Mantle updrafts and mechanisms of oceanic volcanism

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Convection in an isolated planet is characterized by narrow downwellings and broad updrafts—consequences of Archimedes' principle, the cooling required by the second law of thermodynamics, and the effect of compression on material properties. A mature cooling planet with a conductive low-viscosity core develops a thick insulating surface boundary layer with a thermal maximum, a subadiabatic interior, and a cooling highly conductive but thin boundary layer above the core. Parts of the surface layer sink into the interior, displacing older, colder material, which is entrained by spreading ridges. Magma characteristics of intraplate volcanoes are derived from within the upper boundary layer. Upper mantle features revealed by seismic tomography and that are apparently related to surface volcanoes are intrinsically broad and are not due to unresolved narrow jets. Their morphology, aspect ratio, inferred ascent rate, and temperature show that they are passively responding to downward fluxes, as appropriate for a cooling planet that is losing more heat through its surface than is being provided from its core or from radioactive heating. Response to doward flux is the inverse of the heat-pipe/mantle-plume mode of planetary cooling. Shear-driven melt extraction from the surface boundary layer explains volcanic provinces such as Yellowstone, Hawaii, and Samoa. Passive upwellings from deeper in the upper mantle feed ridges and near-ridge hotspots, and others interact with the sheared and metasomatized surface layer. Normal plate tectonic processes are responsible both for plate boundary and intraplate swells and volcanism.

mantle convection | geochemistry

Recent papers dealing with seismic tomography of the Earth's interior (1–3) confirm earlier studies that showed that broad upwellings, or updrafts, rather than narrow pipes, underlie or run parallel to linear volcanic chains (4–6). These wide features would have to be due to unresolved narrow (<200 km diameter) conduits if there is any validity to the mantle plume hypothesis. In addition, these hypothetical narrow conduits would have to be significantly hotter, and to be ascending at significantly greater rates, than inferred from tomographic and tectonic features and mass balance calculations. That such narrow features have not been detected is almost certainly because they do not exist and not because of poor resolution. That they do not exist can be argued from general geophysical principles, which we propose to do in this contribution. Those principles were established before plumes became the favored hypothesis of many Earth scientists for midplate volcanism. Geochemists especially did not take physical considerations into account in the formulation of their reservoir, marble cake, and whole-mantle convection models. Before considering the implications of the current tomographic state of the art, we shall briefly explain how these stark differences in opinion came about.

In 1952, two influential but diametrically opposite views of the origin, evolution, and structure of the Earth were published* (7, 8). The first was based on classical physics, thermodynamics, and seismology (9–12), and the second was based on meteorites, observations of lunar and planetary surfaces, a belief that planets accreted slowly, and that primordial objects survive in the solar system.

From the first perspective, thermodynamics and mass balance require that the Earth's interior, including the core–mantle boundary, be cooling and that displaced material rises passively to replace the cold, dense, convectively unstable parts of the surface layer that sink back into the interior (Archimedes' principle). Buoyant differentiated material, the dross that collects at the surface, becomes unstable as it cools and/or undergoes phase changes such as basalt-eclogite. Residual refractory material, the result of radial zone refining during accretion, forms the intrinsically dense lower mantle. The effects of cooling and pressure results in irreversible stratification (13). The net result of density sorting during high-temperature accretion and during subsequent cooling (e.g., delamination, crustal foundering, recycling) is a concentrically zoned differentiated planet (14) with a chemically stratified mantle and subadiabatic thermal gradients between boundary layers. Buoyant material in the outer reaches of the planet includes volatiles, magma, and refractory olivine-rich harzburgite. The Earth overall is stably stratified, with the densest and most refractory material at the base of the silicate shell and the lightest and most volatile material in the crust and exosphere. Core formation occurred early (9, 15), producing heat that dissipated over time. Radioactive elements were concentrated in the crust and uppermost mantle (7, 13) at that time. The entire planet cooled substantially from its initial state and is still cooling; heat is being lost from the core because of mantle cooling.

From the second, quite different, perspective, the concepts of primordial matter and slow accretion of the planets, with long drawn-out periods of crustal, core, and atmospheric growth (8, 16), strongly influence modern canonical models of geochemistry. In

Significance

Lord Kelvin's name is associated with the laws of thermodynamics and the cooling Earth hypothesis. The widely accepted mantle plume conjecture has been justified by experiments and calculations that violate the laws of thermodynamics for an isolated cooling planet. Hotspots such as Hawaii, Samoa, Iceland, and Yellowstone are due to a thermal bump in the shallow mantle, a consequence of the cooling of the Earth. They are not due to ∼100- to 200-km-wide tubes extending upward from fixed points near the Earth's core. Seismic imaging shows that features associated with hotspots are thousands of kilometers across, and inferred ascent rates are low. Plate tectonic-induced updrafts and a cooling planet explain hotspots and the volcanoes at oceanic ridges.

