Geological Society of America
Special Paper 388
2005

A brief history of the plume hypothesis and its competitors: Concept and controversy

Don L. Anderson
California Institute of Technology, Seismological Laboratory 252-21, Pasadena, California 92125, USA
James H. Natland
Rosenstiel School of Marine and Atmospheric Science, University of Miami,
4600 Rickenbacker Causeway, Miami, Florida 33149, USA

ABSTRACT

The modern plume hypothesis began as a concept for a special form of thermal convection in which narrow, geographically well-defined regions of upwelling are balanced by diffuse downwelling in a manner similar to atmospheric phenomena such as thunderheads (Morgan, 1972b). These narrow active upwellings were an alternative to giant convection cells (e.g., Holmes, 1929, 1944; Hess, 1962); they drove plate tectonics and fueled the asthenosphere. The number of plumes has varied from the original "~20" to recent estimates of 5200 for the number of moderate-sized plumes and 6 or so for the number of "primary" plumes; this suggests some uncertainty in what constitutes a plume. Tozer (1973) showed that what geologists had in mind for mantle upwellings could not be the same as fluid dynamic plumes and could not be explained by the same physics. The effects of pressure on material properties reinforce these conclusions. Interest in various versions of the diapir and plume hypotheses peaked in 1950, 1970, and especially 1990, but these versions fell into disfavor or disinterest in the intervening years because of various paradoxes, contradictions, and increasing interest in alternative mechanisms. The physical basis of plumes was questioned, and still is. Since 1990 specialists in diverse disciplines have adopted the plume hypothesis in spite of the various paradoxes and the still outstanding lack of a physical basis under conditions appropriate for the Earth's mantle. In this highly selective view of the history of explanations for "melting anomalies" we focus on the underlying assumptions, physics, and philosophy and on key turning points in that history. We concentrate on the anomalies, neglected physics, petrology, and deep mantle aspects rather than on the better-known tectonic, geochronological, and geochemical ones. We also discuss briefly the alternatives to the plume hypothesis.

A primary assumption of the plume hypothesis is that the mantle is to the first order composed of a homogenous lherzolite or pyrolite. Mantle homogeneity is the cornerstone of petrological models that attempt to estimate the potential temperature and magma productivity of the mantle. A general theory of plate tectonics, one that involves recycling, incipient and reactivated plate boundaries, and ephemeral plates, may

---

*E-mails: dla@gps.caltech.edu; jnatland@rsmas.miami.edu.

Anderson, D.L., and Natland, J.H., 2005, A brief history of the plume hypothesis and its competitors: Concept and controversy, *in* Foulger, G.R., Natland, J.H., Presnall, D.C., and Anderson, D.L., eds., Plates, plumes, and paradigms: Geological Society of America Special Paper 388, p. 119–145, doi: 10.1130/2005.2388(08).

remove the necessity to have different theories for plate tectonics, large igneous provinces, and linear island chains. Cooling of the mantle from above, and forces from cooling plates and subducting slabs, may be adequate to drive the plates, break the plates, close up or reactivate plate boundaries, reorganize plates, and drive underlying mantle flow. In such a scenario the mantle—variable in fertility and melting point because of recycling—is by and large passively responding to gravitationally driven motions of the top; dikes and plate boundaries are the result of variable stress in the lithosphere, and melting anomalies reflect the variable fertility of the underlying mantle.

Keywords: plumes, plates, convection, mantle, history

PROLOGUE

In an exchange with one of our reviewers, we were posed the problem of which philosophical metaphor, the oriental yin and yang, or the Hegelian dialectical syllogism—thesis-antithesis-synthesis—is more appropriate to describe the development of plume theory. We had written, "In the Chinese view, all manifestations of the Tao are generated by the dynamic interplay of two polar, opposite forces, yin and yang. These forces, one above and one below, one firm and one yielding, one full of movement and one fixed, give rise to cyclic patterns, with one replacing the other. This analogy also describes the history of ideas, with paradoxes replacing paradigms replacing paradoxes, in an endless cycle."

We viewed plume theory as arising at least in part from the need to define forces acting within the interior of the Earth to drive the motion of lithospheric plates (yang), this being opposed to ideas that external forces, those acting on the outermost shells of the Earth (yin), are sufficient to the same purpose. Our reviewer countered that the metaphor is inapt, and that instead we are dealing with the history of ideas, which can better be treated in the form of syntheses or paradigms, which, when confronted with information that they cannot explain, that is, antithesis, result in a new synthesis. Kuhn (1962) described this process as the overthrow of scientific paradigms, adding the social observation that paradigms for a time are stubbornly, even irrationally, supported by adherents of the status quo.

We consider our initial stance—that yin and yang, or external and internal forces, act to drive plate motion—is a proper metaphor to describe plume theory in the context of plate tectonics. At the time, this proposed synthesis was devised in light of the difficulties faced by large-scale ridge-centered cellular convection in splitting continents and driving motions of plates. The plume theory of Morgan (1971, 1972a,b) was thus proposed in part to maintain some version of internal forces—deep mantle plumes rather than cellular convection, that is to say, yang—in the prevailing synthesis. We are now faced with new paradoxes, so perhaps a resulting synthesis will demolish the need for yang. The reader of this volume may now judge whether we have reached such a point.

INTRODUCTION

Plate tectonics was developed during the 1960s and 1970s as a kinematic and descriptive theory that involved such idealizations as rigid (or elastic) and permanent plates, sharp plate boundaries, uniform isothermal mantle, homogeneous plates, and steady-state conditions. Diffuse plate boundaries, volcanism, and associated tectonism within plates; continental deformation; linear island chains; swells; vertical motions; and "anomalies" of melting and elevation along the global spreading ridge system were apparently not explained by the plate hypothesis, at least not by the idealized version used in developing the initial ideas about plumes. The driving forces of plate tectonics, mantle convection and seafloor spreading, were also not treated by the original theory.

The plume hypothesis (Morgan, 1971, 1972a,b) was one among several developed during the 1970s to explain the variety of volcanic phenomena on the Earth apparently not explained by plate tectonics (see www.mantleplumes.org for references). A partially molten asthenosphere versus an entirely subsolidus upper mantle in the absence of perturbations distinguished the shallow from the deep models. Plume theory emphasized fluid dynamics, active upwellings, and high temperature. The other theories emphasized lithospheric rheology, architecture, stress, shallow return flow, and passive convection, with cooling plates and slabs the active elements. In this contribution we summarize the early history and the development of key ideas for features that have been called melting anomalies, midplate volcanism, hotspots, and linear volcanic chains or hotspot tracks. We also point out the critical assumptions that at various stages have controlled thinking as much as, or more than, observation and theory.

Since ca. 1990 most workers have assumed the existence of deep mantle plumes and have either modified the basic plume hypothesis or, in the case of modelers, explored the evolution of hot buoyant blobs rather than the origin or the veracity of plumes (e.g., Sleep, 1990, 1992, 1994, 1996; Kellogg and King, 1997). These recent technical developments will not be reviewed here. Also, amendments to the plume hypothesis include a large number of ad hoc modifications, such as incubating plumes, fossil plumes, plumelets, superplumes, lateral plumes, secondary plumes, chemical plumes, radially zoned plumes, and so on. We do not consider these significant milestones in the intellectual history of the subject and they likewise are not treated. The geochronology of islands and seamounts has played an important role in the acceptance of the plume idea, but because the same data can be, and have been, used in support of other mechanisms, such as propagating fractures, membrane stresses, and sequential volcanic loading, they will likewise not be discussed. Age-progressive volcanism is not uniquely diagnostic of a plume. Clague and Dalrymple (1987, 1989), Koppers et al. (2001), and Glen (this volume) give complete reviews of these aspects of the problem. We attempt to give equal space to other ideas about the origins of volcanic chains and large igneous provinces—a throwback to the principle of multiple working hypotheses adhered to by several generations of geologists.

The idea that volcanoes at the Earth's surface are fueled by hot, narrow tubes of ascending mantle originating just above the core, 3000 km away, is truly an extraordinary one. Carl Sagan (1934–1996) reminded us repeatedly that *extraordinary claims require extraordinary evidence or extraordinary proof.* This article is about the thirty-year search for this extraordinary evidence —the smoking gun for deep mantle plumes. At various times proof of plumes was thought to be fixity of hotspots, parallelism of island chains, temperatures of magmas, heatflow around hotspots, the driving mechanism of plate tectonics, precursory uplift of large igneous provinces, chondritic (or primordial) Nd-isotopic ratios, high ^{3}He contents of magmas, and mantle tomography. At one time or another, all have been taken to support the hypothesis. Now, as it turns out, plume theorists hold to virtually none of these as definitive evidence for plumes. Some have been abandoned as criteria altogether. Instead, *combinations* of a few of these, but not necessarily any consistent set of them, are used to validate the existence and establish the type of any particular plume (e.g., Courtillot et al., 2003). This complex elaboration of the original hypothesis, and continuing difficulties with the undisputed demonstration of any part of it, signal that the concept itself is in trouble and both that it should be questioned and that its assumptions should be carefully scrutinized. Many of the contributions to this volume do this.

The plume hypothesis thus is currently subject to unusual controversy and discussion. How the hypothesis came to this point is what we wish to outline in this essay. We begin with a brief narrative history of the growth and acceptance of the plume hypothesis out of and amidst many other ideas, follow this with a section on terminology, and then present a critique in several parts that is founded on the history of the hypothesis. We conclude with a prognosis.

HISTORY OF THE PLUME CON0CEPT

Beginnings: The Great Hawaiian Fissure

The geology of a chain of volcanoes in the central Pacific spawned most of the ideas discussed here. The early Hawaiians knew the distinctive northwest-southeast alignment of the Hawaiian chain and knew that the goddess Pele lived in the active volcanoes of the southeastern island of Hawaii. They recognized that the islands are progressively younger from the northwest to the southeast (Westervelt, 1963; Vitaliano, 1973). Charles Darwin noted in 1837 that volcanic islands grouped in island chains go through changes, progressing from younger, volcanically active and reefless formations to older, inactive volcanic stumps first ringed and then capped with coral atolls. The first geologic study of the Hawaiian Islands (1840–1841) was conducted during the U.S. Exploring Expedition by James Dwight Dana, who deduced that the islands are younger to the southeast from the differences in their degree of erosion and the distance of eroded volcanic remnants from offshore reefs (Dana, 1849). He also suggested that other island chains in the Pacific showed a similar general decrease in age from northwest to southeast. The alignment of the Hawaiian Islands, Dana proposed, reflected localized volcanic activity along segments of a major fissure zone on the ocean floor. The fissure was produced by simple cooling, thence shrinkage of the Earth, the shrinkage being necessarily greater at the planet's surface. Island chains in the Pacific are parallel because that is the pattern of shrinkage cracks on a sphere. Dana's "great fissure" origin for the islands served as a working hypothesis for many subsequent studies.

The Hawaiian Islands subsequently played a special role in the development of hypotheses for age-progressive volcanic chains. These hypotheses include fixed mantle hotspots, propagating cracks, membrane tectonics of a thin lithospheric shell on a nonspherical Earth, self-perpetuating volcanic chains, ascent of reheated slabs, and reactivation of weak zones or previous plate boundaries. Concepts such as hotspot fixity, parallelism of island chains, asthenospheric bumps, and shear melting were also developed in attempts to explain Hawaiian and other volcanoes. The Hawaiian chain is usually linked with the Emperor seamount chain, although the two may have independent origins; they are separated by the giant Mendocino fracture zone and have quite different trends, volcanic output, and morphology. In the plume hypothesis the differing trends of the two chains represent a change in plate motion. In other hypotheses cracks, preexisting seafloor fabric, variable fertility of the mantle, lithospheric architecture, and changes in stress cause changes in trend and productivity of volcanic features.

Early Precognition: Diapirs

Prior to the ideas of lateral mobilism—drift, seafloor spreading, and plate tectonics—geologists tended to be stablists, permanentists, contractionists, or expansionists. The earliest development of structural and tectonic ideas pertinent to plumes probably came from extending the mechanics of emplacement of salt domes, first described by several workers in the early years of the twentieth century, to aspects of orogeny in the laboratory experiments of D.T. Griggs (1939; see discussion of Glen, this volume). Just before the time that the idea of plate tectonics was being developed in the west, V.V. Beloussov in Russia was formulating his theory of vertical tectonics, or mantle diapirism, in order to explain continental geology. His text, published in 1956 in Russian, was translated into English in 1962, the year of publication of Hess's enunciation of seafloor spreading (Hess, 1962). Beloussov described a vertical tectonic undulation theory as an alternative to concepts of horizontal mobility implied by continental drift, which later was transformed into plate tectonics. Much as in a lava lamp, material in the interior heats and rises, then cools and sinks. Chemical and phase change buoyancies were important, and the buoyancy was not entirely created by high-temperature thermal expansion. Floating icebergs (phase changes) and rising salt domes (chemical plumes) are examples of what Beloussov had in mind. Horizontal motions were minimal and were essentially limited to gravity-induced sliding of material from the top of the upwellings. Beloussov considered the mantle to be gravitationally stratified and vertical tectonics to be the main form of convection. In his view, as the Earth formed the lower mantle expelled the light materials upward to form the crust and upper mantle, and dense materials sank downward to form the core. In other words, the Earth and the mantle are chemically stratified. Diapirs from upper-mantle layers were responsible for swells, folded mountain belts, and rifts.

Beloussov (1956/1962) considered mantle diapirism the alternative to continental drift; he thought that it was required in order to form mountain belts and rift plateaus. Plumes are currently being used in a similar way to rationalize features that are not readily explained by simple rigid plate tectonics and horizontal motions. Adherents of plate tectonics rapidly shunted aside Beloussov's ideas of vertical tectonics, deep diapirs, and plumes, but, phoenixlike, his ideas have had several rebirths. The domes and vertical tectonics of Beloussov's anti–plate tectonic theory have become the swells, superswells, and continental uplifts of current plume scenarios. Lateral flow of the asthenosphere was a dominant feature of early models of plate tectonics (e.g., Elsasser, 1969; Jacoby, 1970) and is implicit in plate tectonic models with shallow return flow. Large-scale shallow lateral transport of material from plumes to spreading ridges and continental interiors is now an amendment to the hypothesis of deep vertical plumes, but such lateral flow is not intrinsic to the hypothesis. Plumes and diapirs were an alternative to the giant convection cells of Holmes (1929, 1944, 1965). Large-scale features of the lower mantle are consistent with the large convective features of Holmes but have unfortunately and misleadingly been labeled "superplumes"—an oxymoron—by plume advocates.

Hans Ramberg (1967a,b, 1970, 1981) developed Beloussov's idea with properly scaled laboratory and centrifuge experiments and showed that low-density layers at depth would form mushroom-shaped diapirs as they rose. Ramberg (1981) considered that *plume* as used in the geophysics literature was the same as *diapir* of structural and upper-mantle geology, citing, e.g., Anderson (1975). His results were similar to those of the injection experiments years later by Campbell and Griffiths (1990, 1993), which reinvigorated the mantle plume hypothesis. Ramberg also reproduced many elements of continental geology. He was one of the pioneers in scaled models. He attempted to scale gravity, material properties, stress, and time so that his results could be applied to the Earth. Scaling relations are very important in geodynamic modeling and convection simulations, but they are often ignored. The effect of pressure on material properties is difficult to scale; it is not and cannot be treated in laboratory experiments, and it is usually left out of computer simulations of mantle convection. The pressures at the base of the mantle are enormous (1.4 million atmospheres, 1.4 megabar or 200 times the pressure at the base of the continental crust); the physics of high pressure indicates that deep convection must be extremely sluggish and that only enormous features can carry significant buoyancy (e.g., Birch, 1952; Tackley, 1998). Laboratory and computer models that ignore these scaling relations cannot be applied to conditions in the mantle.

Wilson (1963) suggested that the time-progressive volcanism along the Hawaiian chain could be explained by the lithosphere's moving across a "jetstream of lava" situated in the mantle under the island of Hawaii. This suggestion revived Beloussov's theory of mantle diapirism from the asthenosphere. Wilson thought the deep mantle was rigid and nonconvecting, so his fixed reference point was the top of the lower mantle. Many or all hotspots occur in extensional regions of the lithosphere, at either plate boundaries or intraplate boundaries (e.g., Afar, the Azores, Tristan). Wilson (1963) noted that many hotspots were on mid-ocean ridges. He even suggested that such locations were perhaps responsible for the apparent fixity of hotspots. Morgan (1971, 1972a,b) argued that plumes were the main mode of mantle convection and that they kept the ridges open. He argued that plumes were a separate form of convection and that they are independent of plate tectonics and normal mantle convection. Still later authors assumed that plumes are so weak that they can easily be swept around in the mantle wind (e.g., Steinberger and O'Connell, 2000). These views of plumes (weak plumes, lateral plumes, superplumes) are mutually contradictory; they are, in effect, different theories. The common elements in the various plume models are high temperature and origin in a deep thermal boundary layer.

The Role of Petrology: Homogeneity or Heterogeneity of the Mantle?

A concept with its roots in the halcyon days of igneous petrology has factored strongly into arguments on behalf of the plume hypothesis. It is that with respect to basic lithology the mantle sources of basalt are a nearly homogeneous, globally distributed peridotite. Of course everyone understands that this cannot really be the case. Nevertheless, mantle homogeneity is a premise in a number of models of partial melting of the mantle that attempt to simulate the production of mid-ocean ridge basalts

(MORB) and ocean island basalts and from which one may infer both melt volumes and temperatures at the source.

The idea probably originated with Daly's (1914, 1933/1962) demonstration that basalt is present and usually abundant in all igneous associations and that there is no essential difference in the composition of basalt in those provinces. Daly concluded that basalt is ubiquitous in time and space. Bowen (1928) described Daly's result as "evidently satisfactory" (p. 5), and pursued the argument that basalt is the one fundamental primary magma at the head of all major magmatic lineages, as he had originally proposed some years earlier (Bowen, 1915a,b). These experience crystallization differentiation and reaction with other rocks, leading to granitic (i.e., rhyolitic), trachytic, and phonolitic residua in orogenic and rift provinces. Turning to the origin of basalt, Bowen noted the evidence from geophysics for the high density of rocks of the uppermost mantle, and the assumption of Washington (1925) that achondritic meteorites, which are ultrabasic in composition, are comparable in composition to the Earth's mantle, and then proposed that basalt derives from partial melting of peridotite. Daly (1914, 1933/1962), on the other hand, citing the huge volume of basalt in some provinces and its presence in all, drew on earlier speculation about the shell-like structure of the Earth to propose that the outermost crustal shells of the Earth are underlain by a vitreous basaltic substratum from which any volume of basalt could be extracted under suitable circumstances. The problem persists today in the questions of how to produce crust along almost any region undergoing sustained extension, and why along the Mid-Atlantic Ridge the crust varies in thickness by a factor of four (e.g., Foulger et al., this volume). Does the nearly homogeneous and isothermal mantle convect more vigorously beneath Iceland (a proposed plume), or is there something extra in its composition beneath Iceland that adds to the volume of melt without unusual heat or mantle turnover?

Although the vitreous substratum has passed out of consideration as a general source for basalt, the idea has its parallel today in suggestions that some fraction of melt is generally present in a low-velocity layer beneath the moving lithospheric plates (e.g., Anderson and Spetzler, 1970; Lambert and Wyllie, 1970; Eggler, 1976; Presnall and Gudfinnsson, this volume). Bowen's general scheme relating all differentiates to a common parental basalt began to fall from favor when Kennedy (1933), following the concept of magma type outlined in the Mull Memoir (Bailey et al., 1924), presented strong arguments that basalt itself consists of two general types, tholeiitic and alkalic, with their global distribution suggesting derivation from different shells, respectively shallow and deep, within the upper mantle. This notion, too, holds over in the idea that the enriched components of basalt, particularly alkalic basalt, come from underneath the shallow MORB reservoir, indeed potentially from just above the core-mantle boundary. Continental contamination and wall-rock reaction were early concepts for "enriched magmas" that also have their counterparts today.

