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The Controversy over Plumes: Who Is Actually Right?

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Abstract—The current state of the theory of mantle plumes and its relation to classic plate tectonics show that the “plume” line of geodynamic research is in a period of serious crisis. The number of publications criticizing this concept is steadily increasing. The initial suggestions of plumes' advocates are disputed, and not without grounds. Questions have been raised as to whether all plumes are derived from the mantle–core interface; whether they all have a wide head and a narrow tail; whether they are always accompanied by uplifting of the Earth’s surface; and whether they can be reliably identified by geochemical signatures, e.g., by the helium-isotope ratio. Rather convincing evidence indicates that plumes cannot be regarded as a strictly fixed reference frame for moving lithospheric plates. More generally, the very existence of plumes has become the subject of debate. Alternative ideas contend that all plumes, or hot spots, are directly related to plate-tectonic mechanisms and appear as a result of shallow tectonic stress, subsequent decompression, and melting of the mantle enriched in basaltic material. Attempts have been made to explain the regular variation in age of volcanoes in ocean ridges by the crack propagation mechanism or by drift of melted segregations of enriched mantle in a nearly horizontal asthenospheric flow. In the author’s opinion, the crisis may be overcome by returning to the beginnings of the plume concept and by providing an adequate specification of plume attributes. Only mantle flows with sources situated below the asthenosphere should be referred to as plumes. These flows are not directly related to such plate-tectonic mechanisms as passive rifting and decompression melting in the upper asthenosphere and are marked by time-progressive volcanic chains; their subasthenospheric roots are detected in seismic tomographic images. Such plumes are mostly located at the margins of superswells, regions of attenuation of seismic waves at the mantle–core interface.

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INTRODUCTION

The history of Earth sciences has frequently involved crises accompanied by vigorous debate. The well-known controversies of neptunists and plutonists, catastrophists and evolutionists, and mobilists and fixists are examples. These great controversies, initiated by irreconcilable opponents with polarized views, led to fruitful search for new arguments and facts pro and contra, to disproofs and compromises, and finally, to a clear understanding of the frames of reference under which the arguments of both sides may carry weight.

A new debate in Earth sciences, which has flared up over the last decade, concerns the existence or nonexistence of so-called plumes. Ranking this discussion among the great controversies in the field, I would call readers' attention not only to its passionate and at times biased character, but also to the great implications of its subject, which concerns processes that develop throughout the mantle, especially its lower part, and are reflected in the Earth’s crust. The resolution of this controversy will influence our basic concepts of global geodynamics and our knowledge of the tectonics and metallogeny of the Earth’s crust and of the tectonosphere as a whole.

This paper is an attempt to investigate the logic of the arguments adduced by confronting sides and to give my own estimate of the current state of the art, avoiding, where possible, the emotions and biases inherent to many participants in the debate.

HOT SPOTS, HOT FIELDS, PLUMES, SUPERPLUMES, AND LIPS

The idea that chains of volcanoes on the oceanic floor are hot spots, i.e., surface manifestations of local anomalous zones of melting in the mantle, was set forth by Wilson [71] more than 40 years ago. Subsequently, this idea was developed into the concept of mantle plumes (plumages) [51], spatially fixed vertical convective flows (upwelling) of hot light material ascending from the mantle–core boundary. The volcanic trail of these flows on the Earth’s surface depends on the motion of lithospheric plates, allowing use of the projection of any such flow on the Earth’s surface as a relatively stable reference point. The Hawaiian–Emperor Seamount Chain (Fig. 1) is a classic example.