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*Classic but often overlooked papers by Francis Birch, J. Tuzo Wilson, Paul Gast, Mitsunobu "Tats" Tatsumoto, Walter Elsasser, Harry Hess, Norman Bowen, and Ted Ringwood contain many of the elements of the present paper. The novel results, to some, that the source for midocean ridge basalts is deep, that most of the radioactivity is in the crust and upper mantle, that most of the mantle is subadiabatic, that the mantle is chemically stratified, and that the mantle and the core–mantle boundary are cooling, have not yet been incorporated by geodynamicists into self-consistent, self-organized models of mantle flow, and these venerable ideas may continue to be overlooked or resisted.

this view, the mantle starts out cold, undegassed and homogeneous, and the interior maintains an adiabatic gradient, appropriate for an originally isothermal, homogeneous, self-compressed sphere, or a vigorously convecting one. Subsequent geochemical and geodynamic modeling adopted these assumptions and further assumed that radioactivity is either uniformly distributed or concentrated in the deep mantle and that the interface between the mantle and the core is maintained at constant temperature. Early geochemical models adopted a primordial, undegassed, deep-mantle reservoir and a depleted upper mantle reservoir from which the crust has been continuously and irreversibly extracted over time. Current geochemical models, influenced by early tomographic pictures, involve one-layer convection, crustal recycling to the core–mantle boundary, and remixing with more primitive less-degassed material in a basal mélange (17). Homogeneity—a key assumption—is maintained by vigorous convection. Enriched primordial plumes are extracted at hotspots, and the voluminous basalts erupted at midocean ridges are the depleted residues.

Whole-mantle, or one-layer, convection (implying vigorous convection at high Rayleigh number), a constant temperature core–mantle boundary (CMB), uniform internal heating (or deep U-rich layers), and adiabatic geotherms are elements of current geochemical and geodynamic models. Vigorous convective stirring with extraction of enriched plumes is the usual explanation for what is perceived as extreme homogeneity of midocean ridge basalts (MORB). The deeper reaches of the mantle provide primitive (e.g., primordial) components to intraplate magmas via narrow conduits. An interesting premise of some geochemical models is that the equivalent of all heat generated in the interior by radioactive decay is simultaneously lost at the surface, i.e., heat production equals heat flow. It is assumed that the mantle cools by whole-mantle convection and that the core cools primarily by extraction of heat through narrow heat pipes to the surface. These models are known for mass–balance and energy–balance anomalies, i.e., the helium, helium heatflow, and Pb paradoxes, and the necessity for "stealth" or hidden reservoirs. When analyzed in detail, they also violate the first and second laws of thermodynamics because they require noncooling boundaries and external sources of energy, material, and information (e.g., Maxwell demons); that is, the model planets are not closed, isolated, self-organizing systems living off of their own resources (13, 18, 19).

Gravity and seismic data show that the mantle is characterized by large-scale structures arranged in a shell-like fashion about a central core; a layered planet and large-scale features are consistent with expectations from fluid dynamics, secular cooling, internal heating, and compression (12–14). Surface plates, their motions, and their return to the mantle via subduction are imposed on this first-order structure, and these control mantle dynamics and heterogeneity. Ultimately, it is the cooling of the Earth, modulated by internal heating, that provides the energy for convection. The scale of convection and the sizes of plates are controlled by fluid-dynamic, solid-state, and other scaling parameters (Rayleigh, Prandtl, and Grüneisen-like numbers), dimensions of the planet and continents, and thicknesses of various layers. Classical and self-consistent theories of mantle physics (7, 9–15, 17) take into account energetics, scaling relations, thermal history, and the effects of compression on material properties and of stress on surface volcanism. A cooling mantle and core are implied. Accretion of the Earth resulted in high initial temperatures, degassing, and radial zone refining (RAZOR), with radioactive and crustal elements being sweated out to the shallowest levels of the planet (7, 20, 21). During accretion, and for a short while afterward, a heat pipe, or plume-like mechanism, removed accretion superheat from the deep interior (22).

An isolated planet, with no external inputs of energy or matter after its accretion, continues to cool gradually with time via narrow cold downwelling and broadly distributed passive updrafts (Fig. 1). Compression, internal heating, and a strong long-lived surface layer, some of which survive today as Archaean cratons, reinforced these characteristics. Other parts of the thick surface boundary layer are also buoyant and strong and can retain ancient components. The Earth eventually settled into a plate tectonic mode of convection in which stress and strength are important parameters (18, 21).

In fluid dynamic models of mantle dynamics, viscosity and temperature are the primary parameters; plate tectonics is sometimes imposed as a boundary condition. Steady-state simulations that have been used to support heat pipe, bottom-up, and whole-mantle convection hypotheses for the modern Earth also impose constant temperature at the CMB (region D″, the basal mélange) and use external sources of energy or fluid to keep it that way. Classical thermodynamics and physics, however, insist that the core does not act as a constant temperature heat source for the mantle; on the contrary, the cooling mantle is what allows the core to cool (13, 23) and causes features at the free-slip boundary to migrate freely (24); the temperatures and features at the CMB cannot be constant in time. The crystallizing inner core and the cooling outer core, consequences of mantle cooling, provide the energy for the magnetic field, but they do not drive mantle convection (23). The high conductivity at high compression, the partitioning of iron into iron-rich and iron-free minerals, radiative conductivity, small-scale convection, melting, and increase of the D″ surface area by crenulation may all be involved in facilitating heat removal from the core.