By 1970 experimental petrology had also forged a general consensus that, whereas tholeiitic basalt is generally a product of fairly shallow partial melting in the mantle, alkalic basalt and even more strongly silica-undersaturated basanites and olivine nephelinites likely originate at depths greater than most tholeiites, that is, no shallower than 70–100 km (e.g., Yoder and Tilley, 1962; Green and Ringwood, 1967; Ito and Kennedy, 1968; O'Hara, 1968). Although Yoder and Tilley (1962) found that ultramafic, eclogitic, and amphibolitic rocks could all be partially or largely melted to produce basaltic magmas, all investigators, essentially following Bowen, favored a mainly lherzolitic source for all basalt types (see Yoder, 1976). Green and Ringwood (1967) hypothesized a fertile mantle source, one not represented in xenolith suites or what we would today recognize in ophiolites or Alpine peridotites, by proposing the existence of pyrolite, a deliberately and carefully contrived composition that combined one part of Hawaiian tholeiite, the material extracted from the mantle, with four parts of an average of several Alpine peridotites, the material presumed to be left behind after the extraction. This, they proposed, best matched the general requirements of composition of both basaltic magmas and natural ultramafic rocks, interpreted as partial melting residues, and of their volume relationships during partial melting. Ringwood (1975) went further and proposed that pyrolite represented the composition of *the entire mantle.* The concept of a single basaltic parental magma thus was transformed into the idea that a lherzolitic mantle source of single composition is what all basalts have in common. Ironically, today we recognize that the Alpine peridotites are the residues of partial melting of abyssal tholeiites at spreading ridges or beneath island arcs and that they cannot be a residue of partial melting of Hawaiian tholeiite. We also recognize that rocks rich in forsteritic olivine are buoyant compared with more iron-rich fertile mantle and primitive mantle (e.g., Jordan, 1979) and that they therefore probably occur in the shallow mantle in excess of average mantle compositions. But the general principal of basalt-peridotite melting relationships and the possibility of a common homogeneous source were established.

A surge of geochemical, especially isotopic, studies of terrestrial basalt compositions (e.g., Gast et al., 1964; Tatsumoto, 1966), coinciding approximately with the start-up of the Apollo lunar sampling program and a consequent increase in laboratory analytical capability, also accompanied the advent of seafloor spreading and the theory of plate tectonics. This unequivocally demonstrated that mantle sources of basaltic melts are far from homogeneous in composition and that they have to derive from various sources, since described as reservoirs (e.g., Allègre, 1987), of significantly different ages. Nevertheless, this did almost nothing to budge the widely held view that the basic mantle lithology, presumed to be lherzolite, was very little different in bulk composition from one place to another. The ideal of a single parental basalt composition continued to be upheld in the earliest studies of basalts from spreading ridges. "Oceanic tholeiite," said Engel et al. (1965), is a fundamental, perhaps the only, primary magma type on the face of the Earth, and the alkalic basalts of islands and seamounts in the main ocean basins are derived from them by complex processes of shallow differentiation. O'Hara's (1973) objection to Schilling's (1973a) interpretation from rare-earth elements that different mantle sources are required beneath Iceland and the southern Reykjanes ridge is fundamentally grounded in the same belief. However, geochemists have not, even today, convinced everyone of the veracity of mantle heterogeneity. And even they adopt the homogeneous upper-mantle view (that of "the convecting upper mantle"). Appeal is still made to tortuous processes that combine differentiation during episodic reinjection and tapping of magma chambers, crystallization within and melt expulsion from boundary-layer mushes, magma mixing, and assimilation of and reaction with altered lava, pelagic sediment, or old crust (cf. O'Hara and Mathews, 1981). These might yet explain all the variability in trace elements and isotope ratios and leave the ultimate mantle source of primitive basalt pristine, uncontaminated, and fundamentally homogeneous (Hamilton, 2002).

The general persuasion that the mantle is lithologically homogeneous emerges as two presumptions in the plume hypothesis: (1) that the bulk of the upper mantle is taken to be roughly isothermal (it has constant potential temperature) and (2) that it is so consistent in composition ("the convecting mantle" is geochemical jargon for what is viewed as "the homogeneous well-stirred upper mantle") that departures from the basic composition of basalts along spreading ridges and within plates *must come from somewhere else.* The only way this could happen is for narrow jets of hot, isotopically distinct (yet still mainly lherzolitic) mantle to arrive from great depths and impinge on the plates. Lithologic homogeneity of the upper mantle is thus one of the linchpins of the plume hypothesis. From this assumption, estimates of high potential temperatures and variable extents of partial melting, presumed proof of plumes, are derived.

Recently experimentalists and geochemists have begun to consider again the possible roles of garnet pyroxenite and eclogite in the mantle sources of flood basalts and the basalts of ocean islands (Yasuda et al., 1994; Hirschmann and Stolper, 1996; Lassiter and Hauri, 1998; Yaxley, 2000; Hirschmann et al., 2003; Pertermann and Hirschmann, 2003a,b). Although the distributions of these materials are most often depicted as being within (assumed) mantle plumes, the full consequences of the possibility that the shallow mantle is lithologically variable, containing materials like these with higher potential basaltic melt fractions than lherzolite, can be simply stated. Such a mantle can be more or less isothermal on a local and regional scale, yet at a given depth closer to the solidi of some of the lithologies than to others. In this situation, thick lava piles can be attributed to fertile patches in the shallow mantle that are capable of producing more than the average amount of basaltic melt through a given range of pressures and temperatures, and without great excursions in potential temperature. These erupt through weak, thin parts of the lithosphere or at places where it is under greater tension than elsewhere (e.g., Natland and Winterer, this volume), usually on or near past, present, or future lithospheric boundaries (e.g., Lundin and Doré, this volume). Thus if the upper mantle is sufficiently heterogeneous, plumes need not exist.

Plumes: From Conception to Decline (1971–1978)

The apparent fixity of volcanic islands relative to each other and the plates they were on and the near parallelism of island chains on the Pacific plate provided part of the motivation for the plume hypothesis (Morgan, 1971, 1972a,b). Additional motivations were the search for the driving mechanism for plate motions and the hope that a reference frame fixed with respect to the mantle or the rotation axis of the Earth could be demonstrated. Plate tectonics provided a kinematic description of motions of internally undeformed blocks of the Earth's surface and in itself postulated no particular dynamic mechanism to explain those motions. The existence of symmetrical, two-limbed convection cells centered beneath ridge axes, as proposed by Holmes (1928, 1944, 1965; see Fig. 1A) and Hess (1962), was a separate hypothesis that, as spreading geometries were worked out using magnetic anomalies, seemed increasingly untenable. First of all, not all ridges were "mid-ocean" ridges (e.g., Juan de Fuca ridge, Galapagos spreading center, East Pacific Rise); second, offsets at transform faults, especially the very long ones, were unlikely to mimic a symmetrical two-limbed convection pattern; third, one had to imagine such things as a symmetrically widening pattern of convection about the Africa and Antarctic plates, and in doing so face problems of both scaling and changing the scale of cell dimensions with respect to the thickness of the mantle. In the plume hypothesis, symmetrical convection beneath spreading ridges could still exist beneath ridge-centered hotspots, providing regions of uplift and even forces dragging locally in opposite directions against the undersides of plates, both of which could propel divergent plate motions. The similarity in cross-section between the original ridge-centered two-limbed convection cell proposed for seafloor spreading by Hess (1962), who was in the same department as Morgan at Princeton, and what Morgan (1972a) later proposed for plumes in the Hess Memorial Volume (Shagam et al., 1972) is striking (see Fig. 1B). Although plumes are sometimes described as independent of plate tectonics, the history shows a close relationship between plumes and ridges in the thinking of Wilson and Morgan.

Within-plate volcanic islands appeared to be melting anomalies, so the term *hotspot* was coined to explain them (Wilson, 1963), the assumption being that high absolute temperature was the controlling parameter rather than mantle fertility, focusing of magma, passive mantle heterogeneities, lithospheric stress, or high temperature relative to a potentially variable solidus. On the basis of isotopic distinctions between basalts from islands and spreading ridges (e.g., Gast et al., 1964; Tatsumoto, 1966), Morgan (1971, 1972a,b) proposed that plumes from deep primordial mantle continually supplied Hawaii and other hotspots. From rough mass balances, he then estimated that some twenty

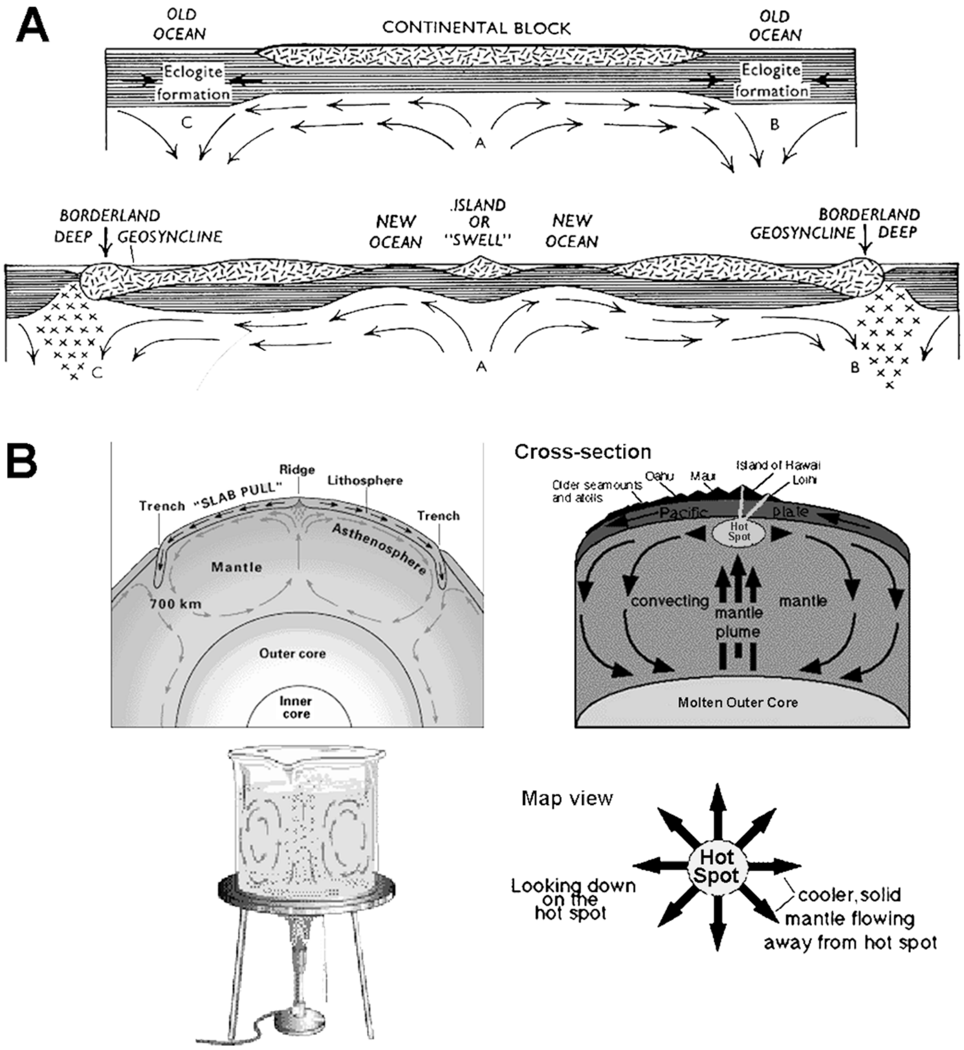

Figure 1. Concepts of mantle convection from Arthur Holmes to W. Jason Morgan. (A) Holmes's early view (1928, p. 579) of the mechanism of continental rupture and drift. The caption he wrote to accompany reproduction of the illustration in Holmes 1965 offers explanations for formation of ocean crust, flood basalts, and islands; proposes that ancient continental crust can be abandoned in the middle of ocean basins; and suggests that eclogite density contributes to downwelling portions of convection cells and that melting of recycled eclogite contributes to basaltic volcanism. We quote the caption as follows:

> Diagrams to illustrate a convective-current mechanism for "engineering" continental drift and the development of new ocean basins, proposed by the author in 1928, when it was thought that the oceanic crust was a thick continuation of the continental basaltic layer (horizontal line shading).
>
> (a) A current ascending at A spreads out laterally, extends the continental block and drags the two main parts aside, provided that the obstruction of the old ocean floor can be overcome. This is accomplished by the formation of eclogite at B and C, where sub-continental currents meet sub-oceanic currents and turn downwards. Being heavy, the eclogite is carried down, so making room for the continents to advance.
>
> (b) The foundering masses of eclogite at B and C share in the main convective circulation and, melting at depth to form basaltic magma, the material rises in ascending currents: e.g. at A, healing the gaps in the disrupted continent and forming new ocean floors (locally with a swell of old sial left behind, such as Iceland). Other smaller current systems, set going by the buoyancy of basaltic magma, ascend beneath the continents and feed great floods of plateau basalts, or beneath the "old" (Pacific) ocean floor to feed the outpourings responsible for the volcanic islands and seamounts.

(B) Modern Web site views of convective mechanisms beneath spreading ridges and hotspots. Diagram at left depicts whole-mantle two-limbed convection in relation to a spreading ridge and subduction zones on either side of an ocean basin and compares this to convection in a beaker placed over a Bunsen burner. From Kious and Tilling (1996), illustrations by Jane Russell. Diagrams at right depict (upper) an almost identical cross-sectional pattern of mantle-plume convection based on Morgan's proposal (1971, 1972a,b), rising from the core-mantle boundary to the active end of the Hawaiian linear volcanic chain, and (lower) a plan view of the possible radial pattern of convection at the level of the "hotspot" or melting region at the base of the plate. Note that the Bunsen burner analogy is more appropriate to a cylindrical mantle plume than to convection beneath spreading ridges. In the upper diagram, movement of the Pacific plate above produced older islands and seamounts. From "Hotspots and Mantle Plumes" by Steve Mattox, available at the University of North Dakota Web page "Volcano World," http://volcano.und.nodak.edu/vwdocs/vwlessons/hot_spots/introduction.html.

hotspots were underlain by deep mantle plumes; this seemed to be close to the required number if plate tectonics were driven by plumes, as outlined earlier, and if plumes were to provide, as Morgan predicted, about half of the world's heatflow. Plumes were originally considered narrow, ~200 km in diameter, but broad plume heads spreading out beneath the lithosphere have been added to the concept in order to explain large igneous provinces (LIPs). This addition is based on the behavior of injected streams of hot fluids in tanks of cold fluid (Campbell and Griffiths, 1990, 1993). Large, plate-scale tomographic features in the lower mantle have also been called plumes or superplumes (e.g., Romanowicz and Gung, 2002), but they are quite different from what Morgan visualized. They have dimensions of normal two-limbed mantle convection cells or plate-driven flow rather than the dimensions of Morgan's plumes. Although they have been introduced as modifications to the plume hypothesis, they are the very phenomena that the plume theory was originally meant to replace or augment.

Morgan's (1971, 1972a,b) conception of mantle convection involved strong, narrow, hot upwellings and broadly distributed downwellings. Morgan combined the idea of narrow stationary upwellings with moving plates. On a global scale, he proposed that plumes were the main form of mantle convection; they broke up the plates, drove them, and were responsible for sustaining spreading at mid-ocean ridges, keeping them open and replenishing the asthenosphere. The deep vertical replenishment assumed by Morgan was the alternative to the pattern of shallow return flow—return above subducting plates through the mantle wedge, and in ocean basins of low-viscosity asthenosphere to ridges—that was the leading model at the time (Elsasser, 1969; Jacoby, 1970). In Morgan's view, if the upwelling plumes were to stop, the plates would grind to a halt. If the plumes were not strong enough, the ridges would close up. Morgan made very specific predictions, and his hypothesis was elegant, testable, and possible to disprove. Among the predictions were these: that plumes bring up a large fraction of the Earth's heat and magma, that plates moving over these narrow plumes have narrow chains of time-progressive volcanism, and that plumes lift, break, and drive the plates. As in Beloussov's theory, plumes were used to explain a variety of phenomena not easily explained by plate tectonics, at least not by the rigid-plate version (with no role for incipient or reactivated plate boundaries).

The most testable and diagnostic predictions of Morgan's version of the plume hypothesis are the diffuse downflow, local and global heat fluxes, temperatures of the magmas, heatflow of the surrounding area, and heating and thinning of the lithosphere. Plumes were also considered as an alternative to plate tectonic processes such as crack propagation, self-perpetuating volcanic chains, reactivated plate boundaries, incipient plate boundaries, membrane stresses, gravitational anchors, dike propagation in rift zones, and self-propelled plates (e.g., Shaw and Jackson, 1973; Oxburgh and Turcotte, 1974; Forsyth and Uyeda, 1975; Jackson and Shaw, 1975; Jackson et al., 1975; Shaw et al., 1980; Clague and Dalrymple, 1987).

Fixity relative to one another and the underlying mantle, time-progressive and parallel volcanic tracks, and a high rate of volcanism were considered the primary characteristics of volcanic regions fueled by deep mantle plumes, even though these particular aspects can have other explanations. Tozer (1973) and Richter and Parsons (1975) immediately challenged the fluid dynamic basis of the mantle thermal plume idea. In fact, the years from 1973 to 1975 saw a large number of challenges to the hypothesis (see *Nature,* volumes 240–244, and Cowen and Lipps, 1975). Both the physics and the observations were questioned, and alternative explanations were offered (McElhinny, 1973; O'Hara, 1973; Smith, 1973a,b,c,d, 1975; Oxburgh and Turcotte, 1974; Richter and Parsons, 1975). An important milestone was the paper by Forsyth and Uyeda (1975) that showed that gravitational and pressure forces, namely slab pull, ridge push, and slab suction, could drive the plates with no need for plumes. Subsequent studies confirmed the dominance of the slab pull force and found no evidence for a force that could be attributed to radial forces from plumes. In fact, it is still not clear whether the basal drag force is a driving force, a resisting force, or neither. Plumes have been invoked as a means of driving plates by dragging along their bases or, in contrary fashion, as lubricating the bottoms of plates in order to reduce the drag force (e.g., Schubert et al., 2001). Ironically, if lubrication is efficient and plate forces drive the plates, even shallow and passive mantle features will be relatively fixed compared to the mobile plates. The low-viscosity asthenosphere can lubricate the bases of plates even if there are no plumes.

The ideas of true polar wander, mantle roll, large radius "spots," and lateral transport became essential parts of the plume hypothesis in order to retain the idea of a fixed hotspot reference frame (Duncan et al., 1972; Hargraves and Duncan, 1973; McElhinny, 1973; Duncan and Richards, 1991). Then loci of magmatism were shown not to be stationery with respect to the rotation axis of the Earth. Shortly after this, "hotspots" were found to move with respect to each other. The plume hypothesis remained intact. Global synchronism in hotspot and arc volcanism (Vogt, 1972) was an early hint of a plate tectonic or lithospheric stress control on hotspot activity. In the years 1972–1974 there were more than 120 papers published that were motivated by the mantle plume hypothesis.

Seismologists soon reported evidence for core-mantle boundary anomalies of all kinds, one of which was thought to be the source for the Hawaiian volcanism. A series of articles (Kanasewich et al., 1972, 1973; Kanasewich and Gutowski, 1975) detailed a *high-velocity* anomaly lying in the lowermost mantle a few degrees northeast of Hawaii. A subsequent study (Nataf, 2000) attributed features found to the northwest and southeast of Hawaii to the Hawaiian plume. Wright (1975) argued that high velocities were not compatible with other observations for the same region and that the analysis was open to other interpretation. These seismologists eventually concluded that lithospheric structure beneath seismic stations in Canada explained the reported anomaly. It was also not clear how a high-velocity anomaly was "proof of a plume." This was only the first of many claims and refutations of connections between deep seismic anomalies and surface hotspots.