The idea of plumes has something in common, but does not coincide completely, with the idea of asthenoliths—columns of heated light material emerging in the mantle—stated by Belousov [2]. In contrast to Belousov, the advocates of the plume concept do not strive to deny horizontal displacements of lithospheric

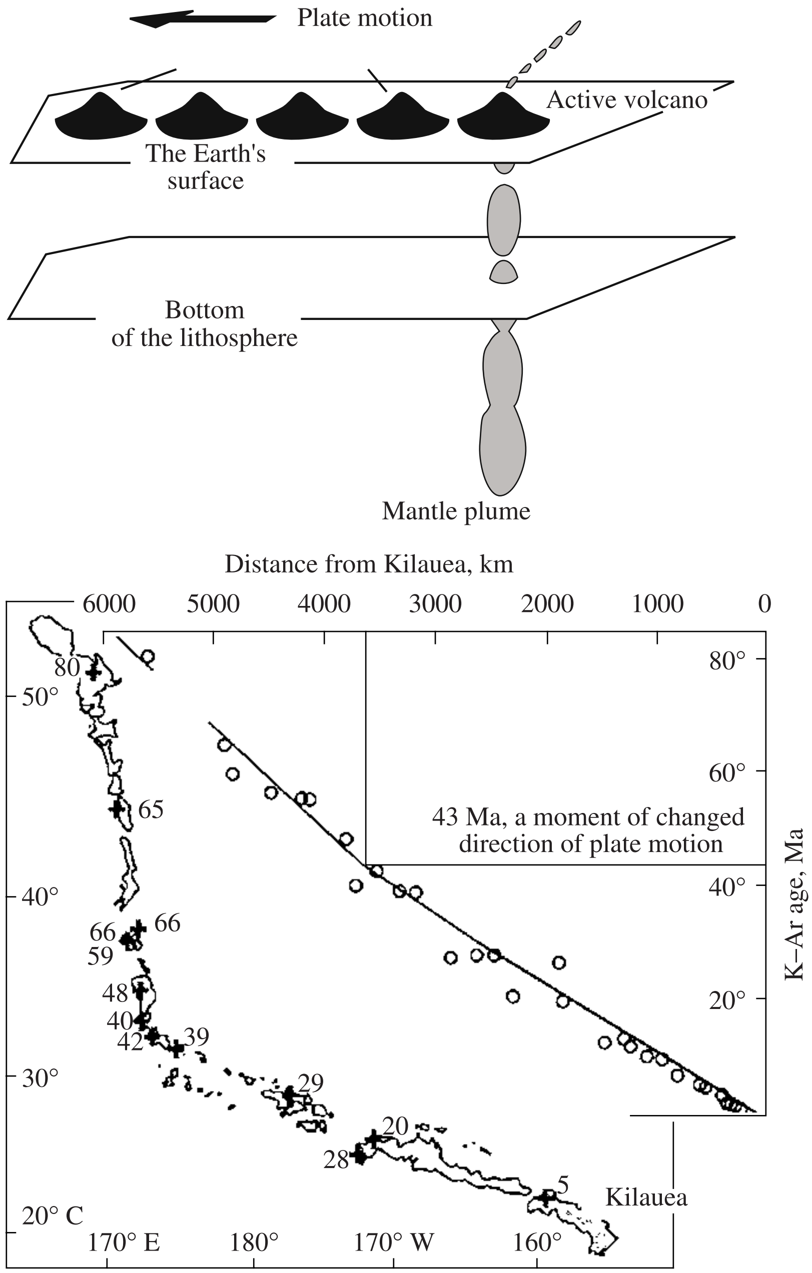

Fig. 1. (Above) The classic model of hot-spot formation in terms of the plume hypothesis. The mantle plume penetrates into the lithosphere and provokes a volcanic eruption. The lithosphere moves relative to the plume with the formation of a volcanic chain. (Below) Hawaiian–Emperor time-progressive volcanic chain with notation of age of igneous rocks, Ma. (Side) The relationship of age vs. distance from the active Kilauea volcano [53].

plates, and regard plume tectonics as a substantial supplement to the classic tectonics of lithospheric plates.

