Supporting Information

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SI Text

Tomography and Mantle Geochemistry. The locations of magma sources and the mechanisms of magma delivery have been debated for more than 40 y. The plume vs. plate debate is part of the broader issue of mantle dynamics and geochemistry. Seismology and other imaging techniques are most likely to settle the issue because the key distinguishing characteristics are not hotspot fixity, heatflow, or chemistry but dimensions, buoyancies, mass balances, and ascent rates, all of which are related. Because of the various scaling relations that have been adopted between seismic wavespeeds, density, and temperature and the perceived lack of resolution of some types of imaging, results to date are inconclusive and are still widely discussed. The present paper addresses the scale arguments, which are simple to understand and are definitive. The other issues in the debate have a vast literature and cannot all be addressed here. The end-member models on the one hand involve narrow plumes, superplumes, strong thermal buoyancy, rapid ascent rates and vigorous bottom-heated whole-mantle convection, and on the other hand, plate- and slab-driven top-down convection, as appropriate for a cooling planet, and large passive updrafts from the transition region that interact with the thick surface boundary layer. These alternatives are characterized, respectively, as bottom-up or anchor models, where the lower mantle provides the motive power and the template for whole mantle convection; and the top-down or plate model in which the cooling surface controls the planform of convection. In the text, we restrict ourselves to geophysical data that distinguish these models from each other. Here we provide additional images and references and comment on geochemical constraints.

Background. The competing explanations for the origin of Hawaii, Samoa, and other intraplate volcanoes include the top-down model, with sources in the low-wavespeed parts of the top and basal boundary layers of the upper mantle, and the bottom-up model, which uses narrow pipes to the base of the mantle or to superplumes deep in the mantle. The arguments for boundary-layer and layered-mantle convection include the evidence for a change in the pattern of the spectrum of the heterogeneity across the 220- and 650-km discontinuities; for large variations of wavelength in the topography of the 400- and 650-km discontinuities and their correlation with velocity anomalies in the transition zone; and evidence of perched eclogite layers or ponded slabs.

In the top-down boundary-layer model, the relatively homogenous basalts that are the results of broad passive upwellings are protected from contamination by dehydration reactions and removal of sediments and metasomatized parts of slabs before they reach the source of midocean ridge basalts (MORB) in the transition zone (TZ). Enriched oceanic island basalts (OIB) have sources in the surface boundary layer or are the result of the interaction of depleted upwellings with that surface layer. In the plume whole-mantle convection models, on the other hand, the mantle is homogenized by vigorous convection, and the upwellings responsible for ridge basalts must be filtered and refined before arriving at ridges.

These issues have already been discussed at great length in the literature, as can be verified by using a search engine on the keyword phrases persistent plume myth; questioning mantle plumes; Hawaii, boundary layers, and ambient mantle; irreversible differentiation of the mantle; decorrelations at the 650-km discontinuity; SUMA mantle mixing; perched eclogite layer; and tracking slabs—an exercise that also gives numerous references.

Tomographic Images. Visual inspection of color tomograms of lateral wavespeed variations is of limited use in deciphering mantle dynamics and petrology because the important diagnostic parameters are absolute wavespeeds, vertical gradients, and anisotropy. Nevertheless, the dimensions and topology of well-constrained seismic images can now rule out certain models that were originally based on low-resolution models.