Best et al. (1974) delivered what at the time seemed a serious blow to the plume hypothesis. In an elegant seismic experiment they showed that the seismic velocity beneath Hawaii was not anomalous. This ruled out a large hot or partially molten region under the world's type-example hotspot. This result was confirmed by subsequent studies. The shear wave speed in the upper and middle mantle under Hawaii inferred from the arrival times of seismic waves is higher than the average for the southwestern Pacific (Katzman et al., 1998), and the propagation efficiency of shear waves is also high (Sipkin and Jordan, 1975). These parameters are sensitive to temperature and melting and argue strongly against unusually high temperatures or extensive melting in the upper or lower mantle beneath Hawaii. Finite-frequency compressional wave seismology has also failed to find a low-velocity region in the deep mantle under Hawaii; "the associated fast anomaly . . . falls somewhat short of expectations" (Montelli et al., 2004). These repeated failures to image a deep structure under the world's largest hotspot, plus the absence of a heatflow anomaly, are serious setbacks to the plume hypothesis. Hadley et al. (1976) also found a high-velocity anomaly in the transition region under Yellowstone, belying the existence there of a deep thermal plume. Other more recent claims for deep seismic anomalies associated with hotspots have also not stood up (Nataf et al., 1981; Bijwaard et al., 1998; Bijwaard and Spakman, 1999; Keller et al., 2000). For further discussion see Dziewonski, this volume; Julian, this volume; and www.mantleplumes.org.

Montelli et al. (2004) cited lack of coverage and resolution, smearing, leakage, and so on, as reasons for these difficulties. Even disregarding these problems, the mantle contains tomographic anomalies of all scales at all depths. Considering the number of hotspots and the resolution of seismic data, approximately six of the anomalies at a given depth will appear to be geographically related to hotspots even if they are randomly placed. Montelli et al. (2004) discuss approximately six low-velocity features in the deep mantle. They associate these with hotspots at the surface. They do not address whether these correlations are statistically significant. For more discussion on this point, see Anderson and Schramm, this volume. Something equivalent to a Monte Carlo test must be performed to test the significance of claimed tomographic correlations.

Geochemists did not take long to adopt the plume hypothesis. Schilling (1973a,b) attributed the unusual chemistry at elevated regions of the Mid-Atlantic Ridge to enriched plumes or blobs. Most of the chemical attributes originally attributed to plumes or primordial lower mantle—the radiogenic isotopes of Sr, Nd, Hf, and Pb and most incompatible trace elements—are now accounted for by involvement of components derived from the Earth's crust, namely varieties of sediment and altered ocean crust (e.g., Zindler and Hart, 1986a; Weaver, 1991; Hofmann, 1997). The principal geochemical signature originally attributed to "deep mantle" plumes originated at the surface of the Earth! In modern plume theory, these components must be carried down into the deep mantle, indeed all the way to the core-mantle boundary, by subduction and then recycled back to the Earth's surface in plumes (e.g., Halliday, 1999). The downward portion of this cycle was not a part of the original plume hypothesis; it is an emendation required by the new geochemical interpretation, and it radically modifies the initial notions that previously untapped primordial sources comprise the hearts of the mantle sources of plumes and that the return flow is a diffuse settling of the whole mantle.

Thus the very attributes originally used to justify a deep mantle source proved false, although the wish that they would do so is still being diligently pursued in the search for a "common mantle component"—variously termed "focus zone" (FOZO; Hart et al., 1992), "primitive helium mantle" (PHEM; Farley et al., 1992), or "common mantle" (C; Hanan and Graham, 1996)—that can be assigned to a deep source. Of course the same shallow components are found in enriched MORB and alkalic basalt obtained from ridge crests, fracture zones, and near-ridge seamounts (Natland, 1989; Cousens, 1996; Niu et al., 2002), and no one has ever postulated plumes for such places. Even at the major island chains, the particular geochemical signal left to verify a deep mantle source is uncertain. Most geochemists adhere to high ^{3}He/^{4}He as an unequivocal indication of a primordial source at great depth (e.g., Farley and Nerona, 1998; Graham, 2000); some invoke the Os isotopes (Walker et al., 1995), although this requires a precision of isotopic measurement that is difficult to obtain (Walker, 2003). Craig and Lupton (1976, 1981) used high ^{3}He/^{4}He at Yellowstone and Iceland as a proxy for high helium-3; this is one of the most critical assumptions in the primordial reservoir and chemical plume concepts. They considered this as evidence for a deep mantle source of primordial helium, although they were surprised that the thick continental crust under Yellowstone appeared to be transparent to deep mantle gases.

In spite of the new geophysical data and the concerns of geophysicists who were most conversant in fluid dynamics (see Smith, 1973d), the number of proposed plumes proliferated, reaching 117 in 1976 (Burke and Wilson, 1976). The plume hypothesis was further challenged in the following years (Tozer, 1973; Jacoby, 1978; Sykes, 1978). Sykes (1978) made a case that the Atlantic "hotspot tracks" are actually along transform faults and fracture zones. This is apparently borne out by satellite altimetry (e.g., Fairhead and Wilson, this volume). The suggestion that there are 117 hotspots (Burke and Wilson, 1976) was one of the peaks of plume proliferation, but this number did not last long. Crough (1979) reduced the number of plumes to ~40 and showed that thermal plumes, if they exist, would heat and thin (rejuvenate) the lithosphere, leading to uplift and thermal swells. Plume advocates (e.g., Koppers et al., 2001; Courtillot et al., 2003; Ritsema and Allen, 2003; Sleep, 2004, personal commun.) now generally agree that only a few hotspots are even candidates for a plume origin, but this begs the question of how to explain the rest, which have similar surface expressions and chemistry, and some have higher buoyancy fluxes and high helium ratios.

The years 1973–1976 were extraordinarily fertile in the development of ideas regarding the origins of volcanic chains. In 1975 alone it was becoming clear that plates were driven by themselves, not by plumes (Forsyth and Uyeda, 1975), that linear volcanic features could be explained by small-scale convection (Richter and Parsons, 1975), and that there is no seismic velocity anomaly under Hawaii (Best et al., 1974). By 1977 the number of studies motivated by the plume hypothesis was down to twenty per year. Interest was steady but low throughout the 1980s.

Early Problems and Alternatives

Since ca. 1990 there has been little discussion of alternative mechanisms for creating midplate volcanoes and island chains. Except for the rapid increase of magmatism over the past 6 m.y., the Hawaiian and Emperor systems appear superficially to fit the fixed deep-mantle-plume hypothesis well, and indeed the hypothesis was inspired by them. However, crack propagation, membrane tectonics, self-perpetuating volcanic chains, reactivated plate boundaries, incipient plate boundaries, gravitational anchors, resurfacing slabs, and dike propagation were also proposed as at least partial explanations for the Emperor and Hawaiian chains (e.g., Shaw and Jackson, 1973; Turcotte and Oxburgh, 1973; Jackson and Shaw, 1975; Jackson et al., 1975; Shaw et al., 1980; Presnall and Helsley, 1982; Clague and Dalrymple, 1987; Hieronymus and Bercovici, 1999). The evident effects of the Mendocino, Murray, and Molokai facture zones on the productivity and trends of the chains and the boundaries of the Hawaiian swell, and the nested sigmoids nature of the chain, are unexplained in the plume hypothesis.

The most widely quoted evidence for fixed plumes has been geometrical, namely fixity, perceived parallelism with other volcanic chains and the regular time progression of volcanism, and high melt productivity. In the geochemical literature any chemical attribute of a magma that differs from what has been defined as a mid-ocean ridge basalt ("away from the influence of hotspots") is often used as evidence for the existence of a plume. Linear time-progressive volcanism and high magmatic productivity were also explained by other mechanisms such as propagating cracks, shear heating, and high mantle fertility. Other aspects of hotspot volcanism, such as global synchroneity with events at plate margins, are not readily explained by the plume hypothesis (Vogt, 1972; Smith, this volume). On the other hand, global synchroneity is expected in plate- and stress-based theories (Anderson, 2002a,b,c).

The Hawaiian swell, which at one time was attributed to high temperatures and lithospheric rejuvenation, may instead be largely the result of recent and ancient buoyant residues (Phipps Morgan, 1997) or underplating by reheated slabs or depleted peridotite (Presnall and Helsley, 1982). The Hawaiian swell is usually assumed to have formed contemporaneously with the islands (Watts, 1978; Crough, 1979; Watts and ten Brink, 1989; ten Brink, 1991; Phipps Morgan, 1997) rather than being a preexisting feature, such as is the case for Kerguelen and Jan Mayen (Müller et al., 2000).

Menard (1973) suggested that bumps at the base of the asthenosphere may give rise to irregularities in standard seafloor bathymetry. Such bumps could be caused by thermal expansion of the deeper mantle or by expansion within a layer in the deeper mantle and do not require material transport from deep regions. This is the inverse of the mechanism used to explain deep portions of ridges, namely, that they overlie mantle that is colder or denser than average, perhaps because it contains over-ridden slabs. Because of the large increase of viscosity with pressure, the timescale of convection in the lower mantle is longer than in the upper mantle. Therefore bumps at the top of the lower mantle can persist for long periods of time, and this may influence convection in the asthenosphere as well as the locations of surface swells and volcanoes. A chemically stratified mantle will have both undulations on the interfaces (bumps) and bottomed-out slabs, either of which could provide a relatively fixed reference frame if the lower mantle has high viscosity. Relative fixity, however, must be put into context. Some continental masses (Eurasia, Africa, and Antarctica) and back-arc basins move with respect to each other at rates comparable to inferred hotspot motions. Mid-ocean ridges move more slowly with respect to each other than with respect to the bounding plates.

The implausibity of narrow thermal plumes (Tozer, 1973) prompted Anderson (1975) and Hadley et al. (1976) to propose and test the concepts of chemical plumes and chemically zoned plumes. In these models, as in Beloussov's and Ramberg's, one had to explain the source of the chemical buoyancy. Partial melting and phase changes have been proposed in addition to intrinsic density differences of the solids at given pressure and temperature. One also had to address the return flow problem, unless chemical plumes were considered part of the ongoing one-way chemical differentiation of the mantle. In some geochemical models the so-called depleted reservoir grows with time. Laboratory simulations of plumes also tend to be one-shot irreversible isolated injections rather than a form of small-scale cyclical convection.

Chemical heterogeneities can also be passive. They can either be carried around by mantle flow or sampled by migrating ridges passing overhead (Sleep, 1984). Because plates are much thinner than the mantle or even the upper mantle, they will move faster than the underlying mantle, especially if they are lubricated. In effect, fertile patches can be considered relatively stationary with respect to the overlying plate. A melting anomaly can occur when a fertile patch of mantle is sampled at a spreading ridge or at a midplate region of extension. Presnall and Helsley (1982) viewed the sources of melting anomalies as passive consequences of plate tectonics and fractionation at spreading centers rather than of the driving forces of plates. Recent petrological and geochemical models also invoke major-element heterogeneities in the upper mantle rather than high-temperatures

(Lassiter and Hauri, 1998; Niu et al., 2002; Meibom and Anderson, 2004). The plume model, or at least most plume modeling, assumes a homogeneous and laterally isothermal upper mantle (e.g., Sleep, 1984, 1990, 1992; McKenzie and Bickle, 1988). The labeling of chemical heterogeneities as "fossil plumes" or "plumelets" is misleading (see the intermezzo on semantics that follows). Subduction is the likely source of mantle heterogeneity (e.g., Weaver, 1991), and much subducted material is potentially trapped in the shallow mantle (e.g., Oxburgh and Parmentier, 1977; Meibom and Anderson, 2004). Recycled crust and sediment may control or influence the incompatible elements, while recycled lithosphere is more relevant to the siderophile and compatible element budget of the upper mantle.

Tozer's Objections

In an elegant and remarkable early critique of the plume hypothesis as it is applied in Earth sciences, Tozer (1973) concluded with a plea that geologists frame a definition of a plume that is amenable to testing, a plea that has gone unanswered for thirty years.

Tozer pointed out that because the Reynolds number of the mantle is $\sim 10^{-20}$ the usual fluid dynamic definition of a plume is not particularly relevant. A more intuitive definition of a thermal plume is a convective flow in which a velocity-dependent length, usually referred to as the thermal boundary layer thickness, is small compared to the linear dimensions of the system. This condition can be written

$$\mathrm{Pe} = vL/\kappa >> 1,$$

where Pe = the Pèclet number, v = velocity, L = length, and κ = thermal diffusivity.

The mantle has $\mathrm{Pe} \sim 10^3$, and this satisfies the condition. This is a necessary, but not sufficient, condition for narrow plumes to occur in a convective flow. The intuitive definition of a plume involves not only a thin thermal boundary layer but also a narrowly confined flow. Such flows have a kinematic viscosity that controls the width of the flow and is comparable to the thermal diffusivity, which controls the thermal thickness; or

$$\mathrm{Pr} = \nu/\kappa,$$

where Pr = the Prandtl number and ν = viscosity.

The Pr of the mantle is 10^{24}. The square root of Pr gives the ratio of thickness of the viscous and thermal boundary layers, so one sees that no large velocity gradients are expected in the mantle. Nevertheless, large velocity gradients and small radius have been taken to be characteristic of thermal plumes, and these are clearly exhibited by flows in the atmosphere, in the ocean, and in laboratory fluids and simulations. The fact that a purely formal calculation of viscous boundary layer thickness greatly exceeds the dimensions of the mantle shows that fluid dynamic scalings do not support the intuitive concepts of narrowly confined flows of hot material in the mantle. Although there may be narrow thermal boundary layers in the mantle, they are not accompanied by narrow flows. The flow dimensions are controlled by the system dimensions. Lower-mantle "plumes" therefore have the dimensions of the lower mantle or of "normal" mantle convection, not the dimension of the thermal boundary layer. That is, the dimensions of the so-called plume-scale flow, the plate-scale flow, and the mantle-wide flow are comparable. No large velocity gradients are expected. The Prandtl number, the Rayleigh number, and the effects of pressure on thermal properties consequently all dictate against narrow plumes in the lower mantle. Large features have been dubbed "megaplumes" or "superplumes," but these are far from the conception of the original plume hypothesis (in fact, the names themselves are oxymorons) and are more akin to the kind of background and large-scale convection that plumes were supposed to replace.

Rebirth and New Complexity

Campbell and Griffiths (1990, 1993) revived the thermal plume hypothesis. They carried out experiments similar to those pioneered by Ramberg, and the results were therefore similar to those illustrated in Ramberg's book and in fluid dynamics textbooks. The dramatic plume head–plume tail visualizations were unfamiliar to most geologists and geochemists, who also were generally unaware of the previous work both pro and con of Beloussov, Ramberg, and Tozer or even of general fluid dynamic investigations of conduction; the images were influential and gave new impetus to Morgan's ideas. Plumes became the default explanation for observations in a variety of fields. Evaluation of the geodynamics and geochemistry of plume heads was quickly adopted as a research agenda by investigators of flood basalts and oceanic plateaus, all under the general phenomenon of LIPs (e.g., Coffin and Eldholm, 1994). This is a tribute to the simplicity and elegance of the plume head idea and the easy-to-understand injection experiments. The most significant new predictions of the injection experiments were the required association of a hotspot track (plume tail) with a LIP (plume head) and the large (kilometer-scale) precursory uplift prior to extrusion.

The same year, Kellogg and Wasserburg (1990) revived the idea of a primordial lower mantle by specifically attributing flux of ^{3}He to the upwelling of deep mantle plumes, an idea that had previously been questioned by Zindler and Hart (1986b). After this, the number of publications annually using the word "plume" in the title increased by nearly an order of magnitude (see Fig. 2), indicating wide acceptance of the concept.

From the perspectives of geology, mantle dynamics, and fluid dynamics, however, the injection experiments did not seem especially relevant. The experimental plumes were created artificially, and in those experiments they were not the result of a convective instability. The concerns expressed by Tozer and others about Morgan's *gedankenexperiment* plumes were even more applicable to the laboratory plumes. The experiments did not address the apparently fatal issues and contradictory data

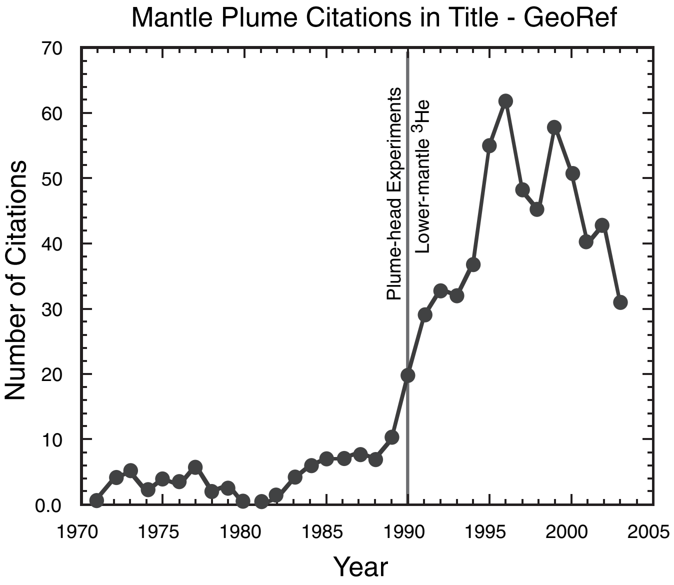

Figure 2. Line histogram showing number of citations with the word *plume* in the title, in reference to mantle plumes, by year since 1971, listed in GeoRef, the online database of the American Geological Institute. The vertical line marks the year of publication of the seminal modeling paper by Campbell and Griffiths (1990) depicting plume heads and tails. The same year saw publication of Kellogg and Wasserburg's (1990) paper describing the contribution of the lower mantle to ^{3}He flux via mantle plumes. After this, the plume hypothesis attained a great degree of acceptance.

discussed earlier and concurrently (Tozer, 1973; Best et al., 1974; Cowen and Lipps, 1975; Richter and Parsons, 1975; Hadley et al., 1976; Jacoby, 1978; Sykes, 1978; Von Herzen et al., 1989; Woods et al., 1991), nor did they address the issues of fluid dynamics and scaling in solid-state physics. The absence of a large-volume start-up pile of lava for Hawaii, the Marquesas, and many other volcanic chains; absence of traces of plume tails following the emplacement of several oceanic plateaus, including the world's largest, the Ontong-Java Plateau; and significant fluctuations in eruptive volume in the histories of island chains like Hawaii pose the most obvious geological problems for the plume head–plume tail hypothesis.

View from the Twenty-first Century

What are the terms of the plume hypothesis today? Current views are quite different from those discussed by Morgan and Wilson. The recent debate about plumes has prompted several of the leading advocates of plumes to explain the modern position. We will give two examples.

DePaolo and Manga (2003) write as follows, mainly concerning Hawaii:

> The Hawaiian volcanic anomaly has remained mostly stationary for tens of millions of years. This phenomenon is not explained by plate tectonics. It requires a separate mantle process that can account for narrow, long-lived upwellings of unusually hot mantle rock. Evidence from geophysics, fluid dynamics, petrology, and geochemistry has supported if not required the existence of mantle plumes. For many geoscientists, the mantle plume model is as well established as plate tectonics.
>
> Tomographic images suggest that the Hawaiian mantle plume can be traced with seismological techniques all the way down to the core-mantle boundary.
>
> Mid-ocean ridges are able to migrate over hotspots without changing the hotspot track, which implies that the hotspot source is deeper than about 200 km.
>
> At Hawaii, the current high magma production rate . . . requires an upwelling velocity of ~50 cm/year, about 10 times the average velocity of plates. The Hawaiian upwelling must therefore be distinct from flow associated with plate motions. The upwelling mantle . . . must be 200 to 300 K hotter than the surrounding mantle. Such hot rock material must come from a thermal boundary layer.
>
> The chemistry . . . of many hotspot lavas, especially the high ^{3}He/^{4}He ratios, indicates that the hotspots sample a part of the mantle distinct from that sampled by mid-ocean ridge basalts.
>
> . . . Studies also predict that plumes should form in the deep Earth . . . because the core is much hotter than the mantle. Plumes provide a constraint on the heat flux from the core.