Over the last 35 years, plume tectonics has developed actively, involving seismic tomography, petrology, geochemistry, and isotope geology in the sphere of consideration. The concepts of hot fields [5], or large igneous provinces (LIPs) [26], have been developed. The recently specified definition of LIP is as follows: "Large igneous provinces are magmatic provinces with areal extents >0.1 Mkm^2, igneous volumes >0.1 Mkm^3, and maximum lifespans of ~50 Ma that have intraplate tectonic settings or geochemical affinities and are characterized by igneous pulse(s) of short duration (~1–5 Ma), during which a large proportion (>75%) of the total igneous volume was emplaced" [19].

The development of LIPs has been attributed to the breakdown of supercontinents, first Pangea [4, 64] and then Rodinia [48, 49]. The formation of LIPs is equated with superplumes, i.e., vast plumelike upwellings of mantle material resulting from relatively short-term melting and eruption of enormous volumes of volcanic rocks. The relationships of plumes to superplumes and of both to superswells—low-velocity regions in the D'' layer at the mantle–core boundary (see below)—have been established. Comprehensive information on LIPs is accessible at the website http://www.largeigneous-provinces.org.

ATTRIBUTES AND PROPERTIES OF PLUMES AND SUPERPLUMES

As the theory was developing, a set of attributes and properties ascribed to plumes and superplumes was proposed.

(1) The aforementioned time-progressive volcanic chains suggested that hot spots and plumes actually exist. As was inferred initially, plumes are strictly fixed and may serve as reference points for plate motions. To date, isotopic timing has confirmed the existence of at least twenty such chains (Fig. 2).

(2) The vertical columns or inclined zones of low-density mantle material detected by seismic tomography beneath active plumes extend to a great depth, often exceeding a few hundred kilometers and occasionally reaching the upper–lower mantle interface and even the mantle–core boundary [75] (Fig. 3). Tectonophysical modeling [24] suggests that these are nearly vertical cylindrical bodies with a thin feeder and a wide frontal portion (head–tail structure). Setting against the lithosphere, the head spreads over a large territory and produces voluminous melts, whereas the volume of melts related to the feeding conduit diminishes.

(3) Individual plumes and superplumes are related to low-density domains in the lower mantle (Fig. 4). Two large low-shear-velocity provinces (LLSVPs) have been revealed beneath the southern Pacific Ocean and Africa with seismic tomography [21]. The LLSVPs reach a thousand kilometers in plan view and extend upward, gradually disintegrating throughout the mantle and concentrating mainly above two superswells of the D'' surface. The location of the Pacific and African superswells, in turn, is correlated with the geoid shape.

It is pointed out that superswells are partly limited by sharp boundaries and thus mark compositional heterogeneities rather than purely thermal phenomena [1, 21, 38, 70].

(4) Plumes are related to doming of the Earth's surface.

(5) Basalts of separate plumes are distinguished from MORB by higher LILE and LREE contents and elevated $^{87}Sr/^{86}Sr$, $^{143}Nd/^{144}Nd$, $^{206}Pd/^{204}Pd$, and especially $^{3}He/^{4}He$ isotope ratios. The latter value is the ratio of primordial solar He to radiogenic He and is regarded as an indicator of deep source [5]. It has been suggested that these characteristics suggest the derivation of volcanic rocks from the upper mantle. The formation of carbonatites and kimberlites in the regions with thick continental lithosphere and on some oceanic islands is also attributed to plumes and related alkaline metasomatism.

Presumably plume-related basalts are classified as ocean-island basalts (OIB), enriched in many lithophile trace elements not only in oceans but also on continents [36].

(6) LIPs, especially the trap provinces of the Siberia, Deccan, Parana, and Etendaka plateaus, and South Africa, are related to superplumes. The same is true of giant swarms of Precambrian dolerite dikes in ancient shields. Such swarms attain hundreds and even thousands of kilometers in extent and are radiate-arranged (Fig. 5). The dikes are considered (not without grounds) to be plumbing systems of older, mainly Precambrian, plateau basalts now eroded [32, 34]. The indications of lateral movement of magma along these channels allow us to avoid the suggestion of a sea of magma beneath the trap field.