Top-Down Tectonics

What now? Wide low-wavespeed features (3–5) beneath or adjacent to regions once hypothesized to harbor narrow plume conduits are now unequivocally broad rather than smeared out, unresolved narrow features (1, 2). Some early studies (25, 26), using near-vertical rays, mapped broad near-vertical low-velocity regions, but these were nevertheless interpreted as "mantle plumes." All of these features are so large that they must be passively rising rather than ascending rapidly due to focused excess

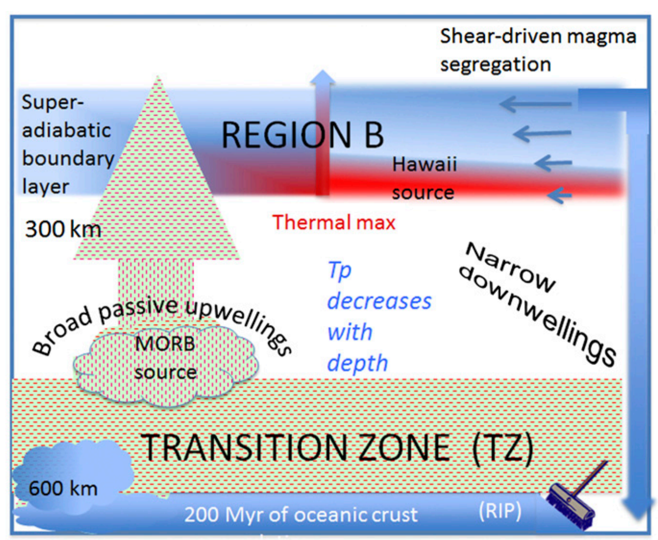

Fig. 1. The plate tectonic cycle in a mantle that is internally heated and cooling with time. Convection is composed of narrow downwellings and broad upwellings, the precise opposite of assumptions in the mantle plume and geochemical models. Region B is a sheared conductive BL with a superadiabatic thermal gradient and decreasing seismic wavespeeds with depth. Most of the underlying mantle has a subadiabatic gradient, giving high positive wavespeed gradients. Cold upwellings, triggered by spreading and subduction, can originate in the transition region because of the subadiabatic nature of the geotherm and the cooling effect of slab trapping in the transition region. The slab flux into the mantle is balanced by about 20 broad updrafts.

thermal buoyancy. Elevated ridges and associated volcanism can result from passive updrafts that are a response to the subduction of plates and the stoping and migration of continents (Fig. 2). A combination of geophysics, thermal history, and now, high-resolution quantitative seismology favor the classical physics, preplume, view of mantle evolution, dynamics, and magmatism (9–15, 21). The Earth had a hot origin, and it subsequently cooled and differentiated; crustal formation and degassing occurred, and a mantle developed with radial subdivisions. In contrast to some early views (8, 16), however, physical considerations point toward the core, the proto-crustal and enriched reservoirs, the depleted reservoirs, both barren and fertile, and boundary layers being formed early in Earth's history (13). In contrast to impressions gained from numerous 2D studies and illustrations, the features under ridges are not sheet-like. The inferred 3D upwellings beneath ridges indicate an ultimately deeper origin for the sources (not the same as average depth of partial melting) of midocean ridge basalts (MORB) than for ocean-island basalts (OIB) and important roles for pressure, subadiabaticity, recycling, and insulation by large plates. Radioactive elements and crustal elements such as Ca and Al are concentrated in the outer shells, a result of radial zone refining (7, 9, 13, 27, 28) during accretion. Some ancient materials have existed near the surface for billions of years (29). This region, of course, is the coldest, strongest, and most buoyant part of the Earth, and only part of it recycles into the mantle. In this respect, as in many others, the Earth does not behave as a homogeneous fluid sphere.

Our intention here is to emphasize anew the picture of the Earth developed by classical geophysics (7, 9–12, 15, 30) and to show that the recent advances in seismic tomography add considerable substance to this endeavor. The plume hypothesis, some assumptions of which were just summarized and on which so much of mantle geodynamics has rested for more than 40 y, is essentially undone by these developments. It is time to reconsider the framework for convective processes in the Earth and begin to set the ship aright. The view that emerges is essentially the inverse of current conventional wisdom; the mantle is driven by a thick, mobile, surface boundary layer and narrow dense downwellings that are balanced by passive, or slowly rising distributed updrafts (Fig. 1). The energy source is secular cooling modulated by inhomogeneous internal heating and variable surface insulation. Internal boundary layers are the results of mantle differentiation and cooling; they are not independent heat sources.