In contrast to DePaolo and Manga, Sleep (2003) encourages skepticism toward the plume hypothesis and admits that it is vulnerable to being modified in ways that make it untestable. However, he expresses little doubt that plumes exist and believes that alternatives will not provide better interpretations of the observations. He modifies the vertical plume scenerio. Sleep hypothesizes that hot, buoyant material rises in plumes and then flows laterally, guided by basal lithospheric topography, which channels it into areas where the lithosphere is thin (the same thing can happen, in the absence of plumes, with normal asthenosphere, refueled by material from slabs). High helium isotope ratios (^{3}He/^{4}He) are used as an "empirical tracer" of plume material because high ratios were observed at Hawaii, Yellowstone, and Iceland, which are all assumed to be underlain by plumes. Sleep's (2003) guarded summary of the current status of the plume hypothesis is as follows:

> Hotspots like Hawaii, Yellowstone, and Iceland do exist and Earth scientists need to find physical mechanisms for their presence. . . . The plume hypothesis can be modified in ways that it untestably represents any given hotspot. [In] the current plume hypothesis . . . plumes arise as cylindrical conduits from the basal thermal boundary layer in the mantle. The shallow part of the hypothesis is complicated by the lateral flow of plume material toward thin lithosphere, including the interaction of the plume material with ridge axes. . . . Plumes begin with instabilities of the basal boundary layer and ascend as a more or less spherical heads followed by tail conduits. The head ponds beneath the lithosphere, and the buoyant hot material within the head spreads out beneath the lithosphere. This results in vast amounts of pressure-release melting over a geologically brief period of time.
>
> Specifically, the arrival of a plume head is an attractive hypothesis for the North Atlantic igneous province at ~65 Ma (e.g., Sleep, 1997). Once ponded, this plume material flowed buoyantly to zones of thin lithosphere. After the arrival of the starting plume head, the plume tail continued to supply buoyant plume material at a modest rate. In general, the passage of plates over plume tails produces hotspot tracks

> just as Hawaii. The buoyant plume material ponds at the base of the lithosphere and tends to flow toward regions of thin lithosphere. . . . On-axis hotspots, like Iceland, continental hotspots, like Yellowstone, and oceanic hotspots, like Hawaii, all result from the same underlying phenomena. One type of hotspot appears to evolve into another.
>
> . . . Actually, plumes are not well understood and current thinking includes partly disjoint hypotheses as well as some excess baggage. . . . Dynamically, plume conduits and the plume source at depth advect with the rest of the flow in the mantle [e.g., as passive tracers rather than active and rapid upwellings as proposed by DePaolo and Manga in the passage cited earlier].
>
> The depth from which plumes ascend is unknown and disjoint from evidence that plumes traverse the upper mantle. The D″ layer at the base of the mantle is the obvious suspect. The core accreted hot after the moon-forming impact and the mantle has cooled over geological time. One thus expects that a significant boundary layer exists at the base of the convecting mantle. . . . Geochemistry, including He isotopes, is at best a local empirical tracer of plume material. The mantle is heterogeneous, composed of the remnants of subducted oceanic lithosphere, the residuum from previous melting events, old "primordial" regions, and entrained continental crust and sediments. The details are poorly understood and samples from modern lavas are poor indicators of the deep geometry.
>
> Overall, the plume hypothesis involves deep dynamics near the limit of what can be resolved with currently tractable numerical models. . . . Tomography provides a difficult way of finding plume conduits. Even in Iceland, the geometry is not ideal. Few recorded seismic waves passed through the probable conduit below 400-km. . . . The situation in the deep mantle is not sanguine. The plume conduit should be a low-velocity region and rays through it should not be first arrivals. . . . The plume hypothesis is somewhat vague because the underlying processes are still poorly understood and the deep structure of the Earth is poorly resolved. . . . Overall, plumes provide an explanation for hotspots and lead to quantitative testable predictions. A major difficulty is that surface processes obscure deeper ones.

Paradigms require assumptions as well as data. The assumptions behind the two passages just cited include the following:

- There is some fixed reference system in which Hawaii is stationary.
- Volcanism is localized by deep, narrow, hot features in the mantle, not by lithospheric effects or fertile patches.
- Temperature is the main variable controlling seismic velocity.
- Stress cannot be transmitted across ridge-transform systems.
- The mantle is homogeneous in composition and melting point.
- Magma volumes are a proxy for mantle temperatures.
- "Empirical tracers" of plume material are defined by the properties of basalts from "known" plumes.
- If there is a thermal boundary layer above the core, it will generate narrow upwellings that traverse the mantle; all we have to do is find them.
- Recycled material sinks into the lower mantle.
- The upper mantle is convecting, well-stirred, and homogeneous.

Now for a final comment. During most of its history, the magmatic output along the Emperor and Hawaiian chains has been five to ten times less than the current output, implying vertical velocities at rates in the range of velocities of fast-moving plates.

INTERMEZZO: SOME SEMANTICS

Paradigms are based not only on assumptions but also on definitions and new classifications or the renaming of familiar features. The literature on hotspots and plumes has developed an unusually rich vocabulary and customs of usage. However, many terms are vague, contradictory, or inconsistently used. We offer a sampling, with a plea for clarity.

Volcanic chains have been dubbed *hotspot tracks,* and LIPs, such as continental flood basalts and oceanic plateaus, are often referred to as *plume heads,* e.g., the Ontong-Java plume head. Volcanoes are called *hotspots* or *melting anomalies.* Enriched components in magmas are called *plume* components. What are *plumes, hotspots,* and *anomalies?* Can they be defined precisely? And how do we recognize them? *Hotspots* are sometimes defined as regions of anomalous volcanism. Other terms for *hotspots* include *midplate volcanism, intraplate volcanism,* and *melting anomalies.* These terms are somewhat misleading, because *hotspots* do not appear to be particularly hot (www.mantleplumes.org/heatflow.html/mantletemp.html/temperature.html), they are not all midplate occurrences, and *anomalous* implies a degree of homogeneity or constancy in the mantle that cannot be justified considering what recycling and other plate tectonic processes can do. Sometimes large-volume or persistent magmatism is taken as a proxy for high temperatures, but mid-ocean ridge and island-arc volcanism also have these characteristics, and other parameters such as stress, fertility, focusing, and ponding can control the volumes of melt and the rapidity of extrusion. What is often meant by the term *hotspot* is a localization of volcanism that differs in some respect from "normal" plate boundary magmatism.

The vagueness of the hotspot concept is reflected in the fact that the number of hotspots increased rapidly from the original 20 defined by Wilson (1963) and Morgan (1971) to 117 (Burke and Wilson, 1976). Most lists include ~50 hotspots (e.g., Courtillot et al., 2003). There is no such uncertainty associated with the terms *mid-ocean ridge, island arc, transform fault* or *backarc basin,* all plate-tectonic concepts. Some hotspots have been labeled "coldspots," "wetspots," "hotlines," or "crackspots," and to this list can be added "fertile spots." Crough (1979) defined a "hotspot" as a region of midplate or anomalous ridge crest volcanism that is either persistent or accompanied by a broad topographic swell. The assumptions behind this definition are that in the absence of hotspots ridges would rise to the same elevation and be equally productive of melt everywhere and that seafloor topography would otherwise be flat after age-dependent subsidence had been subtracted. In other words, the nominal or reference mantle should be isothermal and homogeneous in both composition and melting point. The uncertainty about what hotspots really are has hampered attempts to explain them. If the upper mantle is heterogeneous in composition, fertility, or melting point, melting anomalies in the mantle require not high absolute temperatures, only temperatures high relative to the solidus, which might not be the same everywhere.

Unfortunately the terms *hotspot* and *plume* have become confused. In recent literature the terms are used interchangeably. A plume is a hypothetical mantle feature. A hotspot is a region of magmatism or elevation that has been deemed anomalous in some respect because of its volume or location. In the plume hypothesis a hotspot is the surface manifestation of a plume, but the concepts are different; one is the presumed effect, the other the cause. The word *plume* is also applied to tomographic and other anomalies that have little or no surface expression (Nataf, 2000; Courtillot et al., 2003; Montelli et al., 2004).

Plume has completely replaced *hotspot* in the mantle geochemistry literature (e.g., the Yellowstone plume, the Iceland plume), the assumption being that cause and effect have now been firmly established. In the noble gas literature a plume is defined by high ^{3}He/^{4}He ratios; sometimes any ratio higher than nine times the atmospheric ratio is considered diagnostic of a plume. Geochemical features of basalts that have been labeled "hotspot" or "plume" components do not necessarily require either plumes or high temperatures. The assumption that they do has buoyed the plume hypothesis.

In fluid dynamics plumes technically are buoyant upwellings or density-driven downwellings. Low-density layers in the crust can form buoyant upwellings. These have also been called plumes (Ramberg, 1981), but are more commonly referred to as "diapirs" or "domes" (as in salt domes). Instabilities of the cold upper thermal boundary layer are technically "plumes." More commonly, however, plumes are considered creatures of lower thermal boundary layers in fluids heated, entirely or mostly, from below. As such, they should have temperature excesses of the order of 1000 K, a typical temperature rise calculated to be across mantle thermal boundary layers. Attempts to model plumes in the laboratory have often involved the injection of hot low-viscosity fluid into a tank of static fluid or the instantaneous creation of a hot sphere (e.g., Cordery et al., 1997) rather than the spontaneous development of instabilities in a thermal boundary layer. This begs the question of whether narrow plumes will spontaneously arise under natural conditions in the Earth or other planets.

In summary, the term *plume* does not have a well-defined meaning that is agreed upon in the Earth science community. The term is used differently in different disciplines. For some it is simply a region of magmatism that is anomalous in either volume or chemistry compared with some segments of ocean ridge. Some seismologists use the term to refer to any low-velocity (having slower than average seismic velocity) region of the mantle, regardless of depth or depth extent (e.g., Montelli et al., 2004). Elevated regions of ridges or midplate swells are called plumes. Evidence for elevated temperatures from magmas or refractory peridotites is often attributed to a plume, even if the inferred temperature excess is only 50–100 degrees over some baseline value. Most volcanic islands are attributed to, and referred to as, plumes. The defining characteristic of a plume tends to be any characteristic that is displayed by regions defined as plumes, such as Iceland, Hawaii, and Yellowstone. Explicit definitions and intrinsic attributes such as temperature are clearly needed for the terms *plume* and *anomalous.*

In keeping with Morgan's convention, and to be consistent with the majority of papers from the inception of the hypothesis, we define *plume* as a narrow, buoyant, active upwelling that is continuous from a deep thermal boundary layer to a surface hotspot. We do not consider passive upwellings, upwellings associated with plate tectonics or large-scale mantle convection, or features not originating as instabilities in a deep thermal boundary layer to be plumes. Low-velocity regions of the mantle or basalt that differ in some respect from MORB are not adequate indicators of plumes. Convection in the asthenosphere, lateral transport in the shallow mantle, melting instabilities, small-scale convection, recycling, fractures in plates, and dikes are all intrinsic to plate tectonics but not to plume theory. Passive or embedded mantle heterogeneity is an alternate to the plume and reservoir concepts and is not a plume. Enriched components in magmas should not be called plume components without additional information.

More recently, a large plume head has been considered an essential precursor to plume magmatism and an essential element in the definition of a plume (Campbell and Griffiths, 1990, 1993; Cordery et al., 1997; Courtillot et al., 1999, 2003; Davies, 1999; Clouard and Bonneville, 2001). Models including broad plume heads were embraced, because these appeared to explain simultaneous volcanism over large areas and the generation of LIPs. The assumptions here are that without a plume head the shallow mantle would be far from the melting point, thus incapable of producing so much basalt, and that so much ponding and underplating require much higher than average temperatures.

Semantic confusion has led to unnecessary misunderstanding, controversy, and miscommunication across disciplines. However, lest we leave the reader with the impression that only the plume hypothesis suffers from these difficulties, the terms *lithosphere, asthenosphere, upper mantle,* and *lower mantle* themselves also have different meanings and implications in the geophysics and geochemistry literatures and have produced an equal amount of confusion (Anderson, 1995).

CRITIQUE

The Importance of Fluid Dynamics: An Objection to the Plume Hypothesis

Study of plume behavior is a branch of fluid dynamics. Most of the other explanations involve lithospheric physics, passive convection, or chemical heterogeneity. A fluid heated from below and cooled from above will develop hot upwellings and cold downwellings. Although both of these, upwellings and downwellings, are referred to as plumes in the fluid dynamics literature, they are just part of the normal behavior of a fluid and can be thought of as normal or background convection. Thermal convection, in general, is characterized by two scales; one of them is set by the size of the container (or the depths of individual layers), the other by the thicknesses of thermal boundary layers, which are controlled by the properties of the fluid. In the Earth science literature, plumes are usually thought of as stationary concentrated upwellings that are independent of plate tectonics and of normal or background convection. But Tozer (1973) pointed out that well-known fluid dynamic scaling relations, when applied to the mantle, preclude the existence of narrow plumes that are independent of normal large-scale convection. Thermal boundary layers in the mantle can be thin, whereas mechanical or viscous boundary layers are much thicker. Tozer (1973) suggested that "mantle plume" was simply jargon for a long-recognized geological fact, that igneous or hydrothermal activity is highly localized at any given geological time. In his view, plumes were an ad hoc method of localizing activity. Larsen and Yuen (1997) describe the situation as follows:

> The enigma of . . . nearly stationary plumes . . . in mantle convection arises in the hotspot hypothesis. Some sort of separation of time scales between the fast plume and adjacent mantle is necessary and, in fact, was invoked by Morgan in his original concept of plumes. . . . Plume studies have usually modeled a plume in isolation from the rest of the mantle. There has been a tendency to regard plumes as a distinct, secondary mode of convection . . . such a mode of flow has never been observed in any self-consistent numerical or laboratory experiment. Upwelling plumes always occur as part of the main convecting system (rather than independently). In particular, there is a problem of obtaining hotspot-like plumes, which must satisfy the requirements of being fast as compared to the ambient mantle circulation and fairly thin.

Narrow plumes have been created in fluid dynamic simulations with strong localized heating from below, or in fluids with rheology that is strongly stress- and temperature-dependent and with shear heating, but these simulations have no phase changes, no pressure effects (Larsen and Yuen, 1997), and no internal heating. They do not produce plate tectonics or slablike behavior. Although temperature anomalies (thermal boundary layers) can be small in scale, physical plumes or flow-velocity anomalies (mechanical boundary layers) can be thin only if there are large ratios of the viscosity to thermal diffusivity (technically, this is the Prandtl number, Pr) or if the container, or layer thickness, is small. The effect of pressure on specific volume, thermal expansion, thermal conductivity, viscosity, and Rayleigh number, which involves these parameters plus the layer thickness and the gravity, must also be taken into account (Anderson, 1987, 1989; Tackley, 1998). This scaling of pressure or the specific-volume scaling of physical properties cannot be simulated in laboratory-scale experiments.

The localization issue also arises in fluid dynamic treatments of plate tectonics (e.g., Bercovici and Ricard, 2003). Convection simulations do not explain first-order features of plate tectonics such as coherent plates, localized boundaries, strike-slip faults, global plate reorganizations, one-sided subduction, and the onset of subduction. In the case of volcano localization, the explanation lies in the mechanical properties of the lithosphere, not fluid dynamics. The result is alignment of coeval volcanoes at ridges and island arcs. These are defined as "plate boundaries."

Although most geophysicists accept that the mantle does convect, computer simulations have been able to account neither for first-order plate tectonic features and processes nor for departures from rigid-plate tectonics (e.g., Bercovici and Ricard, 2003). The form of convection assumed by Morgan is consistent with a mantle heated from below, but not with one cooled from above or heated from within, or with mantle motion that is driven by secular cooling, cooling plates, or descending slabs, all of which certainly occur. Core heat; a deep, strongly radioactive layer in the mantle; or both is required by the strong plume hypothesis. In a homogeneous laboratory fluid (e.g., one with a low Prandtl number) heated from below, both the top and bottom boundary layers generate narrow plumes, and the result has symmetry. In the mantle the effects of sphericity and pressure and phase changes, among other things, disrupt the symmetry. In addition, the top part of the boundary layer (the lithosphere) does not behave as a fluid. The mantle beneath the lithosphere behaves as a fluid with a high Prandtl number, which means that mechanical boundary layers cannot be thin; their dimensions must greatly exceed the thickness of the thermal boundary layer. The high viscosity and conductivity of the deep mantle also preclude thin thermal boundary layers and narrow thermal upwellings similar in form to those in the atmosphere.

In summary, many simulations of plumes (experimental, numerical, and analytic) in effect inject hot fluids into a stationary tank of cold fluid (e.g., Campbell and Griffiths, 1990, 1993; Cordery et al., 1997); the plumes do not result from any natural thermal instability. In fact, fluids that are internally heated or are in a pressure gradient do not spontaneously develop narrow upwelling plumes (Tackley, 1998). Strong temperature and stress gradients favor narrow plume formation only if the counteractive effect of pressure is ignored. Simple scaling relations (Anderson, 1987, 1989) show that instabilities at the base of the mantle should be orders of magnitude larger and move more sluggishly than plates and slabs in the upper mantle. The upper mantle is where most of the physical action responsible for localization of volcanism takes place. A thermodynamically self-consistent calculation of convection has yet to be made.

Recent Reaction to the Plume Hypothesis: Is It Testable?

The test of a hypothesis is its ability to make testable predictions. Morgan's (1971, 1972a,b) view of mantle convection involved places with narrow, hot upwelling and regions of broad, distributed downwelling. This is the exact opposite of tomographic results that reveal narrow slices of lithosphere returning into the mantle at subduction zones and no clear-cut narrow upwelling beneath hotspots (e.g., Ritsema and van Heijst, 2000; Ritsema and Allen, 2003). Wilson and Morgan believed that hotspots provide a fixed reference system. Ironically, the fixity and time-progressive arguments are no longer considered either valid (Raymond et al., 2000) or necessary (Koppers et al., 2001). Fixity was one of the factors that motivated Morgan to require that plumes be very strong and independent of plate and mantle motions. Morgan's plumes were assumed to deliver to the surface a large fraction of the Earth's heatflow. This prediction, an essential element of the original plume hypothesis, was not confirmed. We now know that hotspots account for only a small fraction of the surface heatflow (e.g., Malamud and Turcotte, 1999). Therefore plumes should be strongly influenced by mantle motion driven by the creation and movement of tectonic plates and subduction. If hotspots do not define a fixed reference system, other mechanisms are back on the table. High mantle temperatures also do not seem to be a characteristic of hotspots in general (e.g., Von Herzen et al., 1989; Yaxley, 2000; Anderson, 2001; Foulger et al., this volume; Presnall and Gudfinnsson, this volume). Hotspot magma temperatures usually fall within the range expected for the lower part of the upper thermal boundary layer of the mantle (1100–1400 °C; Presnall and Gudfinnsson, this volume). Even Hawaiian basalts appear to have temperatures well within the range expected for potential temperatures in the upper mantle (www.mantleplumes.org/mantletemp.html). The Hawaiian swell, once used as evidence for high temperatures, is underlain by material with high seismic velocities (Woods and Okal, 1996), and the feature may be largely compositional rather than thermal in origin (e.g., Phipps Morgan, 1997).

Malamud and Turcotte (1999) reversed the downward trend of identification of certified plumes with time by suggesting that there are ~5200 plumes (one every 300 km^2 at the surface, or every 150 km^2 at the base of the mantle). Unless all isolated seamounts and short seamount chains represent hotspots, this decouples the concepts of hotspots and plumes and is the opposite of Morgan's concept of strong plumes.