Despite certain problems, it seemed that plate and plume tectonics, initially existing as parallel paradigms, the former responsible largely for the upper tectonosphere and the latter for the lower tectonosphere, would be able to develop without conflicts and merge into a single consistent paradigm of global geodynamics. Attempts to present such a paradigm in the form of a simplified model [28] were rather successful (Fig. 6). However, recently (approximately since the beginning of the 21st century), the existence of plumes (at least in their classic interpretation) has become somewhat problematic and doubtful. Heated debates have flared up in scientific journals and on websites, e.g., www.geolsoc.org and www.mantleplumes.org.

OBJECTIONS OF THE "ANTIPLUME LOBBY"

The "antiplume lobby" (the name given neatly by Saunders [63]) has attacked the plume theory on several fronts. At times, the arguments of various parties, particularly of plume opponents, may seem to be passionate and even biased. This is reflected in the colorful rhetoric of the debate, often departing from academic style: "the plume myth," "a nail into the coffin of plumes," "the love affair with plumes," "hell of a plume," etc.

(1) It is stated (and it seems quite correctly) that geochemical indicators, including even the He-isotope ratio, are not mandatory evidence for the origin of a plume at the mantle–core interface [33, 50]. More and more evidence suggests that large-scale stirring (recycling) of the lithosphere and the mantle in the course of subduction, and more precisely in the process of overall mantle convection with plumes as its ascending streams, results in chemical heterogeneity of the mantle, expressed in the fine geochemical features of volcanic rocks. Numerous enriched and depleted mantle reservoirs with different He, Ar, Sr, Nd, Hf, Os, and Pb isotopic compositions are recognized and abbreviated as PM, BSE, PREMA, UM (MORB), DM, EM1, EM2, SOPITA, HIMU, SCLM, FOZO, etc. [3, 76]. The complex mantle structure with neighboring undepleted,