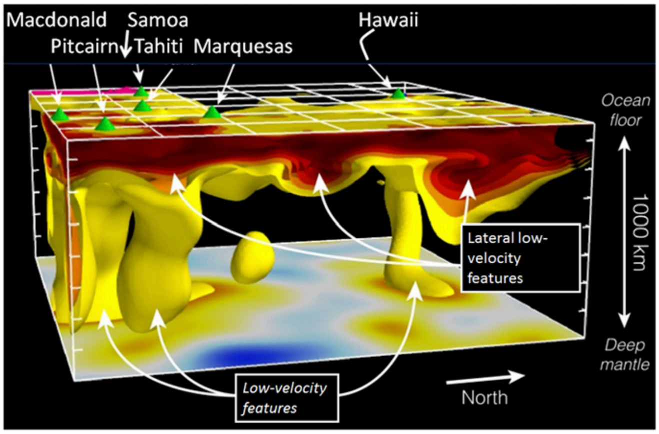

Fig. 2. A 3D perspective of seismic model SEMum2, shear-velocity structure of the upper mantle beneath a portion the Pacific, viewed from the southeast. Low-velocity regions are yellow-orange. Active ends of linear volcanic chains at the surface are green triangles. Active ends of linear volcanic chains at the surface are green triangles. Active ends of linear volcanic chains at the surface are green triangles. Minimum and maximum isosurface levels are −3% and 1%, respectively. See caption to figure 4 in ref. 2 for details. The view shows several low-velocity features extending from 1,000 km in the mantle toward the surface, converging on widespread regions of least velocity (dark red) distributed beneath the lithospheric lid, and comprising the widespread low-velocity region beneath the Pacific plate. The low-velocity features broaden into wide pedestals at 1,000 km (the lower mantle). Adapted from ref. 2; reprinted with permission from AAAS.

Tomographic Images

Most tomographic studies (predominately relative teleseismic travel-time tomography) subtract out a background model and display only differences in shear velocity (Vs) from a reference 1D model. It is the background model—the absolute wavespeeds and gradients—that contain information about layered convection and subadiabaticity, but relative wavespeed teleseismic tomography can constrain lateral dimensions. Results of this crude kind of imaging are presented as false-color cross sections, usually displayed with large vertical exaggerations. The resolved low wavespeed features are actually very broad. The East Pacific Rise and several other near-ridge regions have particularly low wavespeeds and broader and deeper anomalies than occur under most regions defined as hotspots (1, 2, 5). Several midplate regions are also underlain by broad and deep low-Vs columnar anomalies. Higher-resolution studies confirmed the great width of these features and revealed elongate bands or fingers of low shear velocity that trend in the general direction of volcanic chains (2), which are usually taken as the direction of plate motion over fixed points in the mantle (absolute plate motions). Some portions of the elongate bands link to deeper roots broadly parallel to Samoa, Pitcairn, Hawaii, and the Macdonald/Society chains (4). These roots, interpreted here as passive updrafts, are 1,000–3,000 km in lateral dimensions, including the one related to Hawaii, although it is offset at depth (2, 4, 26, 31). Similar anomalies occur in the North Atlantic. The columns (more like squat domes when plotted with no vertical exaggeration; Fig. 3) have been described as "low-velocity, plume-like features, which appear rooted in the lower mantle," but they are clearly much larger than the narrow conduits of conventional plume theory. These postulated updrafts are wider than they are tall, even the one attributed to Hawaii. The vertical exaggeration in plume-like images is often ∼10:1 (2). These are not minor issues because the characteristics of inferred updrafts in the mantle are what would be inferred from normal mantle convection and from passive or nearly passive upwellings driven by internal heating, secular cooling, and subduction rather than by heating from below.

Whether updrafts are rooted in the lower mantle is not resolved by these data, or, indeed, by any tomographic study that is subject to vertical smearing. Studies that include surface waves and types of data other than near-vertical relative travel times do not produce plume-like or deep slab-like features (4, 18, and references therein). Are the relatively low-velocity regions in the vicinity of Tonga-Fiji-Samoa produced by warmer material buoyantly rising from the deep mantle (a mantle plume) or are they passive updrafts, consequences of displacement of mantle material by, or volatile release from, the Pacific slab (32) at this location where the plate–arc convergence rate is highest in the world (33, 34)? The Samoan islands and other "hotspot tracks" are close to but not centered on the inferred updrafts (2, 4, 31).

The argument for narrow hot conduits beneath surface volcanoes thus becomes one of supposing that unresolved narrow pipes exist below, within or above the wide resolved images (35, 36). Such features have often been inferred (35–38) but are, thus far, not detected, and it is questionable whether conduits as narrow as 100–200 km can even be resolved (1). Resolvable mantle anomalies, aside from slabs, are now confirmed to be broad and are not simply unresolved or smeared out narrow conduits. Others anomalies are disconnected irregular fragments that bleed into one another in low-resolution studies. In any case, nothing links them