The noble gases have played an important role in the history of the plume hypothesis, beginning with Craig and Lupton (1976, 1981). Although most of the helium-3 in the universe indisputably was made during the Big Bang and is therefore a "primordial" isotope, it is not clear when this material entered the mantle, how deep it is sequestered, and whether there is a reservoir rich in helium-3 (as opposed to low in U/^{3}He components). High ratios can result from low helium-4 or low U/He ratios instead of high helium-3 concentrations, which is the standard assumption. Mantle components may have variable ratios that are washed out in the process of magma sampling and blending at ocean ridges.

Three of Morgan's hotspots, the respective type examples for intraoceanic, intracontinental, and on-ridge locations (Hawaii, Yellowstone, and Iceland), have high ^{3}He/^{4}He ratios (but not high helium-3 contents) and no deep seismic signatures. Ten of the so-called high-^{3}He hotspots of Courtillot et al. (2003) are judged *not* to have a plume origin. Helium ratios apparently cannot be used as a lower-mantle tracer (see also Meibom and Anderson, 2004, and Anderson, this volume), and an explicitly *upper*-mantle origin for them in the north Atlantic has been proposed by Foulger et al. (this volume).

Plumes were predicted to spread out beneath and then rapidly heat and thin the lithosphere, thus generating heatflow anomalies (Crough, 1979). These predictions were not confirmed (Von Herzen et al., 1989; Woods et al., 1991; Anderson et al., 1992; Woods and Okal, 1996; DeLaughter et al., this volume). Conduction is too slow to explain the inferred rate of uplift if it is due to heating from below. There are alternative mechanisms of swell formation, apparent thinning of the lithosphere, and uplift, such as delamination, stretching, and injection of sills and dikes. Swells may also be supported by buoyant refractory residues (Presnall and Helsley, 1982; Phipps Morgan, 1997). These processes do not require hot mantle. Whether the lithosphere is hot, thin, or rejuvenated under swells, including the Hawaiian swell, has not been determined (Woods and Okal, 1996; Katzman et al., 1998). One expects variations of lithospheric thickness along volcanic chains because of variations in age, tectonic thinning, and intersections of chains with preexisting features such as fracture zones, but thinning and heating by hotspots and the accompanying high heatflow have not yet been demonstrated.

The concept of deep reservoirs in mantle geochemistry and the plume hypothesis are inter-related. The chemical alternatives to deep mantle reservoirs tapped by plumes are shallow distributed heterogeneities or blobs, sometimes called "marble-cake" or "plum pudding" models (Niu et al., 2002; Meibom and Anderson, 2004). In these models the component concept replaces the reservoir concept. Components do not have to be large isolated masses. They can range from grains and grain boundaries to fragments of recycled crust and lithosphere. Plate tectonic processes introduce passive fusible components into the mantle, and this produces fertile regions within the midst of otherwise barren and refractory peridotite. These regions can be sampled by migrating ridges and can even form melting anomalies and swells.

Athermal Mechanisms

Magmatism and deformation can be localized by mechanical processes in the lithosphere such as stress, thermal contraction, and extension; by focused processes of fluid dynamics such as high-temperature plumes; or by the presence of fertile or fusible patches in the mantle. The question is whether volcanoes are controlled by stress or structure (plate tectonics) or by temperature ("convecting mantle" fluid dynamic processes). Localization is also an issue in fluid dynamic theories of plate tectonics and plate boundaries (Bercovici and Ricard, 2003). Methods used to make convection simulations approach plate tectonic behavior include shear heating, nonlinear rheology, reactivation of preexisting faults, lubrication, pore pressure, and so on. These same processes can localize deformation and magmatism at volcanoes and linear island chains. The plume hypothesis assumes that localized high temperature is the cause of volcanic chains unless they are island-arc or ridge volcanoes.

The plume hypothesis focuses on fluid dynamic processes; temperature is the main controlling parameter. Other mechanisms are basically athermal—not requiring large lateral differences in temperature at a given depth—although they require that normal mantle be close to its solidus, at least in the upper 200 km or so. Volcanism is localized by the lithosphere. Variations in melt productivity and chemistry result from the normal variations in mantle chemistry, melting point, and mineralogy expected from plate tectonic recycling. Variations in mid-ocean ridge depths reflect a combination of large-scale, moderate thermal variations and localized chemical variations, both resulting from plate tectonics. Other ways of localizing magmatism and separating time and spatial scales are to have eruptions and extrusions controlled by lithospheric physics rather than fluid dynamics (e.g., www.mantleplumes.org/cracks&stress.html; Jackson et al., 1975; Favela and Anderson, 2000; Bercovici and Richard, 2003; Natland and Winterer, this volume). For example, volcanic chains or alignments with alkalic or otherwise enriched basalt may form at incipient or embryonic ocean basins such as the Red Sea (e.g., Haase et al., 2000; Moghazi, 2003) and the Gulf of California (Saunders et al., 1987), and they can also form at abandoned ridges such as the Mathematician seamounts in the eastern Pacific (Vanko and Batiza, 1982; Batiza and Vanko, 1985). The coast-parallel dike swarms and nearly simultaneous Tertiary intrusive centers of East Greenland and the thick lava sequences making up the seaward-dipping reflectors offshore are a clear illustration of the strong influence of rift tectonics on the distribution of volcanism rather than that of a plume (Lundin and Doré, this volume). These, however, are concepts of plate tectonics, not fluid dynamics. The localization of strain is not readily accomplished in fluids with high Prandtl numbers (indicating that they have high viscosity; i.e., the mantle) and uniform Newtonian rheology (e.g., Tozer, 1973). Localization naturally occurs in deformed solids (as opposed to high-viscosity fluids), even in fragile materials such as bubble rafts and granular materials. Conditions in the shallow mantle, however, may control whether melting is possible, how much melt is available, and how fast it can be erupted. This is a function of melting point, volatile content, fertility, and whether ponding occurs, not just of absolute temperature. Ponding of magma beneath the plate or in the lithosphere may be a prerequisite for large-scale and rapid surface magmatism; the stress in the lithosphere may control the timing and location. Long-term ponding is more likely under middles of plates or thick continental crust and in compressional environments. Ponding and long-distance lateral transport are recent additions to the plume hypothesis, but these can also occur without plumes. Low-viscocity asthenosphere and asthenospheric melts will naturally migrate and pond under thin plate regions.

In the plume hypothesis the upper mantle is taken to be roughly isothermal, that is, to have constant potential temperature, and it is homogeneous (it is termed "the convecting mantle") except where narrow jets of hot mantle impinge on the plates. In the plate model (described later) normal mantle can be more or less isothermal on a local and regional scale, but it is close to the solidus. In this situation melting anomalies can be attributed to fertile patches of variable melting points in the shallow mantle, which erupt through weak or thin parts of the lithosphere, usually on or near past or present lithospheric boundaries (see Lundin and Doré, this volume; Natland and Winterer, this volume) and are precursors to ones about to form.

The Plate Model

All the nonplume explanations for volcanic chains and other volcanic features are implicit in plate tectonics. Incipient and dying plate boundaries, leaky transform faults, cracks, extensional terrains, reactivated sutures and fracture zones, small-scale convection associated with plate motions and architecture, edge effects, focusing, and fertility variation are consequences of plate tectonics and are basically athermal in character; they do not require an external heat source. Cooling of the plates rather than heating them from the bottom drives plate tectonics and mantle convection. Collectively these features, attributes, and associated mechanisms can be referred to as "the plate hypotheses," "plate mechanisms," or simply "the plate model." The general concept was first proposed by Daly (1926) as a mechanism to explain continental drift. Whereas the plume hypothesis was based on parallelism of volcanic chains and strict unilateral age progressions, the plate hypotheses allow for nonparallel chains, stress-controlled sigmoidal and nested cracks, and bilateral age progressions. The size of a linear volcanic feature depends on tectonic stress. Stress can turn on and shut off dikes, and it can modulate magmatism along a crack or boundary. An essential assumption of the plate hypotheses for volcanic chains is that the mantle is near the melting point, although it can be variable in fertility and solidus temperature. A small change in temperature, volatile content, and composition can have a large effect on melt volume for a near-solidus mantle. Incipient and dying plate boundaries can be recognized only after the fact.

Suggestions for Tomographic Tests

Tomography will play an increasingly important role in studies of mantle dynamics. Although seismology is a quantitative science, the interpretation of seismic images can be very subjective. Because of the lack of resolution and coverage, the best seismic experiments will be in the form of hypothesis tests. For example, do multiple ScS waves between Hawaii and the core-mantle boundary give evidence for low velocities and high attenuation? Are surface wave measurements along the Hawaiian chain consistent with thin lithosphere and hot asthenosphere? Because plume head thermal anomalies beneath thick lithosphere should last for times equivalent to the age of the plate, is the seismic velocity in the upper mantle in the region surrounding LIPs particularly slow? Is the separation between the discontinuities at nominal depths of 410 and 650 km beneath hotspots particularly small? A tomographic experiment to detect a plume under Iceland has to be able to distinguish a hot plume from other possibilities such as passive upwelling, convection induced by edge-driven gyres and eddies, and the presence of partially molten slab or suture material. All of these are expected to yield a wedge-shaped or cone-shaped low-velocity anomaly centered between Greenland and Norway, so a definitive experiment must involve more than just an array on Iceland tuned to detect near-vertical rays.

If plumes really are 200-km-wide low-velocity features that get blown around by the "mantle wind," they will indeed be harder to image than dipping slabs. However, certain aspects of plumes should be easy to image. As plumes rise through the mantle they spread out beneath mantle regions where there are certain types of phase changes (such as the 650 km seismic discontinuity) and beneath the lithosphere. They should both heat and thin the lithosphere. These types of plume-related effects should be easy to image but are generally lacking where the plume hypothesis predicts them to be (Anderson et al., 1992; Woods and Okal, 1996).

One of the most important calculations that can be done in order to test the believability of deep mantle features is to compute traveltimes, finite frequency effects, dispersion curves, and normal modes through a synthetic Earth model with a fully three-dimensional anisotropic code, and then to invert these data in the same way as is currently done (Gu and Dziewonski, 2001; Ritsema et al., 2002; Montelli et al., 2004). The resulting synthetic model could even have a homogeneous mantle below 650 km. The idea is to see how much of our current understanding of the lower mantle is based on smearing, leakage, source anisotropy, slab effects, and other projection artifacts rather than on real features of the lower mantle. Whether the low-velocity and high-velocity zones found at various depths in the mantle are related to plumes and slabs, are unrelated, or are artifacts is partly a matter of improved methods of tomographic inference and partly a matter of statistics.

The Importance of Statistics

Tomographic data are often presented as color-banded contours on depth slices within the Earth. Suppose that 25% of the area at a given depth in the lower mantle has seismic velocities in the lower quartile of the distribution. There is then a 25% chance that a randomly selected point on the Earth's surface will be above these low-velocity regions. If there are forty-eight hotspots, then, by chance, approximately twelve will be above a low-velocity feature. The number of recognized hotspots has varied over time from twenty to over one hundred and is in the process of shrinking to fewer than ten "primary" or possibly plume-related hotspots. The actual number is of more than passing interest. If the number is over forty, there is almost a 100% chance that some seismic anomaly in the lower mantle, in some tomographic study, will fall within 200–300 km of a hotspot. Considering the resolution and coverage of seismic data, there is a high probability that at least six hotspots, on some hotspot list, will be within 300 km of an extended vertical region of low velocity in some tomographic study. This is true even if the low-velocity anomalies (redspots) in various layers of the lower mantle are distributed at random (i.e., they have no causal relationship to hotspots). Correlations between tomographic models and hotspots or subducted slabs must be tested by Monte Carlo or similar simulations in order to show that the results could not have been obtained by chance, to a high level of significance. The idea that narrow jets of hot mantle extend from the surface to the core and that seismic anomalies in the lower mantle are connected to surface volcanoes is an extraordinary claim and requires an extraordinary degree of proof, which in this case only proper statistical evaluation can provide. Visual inspection of tomographic maps or cross-sections is not adequate. Seismic tomography is a relatively young science, and the statistics of correlations, coincidences, and hypothesis testing for it have not been developed.

Statistics are also important in deciding if there are differences between hotspot and mid-ocean ridge chemistry and if they can be explained by differences in sampling differences or differences in reservoirs (Meibom and Anderson, 2004).

The Meaning of Temperature

The defining characteristic of a hotspot or a thermal plume is high temperature. Surprisingly, magma temperature and heatflow data are seldom discussed in the context of tests for the presence of plumes (e.g., Courtillot et al., 2003). Instead volumes or rates of magmatism are assumed to be proxies for temperature. What absolute temperature defines a plume? Plate tectonics is driven by cooling of the thermal boundary layer at the surface. Temperatures in the boundary layer rise from roughly 0 °C at the seafloor to 1400 °C at the base of the lithosphere, with a range in the latter of ~200° (Anderson, 2001). Mid-ocean ridge basalt eruptive temperatures range from ~1100–1230 °C, but only basalt, with temperatures above say 1200 °C, is representative of liquids that might have been in equilibrium with the mantle at some depth. These temperatures are not necessarily representative of the sublithospheric adiabat, which can be higher. Mantle from a deeper thermal boundary layer (the conjectured plume layer) can be expected to arrive at the surface with temperature excesses of at least 400 °C if the thermal boundary layer is at mid-mantle depths (e.g., McKenzie and Bickle, 1988) or about twice this if the only deep thermal boundary layer is at the core-mantle boundary (Albers and Christensen, 1996). Inferred magma temperatures of 1400–1500 °C, or temperature excesses of 170–270 °C, which are about the most that anyone has inferred for primitive magmas erupting at the Earth's surface (e.g., Herzberg and O'Hara, 2002), are candidates for derivation from the shallow mantle or even the surface thermal boundary layer (i.e., depths above ~150 km). Little evidence exists for high magma temperatures or high heatflow at hotspots. This is a difficulty for the plume hypothesis but is an expected outcome for plate model mechanisms of excess magma production and production of swells. At the inception of the "hotspot" hypothesis many workers simply assumed that high magma volumes required high absolute temperatures, but the evidence for this has not emerged from any technique even at well-studied places such as Iceland (Anderson, 2000a,b; Breddam, 2002; Foulger et al., this volume). This and the absence of both fixity and parallelism for island chains justify the approach of multiple working hypotheses to "melting anomalies." The hypotheses of fluid dynamics and high temperatures deduced from the assumption of deep mantle plumes need to be evaluated alongside the athermal mechanisms for localizing magmatism. If temperature is not the dominant control parameter for mantle magmatism, what is?

The Myth of Mantle Homogeneity

The presumption of a basic level of homogeneity of the mantle plays strongly into the plume hypothesis. Thus the melt-column models for spreading ridges of Klein and Langmuir (1987), Langmuir et al. (1992), and Plank and Langmuir (1992) start with the assumption of a homogeneous lherzolite upper mantle. These authors' index of partial melting, Na_8 (Na_2O content of basalt corrected to a near-parental value of MgO = 8%), is reproduced in their models on this assumption, then used to attempt regional correlations with seismic crustal thickness and make predictions about mantle temperature near and away from ridge-centered hotspots like Iceland. They allow that some of the scatter in Na_8 compared with other parental parameters might reflect a small degree of heterogeneity, but their model calculations are based on what is still a homogenous lherzolite source. Their modeling includes Iceland and predicts higher potential temperatures and greater extents of melting there than along any other portion of the global system of spreading ridges.

Desiring to estimate melt productivity under the range of thermal conditions appropriate to spreading ridges and mantle plumes, McKenzie and Bickle (1988) also assumed a lherzolite source. Although the experimental data from many sources that they used to identify a mantle solidus and establish extents of melting were obtained on a variety of peridotite compositions, they derived their melt productivity curve by calculating a best-fit second-order polynomial regression to all the data forced through end points at melt fractions of 0 and 1. This necessarily produced a fit to some sort of average of the experimental data, in effect a single composition. Although some of the experimental data were originally obtained to assess the effect of lherzolite heterogeneity (e.g., Jaques and Green, 1980), this appears in relation to the polynomial curve as scatter of the data.

Therefore application of a best-fit curve through all the data is tantamount to assuming constant phase proportions and compositions, and one may well ask whether this is geologically reasonable. It is assuredly *not* the case with either the regional or the local variability of abyssal peridotites (e.g., Dick et al., 1984; Dick, 1989), of subcontinental lithosphere (e.g., Bizarro and Stevenson, 2003), of xenolith suites in the ocean basins (e.g., Jackson and Wright, 1970; Sen, 1983, 1988; Wright, 1987), or of peridotite massifs such as Ronda (Frey et al., 1985; Garrido and Bodinier, 1999). The experimental data derived from peridotites with different modal proportions of major silicate minerals define quite a precise solidus curve, but obviously the fraction of melt that can be derived from any peridotite depends on the modal proportions of minerals that contribute most strongly to the basaltic melt, particularly clinopyroxene, in the phase assemblage (e.g., Presnall, 1969; Schwab and Johnston, 2001). The solidi of different lherzolites can be very similar, but the amount of basalt that can be extracted from them for a given amount of heat added above the solidus will differ.

Calculating melt productivity therefore is analytically tractable only if the restrictive assumptions are made that the mantle is lithologically homogeneous and that chemical indexes of extent of partial melting, such as Na_2O content, are always and everywhere the same in early-melting minerals that contribute most significantly to the melt fraction (i.e., in clinopyroxene). However, the assumption of source homogeneity is among the factors that contribute to the clearly preemptive presumption that the depleted MORB mantle is well mixed even though the implied global homogeneity finds no parallel in any ultramafic suite that has ever been examined. The assumption of homogeneity ensures that the maximum possible differences in potential temperature are derived.

The origin of the global compositional array of parental abyssal tholeiites has been considered using two other approaches. Hirschmann et al. (1999) used the MELTS thermodynamic algorithm, which was designed to assess phase relations during partial melting of spinel peridotite (Ghiorsio and Sack, 1995), to evaluate the effects of peridotite heterogeneity on aggregated melts. Hirschmann et al. (1999) showed that some of the effects of source depletion on melt composition (decrease in Na_2O, increase in CaO/Al_2O_3) are similar to the results of increasing the total extent of melting of a fixed source composition (Klein and Langmuir, 1987) and in contrast to the inferences of Langmuir et al. (1992) concerning mantle peridotite. The same effects were previously produced in the batch-melting experiments on peridotites of different composition (Jaques and Green, 1980; cf. Natland, 1989).

Presnall et al. (2002) considered phase relations pertinent to MORB genesis. The effect of CO_2 is to lower the basalt solidus considerably (see Presnall and Gudfinnsson, this volume). Melt productivity can increase from 0% to 24% over a small range in potential temperature (1240–1260 °C). The maximum inferred potential temperature globally is ~1400 °C—about the same as the average potential temperature inferred from geophysics (Kaula, 1983; Anderson, 1989)—and the general patterns of global systematics in FeO, Na_2O, and CaO/Al_2O_3 are reproduced by lithologic heterogeneity of the source as long as four crystalline phases—olivine, orthopyroxene, clinopyroxene, and either spinel or plagioclase—are all present at the solidus. Places such as Iceland, where primitive basalts generally multiply saturated in olivine, plagioclase, and clinopyroxene (e.g., Hansteen, 1991) and where the maximum MgO content of glass is 10.65% (Breddam, 2002), have potential temperatures similar to those of other spreading ridges (Foulger et al., this volume).

These studies have dealt only with the possibility that partial melting of a single peridotite lithology, spinel lherzolite, which at high pressure will have garnet in it rather than spinel and at low pressure will have plagioclase, is responsible for all basalt on the face of the Earth. However, if only one composition is assumed for the mantle (pyrolite, the most aluminous lherzolite from Ronda, etc.), essentially fixing phase proportions, one can derive functions that will yield melt productivity (crustal thickness) and potential temperature at spreading ridges and "hotspots" that will correlate with aspects of the global MORB compositional array. Simply allowing the phase proportions to vary confounds calculations that estimate melt productivity and potential temperature and provides another explanation—bulk lithologic heterogeneity of the source—for the compositional array.