A block diagram of a portion of the Pacific mantle from the northwest, focusing on Hawaii, the largest active intraplate volcanic system on the globe —the one producing the largest volcanoes—is provided in Fig. S1*A*. A 1:1 cross section of the portion of the diagram nearest Hawaii is shown in Fig. S1*B*. The updraft in the upper mantle beneath Hawaii appears to be almost plume-like when shown at high vertical exaggeration (~10:1; Fig. S1*A*), but it is clearly a broad and undulating feature when properly scaled (Fig. S1*B*), far wider than the 200 km often postulated for plume conduits, but a feature consistent with the wide span of volcanism across the Hawaiian swell, including at the crests of adjacent seafloor arches. A map view of the basal plane of a portion of the Pacific encompassing several linear volcanic chains (numbered 1–6 as detailed in the caption) at 1,000 km depth is shown in Fig. S2*A*. Currently, active portions of those chains (green dots) are near but not centered on the updrafts, and the updrafts are not vertical structures. The chains themselves parallel the elongations of the updrafts, which are in the direction of motion of the Pacific plate (1). Fig. S2*B* shows a map view at 250 km depth, plus a curving cross section corresponding to profile 1 on the map. The yellow-orange columns beneath the several island chains, interpreted here as passive updrafts, are 1,000–3,000 km in width, including the one beneath Hawaii, and at the base they are even broader. The one near Samoa vertically parallels the inclined seismic zone of the Tongan subduction system, extends to about the same depth, and may be related to it. It reaches east of the Tonga Trench by more than 1,000 km. Similar broad anomalies occur in the North Atlantic. The columns were described as "low-velocity, plume-like features, which appear rooted in the lower mantle" (1), but these are clearly much larger than the narrow plume conduits of conventional plume theory. These postulated updrafts are as wide as or wider than they are tall, even the one beneath Hawaii (Fig. S1*B*).

The Transition Zone. The hypotheses of whole mantle convection and plume generation at the core–mantle boundary are related. The transition zone holds the key to these hypotheses, as well as to a number of other geophysical problems (2). In a homogeneous mantle, the 410- and 650-km discontinuities result from temperature-dependent phase changes, and their depths should be anticorrelated (1). Thoroughgoing slabs and plumes should be associated with thicker and thinner TZs, respectively. The correlation of TZ wavespeeds and past subduction regions suggests instead that slabs accumulate at the 650-km boundary and cool off the underlying mantle. At long wavelengths, the wavespeeds and depths at the base of the TZ correlate with inferred positions of slabs, but the 410-km discontinuity is often shallower than average or is anticorrelated with the base of the TZ, suggesting that warmer mantle has been displaced upward by slabs (3).

Geochemistry. A steady concentration of enriched components within the shear region over time explains the progressive enrichment of eruptive lavas with respect to crustal age and eventual suppression of the signal of depleted MORB mantle in many ocean island basalts. The signal of enrichment is feeble at spreading ridges; it is stronger at seamounts on crust of intermediate age; and it is overwhelming at islands such as Tahiti and Samoa where the signal of depleted MORB mantle cannot be detected in any basalt. Regional and local stresses on the plate, and possibly the simple buoyancy forces of collected melt (magma fracture), rupture the plate and lead to eruption. The overall elongation of broad, finger-like projections of regions of low shear velocity beneath the Pacific plate (Fig. S1*B*) provides the general control on the progression and orientation of linear island chains in the Pacific. At Samoa, late-stage plate rupture associated with plate bending at the curving corner of the Tonga Trench allows large-scale eruption of late-stage alkalic lavas on the western portion of the island chain (4).

The character of isotopic enrichments in this scenario depends on what enriched materials are in the upper mantle and, separately, the broad regions of reduced wave speed and their concentration. This is clearly a function of the prehistory of each particular region, but broad diversity is indicated even at the larger scale of ocean basins (5, 6). Within this framework, some elevated ridges such as Iceland and even the superfast-spreading portion of the East Pacific Rise, which is not elevated, are more enriched than others.

In all of this, the key is that diverse materials—both enriched and strongly depleted—are comingled by shear and other processes in the melt sources of the various basalts. A variant of this is formation of the basal mélange of the deepest mantle, but convective mixing, rather than boundary layer shearing, is usually invoked. Nevertheless, comingling means that two major geochemical reservoirs separated by thousands of kilometers of mantle do not exist. The enriched materials have higher concentrations of volatiles and therefore lower solidus temperatures than depleted or refractory rock. The lower solidus temperatures mean that they should be preferentially sampled during incipient stages of partial melting. Melt fractions incorporating them are necessarily buoyant at the mantle depths in question. They must ascend, but will stall and collect at permeability barriers. They can also be shear driven, in addition to being buoyancy driven. The base of the 200-km-thick shear zone (sliding plates) is not only relatively stationary, but it is the most prominent permeability barrier. It should be the most important location for such barriers in the outer part of the planet. The signal of enrichment thus is feeble at spreading ridges where not much of this collection has or can occur; it is stronger at seamounts on crust of intermediate age; and it is overwhelming at islands such as Tahiti and Samoa where no basalt is formally depleted, and most are significantly enriched beyond bulk silicate earth. This hypothesis is consistent with the interpretations both of experimental petrology about depths of partial melting and of regional geophysics about depths to the low-velocity zone. Plumes with narrow conduits are not necessary to explain island or seamount volcanism.