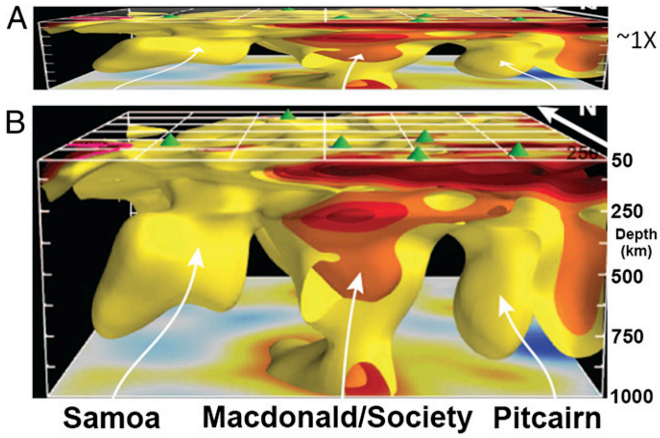

Fig. 3. A 3D perspective of seismic model SEMum2, shear-velocity structure of the upper mantle from 1,000 to 50 km beneath a portion the Pacific, viewed from the south. Low-velocity regions are yellow-orange. Minimum and maximum isosurface levels are −3% and 1%, respectively. Active ends of linear volcanic chains at the surface are green triangles. See caption to figure 4 in ref. 2 for details. The view shows wide regions of low velocity reaching to 1,000 km beneath several linear island chains. (*A*) Profile with no vertical exaggeration. (*B*) Details of the structures are revealed at ∼10:1, but they cannot be construed as narrow (∼200 km diameter) plume conduits. Shearing by plate motion concentrates melt into shear gashes and dilatancy structure beneath a relatively impermeable lid (the plate), giving especially low velocities (red) near the tops of these structures, and may drag chemical heterogeneity from one to the other. Adapted from ref. 2; reprinted with permission from AAAS.

to the core–mantle boundary or to the large structures in the deep mantle. Volcanoes in the Pacific, including Hawaii, appear to overlie neutral density ambient mantle or broad passive upper-mantle upwellings, similar to those under some ridge segments, which are best interpreted as normal results of plate tectonics (38, 39). There is no seismic evidence for secondary plumes arising from upper mantle superswells or lower mantle superplumes (35, 40, 41). Furthermore, the regions in the Pacific with the lowest wavespeeds are far from hotspots and swells and are often near plate boundaries (2, 5). The majority of hot spots occur on or near broad low-wavespeed regions associated with spreading, past and present (5), but this is expected from plate tectonics and the effects of spreading on mantle flow (42). We should now be considering their origin primarily in terms of the properties of ambient mantle or broad passive updrafts rather than hypothetical narrow and undetected hot spinoffs from them. It is significant that the so-called "plume generation zones" at the CMB fall in the band between large low- and high-wavespeed regions of the lower mantle and most actually fall in the median wavespeed area, e.g., the second quartile or no-anomaly band (36). Statistical correlations, however, are low compared with the correlation of hotspots with upper mantle low-velocity zones.

Upwelling and Downwelling: Bearing on Temperature

According to Archimedes, upwelling and downwelling are flip sides of the same coin; displacement and replacement is the key. Slabs displace mantle, which ascends, partially melts, and forms new ocean crust and lithosphere (Fig. 1). Slabs apparently bottom out in the transition zone (TZ) (43–45), and this is where passive updrafts probably originate (46). The regions above slab graveyards are fluxed with volatiles from the slabs (32), have low seismic wavespeeds, and are often geoid lows, e.g., low wavespeeds are not plume diagnostics.

The upper portions of the Earth behave like a waterbed; narrow sinkers or depressions of the surface depressions cause broad, compensating swells. This linkage is the precise opposite of the Morgan hypothesis in which narrow ascending plumes are compensated by uniform (passive) sinking of the rest of the mantle. Updrafting regions also exist beneath plate interiors because subduction zones are not uniformly distributed, ridges migrate, there is roll-back at trenches, transform faults deflect shallow mantle flow, continents collide, and arcs, orogenic belts, and delamination systems form with their own local geodynamic requirements. Lateral flow is expected to emanate from subduction zones and the margins of converging plates and to form the tops of passive upwellings. Surface material that interacted with the hydrosphere, atmosphere, and biosphere is carried into the mantle by subduction and by major stoping (47) or delamination, where it imposes lithologic, petrologic, thermal, and geochemical heterogeneity on the mantle (creating the isotopic Mantle Zoo) (48). Migrating plates, plate boundaries, including triple junctions, overrun that diversity. From a plate tectonic or top-down point of view, there is no reason to expect the shallow mantle beneath plates to be the same as under ridges or homogeneous in fertility or temperature, but these are the assumptions in canonical models of geochemistry and dynamics (19, 40).

The range of wave speeds in early tomographic models was reduced by averaging and smoothing, and this was used to argue that observed travel-time delays could not be explained by crustal and boundary layer delays alone and required deep, extended seismic anomalies; such deep anomalies are not needed. The prior interpretation, based on inadequate amplitude resolution, plus neglected upper mantle anisotropy, resulted in streaking, plume-like artifacts. The artifacts disappear in better constrained models. An excess temperature of ∼+200 K is adequate to explain wavespeed fluctuations in models that take resolution, anisotropy, volatiles, and melting into account; this value is consistent with plate tectonic processes such as large-plate insulation and slab cooling and is enough to cause shallow melting.