What if other lithologies altogether are involved? Thus some aspects of MORB geochemistry have been attributed to veins of pyroxenite, garnet pyroxenite, or eclogite (Hirschmann and Stolper, 1996; Salters and Dick, 2002; Pertermann and Hirschmann, 2003a,b). On the basis of trace element and isotopic data, melting of "complete sections of ocean crust" has been proposed for both Hawaii and Iceland (Hofmann and Jochum, 1996; Lassiter and Hauri, 1998; Chauvel and Hémond, 2000), with the ocean crust materials, of course, entrained in mantle plumes. Involvement of eclogite transformed from ocean crust is inferred from high concentrations of Sr relative to rare-earth elements indicating the influence of "ghost plagioclase" in the Hawaiian mantle source (Sobolev et al., 2000). Involvement of pyroxenite or eclogite at Iceland is also inferred from the compositions of melt inclusions in olivine found in picritic basalt (Gurenko and Chaussidon, 1995; Sigurdsson et al., 2000), with the overall geochemistry of primitive basalts possibly explained by sources combining recycled depleted ocean crust and recycled volcanic islands with enriched basalt (Natland, 2003; McKenzie et al., 2004; Foulger et al., 2005 and this volume). Experimental petrology suggests that eclogite might be a principal source of some ocean islands (Kogiso et al., 1998) and flood basalts (Takahashi et al., 1998). Peridotite refertilized with melt derived from eclogite has been proposed to explain the enhanced melt fertility at some hotspots (Yaxley, 2000). All of the principal enriched isotopic "end-members" have now also been attributed to the incorporation into mantle melts of ancient pelagic clay, mature continental sediment, and altered ocean crust (e.g., Weaver, 1991; Hofmann, 1997). Most plume materials thus seem to acquire whatever characteristic geochemical signature they have *at the Earth's surface in contact with the atmosphere, the oceans, the hydrothermal processes that ultimately drive differentiation in the ocean crust, and the water of rivers and streams!*

Every suggestion of this sort increases the likelihood that the solidus of the bulk rock assemblage experiencing melting is lower than that of dry lherzolite with a homogeneous composition, as assumed in the melting models of McKenzie and Bickle (1988) and Langmuir et al. (1992). These possibilities further confound the likelihood that either potential temperatures or a consistent melt productivity function can be defined or used to explain variations in crustal thickness. Inferences of *hot* mantle plumes and extended degrees of partial melting of a homogeneous lherzolite source can thus be questioned. There is no a priori reason why pyroxenite, eclogite, and varieties of recycled sediment must traverse the entire mantle twice before they emerge at volcanic islands in the ocean basins. Instead emplacement of such materials into the upper few hundred kilometers of the mantle at subduction zones and their continued residence in the upper mantle may well be all that is necessary to explain the volume and composition of basalts at seamounts, linear island chains, and LIPs that later tap into them.

Recycling

If any lithology is important in the upper mantle besides that of lherzolite, it will be that of eclogite. This is because the first-order differentiation on Earth today is formation of ocean crust at spreading ridges, coupled with its almost total disappearance at subducting plate boundaries; only the merest fraction of ocean crust has ever survived in ophiolites. Over the past 2 b.y., ~14% of the volume of the upper mantle has accumulated from recycled ocean crust returned to the mantle by subduction (Yasuda et al., 1994). Even if mixing of the depleted MORB source is sufficient to iron out all heterogeneities in lherzolite, the mantle at spreading ridges is unmixing—which is to say that it is differentiating—as fast as ocean crust is being created; consequently major facies heterogeneity is being imposed on the mantle at trenches at the rates that ocean crust is being produced and ridges are spreading. The facies heterogeneity includes more than eclogite; it also includes the entire mass of residual abyssal peridotite beneath the ocean crust and some amount of overlying sediment. It includes partitioning of the basaltic portion of the lithosphere into extrusives and dikes on the one hand, and gabbro cumulates of great diversity (e.g., Natland and Dick, 2001) on the other. Seismicity tells us that most of this must remain intact for tens of millions of years, at least as long as it takes oceanic lithosphere to reach depths of ~700 km. What process, what form of stirring, of the upper or lower mantle could possibly cause this, let alone the huge mass of ancient subducted material complementary to continental crust, to rehomogenize and create a lithologically uniform depleted reservoir?

The plume hypothesis has subsumed these possibilities into the idea that ocean lithosphere subducts at least into the lower mantle, although the geophysical evidence for this is not very substantial (Anderson, 2002c). The slabs descend all the way to the core (Kellogg, 1991; Kellogg et al., 1999), somewhere along the way picking up at least helium but also a great deal of heat and perhaps geochemical indications of the core. Billions of years later, they return to the Earth's surface in plumes (e.g., Halliday, 1999). The question could well be posed whether such deep descent and return is necessary to explain the geochemistry of places like Iceland and Hawaii. In the first place, descent of slabs to the deepest extent (~700 km) we have ever detected it is associated with the cold, old edges of very large and thick plates. However, plates of a wide variety of ages and thicknesses are entering subduction zones (Rowley, 2002). They equilibrate and bottom out at a variety of depths (Wen and Anderson, 1997; Meibom and Anderson, 2004). The oldest and thickest plates may eventually penetrate the 650 km phase change boundary and pile up at deep chemical discontinuities, but many subducting plates will not do this.

The crust entering many trenches, particularly the myriad trenches in the western Pacific and the Mediterranean and even in parts of the main Pacific basin, is young, a few million years old; the subducting lithosphere is also thin, hot, and relatively buoyant. We can surmise that regions of complex continental collision are like this in general, thus that entire regions of the mantle have many times in Earth history been strongly inoculated with slabs that are both too hot and too buoyant to sink into the lower mantle. Some are clearly caught in continental collisions.

What if much later the overlying continental crust and some of its underlying lithosphere drift away, and then some spreading ridge passes overhead in the endless pattern of ridge migrations that plate tectonics so consistently demonstrates? Could the ridge not sample this mantle just as it is? Could a plate experience a pattern of stress, resulting in fractures that would allow melts from such an aggregate of mantle rock with lots of marbled eclogite to provide magma of very mixed isotopic and trace-element signatures indicating the *shallow* heterogeneity of the source? Is it geologically more reasonable for this to occur or for materials at the Earth's surface to transit the entire thickness of mantle twice, once down to the core-mantle boundary, and then back up to the surface? What is geologically and geophysically more plausible?

Further, do we imagine that the formation of an ocean basin like the Atlantic by rifting and seafloor spreading is a perfectly clean process—that depleted MORB mantle or deep plume mantle instantly, at the sharp edges of the splitting ocean basin, provides the *only* mantle melts that enter the rift? What of the subcontinental mantle roots that are fairly often left in the lee of detached continental crust and stay, perhaps stretched thin, within ocean basins, like the mantle that must certainly underlie or surround Jan Mayen north of Iceland, Rockall Bank west of France, the Seychelles Islands on the Mascarene plateau near the Central Indian ridge, and portions of the Kerguelen plateau off the Southeast Indian ridge? What aspects of their isotopic signatures have we convolved into components of deep mantle plumes at those places? How do they influence melt productivity and crustal thickness? There can be little doubt that they must have some influence.

The Fates of Plates

Plates of a wide variety of ages and thicknesses are entering subduction zones (Rowley, 2002). They equilibrate and bottom out at a variety of depths (Wen and Anderson, 1997; Meibom and Anderson, 2004). The oldest and thickest plates may eventually penetrate the 650 km phase change boundary and pile up at deep chemical discontinuities. Slabs are composed, in part, of oceanic crust and, in part, of serpentinized peridotite. Both CO_2 and water occur in the upper part of the slab. These effects lower the melting point and seismic velocities of slabs compared to dry refractory peridotite. After the conversion of basalt to eclogite, the melting point is still low. A slab placed into mantle of normal temperature will partially melt.

Recycled slabs can be converted to features that not only have low velocity but are also fertile, thus having characteristics associated with plumes. The timescale of this conversion is much less than that of radioactive heating, probably less than 20 m.y. As far as the slab is concerned, the surrounding mantle is an infinite heat source. Deeper than some 600 km, the eclogite in the slab becomes lower in density and velocity than normal mantle (Anderson, 2002c); thus the slabs stop sinking, but very cold and thick slabs may sink deeper.

SUMMARY

The modern plume hypothesis postulates a special form of thermal convection with narrow upwellings and diffuse downwellings similar to atmospheric phenomena such as thunderheads (Morgan, 1972a). These narrow upwellings were proposed as an alternative to the giant convection cells of Holmes (1944), which Hess (1962) imagined to be centered beneath spreading ridges. Plumes thus were imagined to drive plate tectonics and fuel the asthenosphere. The number of plumes proposed has varied from the original "~20" to recent estimates as high as 5200 for the number of moderate-size plumes and 6 or so for the number of "primary" deep mantle plumes. What constitutes a plume is thus uncertain. Tozer (1973) showed that what geologists had in mind for mantle upwellings could not be the same as fluid dynamic plumes and could not be explained by the same physics. The effects of pressure on material properties of the mantle reinforce his conclusions.

The plume hypothesis persists and indeed has flourished despite questions, disagreements, and criticisms that have been leveled against it almost from the start. If this history is any guide, it will continue to be the reigning paradigm for some time to come, in spite of its shortcomings. Internal heating, plate tectonics, "normal" mantle convection, and high ratios of viscosity to thermal conductivity (the mantle situation) do not favor narrow plume formation from deep thermal boundary layers. Plates occupy the upper boundary layer and have properties of buoyancy, coherence or strength, sharp boundaries, strike-slip motions, and elasticity that are incompatible with fluid behavior. Plumes are fluid dynamic phenomena; plates are solids. Formation of the diapir or plume hypothesis was motivated by perceived limitations of the plate tectonic hypothesis and by observations of plumelike structures in the atmosphere, in the crust, and in fluid dynamics textbooks. Fixity and high temperature were once believed necessary to explain parallel island chains and LIPs. These constraints have been dropped (www.mantleplumes.org; Wessel and Kroenke, 1997; Raymond et al., 2000; Koppers et al., 2001; Anderson, this volume).

The crack and stress ideas fell into disfavor because there was no apparent way for them to account for relative fixity, midplate volcanism, and large and variable volumes of basalt (Clague and Dalrymple, 1987). These are not intrinsic limitations but are a result of approximations and assumptions in the kinematic theory of plate tectonics, such as an isothermal, homogeneous mantle of fixed melting point, uniformitarianism, and absolute plate rigidity. A more general theory of plate tectonics, one that involves the end games (transients and plate boundaries associated with collision between arcs, arcs and continents, and continents), recycling, incipient and reactivated plate boundaries, and ephemeral plates, may remove the necessity to have different theories for plate tectonics, LIPs, and linear island chains.

Many of the data that have been used to support the plume hypothesis are subject to multiple interpretations, or they are ambiguous or even contradictory. For example, numerous studies of the core-mantle boundary in the region around Hawaii have been conducted (Nataf, 2000). Some of these have inferred velocity anomalies 1000 km away from Hawaii to the northwest, and others have proposed anomalies to the southeast and northeast. Other studies have found regions of high seismic gradient, changes in anisotropy, high velocity, low velocity, or high scattering in the deep mantle, and all have been attributed to the base of the Hawaiian plume (Nataf, 2000). Such features have also been found elsewhere, where they are not associated with hotspots, or they are offset a considerable distance from a hotspot (e.g., up to 4000 km in the case of Tristan). These have been termed "surprising" and "not up to expectations" (Nataf, 2000; Montelli et al., 2004). Because there are "anomalies" (in seismic velocity, gradients of velocity, anisotropy, gradients of anisotropy, and scattering) at all depths, methods need to be developed for confirming that these really are related to surface features (rather than being random or unrelated) and for determining whether they are continuous rather than isolated deep features.

Petrological aspects of the plume hypothesis depend on the assumption that the mantle is to the first order a homogenous lherzolite in composition. Mantle homogeneity is the cornerstone of models that estimate potential temperature and magma productivity. Indications from geochemistry that such homogeneity is not the case, and instead, for example, that "complete sections of ocean crust" (e.g., Chauvel and Hémond, 2000) have been involved in the derivation of primitive magma beneath Hawaii and Iceland, have not moved many investigators to explore beyond the geometry of plumes to explain temporal sequences and lateral variability in basalt compositions.

The plume hypothesis is still unsupported by a sound or complete theory of thermal convection. Laboratory injection experiments (e.g., those of Campbell and Griffiths, 1990) do not take into account pressure, background convection, or fluid dynamic scaling. Computer simulations usually have appropriate Prandtl numbers but do not take into account pressure or allow the conjectured instabilities to arise naturally (e.g., Cordery et al., 1997). These and similar experiments and calculations provide the experimental and theoretical support for plumes, but the initial and boundary conditions and the physics used to date have been unrealistic. The simulations are not thermodynamically consistent.

A general theory of plate tectonics, one that involves recycling, incipient and reactivated plate boundaries, and ephemeral plates, may remove the necessity to have different theories for plate tectonics, LIPs, and linear island chains (Anderson, 2002a,b,c and this volume; Natland and Winterer, this volume). Cooling of the mantle from above and forces from cooling plates and subducting slabs may be adequate to drive the plates, break the plates, close up or reactivate plate boundaries, reorganize plates, and drive underlying mantle flow. In such a scenario the mantle is by and large passively responding to gravitationally driven motions of the top; dikes and plate boundaries are the result of variable stress in the lithosphere. Melting anomalies may reflect the variable fertility of the underlying mantle.

ACKNOWLEDGMENTS

We thank Gillian Foulger, Warren Hamilton, Anders Meibom, Mike O'Hara, Carol Stein, Seth Stein, Peter Vogt, and Jerry Winterer for discussion of many of the points considered here over the past two years. The manuscript was greatly improved by suggestions made by Bill Dickinson, Eric Lundin, Axel Björnsson, and an anonymous reviewer, plus additional comments by Warren Hamilton, William Glen, and editors Gillian Foulger and Dean Presnall.

REFERENCES CITED

Albers, M., and Christensen, U., 1996, The excess temperature of plumes rising from the core-mantle boundary: Geophysical Research Letters, v. 23, p. 3567–3570, doi: 10.1029/96GL03311.

Allègre, C.J., 1987, Isotope geodynamics: Earth and Planetary Science Letters, v. 86, p. 175–203.

Anderson, D.L., 1975, Chemical plumes in the mantle: Geological Society of America Bulletin, v. 86, p. 1593–1600.

Anderson, D.L., 1987, A seismic equation of state II: Shear properties and thermodynamics of the lower mantle: Physics of Earth and Planetary Interiors, v. 45, p. 307–323.

Anderson, D.L., 1989, Theory of the Earth: Boston, Blackwell Scientific Publications, 366 p.

Anderson, D.L., 1995, Lithosphere, asthenosphere and perisphere: Reviews of Geophysics, v. 33, p. 125–149, doi: 10.1029/94RG02785.

Anderson, D.L., 2000a, The statistics and distribution of helium in the mantle: International Geology Review, v. 42, p. 289–311.

Anderson, D.L., 2000b, The statistics of helium isotopes along the global spreading ridge system: Geophysical Research Letters, v. 27, p. 2401–2404, doi: 10.1029/1999GL008476.

Anderson, D.L., 2001, Top-down tectonics: Science, v. 293, p. 2016–2018, doi: 10.1126/science.1065448.

Anderson, D.L., 2002a, How many plates?: Geology, v. 30, p. 411–414, doi: 10.1130/0091-7613(2002)030<0411:HMP>2.0.CO;2.

Anderson, D.L., 2002b, Occam's razor: Simplicity, complexity, and global geodynamics: Proceedings of the American Philosophical Society, v. 146, no. 1, p. 56–76.

Anderson, D.L., 2002c, Plate tectonics as a far-from-equilibrium self-organized system, *in* Stein, S., and Freymueller, J.T., eds., Plate boundary zones: Washington, D.C., American Geophysical Union Geophysical Monograph, Geodynamics Series 30, p. 411–425.

Anderson, D.L., and Spetzler, H.A.W., 1970, Partial melting and low-velocity zone: Physics of Earth and Planetary Interiors, v. 4, p. 62–64.

Anderson, D.L., Tanimoto, T., and Zhang, Y.-S., 1992, Plate tectonics and hotspots: The third dimension: Science, v. 256, p. 1645–1650.

Bailey, E.B., Clough, C.T., Wright, W.B., Richey, J.E., and Wilson, G.V., 1924, The Tertiary and Post-Tertiary geology of Mull, Loch Aline, and Oban: Memoir of the Geological Survey of Scotland, 445 p.

Batiza, R., and Vanko, D.A., 1985, Petrologic evolution of large failed rifts in the eastern Pacific: Petrology of volcanic and plutonic rocks from the Mathematician Ridge area and the Guadalupe Trough: Journal of Petrology, v. 26, p. 564–602.

Beloussov, V.V., 1956/1962, Basic problems in geotectonics (trans.): New York, McGraw-Hill.

Bercovici, D., and Ricard, Y., 2003, Energetics of a two phase model of lithospheric damage, shear localization and plate boundary formation: Geophysical Journal International, v. 152, p. 581–596, doi: 10.1046/j.1365-246X.2003.01854.x.

Best, W.J., Johnson, L.R., and McEvilly, T.V., 1974, ScS and the mantle beneath Hawaii: Eos (Transactions, American Geophysical Union), Fall Meeting Supplement, v. 55, p. 1147.

Bijwaard, H., and Spakman, W., 1999, Tomographic evidence for a narrow whole mantle plume below Iceland: Earth and Planetary Science Letters, v. 166, p. 121–126, doi: 10.1016/S0012-821X(99)00004-7.

Bijwaard, H., Spakman, W., and Engdahl, E.R., 1998, Closing the gap between regional and global travel time tomography: Journal of Geophysical Research, v. 103, p. 30,055–30,078, doi: 10.1029/98JB02467.

Birch, F., 1952, Elasticity and constitution of the Earth's interior: Journal of Geophysical Research, v. 57, p. 227–286.

Bizzarro, M., and Stevenson, R.K., 2003, Major element composition of the lithospheric mantle under the North Atlantic craton: Evidence from peridotite xenoliths of the Sarfartoq area, southwestern Greenland: Contributions to Mineralogy and Petrology, v. 146, p. 223–240, doi: 10.1007/s00410-003-0499-1.

Bowen, N.L., 1915a, The crystallization of haplobasaltic, haplodioritic, and related magmas: American Journal of Science, v. 40, p. 161–185.

Bowen, N.L., 1915b, The later stages of the evolution of the igneous rocks: Journal of Geology, v. 23, Supplement, p. 1–89.

Bowen, N.L., 1928, The evolution of the igneous rocks: Princeton, New Jersey, Princeton University Press, 332 p.

Breddam, K., 2002, Kistufell: Primitive melt from the Iceland mantle plume: Journal of Petrology, v. 43, p. 345–373, doi: 10.1093/petrology/43.2.345.

Burke, K.C., and Wilson, J.T., 1976, Hot spots on the Earth's surface: Journal of Geophysical Research, v. 93, p. 7690–7708.

Campbell, I.H., and Griffiths, R.W., 1990, Implications of mantle plume structure for the evolution of flood basalts: Earth and Planetary Science Letters, v. 99, p. 79–93, doi: 10.1016/0012-821X(90)90072-6.

Campbell, I.H., and Griffiths, R.W., 1993, The evolution of the mantle's chemical structure: Lithos, v. 30, p. 389–399, doi: 10.1016/0024-4937(93)90047-G.

Chauvel, C., and Hémond, C., 2000, Melting of a complete section of recycled oceanic crust: Trace element and Pb isotopic evidence from Iceland: Geochemistry, Geophysics, Geosystems, v. 1, 1999GC000002.

Clague, D.A., and Dalrymple, G.B., 1987, The Hawaiian-Emperor volcanic chain: Part I, Geologic evolution, *in* Decker, R.W., et al., eds., Volcanism in Hawaii: Reston, Virginia, United States Geological Survey Professional Paper 1350, p. 5–73.