The warmest portions of the large, low-velocity regions beneath plates occur where upwardly buoyant migrating partial melts are concentrated in the sheared region at the base of the lid. Both above and below the region of greatest melt concentration and entrapment, temperatures are lower. The warmest portions of the sheared boundary layer are near the axis of the low-velocity zone (LVZ). Buoyant migrating partial melts are concentrated below the base of the lithosphere, which is the cold upper part of the conductive lid. Maximum temperatures associated with the thermal overshoot (7) appear to be about 200 K higher than the maximum temperatures beneath spreading ridges. The only place where the higher inferred temperatures are reflected in lava eruptive temperatures, however, is Hawaii (8, 9). Very high potential temperatures estimated from some petrological techniques (~1,500 °C) (10, 11) are model-based deductions based on assumptions involving crystallization histories (e.g., no magma mixing; olivine crystallization has occurred along a single liquid line of descent; no other minerals have crystallized) that are probably incorrect.

Helium: Follow the Bubbles (and Sulfides the Droplets). Plume-like color images of relative seismic wavespeeds (not absolute wavespeeds) and ratios of helium isotopes (not absolute helium concentrations) are the remaining arguments for the existence of thermal plumes and whole-mantle convection. Although the noble gases are not chemically reactive, they play a dominant role in geochemical models of the mantle, being assumed to behave the same as the large ion incompatible elements. The presence of small amounts of the primordial isotope, ^{3}He, has been taken as evidence that the mantle is undegassed. Helium and other noble gases are truly fugitive constituents during partial melting, neither reacting with nor fitting into any crystal structure, and simply having solubility in melt that decreases during magma ascent. Where glass is unavailable, helium is usually extracted from olivine by crushing before it is subjected to MS. It occurs within volatile inclusions trapped in olivine phenocrysts (12) or in trains of volatile inclusions found within minerals of refractory ultramafic xenoliths (13). In either case, it is physically separated from locations within crystals or melts where any of the other radiogenic isotopes residec, as well as from the U and Th that ultimately give rise to differences in noble gas isotope geochemistries, which travel with melts. There is no partition coefficient for He, Ne, etc., between liquid and melt; partitioning, such as it is, occurs in lavas and xenoliths between crystals and bubbles entrained in melts. That in turn depends on the nucleation of bubbles on the growing or irregular fracture surface of a crystal. A crystal with a myriad of volatile inclusions need not contain any associated melt. Absence of melt in the crystals that have bubbles means that whatever the isotope ratio of ^{3}He/^{4}He in the transiting vapor phase happens to be, that is what will be recorded in the crystal, and nothing henceforward within the crystal will change it. In this sense, olivine is a time capsule. Diffusion is also very low at upper boundary-layer temperatures.

Volatiles derived from an ancient source, and perhaps preserved for eons in a cold, buoyant, crystalline matrix, might be released by magma penetrating the rock along fractures and impart an ancient (high ^{3}He/^{4}He) signal to the magma. If an ancient age becomes attached to modern lava, no necessary relationship exists between high ^{3}He/^{4}He and a deep mantle reservoir (14), only an old one that might be circulating or embedded in the outer mantle as a consequence of past tectonic arrangements of plates, migrating triple junctions, and subduction zones. As at Samoa, ^{3}He/^{4}He will not correlate with other isotopic ratios (Fig. S3). This lack of correlation is often described as decoupling.