Maximum eruptive temperatures at subaerial Iceland volcanoes are the same as those of primitive MORB along deep portions of the Mid-Atlantic Ridge (49, 50). If inferred excess temperatures are several hundred degrees (less if there are volatiles), melting is inevitable, but melt–matrix reactions can seal off continuous permeability to the surface, and melts can be trapped in shear pockets beneath the base of the moving plate (18, 19). Besides this, the term "excess" presupposes that the subridge mantle is ambient, or normal, whereas subplate mantle, where it is sampled beneath volcanoes, is anomalous. Tomography, heat flow, and subsidence rates indicate that the hotspot mantle is actually typical for the Pacific, i.e., it is ambient mantle, and ridge mantle has a temperature deficit. Thus, lateral dimensions of inferred upwellings are thousands and not hundreds of kilometers (1–6), inferred rates of upwelling even at Iceland (51) are the same as normal plate tectonic rates (centimeters per year and not meters per year) (52–55), and inferred intraplate temperatures are not localized.

Mass balance calculations show that about 20 hypothetical (unresolved) narrow conduits (52–55) can provide much of the surface heat flow and can comprise the return flow that matches either that of diffuse sinking of the mantle or that of narrow slabs. Twenty is about that number of broad regional upwellings beneath ridges and midplate regions, and the same mass balance calculation shows that neither their average rate of ascent nor their temperatures need be extreme. Normal rates of mantle convective and plate motion fall in the range of 1–10 cm/y. High ascent speeds, on the other hand, are a unique attribute of the mantle plume hypothesis; these rates must be in the range of meters per year if the hypothesis is to be viable (52–55). Features designated as plumes in unsmoothed seismic images, in addition to being of large lateral extent, are tilted, discontinuous, and distorted (3, 31, 38), which indicates that they have either neutral buoyancy (zero ascent rate) or are passive, slowly rising features; they are not fast-rising jets that ascend vertically and independently of mantle flow because of their large excess thermal buoyancy (36, 52).

The low-wavespeed regions that may feed hotspots (and ridges) continue to be large in lateral dimensions throughout the upper mantle (2, 6, 18, and references therein). If they were much smaller,

EARTH, ATMOSPHERIC, AND PLANETARY SCIENCES there would be no correlations between backtracked hotspots and large igneous provinces or between hotspots and mantle low-velocity zones (LVZs) or conjectured plume-generation zones. Such broad features, if they are indeed rising, would ascend at speeds that are two orders of magnitude less than the ascent speeds required of narrow plumes to satisfy the various assumptions and mass-balance constraints used in the plume hypothesis. Low ascent speeds over large areas have been confirmed for the Iceland region (51, 56). We call these upwellings or updrafts to distinguish them from mantle plumes, which implies active self-driven buoyancy-driven dynamics.

Mantle temperatures derived from seismology need to be properly scaled, and the effects of seismic waves on melting need to be considered. The strengths of raw tomographic anomalies are underestimated by at least a factor of two. If these represent smeared-out 200-km-wide thermal plumes, then the actual excess temperatures are five times those estimated from petrology (1, 50), which, like the +700 °C excess calculated to be beneath Iceland, is unreasonable. The inferred dimensions, temperatures, and ascent speeds of Iceland are consistent with a deep, passive updraft. Iceland, and other anomalous ridge segments, may be rooted in the transition zone, but there is no evidence that they are rooted deeper.

Fig. 1 summarizes the various elements of the tectonic model developed from geophysical considerations by a number of investigators over the years. They have been referred to as plate, top-down, perched-eclogite, metasomatized-lithosphere, slab-splash, boundary-layer, subadiabatic, stagnant-slab, tectosphere, perisphere, laminated layers with aligned melt accumulations (LLAMA), RAZOR, depleted-plume, and chemical-plume models, and it has not been clear that they all represent elements of plate tectonics and top- and slab-driven convection with no requirement for bottom heating. It has repeatedly been stated that the key to mantle dynamics and chemistry is to be found in boundary layers, including the transition region (7, 10, 17), and that the silver bullet for proof or disproof of the plume model will be provided by seismology and not geochemistry. Seismology has indeed provided the disproof of the plume hypothesis.

Geochemical Reservoirs

In classical geophysics, accretion and core formation produced excess heat during the formation of the Earth that could not be removed by ordinary large-scale convection; concurrent fractional melting of the mantle consigned buoyant products and radioactive elements to the outer part of the planet (7, 13, 15) as incoming planetesimals were fed through the impact-heated surface layer (the furnace). Earth as a whole, including the core, is still cooling, and neither the core nor the lower mantle contain much in the way of heat-producing elements, at least compared with the crust and upper mantle fluids. The distribution of radioactive elements is inferred from heat flow, mass balance, and cosmic abundances (13). The solid inner core crystallizes and grows as heat is lost through the CMB, a consequence of the way the Earth cooled and continues to cool; the core is not an isolated, self-driven thermal engine. The lower mantle has low thermal expansivity, and is too dense, conductive, and viscous to produce, or to require, hot narrow instabilities, plume conduits, and heat pipes to short circuit the normal convective processes. The mode of flow under current deep mantle conditions is broad and dome-like (24).