Clague, D.A., and Dalrymple, G.B., 1989, Tectonics, geochronology and origin of the Hawaiian-Emperor volcanic chain, *in* Winterer, E.L., et al., eds., Decade of North American geology, N: The Eastern Pacific Ocean and Hawaii: Boulder Colorado, Geological Society of America, p.188–217.

Clouard, V., and Bonneville, A., 2001, How many Pacific hotspots are fed by deep-mantle plumes?: Geology, v. 29, p. 695–698, doi: 10.1130/0091-7613(2001)029<0695:HMPHAF>2.0.CO;2.

Coffin, M.F., and Eldholm, O., 1994, Large igneous provinces: Crustal structure, dimensions and external consequences: Reviews of Geophysics, v. 32, p. 1–36, doi: 10.1029/93RG02508.

Cordery, M. J., Davies, G. F., and Campbell, I. H., 1997, Genesis of flood basalts from eclogite-bearing mantle plumes: Journal of Geophysical Research, v. 102, p. 20,179–20,197.

Courtillot, V., Jaupart, C., Manighetti, I., Tapponnier, P., and Besse, J., 1999, On causal links between flood basalts and continental breakup: Earth and Planetary Science Letters, v. 166, p. 177–195, doi: 10.1016/S0012-821X(98)00282-9.

Courtillot, V., Davaille, A., Besse, J., and Stock, J.M., 2003, Three distinct types of hotspots in the Earth's mantle: Earth and Planetary Science Letters, v. 205, p. 295–308, doi: 10.1016/S0012-821X(02)01048-8.

Cousens, B.L., 1996, Depleted and enriched upper mantle sources for basaltic rocks from diverse tectonic environments in the northeast Pacific Ocean: The generation of oceanic alkaline vs. tholeiitic basalts, *in* Hart, S.R., and Basu, A., eds., Earth processes: Reading the isotopic code: Washington, D.C., American Geophysical Union Geophysical Monograph 95, p. 207–232.

Cowen, R., and Lipps, J.H., 1975, Controversies in the Earth sciences: San Francisco, West Publishing Company, 437 p.

Craig, H., and Lupton, J., 1976, Primordial Ne, He and H in oceanic basalts: Earth and Planetary Science Letters, v. 31, p. 369–385, doi: 10.1016/0012-821X(76)90118-7.

Craig, H., and Lupton, J., 1981, Helium-3 and mantle volatiles in the ocean and the oceanic crust, *in* C. Emiliani, ed., The sea, v. 7: New York, Wiley, p. 391–428.

Crough, S.T., 1979, Hotspot epeirogeny: Tectonophysics, v. 61, p. 321–333.

Daly, R.A., 1914, Igneous rocks and their origin: New York, McGraw-Hill, 563 p.

Daly, R.A., 1926, Our mobile Earth: New York, Charles Scribner's Sons, 342 p.

Daly, R.A., 1933/1962, Igneous rocks and the depths of the Earth: New York, McGraw-Hill (1933); reprint New York, Hafner Reprint (1962), 598 p.

Dana, J.D., 1849, Geology, *in* Wilkes, C., United States Exploring Expedition, v.10: Philadelphia, C. Sherman; with atlas: New York, Putnam, 756 p.

Darwin, C., 1837, On certain areas of elevation and subsidence in the Pacific and Indian Oceans, as deduced from the study of coral formations: Geological Society of London Proceedings, v. 2, p. 552–554.

Davies, G.F., 1999, Dynamic Earth: Plates, plumes and mantle convection: Cambridge, England, Cambridge University Press, 458 p.

DePaolo, D., and Manga, M., 2003, Deep origin of hotspots: Is only seeing believing?: Science, v. 300, p. 920–921, doi: 10.1126/science.1083623.

Dick, H.J.B., 1989, Abyssal peridotites, very slow spreading ridges and ocean ridge magmatism, *in* Saunders, A.D., and Norry, M.J., eds., Magmatism in the ocean basins: Geological Society (London) Special Publication 42, p. 71–105.

Dick, H.J.B., Fisher, R.L., and Bryan, W.B., 1984, Mineralogic variability of the uppermost mantle along mid-ocean ridges: Earth and Planetary Science Letters, v. 69, p. 88–106.

Duncan, R.A., and Richards, M.A., 1991, Hotspots, mantle plumes, flood basalts, and true polar wander: Reviews of Geophysics, v. 29, p. 31–50.

Duncan, R.A., Petersen, N., and Hargraves, R.B., 1972, Mantle plumes, movement of the European Plate, and polar wandering: Nature, v. 239, p. 82–86.

Eggler, D.H., 1976, Does CO_2 cause partial melting in the low-velocity layer of the mantle?: Geology, v. 4, p. 69–72, doi: 10.1130/0091-7613(1976)4<787:DCCPMI>2.0.CO;2.

Elsasser, W.M., 1969, Convection and stress propagation in the upper mantle, *in* Runcorn, S.K., ed., The application of modern physics to the Earth and planetary interiors: London, Wiley-Interscience, p. 223–245.

Engel, A.E.J., Engel, C.G., and Havens, R.G., 1965, Chemical characteristics of oceanic basalts and the upper mantle: Geological Society of America Bulletin, v. 76, p. 719–734.

Farley, K.A., and Nerona, E., 1998, Noble gases in the Earth's mantle: Annual Reviews of Earth and Planetary Sciences, v. 26, p. 189–218, doi: 10.1146/annurev.earth.26.1.189.

Farley, K.A., Natland, J.H., and Craig, H., 1992, Binary mixing of enriched and undegassed (primitive?) mantle components in lavas from Tutuila, American Samoa: Earth and Planetary Science Letters, v. 111, p. 183–199, doi: 10.1016/0012-821X(92)90178-X.

Favela, J., and Anderson, D.L., 2000, Extensional tectonics and global volcanism: *in* E. Boschi, G. Ekström, and A. Morelli, eds., Problems in Geophysics for the New Millennium, Bologna, Editrice Compositori, p. 463–498.

Forsyth, D., and Uyeda, S., 1975, On the relative importance of the driving forces of plate motion: Geophysical Journal of the Royal Astronomical Society, v. 43, p. 163–200.

Foulger, G.R., Natland, J.H., and Anderson, D.L., 2005, A source for Icelandic magmas in remelted Iapetus crust: Journal of Volcanology and Geothermal Research, v. 141, p. 23–44.

Frey, F.A., Suen, C.J., and Stockman, H.W., 1985, The Ronda high-temperature peridotite: Geochemistry and petrogenesis: Geochimica et Cosmochimica Acta, v. 49, p. 2469–2491, doi: 10.1016/0016-7037(85)90247-9.

Garrido, C.J., and Bodinier, J.-L., 1999, Diversity of mafic rocks in the Ronda peridotite: Evidence for pervasive melt-rock reaction during heating of subcontinental lithosphere by upwelling asthenosphere: Journal of Petrology, v. 40, p. 729–754, doi: 10.1093/petrology/40.5.729.

Gast, P.W., Tilton, G.R., and Hedge, C., 1964, Isotopic composition of lead and strontium from Ascension and Gough islands: Science, v. 145, p. 1181–1185.

Ghiorsio, M.S., and Sack, R.O., 1995, Chemical mass transfer in magmatic processes IV: A revised and internally consistent thermodynamic model for the interpolation and extrapolation of liquid-solid equilibria in magmatic systems at elevated temperatures and pressures: Contributions to Mineralogy and Petrology, v. 119, p. 197–212.

Graham, D.W., 2000, Noble gas isotope geochemistry of mid-ocean ridge and ocean island basalts: Characterization of mantle source reservoirs, *in* Porcelli, D., et al., eds., Noble gases in geochemistry and cosmochemistry: Reviews of Mineralogy and Geochemistry, v. 47, p. 247–317.

Green, D.H., and Ringwood, A.E., 1967, The genesis of basaltic magmas: Contributions to Mineralogy and Petrology, v. 15, p. 103–190, doi: 10.1007/BF00372052.

Griggs, D.T., 1939, A theory of mountain building: American Journal of Science, v. 237, p. 611–650.

Gu, Y.J., and Dziewonski, A.M., 2001, Variations in thickness of the upper mantle transition zone, *in* Romanowicz, B., and Suyehiro, K., eds., Long-term observations in the oceans: Proceedings of the OHP/ION Joint Symposium, Japan, January 21–27: Tokyo, International Ocean Network, 6 p.

Gurenko, A.A., and Chaussidon, M., 1995, Enriched and depleted primitive melts included in olivine from Icelandic tholeiites: Origin by continuous melting of a single mantle column: Contributions to Mineralogy and Petrology, v. 59, p. 2905–2917.

Haase, K.A., Mühe, R., and Stoffers, P., 2000, Magmatism during extension of the lithosphere: Geochemical constraints from lavas of the Shaban Deep, northern Red Sea: Chemical Geology, v. 166, p. 225–239, doi: 10.1016/S0009-2541(99)00221-1.

Hadley, D.M., Stewart, G.S., and Ebel, J.E., 1976, Yellowstone: Seismic evidence for a chemical mantle plume: Science, v. 193, p. 1237–1239.

Halliday, A.N., 1999, Unmixing Hawaiian cocktails: Nature, v. 399, p. 733–734, doi: 10.1038/21533.

Hamilton, W.B., 2002, The closed upper-mantle circulation of plate tectonics, *in* Stein, S., and Freymueller, J.T., eds., Plate boundary zones: Washington, D.C., American Geophysical Union Geophysical Monograph, Geodynamics Series 30, p. 359–410.

Hanan, B.B., and Graham, D.W., 1996, Lead and helium isotope evidence from oceanic basalts for a common deep source of mantle plumes: Science, v. 272, p. 991–995.

Hansteen, R.H., 1991, Multi-stage evolution of the picritic Mælifell rocks, SW Iceland: Constraints from mineralogy and inclusions of glass and fluid in olivine: Contributions to Mineralogy and Petrology, v. 109, p. 225–239, doi: 10.1007/BF00306481.

Hargraves, R.B., and Duncan, R.A., 1973, Does the mantle roll? Nature, v. 245, p. 361.

Hart, S.R., Hauri, E.H., Oschmann, L.A., and Whitehead, J.A., 1992, Mantle plumes and entrainment: Isotopic evidence: Science, v. 256, p. 517–520.

Herzberg, C., and O'Hara, M.J., 2002, Plume-associated ultramafic magmas of Phanerozoic age: Journal of Petrology, v. 43, p. 1857–1883, doi: 10.1093/petrology/43.10.1857.

Hess, H.H., 1962, A history of ocean basins, *in* Engel, A.E.J., et al., eds., Petrologic studies: A volume in honor of A.F. Buddington: Boulder, Colorado, Geological Society of America, p. 599–620.

Hieronymus, C.F., and Bercovici, D., 1999, Discrete alternating hotspot islands formed by interaction of magma transport and lithospheric flexure: Nature, v. 397, p. 604–607, doi: 10.1038/17584.

Hirschmann, M.M., and Stolper, E.M., 1996, A possible role for garnet pyroxenite in the origin of the "garnet signature" in MORB: Contributions to Mineralogy and Petrology, v. 124, p. 185–208, doi: 10.1007/s004100050184.

Hirschmann, M.M., Ghiorso, M.S., and Stolper, E.M., 1999, Calculation of peridotite partial melting from thermodynamic models of minerals and melts, II: Isobaric variations in melts near the solidus and owing to variable source composition: Journal of Petrology, v. 40, p. 297–313, doi: 10.1093/petrology/40.2.297.

Hirschmann, M.M., Kogiso, T., Baker, M.B., and Stolper, E.M., 2003, Alkalic magmas generated by partial melting of garnet pyroxenite: Geology, v. 31, p. 481–484, doi: 10.1130/0091-7613(2003)031<0481:AMGBPM>2.0.CO;2.

Hofmann, A.W., 1997, Mantle geochemistry: The message from oceanic volcanism: Nature, v. 385, p. 219–229, doi: 10.1038/385219a0.

Hofmann, A.W., and Jochum, K.P., 1996, Source characteristics derived from very incompatible trace elements in Mauna Loa and Mauna Kea basalts, Hawaii Scientific Drilling Project: Journal of Geophysical Research, v. 101, p. 11,831–11,839, doi: 10.1029/95JB03701.

Holmes, A., 1928, Radioactivity and earth movements: Transactions of the Geological Society of Glasgow, v. 18, p. 559–606.

Holmes, A., 1944, Principles of physical geology (1st edition): London, Thomas Nelson & Sons, 532 p.

Holmes, A., 1965. Principles of Physical Geology (2nd edition): New York, Ronald Press, 1288 p.

Ito, K., and Kennedy, G.C., 1968, Melting and phase relationships in the plane tholeiite-lherzolite-nepheline basanite to 40 kilobars with geological implications: Contributions to Mineralogy and Petrology, v. 19, p. 177–211.

Jackson, E.D., and Shaw, H.R., 1975, Stress fields in central portions of the Pacific plate: Delineated in time by linear volcanic chains: Journal of Geophysical Research, v. 80, p. 1861–1874.

Jackson, E.D., and Wright, T.L., 1970, Xenoliths in the Honolulu volcanic series, Hawaii: Journal of Petrology, v. 11, p. 405–430.

Jackson, E.D., Shaw, H.R., and Bargar, K.E., 1975, Calculated geochronology and stress field orientations along the Hawaiian chain: Earth and Planetary Science Letters, v. 26, p. 145–155, doi: 10.1016/0012-821X(75)90082-5.

Jacoby, W.R., 1970, Instability in the upper mantle and global plate movements: Journal of Geophysical Research, v. 75, p. 5671–5680.

Jacoby, W.R., 1978, One-dimensional modeling of mantle flow: Pure and Applied Geophysics, v. 116, p. 1231–1249, doi: 10.1007/BF00874683.

Jaques, A.L., and Green, D.H., 1980, Anhydrous melting of periodotite at 0–15 Kb pressure and the genesis of tholeiitic basalts: Contributions to Mineralogy and Petrology, v. 73, no. 3, p. 287–310, doi: 10.1007/BF00381447.

Jordan, T.L., 1979, Mineralogies, densities, and seismic velocities of garnet lherzolites and their geophysical implications, *in* Boyd, F.R., and Meyer, H.O.A., eds., The mantle sample: Inclusions in kimberlites and other volcanics: Proceedings of the 2nd International Kimberlite Conference: Washington, D.C., American Geophysical Union, v. 2, p. 1–14.

Kanasewich, E.R., and Gutowski, P.R., 1975, Detailed seismic analysis of a lateral mantle inhomogeneity: Earth and Planetary Science Letters, v. 25, p. 379–384, doi: 10.1016/0012-821X(75)90256-3.

Kanasewich, E.R., Ellis, R.M., Chapman, C.H., and Gutowski, P.R., 1972, Teleseismic array evidence for inhomogeneities in the lower mantle and the origin of the Hawaiian Islands: Nature, v. 239, p. 99–100.

Kanasewich, E.R., Ellis, R.M., Chapman, C.H., and Gutowski, P.R., 1973, Seismic array evidence of a core boundary source for the Hawaiian linear volcanic chain: Journal of Geophysical Research, v. 78, p. 1361–1371.

Katzman, R., Zhao, L., and Jordan, T.H., 1998, High-resolution, two-dimensional vertical tomography of the central Pacific using ScS reverberations and frequency-dependent travel times: Journal of Geophysical Research, v. 103, p. 17,933–17,971, doi: 10.1029/98JB00504.

Kaula, W.M., 1983, Minimal upper mantle temperature variations consistent with observed heat flow and plate velocities: Journal of Geophysical Research, v. 88, p. 10,323–10,332.

Keller, W., Anderson, D.L., and Clayton, R.W., 2000, Resolution of tomographic models of the mantle beneath Iceland: Geophysical Research Letters, v. 27, p. 3993–3996, doi: 10.1029/2000GL011798.

Kellogg, L.H., 1991, Interaction of plumes with a compositional boundary at 670 km: Geophysical Research Letters, v. 18, p. 865–868.

Kellogg, L.H., and King, S.D., 1997, The effect of temperature dependent viscosity on the structure of new plumes in the mantle: Results of a finite element model in a spherical, axisymmetric shell: Earth and Planetary Science Letters, v. 148, p. 13–26, doi: 10.1016/S0012-821X(97)00025-3.

Kellogg, L.H., and Wasserburg, G.J., 1990, The role of plumes in mantle helium fluxes: Earth and Planetary Science Letters, v. 99, p. 276–289, doi: 10.1016/0012-821X(90)90116-F.

Kellogg, L.H., Hager, B.H., and van der Hilst, R.D., 1999, Compositional stratification in the deep mantle: Science, v. 283, p. 1881–1884, doi: 10.1126/science.283.5409.1881.

Kennedy, W.Q., 1933, Trends of differentiation in basaltic magmas: American Journal of Science, v. 25, p. 239–256.

Kious, W.J., and Tilling, R.I., 1996, This dynamic Earth: The story of plate tectonics: Washington, D.C., United States Geological Survey, available online at http://pubs.usgs.gov/publications/text/dynamic.html.

Klein, E.M., and Langmuir, C.H., 1987, Global correlations of ocean ridge basalt chemistry with axial depth and crustal thickness: Journal of Geophysical Research, v. 92, p. 8089–8115.

Kogiso, T., Hirose, K., and Takahashi, E., 1998, Melting experiments on homogeneous mixtures of peridotite and basalt: application to the genesis of ocean island basalts: Earth and Planetary Science Letters, v. 162, p. 45–61, doi: 10.1016/S0012-821X(98)00156-3.

Koppers, A.A.P., Phipps Morgan, J., Morgan, W.J., and Staudigel, H., 2001, Testing the fixed hotspot hypothesis using ^{40}Ar/^{39}Ar age progressions along seamount trails: Earth and Planetary Science Letters, v. 185, p. 237–252, doi: 10.1016/S0012-821X(00)00387-3.

Kuhn, T.S., 1962, The structure of scientific revolutions: Chicago, University of Chicago Press, 172 p.

Lambert, I.B., and Wyllie, P.J., 1970, Low-velocity zone of the Earth's mantle: Incipient melting caused by water: Science, v. 169, p. 764–766.

Langmuir, C.M., Klein, E.M., and Plank, T., 1992, Petrological systematics of mid-ocean ridge basalts: Constraints on melt generation beneath ocean ridges, *in* Phipps Morgan, J., et al., eds., Mantle flow and melt generation at mid-ocean ridges: Washington, D.C., American Geophysical Union Geophysical Monograph 71, p. 183–280.

Larsen, T., and Yuen, D., 1997, Fast plumeheads: Geophysical Research Letters, v. 24, p. 1995–1998, doi: 10.1029/97GL01886.

Lassiter, J.C., and Hauri, E.H., 1998, Osmium-isotope variations in Hawaiian lavas: Evidence for recycled oceanic lithosphere in the Hawaiian plume: Earth and Planetary Science Letters, v. 164, p. 483–496, doi: 10.1016/S0012-821X(98)00240-4.

Malamud, B.D., and Turcotte, D.L., 1999, How many plumes are there?: Earth and Planetary Science Letters, v. 174, p. 113–124, doi: 10.1016/S0012-821X(99)00257-5.

McElhinny, M.W., 1973, Mantle plumes, paleomagnetism and polar wandering: Nature, v. 241, p. 523–524.

McKenzie, D., and Bickle, J., 1988, The volume and composition of melt generated by extension of the lithosphere: Journal of Petrology, v. 29, p. 625–679.

McKenzie, D., Stracke, A., Blichert-Toft, J., Albaréde, F., Grönvold, K., and O'Nions, R.K., 2004, Source enrichment processes responsible for isotopic anomalies in oceanic island basalts: Geochimica et Cosmochimica Acta, v. 68, p. 2699–2724, doi: 10.1016/j.gca.2003.10.029.

Meibom, A., and Anderson, D.L., 2004, The statistical upper mantle assemblage: Earth and Planetary Science Letters, v. 217, p. 123–139, doi: 10.1016/S0012-821X(03)00573-9.