Melt can, of course, form below the depth of vesiculation, but helium still will concentrate in melt porosity structure according to its propensity to stay with the melt until it enters the vapor phase and then be trapped on and in crystals; it will be diluted by high extents of partial melting. If, however, melt porosity becomes interconnected, perhaps where it is trapped in larger or more concentrated melt gashes where the low-velocity regions intersect the LVZ, then He will behave according to the usual tendency of volatiles and migrate toward regions of least pressure and temperature (15). When that magma ascends, experiences pressure release, and finally vesiculates, then bubble flotation will determine how many fluid inclusions nucleate on a given crystal. Inclusion density in single crystals indicates that some olivine literally crystallized in foam (12).

Recently, segregation of sulphides as immiscible droplets into mafic cumulates in the deep continental crust has been proposed to explain a correlation between high ^{3}He/^{4}He and unradiogenic Pb isotopes in ocean-island basalts (16). The correlation exists because Pb but not U is strongly partitioned into sulphides, which are abundant in mafic cumulates from both arcs and the ocean crust (17). Our view is that mafic cumulates combine dense immiscible sulphide droplets with olivine phenocrysts, which carry bubbles, the two together locking in the He and Pb isotopic values at the time of cumulate formation and separating each from radioactive precursors; those travel with the melt. The time capsule effect is the same for both. Both sulphides and gas bubbles are then readily incorporated into later, often times much later, magmas that pass as dikes or dikelets through the cumulates, and those impart their He and Pb signatures to them.

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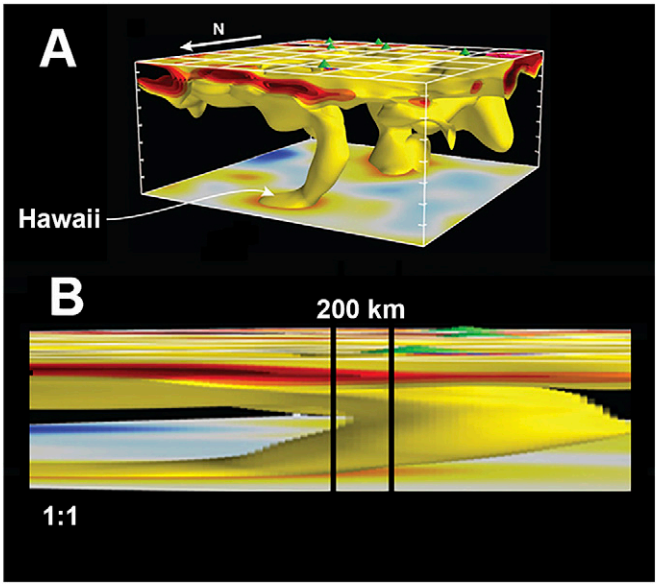

Fig. S1. (*A*) 3D perspective of seismic model SEMum2, a shear-velocity structure beneath the Pacific, showing the updraft beneath Hawaii from the northwest. Low-velocity regions are yellow-orange. Minimum and maximum isosurface levels are −3% and 1%, respectively. See caption to figure 4 in ref. 1 for details. (*B*) Portion showing the Hawaiian low-velocity region with no vertical exaggeration. The vertical lines span ∼200 km, which is the nominal minimum width of a mantle-plume conduit (2, 3). Adapted from ref. 1; reprinted with permission from AAAS.

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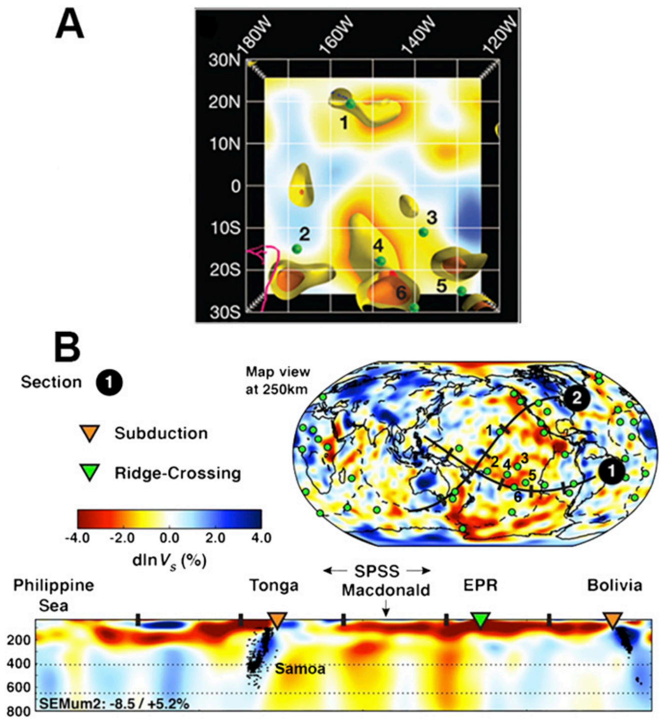