Subduction-driven convection acts on the outer mantle, and there is no evidence that it penetrates deeply, or permanently, into the lower mantle, >1,000 km depth (13, 36, 43–45), or is connected to deep mantle features. Isolated high-wavespeed areas at the top of the lower mantle may be lithological or due to cooling from above. Slabs plate out in the mantle transition zone and cool off the deeper mantle by conduction (Fig. 1). Otherwise, the lower mantle is almost isolated, and everything below the transition represents dregs, the refractory residue of crustal and upper mantle extraction during accretion of the Earth. The transition region, 410–1,000 km depth (7), is a density filter, or trap, that inhibits, and likely prohibits, transfer of material between the two major mantle shells of the Earth. These shells plus their associated boundary layers account for the five mantle regions of classical seismology. Any convection or turnover of the lower mantle occurs slowly and on a very large (lower-mantle) scale. Low-velocity anomalies in the outer Earth are broad throughout the upper mantle and even broader at their detectable bases (2). Plume heads should only be broad in the upper ~200 km, where they flatten out beneath the plates. Features in high-resolution imaging of the mantle remain broad at depth and, if they are rising at all, must be doing so slowly to maintain mass balance.

If midplate regional upwellings have the same origin as those that occur beneath some spreading ridge segments, and if geochemical heterogeneities are introduced and extracted by migration of plate boundaries, then we need a shallow, top-down explanation for the composition and geochemical variability of ocean-island and seamount basalts. Broad regions of upwelling mantle are attracted to ridges (57) and are likely to have depleted, MORB-like compositions. Because internally heated mantle is characterized by subadiabatic geotherms (58) and because recycled crustal components are likely removed from slabs at relatively shallow depths, deep upwellings are relatively cold and uncontaminated by subduction debris, producing characteristics of the MORB source.

Regional intraplate updrafts probably start the same as ridge-feeding upwellings. Where then do enrichments and contaminations come from, if the rapidly circulating part of the mantle is shallow and regional upwellings are not enriched? It turns out that the MORB source material, once it rises into the shallow mantle, is not utterly depleted or homogeneous because enriched basalt (E-MORB) occurs along some spreading ridge segments, transform faults and in near-ridge seamounts. E-MORB erupts in close proximity, and probably sequentially, with otherwise depleted and sometimes very strongly depleted MORB; the mantle beneath spreading ridges therefore is clearly not uniform but has localized enriched patches, schlieren, or plums on a scale that is small with respect to axial melting domains (59, 60). Up-currents (57) at spreading ridges also tend to clean out the shallow mantle. Either the spreading process is not 100% effective in removing preexisting material from the mantle under ridges or some boundary-layer mantle and crustal material flows back in.

Having dealt with the problem of the source region of midocean ridge basalts, a problem that was considered to be solved a long time ago by assumption (18), we must now deal with the contentious issue of the source of more consistently enriched intraplate magmas. A general observation is that basalts from seamounts and islands near ridges are distinctly different from basalts that make up most of the oceanic crust (61–67), but they have only slightly enriched isotope and trace element geochemistry relative to MORB (49, 68, 69). This pattern is consistent with the great breadth of passive upwellings. Further out on the Pacific plate, distinctive magmatic and isotope lineages develop on oceanic islands that are derived from low-SiO_2 mafic parents. Magma from depths of 100 km or more produces rocks with even lower SiO_2 (62–64). With great distance and lithospheric age, basalts from oceanic islands are even more enriched and diverse (48, 49), indications of still lower fractions of partial melting. The general pattern indicates a progressive divergence from melting temperatures and compositions of basalts found along the global-ridge system and enrichment of accessible sources regions with lithospheric age. Isotopic signatures also differ in both intensity and in kind from place to place (e.g., Hawaii and Samoa are very different) and indeed differ from island to island (e.g., Samoa). This complexity is all consistent with a shallow source—a heterogenous sheared boundary layer mélange in the low-velocity region—for intraplate volcanoes.

The signal attribute of these variations is enrichment over time coupled with deepening of melt extraction as a function of crustal age. The idea that small volumes of melt are responsible for the low-velocity zone is long established (30, 69–71). Depths of melting inferred from experimental petrology are in agreement with estimated depths to the low velocity zone beneath the old ocean crust. The tricky part is to envision how small melt volumes, which erupt during later stages of volcanism at ocean islands, come to be so enriched at places like Samoa and able to erupt in considerable volume.

The answer appears to be the trapping effect of impermeable lamellae in the shear zone in and below the cold and strong lid (18, 20, 72). This trapping is intrinsic to the mélange hypothesis for the distribution of melt in the upper mantle, which has been termed LLAMA (18). This model distinguishes the entire upper 150–200 km of the mantle (region B) as a physically coherent but shearing boundary layer that is much thicker than the strong, cold lithosphere and the seismic high-velocity lid. Seismic properties of the global low-velocity zone depend on frequency and the proportion, orientation, and dimensions of localized melt-rich shear zones. A combination of downward cooling, along with porosity and grain-size reductions in sheared rocks, produces permeability barriers against which ascending melt can collect. Enrichments may also develop by a process of downward zone refining as the plates thicken (28). Where there is no plate or boundary layer, e.g., at a spreading ridge, the tops of updrafts are not significantly infiltrated with enriched melt. Progressive entrapment of enriched melts beneath a permeable lid accounts for the geochemical trends of oceanic islands as a function of distance from the ridge. Updrafts do not have to be filtered before erupting depleted magmas at spreading centers.

