity (Jordan, 1979), and this is one of the few cases where density and velocity correlate inversely. There is only one reasonable explanation for the imaged upper mantle structure: The slow mantle is partially molten and the fast mantle has been depleted of basaltic melt and currently is essentially devoid of significant melt. The observed ~7% contrast in P-wave velocity across the width of the swell requires melt fractions of up to ~2% in the red areas. The

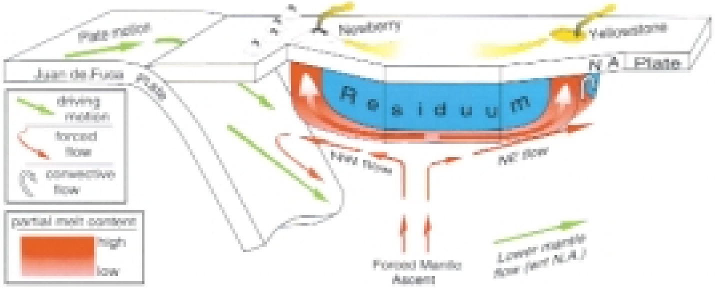

Figure 5. Forced mantle flow and decompression melting resulting from local plate motions. Far from subduction zone, a northeast-directed forced shear across upper mantle (right red arrow) results from northeast motion of stable lower mantle relative to southwest-moving North America (NA). Near the subduction zone upper mantle is forced to flow northwest (left red arrows) because of corner flow driven by subducting plate. Yellowstone and Newberry magmatism follows these trends as fertile mantle flows past residuum and ascends (red-to-white arrows). Decompression melting causes convection (white arrows) and magmatism, creating new residuum at ends of residuum body (Fig. 4 shows details of process). Diverging upper mantle flow evacuates asthenosphere from central area, forcing mantle ascent.

Beneath Yellowstone *continued on p. 6*

Beneath Yellowstone *continued from p. 5*

inferred compositional buoyancy of the blue mantle results from 5%–10% basalt segregation, and this compositional buoyancy accounts for much of the swell's high elevation (Saltzer and Humphreys, 1997).

ASSESSING YELLOWSTONE'S ORIGIN

Imaged seismic structures and calculated mantle buoyancy beneath the Yellowstone swell imply that the swell mantle is anomalously hot to depths of ≥200 km, is not anomalously hot at 410 km, and is hot again at 660 km. The red mantle beneath the Snake River Plain in Figure 3 is 1%–2% partially molten, and the blue mantle beneath the adjoining swell is 5%–10% depleted of basaltic components. Mantle is anisotropic beneath the swell, with finite extension oriented approximately N65E, and this orientation does not vary with depth. This anisotropy is unique to the Yellowstone swell; it contrasts with the western U.S. mantle away from the swell, which is more complexly strained in different orientations.

Plume or no plume, we can make sense of these results only if we include local convection beneath Yellowstone, as illustrated in Figure 4 (Saltzer and Humphreys, 1997). A source of hot and fertile mantle is needed to produce significant basaltic melt upon adiabatic ascent, and the melt buoyancy drives convection (as modeled by Tackley and Stevenson, 1993). Melt release occurs when melt migration rates exceed convective flow rates (probably at melt fraction of ~2%). The escaping melt underplates and intrudes the crust. Convection ceases when the buoyancy of accumulating residuum equals that of the partially molten core. This mantle overturn occurs beneath the active caldera system (currently at Yellowstone). Then, the entire buoyant mass flattens as it is transported by plate motion away from the site of magma release, creating the southwest-widening swell. Mantle strain occurs primarily through southwest-northeast–directed simple shear. This could result from plate motion over a more stable interior, or by flow of Yellowstone asthenosphere away from Yellowstone and confined to the low-viscosity volume of hotspot asthenosphere previously deposited. These conclusions are sound in that they explain the peculiar seismic and density structure observed beneath our array, and they account for the magmatism. They do not specify a source for hot and fertile mantle. In particular, they permit the plume hypothesis for Yellowstone (but require convection to occur within the flattening hotspot asthenosphere).

However, once local upper mantle convection is recognized, there is potential to interpret Yellowstone entirely as an upper mantle phenomenon. Our model for this incorporates the flow interaction of asthenosphere with the volume of residuum created by prior melt release. Because this residuum is buoyant and relatively viscous, it tends to attach itself to the North America plate and move with this plate. The residuum protects the overlying plate by inhibiting subsequent magmatism, and as it is dragged along, asthenosphere flows beneath it and up as it passes the leading edge of the residuum body (as illustrated in Fig. 5). Melting occurs with ascent, driving the local convection that produces focused magmatism (as in Fig. 4) and adds to the residuum body.

Magmatic propagation therefore can be seen as a natural upper mantle process when hot, fertile mantle is subjected to shear, as in plate transport. Schmelling (2000) is producing such propagating melt-driven convective instabilities in computer simulations. An especially attractive feature of this model is that to the west, near the plate margin, upper mantle flow and shear directions probably are directed west-northwest, in the direction of Newberry propagation, as a result of subduction-driven corner flow (Fig. 5). Hence, both Yellowstone and Newberry magmatism can be explained by a single (upper mantle) mechanism. Furthermore, the divergence of upper mantle flow drives mantle ascent between Newberry and Yellowstone (Fig. 5) that can account for the initiation of magmatism over an elongate region. This could occur if unusually hot or fertile mantle were drawn up in a zone parallel to the subducting plate, or if the ascending mantle were focused on an area of fertile North America lithosphere, such as the Precambrian rift margin (where fertile asthenosphere "froze" onto North America during Paleozoic downwarping of this margin). And the observed ^{3}He/^{4}He anomaly can be attributed to drawing up some primordial lower mantle.

One can ask why other Yellowstones and Newberrys are not distributed around the western United States. In fact, there are other magmatic trends oriented northwest (most western Great Basin magmatism) and northeast (e.g., Jemez, St. George) with associated low-velocity mantle trends (Humphreys and Dueker, 1994). The relative vigor of Yellowstone magmatism may result from its tectonic setting (adjacent to the Cascadia subduction zone and where focused northeast-oriented extension occurs), or perhaps it may simply represent the activity of an unusual lithospheric trend (Iyer and Healey, 1972) or relatively hot mantle.

ACKNOWLEDGMENTS

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