Fig. S2. (*A*) Map view of low velocity regions (yellow-orange) centered on the Pacific Ocean, model SEMum2, and (*B*) horizontal profile along path 1. In *A*, low-velocity fingers project away from the East Pacific Rise in the general direction of Pacific Plate motion. In *B*, the profile shows cross sections of three low-velocity regions in the Pacific between the East Pacific Rise and Tonga Trench. Projected epicenters of seismicity west of the Tonga Trench are indicated by black dots. Adapted from ref. 1; reprinted with permission from AAAS.

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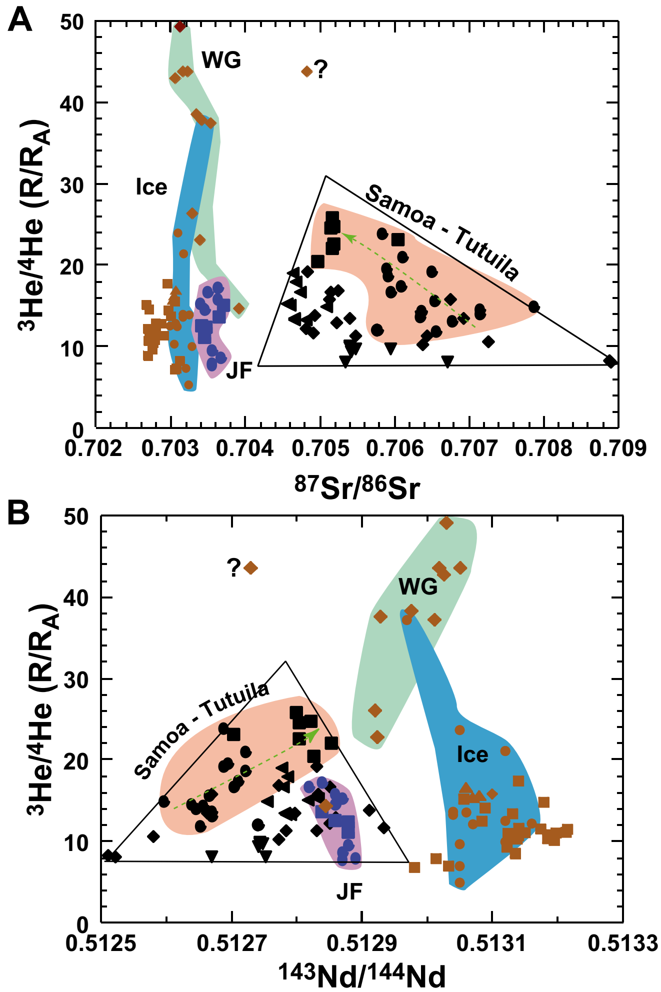

Fig. S3. $^{3}He/^{4}He$ (R/Ra) vs. (*A*) $^{87}Sr/^{86}Sr$ and (*B*) $^{143}Nd/^{144}Nd$ for Samoa, Juan Fernandez Islands (JF); Iceland (ICE); West Greenland (WG); and Hawaii (orange squares). Data sources are 1–7. The overall range indicates three principal end components: depleted MORB mantle (lower left in *A* and lower right in *B*); depleted but old MORB-like mantle (highest West Greenland), and Samoan EM 2 (lower right in *A* and lower left in *B*). Colored fields are probable mixing trends. The data spread demonstrates the unique isotopic characteristics of each volcano. The trends do not imply that the high $^{3}He/^{4}He$ components are high in 3He. Similar trends occur for He vs. Pb and Os isotopes.

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