Menard, H.W., 1973, Epeirogeny and plate tectonics: Eos (Transactions, American Geophysical Union), v. 54, p. 1244–1255.

Moghazi, A.-K.G., 2003, Geochemistry of a Tertiary continental basalt suite, Red Sea coastal plain, Egypt: Petrogenesis and characteristics of mantle source regions: Geological Magazine, v. 140, p. 11–24, doi: 10.1017/S0016756802006994.

Montelli, R., Nolet, G., Dahlen, F.A., Masters, G., Engdahl, E.R., and Hung, S.-H., 2004, Finite-frequency tomography reveals a variety of plumes in the mantle: Science, v. 303, p. 338–343, doi: 10.1126/science.1092485.

Morgan, W.J., 1971, Convective plumes in the lower mantle: Nature, v. 230, p. 42–43.

Morgan, W.J., 1972a, Deep mantle convection plumes and plate motions: Bulletin of the American Association of Petroleum Geologists, v. 56, p. 203–213.

Morgan, W.J., 1972b, Plate motions and deep mantle convection, *in* Shagam, R., et al., eds., Studies in Earth and space sciences: A volume in honor of Harry Hammond Hess: Boulder, Colorado, Geological Society of America Memoir 132, p. 7–22.

Müller, R.D., Gaina, C., Tikku, A., Mihut, D., Cande, S.C., and Stock, J.M., 2000, Mesozoic/Cenozoic tectonic events around Australia, *in* Richards, M.A., et al., eds., The history and dynamics of global plate motions: Washington, D.C., American Geophysical Union, Geophysical Monograph 121, p. 161–188.

Nataf, H.-C., 2000, Seismic imaging of mantle plumes: Annual Reviews of Earth and Planetary Science, v. 28, p. 391–417, doi: 10.1146/annurev.earth.28.1.391.

Nataf, H.C., and Lay, T., Anderson, D.L., and Okal, E. A., 1981, Reassessment of a reported S-delay under Trinidade: Geophysical Research Letters, v. 8, p. 1027–1030.

Natland, J.H., 1989, Partial melting of a lithologically heterogeneous mantle, *in* Saunders, A.D., and Norry, M.J., eds., Magmatism in the ocean basins. Geological Society of London Special Publication 42, p. 41–77.

Natland, J.H., 2003, What's going on at Iceland? *in* The hotspot handbook: Abstracts, Penrose Conference Plumes IV: Beyond the Plume Hypothesis: Boulder, Colorado, Geological Society of America.

Natland, J.H., and Dick, H.J.B., 2001, Formation of the lower ocean crust and the crystallization of gabbroic cumulates at a very slowly spreading ridge: Journal of Volcanology and Geothermal Research, v. 110, p. 191–233, doi: 10.1016/S0377-0273(01)00211-6.

Niu, Y.-L., Regelous, M., Wendt, I., Batiza, R., and O'Hara, M.J., 2002, Geochemistry of near-EPR seamounts: Importance of source vs. process and the origin of enriched mantle component: Earth and Planetary Science Letters, v. 199, p. 327–345, doi: 10.1016/S0012-821X(02)00591-5.

O'Hara, M.J., 1968, The bearing of phase equilibria studies in synthetic and natural systems on the origin and evolution of basic and ultrabasic rocks: Earth Science Reviews, v. 4, p. 69–133, doi: 10.1016/0012-8252(68)90147-5.

O'Hara, M.J., 1973, Non-primary magmas and dubious mantle plume beneath Iceland: Nature, v. 243, p. 507–508.

O'Hara, M.J., and Mathews, R.E., 1981, Geochemical evolution in an advancing, periodically replenished, periodically tapped, continuously fractionated magma chamber: Journal of the Geological Society of London, v. 138, p. 237–277.

Oxburgh, E.R., and Parmentier, E.M., 1977, Compositional and density stratification in oceanic lithosphere: Causes and consequences: Journal of the Geological Society of London, v. 133, p. 343–355.

Oxburgh, R., and Turcotte, D., 1974, Membrane tectonics and the East African rift: Earth and Planetary Science Letters, v. 22, p. 133–140, doi: 10.1016/0012-821X(74)90073-9.

Pertermann, M., and Hirschmann, M.M., 2003a, Anhydrous partial melting experiments on MORB-like eclogite: Phase relations, phase compositions and mineral melt-partitioning of major elements at 2–3 GPa: Journal of Petrology, v. 44, p. 2173–2201, doi: 10.1093/petrology/egg074.

Pertermann, M., and Hirschmann, M.M., 2003b, Partial melting experiments on a MORB-like pyroxenite between 2 and 3 GPa: Constraints on the presence of pyroxenite in basalt source regions from solidus location and melting rate: Journal of Geophysical Research, v. 108, doi:10.1029/2000JB000118.

Phipps Morgan, J., 1997, The generation of a compositional lithosphere by mid-ocean ridge melting and its effect on subsequent off-axis hotspot upwelling and melting: Earth and Planetary Science Letters, v. 146, p. 213–232, doi: 10.1016/S0012-821X(96)00207-5.

Plank, T., and Langmuir, C.H., 1992, Effects of melting regime on the composition of the oceanic crust: Journal of Geophysical Research, v. 97, p. 19,749–19,770.

Presnall, D.C., 1969, The geometrical analysis of partial fusion: American Journal of Science, v. 267, p. 1178–1194.

Presnall, D.C., and Helsley, C.E., 1982, Diapirism of depleted peridotite: A model for the origin of hot spots: Physics of the Earth and Planetary Interiors, v. 29, p. 148–160, doi: 10.1016/0031-9201(82)90069-3.

Presnall, D.C., Gudfinnsson, G.H., and Walter, M.J., 2002, Generation of mid-ocean ridge basalts at pressures from 1 to 7 GPa: Geochimica et Cosmochimica Acta, v. 66, p. 2073–2090, doi: 10.1016/S0016-7037(02)00890-6.

Ramberg, H., 1967a, Gravity, deformation and the Earth's crust: London, Academic Press, 214 p.

Ramberg, H., 1967b, Model experimentation of the effect of gravity on tectonic processes: Geophysical Journal of the Royal Astronomical Society, v. 14, p. 307–329.

Ramberg, H., 1970, Model studies in relation to intrusion of plutonic bodies, *in* Newall, G., and Rast, N., eds., Mechanism of igneous intrusion: Geological Journal, Special Issue, v. 2, p. 261–286.

Ramberg, H., 1981, Gravity, deformation and the Earth's crust (2nd edition): London, Academic Press, 452 p.

Raymond, C.A., Stock, J.M., and Cande, S.C., 2000, Fast Paleogene motion of the Pacific hotspots from revised global plate circuit constraints, *in* Richards, M.A., et al., eds., History and dynamics of global plate motions: Washington, D.C., American Geophysical Union, Geophysical Monograph 121, p. 359–375.

Richter, F.M., and Parsons, B., 1975, On the interaction of two scales of convection in the mantle: Journal of Geophysical Research, v. 80, p. 2529–2541.

Ringwood, A.E., 1975, Composition and origin of the Earth's mantle: New York, McGraw-Hill, 618 p.

Ritsema, J., and Allen, R.M., 2003, The elusive mantle plume: Earth and Planetary Science Letters, v. 207, p. 1–12, doi: 10.1016/S0012-821X(02)01093-2.

Ritsema, J.H., and van Heijst, J., 2000, Seismic imaging of structural heterogeneity in Earth's mantle: Evidence for large-scale mantle flow: Science Progress, v. 83, p. 243.

Ritsema, J.H., Rivera, L.A., Komatitsch, D., Tromp, J., and van Heijst, H.-J., 2002, Effects of crust and mantle heterogeneity on PP/P and SS/S amplitude ratios: Geophysical Research Letters, v. 29, no. 10, doi: 10.1029/2001GLO13831, 4 p.

Romanowicz, B., and Gung, Y., 2002, Superplumes from the core-mantle boundary to the lithosphere: Implications for heat flux: Science, v. 296, p. 513–516, doi: 10.1126/science.1069404.

Rowley, D.B., 2002, Rate of plate creation and destruction: 180 Ma to present: Geological Society of America Bulletin, v. 114, p. 927–933, doi: 10.1130/0016-7606(2002)114<0927:ROPCAD>2.0.CO;2.

Salters, V.J.M., and Dick, B.J.B., 2002, Mineralogy of the mid-ocean-ridge basalt source from neodymium isotopic composition of abyssal peridotites: Nature, v. 418, p. 68–72, doi: 10.1038/nature00798.

Saunders, A.D., Rogers, G., Marriner, G.F., Terrel, D.J., and Verma, S.P., 1987, Geochemistry of Cenozoic volcanic rocks, Baja California, Mexico: Implications for the petrogenesis of post-subduction magmas: Journal of Volcanology and Geothermal Research, v. 32, p. 223–245, doi: 10.1016/0377-0273(87)90046-1.

Schilling, J.G., 1973a, Iceland mantle plume: Geochemical study of Reykjanes ridge: Nature, v. 242, p. 565–571.

Schilling, J.G., 1973b, Mantle plume–spreading ridge system: Geochemical evidence: Eos (Transactions, American Geophysical Union), v. 54, p. 243.

Schubert, G., Turcotte, D.L., and Olson, P., 2001, Mantle convection in th Earth and planets: Cambridge, England, Cambridge University Press, 940 p.

Schwab, B.E., and Johnston, A.D., 2001, Melting systematics of modally variable, compositionally intermediate peridotites and the effects of mineral fertility: Journal of Petrology, v. 42, p. 1789–1811, doi: 10.1093/petrology/42.10.1789.

Sen, G., 1983, A petrologic model for the constitution of the upper mantle and crust of the Koolau Shield, Oahu, Hawaii, and Hawaiian magmatism: Earth and Planetary Science Letters, v. 62, p. 215–228, doi: 10.1016/0012-821X(83)90085-7.

Sen, G., 1988, Petrogenesis of spinel lherzolite and pyroxenite suite xenoliths from the Koolau Shield, Oahu, Hawaii: Implications for petrology of the post-eruptive lithosphere beneath Oahu: Contributions to Mineralogy and Petrology, v. 100, p. 61–91, doi: 10.1007/BF00399440.

Shagam, R., Hargraves, R.B., Morgan, W.J., Van Houten, F.B., Burk, C.A., Holland, H.D., and Hollister, L.C., eds., 1972, Studies in Earth and space sciences: A memoir in honor of Harry Hammond Hess: Boulder, Colorado, Geological Society of America Memoir 132, 683 p.

Shaw, H.R., and Jackson, E.D., 1973, Linear island chains in the Pacific: Result of thermal plumes or gravitational anchors?: Journal of Geophysical Research, v. 78, p. 8634–8652.

Shaw, H.R., Jackson, E.D., and Bargar, K.E., 1980, Volcanic periodicity along the Hawaiian-Emperor chain: American Journal of Science, v. 280A (Jackson volume), p. 667–708.

Sigurdsson, I.A., Steinthorsson, S., and Grönvold, K., 2000, Calcium-rich melt inclusions in Cr-spinels from Borgarhraun, northern Iceland: Earth and Planetary Science Letters, v. 183, p. 15–26, doi: 10.1016/S0012-821X(00)00269-7.

Sipkin, S.A., and Jordan, T.H., 1975, Lateral heterogeneity of the upper mantle determined from the travel times of ScS: Journal of Geophysical Research, v. 80, p. 1474–1484.

Sleep, N.H., 1984, Tapping of magmas from ubiquitous mantle heterogeneities: An alternative to mantle plumes?: Journal of Geophysical Research, v. 89, p. 10,029–10,041.

Sleep, N.H., 1990, Hotspots and mantle plumes: Some phenomenology: Journal of Geophysical Research, v. 95, p. 6715–6736.

Sleep, N.H., 1992, Hotspot volcanism and mantle plumes: Annual Reviews of Earth and Planetary Science, v. 20, p. 19–43, doi: 10.1146/annurev.ea.20.050192.000315.

Sleep, N.H., 1994, Lithospheric thinning by midplate mantle plumes and the thermal history of hot plume material ponded at sublithospheric depths: Journal of Geophysical Research, v. 99, p. 9327–9343, doi: 10.1029/94JB00240.

Sleep, N.H., 1997, Lateral flow and ponding of starting plume material: Journal of Geophysical Research, v. 102, p. 10,001–10,012.

Sleep, N.H., 2003, Mantle plumes?: Astronomy and Geophysics, v. 44, no. 1, p. 1.11–1.13.

Sleep, N.H., 1996, Lateral flow of hot plume material ponded at sublithospheric depths: Journal of Geophysical Research, v. 101, p. 28,065–28,083, doi: 10.1029/96JB02463.

Smith, P.J., 1973a, Alternative to mantle plumes: Nature, v. 244, p. 327.

Smith, P.J., 1973b, Are mantle plumes fixed?: Nature-Physical Science, v. 241, p. 153.

Smith, P.J., 1973c, Dubious mantle plume: Nature, v. 243, p. 491–492.

Smith, P.J., 1973d, Mantle plumes get cool reception: Nature, v. 243, p. 192.

Smith, P.J., 1975, Canary mantle plume unlikely: Nature, v. 258, p. 385–386.

Sobolev, A.V., Hofmann, A., and Nikogosian, I.K., 2000, Recycled oceanic crust observed in "ghost plagioclase" within the source of Manua Loa lavas: Nature, v. 404, p. 986–999, doi: 10.1038/35010098.

Steinberger, B., and O'Connell, R.J., 2000, Effects of mantle flow on hotspot motion, *in* Richards, M.A., et al., eds., History and dynamics of global plate motions: Washington, D.C., American Geophysical Union, Geophysical Monograph 121, p. 377–398.

Sykes, L.R., 1978, Intraplate seismicity, reactivation of preexisting zones of weakness, alkaline magmatism, and other tectonism post-dating continental fragmentation: Reviews of Geophysics and Space Physics, v. 16, p. 621–688.

Tackley, P., 1998, Three dimensional simulations of mantle convection with a thermo-chemical basal boundary layer, *in* Gurnis, M., et al., eds., The core-mantle boundary region: Washington, D.C., American Geophysical Union, Geodynamics Series 28, p. 231–353.

Takahashi, E., Nakajima, K., and Wright, T.L., 1998, Origin of the Columbia River basalts: Melting model of a heterogeneous plume head: Earth and Planetary Science Letters, v. 162, p. 63–80, doi: 10.1016/S0012-821X(98)00157-5.

Tatsumoto, M., 1966, Genetic relations of oceanic basalts as indicated by lead isotopes: Science, v. 153, p. 1094–1101.

ten Brink, U.S., 1991, Volcano spacing and plate rigidity: Geology, v. 19, p. 397–400, doi: 10.1130/0091-7613(1991)019<0397:VSAPR>2.3.CO;2.

Tozer, D.C., 1973, Thermal plumes in the Earth's mantle: Nature, v. 244, p. 398–400.

Turcotte, D.L., and Oxburgh, E.R., 1973, Mid-plate tectonics: Nature, v. 244 S, p. 337–339.

Vanko, D.A., and Batiza, R., 1982, Gabbroic rocks from the Mathematician Ridge failed rift: Nature, v. 300, p. 742–744, doi: 10.1038/300742a0.

Vitaliano, D.B., 1973, Legends of the Earth: Bloomington, Indiana University Press.

Vogt, P.R., 1972, Evidence for global synchronism in mantle plume convection, and possible significance for geology: Nature, v. 240, p. 338–340.

Von Herzen, R.P., Cordery, M.J., Detrick, R.S., and Fang, C., 1989, Heat-flow and the thermal origin of hot spot swells: The Hawaiian swell revisited: Journal of Geophysical Research, v. 94, p. 13,783–13,799.

Walker, R.J., 2003, Isotopic detection of possible core-mantle interactions in plume sources: Rules of engagement: Abstract *in* The hotspot handbook: Proceedings of Penrose Conference, Plume IV: Beyond the Plume Hypothesis, Hveragerdi, Iceland, August 25–29.

Walker, R.J., Morgan, J.W., and Horan, M.F., 1995, ^{187}Os enrichment in some plumes: Evidence for core-mantle interaction: Science, v. 269, p. 819–822.

Washington, H.S., 1925, The chemical composition of the earth: American Journal of Science, v. 9, p. 351–378.

Watts, A.B., 1978, An analysis of isostasy in the world's oceans: 1, Hawaiian-Emperor seamount chain: Journal of Geophysical Research, v. 83, p. 5989–6004.

Watts, A.B., and ten Brink, U.S., 1989, Crustal structure, flexure and subsidence history of the Hawaiian Islands: Journal of Geophysical Research, v. 94, p. 10,473–10,500.

Weaver, B., 1991, Trace element evidence for the origin of ocean-island basalt: Geology, v. 19, p. 123–126, doi: 10.1130/0091-7613(1991)019<0123:TEEFTO>2.3.CO;2.

Wen, L., and Anderson, D.L., 1997, Slabs, hotspots, cratons and mantle convection revealed from residual seismic tomography in the upper mantle: Physics of the Earth and Planetary Interiors, v. 99, p. 131–143, doi: 10.1016/S0031-9201(96)03162-7.

Wessel, P., and Kroenke, L.W., 1997, A geometric technique for relocating hotspots and refining absolute plate motions: Nature, v. 387, p. 365–369, doi: 10.1038/387365a0.

Westervelt, W.D., 1963, Hawaiian legends of volcanoes: Rutland, Vermont, Charles E. Tuttle.

Wilson, J.T., 1963, A possible origin of the Hawaiian Islands: Canadian Journal of Physics, v. 41, p. 863–870.

Woods, M., and Okal, E., 1996, Rayleigh-wave dispersion along the Hawaiian swell: A test of lithospheric thinning by thermal rejuvenation at a hot spot: Geophysical Journal International, v. 125, p. 325–339.

Woods, M., Lévêque, J.J., Okal, E., and Cara, M., 1991, Two-station measurements of Rayleigh wave group velocity along the Hawaiian swell: Geophysical Research Letters, v. 18, p. 105–108.

Wright, C., 1975, Comments on "Seismic array evidence of a core boundary source for the Hawaiian linear volcanic chain" by E.R. Kanasewich et al.: Journal of Geophysical Research, v. 80, p. 1915–1919.

Wright, E., 1987, Mineralogical studies of Samoan ultramafic xenoliths: Implications for upper mantle processes, *in* Keating, B.H., et al., eds., Seamounts, islands, and atolls: Washington, D.C., American Geophysical Union, Geophysical Monograph 143, p. 221–234.

Yasuda, A., Fujii, T., and Kurita, K., 1994, Melting phase relations of an anhydrous mid-ocean ridge basalt from 3 to 20 GPa: Implications for the behavior of subducted oceanic crust in the mantle: Journal of Geophysical Research, v. 99, p. 9401–9414, doi: 10.1029/93JB03205.

Yaxley, G.M., 2000, Experimental study of the phase and melting relations of homogeneous basalt + peridotite mixtures and implication for the petrogenesis of flood basalts: Contributions to Mineralogy and Petrology, v. 139, p. 326–338, doi: 10.1007/s004100000134.

Yoder, H.S., 1976, Generation of basaltic magma: Washington, D.C., National Academy of Sciences, 265 p.

Yoder, H.S., Jr., and Tilley, C.E., 1962, Origin of basalt magmas: An experimental study of natural and synthetic rock systems: Journal of Petrology, v. 3, p. 342–532.

Zindler, A., and Hart, S.R., 1986a, Chemical geodynamics: Annual Reviews of Earth and Planetary Science, v. 14, p. 493–571, doi: 10.1146/annurev.ea.14.050186.002425.

Zindler, A., and Hart, S., 1986b, Helium: Problematic primordial signals: Earth and Planetary Science Letters, v. 79, p. 1–8, doi: 10.1016/0012-821X(86)90034-8.

MANUSCRIPT ACCEPTED BY THE SOCIETY JANUARY 3, 2005