The most widely quoted geochemical evidence in favor of deep sources of intraplate magmas (25, 39), at least in papers written by seismologists, is the observation that the extremes of $^3He/^4He$ ratios in such magmas often exceed the average values found in MORB (after filtering or correcting for plume influence) and that high $^3He/^4He$ ratios are evidence for high intrinsic ^3He concentrations and a deep undegassed source (73, 74). The problems with these inferences are self-evident but are developed in ref. 19 and in *SI Text*. Shallow sources of ancient gases and high $^3He/^4He$ ratios are consistent with the model developed here (13). The isotopic ratios are indigenous and need not be recent imports from the deep mantle. Broad, passive upwellings tend to be very high in total helium compared with midplate volcanoes, and this overwhelms the high-$^3He/^4He$/low-He materials that may exist near ridges. This is why high $^3He/^4He$ generally occurs at midplate locations or at the onset of spreading but not in basalts at mature ridges.

Shear-Driven Melt Extraction

The thermal overshoot that characterizes thermal boundary layers (58) and the subadiabatic gradient at greater depths explain the general topology of seismic profiles with depth. Concentration of melt in the shearing region beneath plates and at the tops of the large, low-velocity regions of the upper mantle accounts for the observed minimum seismic wavespeeds in the LVZ and of the localization of volcanism (Fig. 1). The elongate arrangement of those regions in the direction of Pacific Plate motion controls the distribution and orientation of linear island chains. A combination of bending and shear stresses acting on the plate (for which Samoa may be the most obvious example), buoyancy forces of aggregated melts, magma fracture, fracture zones, and shear all cause or allow melt to leak out, with the leading edges of this activity comprising the zero-age ends of the island chains. No seismic evidence yet links even the widest and more deeply rooted low-velocity areas of the surface boundary layer to the lower mantle or the core–mantle boundary. The broad low-velocity areas under some ridge segments and midplate locations instead bottom out in the transition zone (2, 4). They have the properties of passive upwellings responding to and balancing subduction, plate motions, and continental migration at the planetary surface and are only one aspect of upwellings responsible for volcanism at spreading ridges and the formation of oceanic plates. Narrow plume conduits have neither been detected, nor do they need to be responsible for midplate volcanism. Even studies with good lateral resolution (25, 26) and ocean bottom arrays that were designed to detect narrow vertical plumes confirm the great width of the mantle features that appear to be associated with surface volcanism. In some cases, to support the plume model, the conjectured associations would require lateral flow of thousands of kilometers and in other cases would require no lateral flow and absolutely vertical ascent through the entire mantle. The more obvious associations with volcanism are with fracture zones, former plate boundaries, extensional regions of the plate, and shearing regions of the mantle.

Summary

The strictures of classical physics combined with modern seismic imaging (use of body waves, surface waves, normal models, waveforms, polarization, and absolute travel-time data) require that convective circulation in the upper mantle is plate driven and that the principal response to plate subduction and delamination is large, wide, slowly upwelling regions of mantle that occur beneath both spreading ridges and older portions of plates (Fig. 2). Broad uplifts rather than narrow conduits underlie or are adjacent to linear island chains in the Pacific (2, 4). Broad regional upwellings beneath plates imply excess temperatures that are more consistent with experimental petrology and actual eruptive temperatures of basalts than with expectations based on the temperatures required of rapidly ascending narrow plumes. Passive upwellings do not need to have thermal buoyancy, but slowly rising features will warm as they rise due to internal heating, resulting in a subadiabatic, or even negative, thermal gradient.

Plate- and slab-driven flow, plus melting that is primarily restricted to the upper mantle, requires reconsideration of the sources of both the enriched and depleted end members of oceanic basalts, with the likely implication that both sources may be ultimately and intimately comingled within the same melting domains. Such mélanges can form by shear in the thick surface boundary layer, as well as by vigorous convection in the convecting mantle and in the basal mélange next to the core. The patterns of isotopic enrichment and deepening of melt sources with plate age are consequences of plate aging, cooling, and thickening, coupled with buoyant and shear-driven migration of small and enriched partial-melt packets to permeability barriers. Aggregated small partial melts can then erupt, even in large volumes, whenever stress fractures the plate. The tilting and stretching of lamellae by shear explains the patterns of anisotropy and shear-wave splitting, which are alignments in the direction of plate motion rather than in the radial pattern predicted for a plume-like upwelling (75) or along the trends of island chains. The azimuthal dependence of surface wave velocities is controlled by melt-zone structure rather than by the orientation of olivine crystals.

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