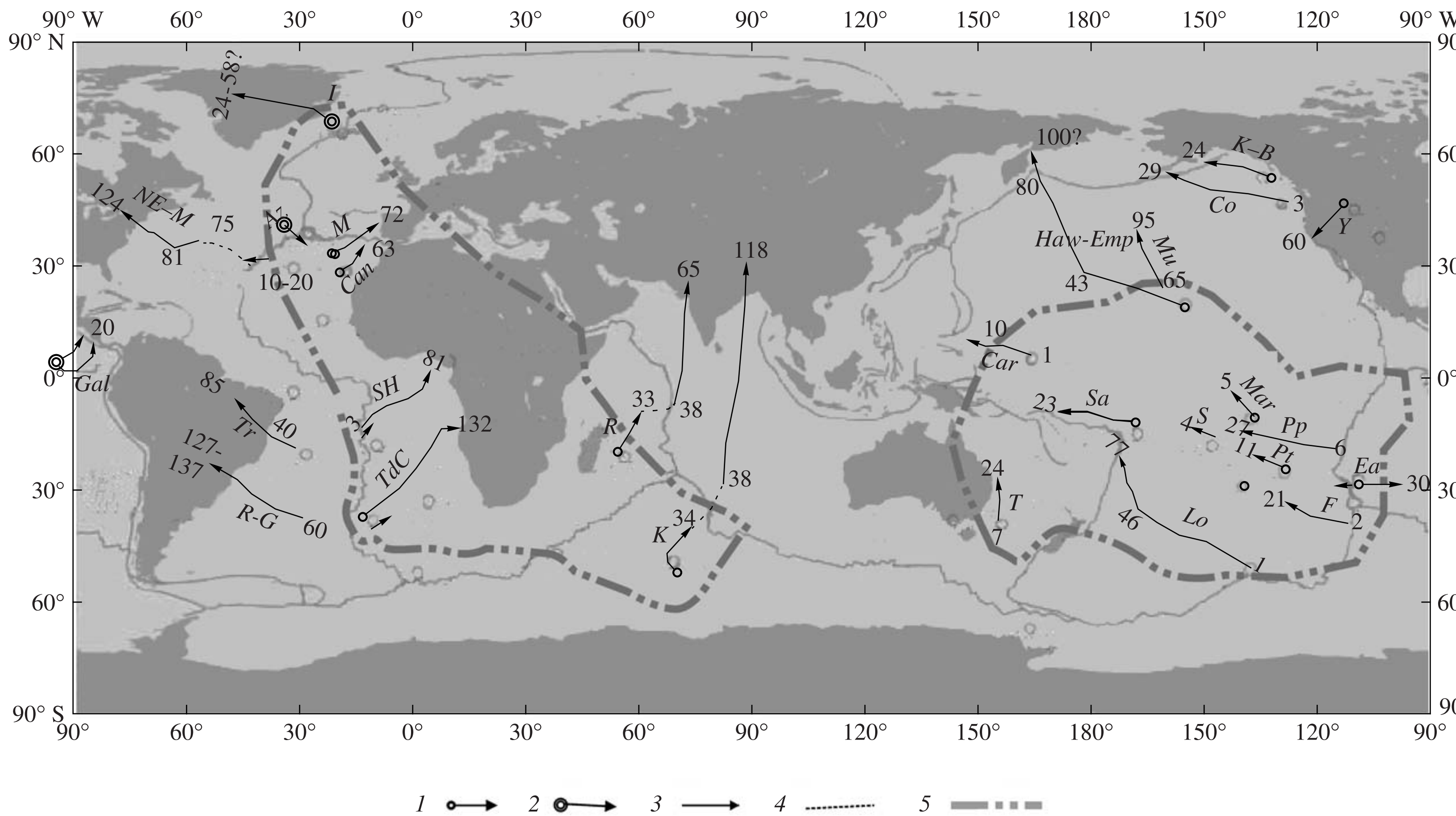

Fig. 2. Location of Mesozoic and Cenozoic time-progressive volcanic chains. The map is compiled on the basis of the data published for the Pacific, Indian, and Atlantic oceans and their continental margins [17, 24, 25, 27, 37, 39, 41, 46, 52–56, 59]. (*1*) Volcanic chains with active or recently extinct (<1 Ma) volcano at one end. The arrow indicates the direction of increasing age, i.e., the direction of the lithospheric plate without correction for much less significant displacement of the plume itself. The numeral at the other end indicates the age of the oldest volcanic event (on continents, these are traps, ring intrusions, and carbonatites); (*2*) frontal volcano is located on mid-ocean ridge; (*3*) volcanic chains where the youngest extinct volcano is older than 1 Ma (numeral is the volcano's age, Ma); (*4*) line connecting the volcanoes formerly belonging to a single chain, which had crossed an active spreading zone and subsequently was divided by this zone; (*5*) approximate contour of the African and Pacific large low-shear-velocity provinces (LLSVPs) at the mantle–core boundary projected on the Earth's surface [21]. All active or recently extinct volcanoes of time-progressive volcanic chains are located within these contours, except the Cobb and Kodiak–Bowie volcanoes near Alaska, which are likely related to the Columbia River Province in the west of North America, controlled by a minor superswell [21].

Notations of plumes (counterclockwise from the northwestern corner of the map): *I*, Iceland; *Az*, Azores; *NE–M*, New England–Meteor; *M*, Madeira; *Can*, Canary; *SH*, St. Helena; *TdC*, Tristan da Cunha; *R-G*, Rio Grande; *R*, Reunion; *K*, Kerguelen; *T*, Tasmanian; *Car*, Caroline; *Sa*, Samoa; *Lo*, Louisville; *S*, Society; *Mar*, Marquises; *Haw–Emp*, Hawaiian–Emperor; *Mu*, Musicians; *K–B*, Kodiak–Bowie; *Co*, Cobbs; *Pp*, Pukapuka; *Pt*, Pitcairn; *Ea*, Easter; *F*, Foundation; *Gal*, Galapagos; *Y*, Yellowstone.

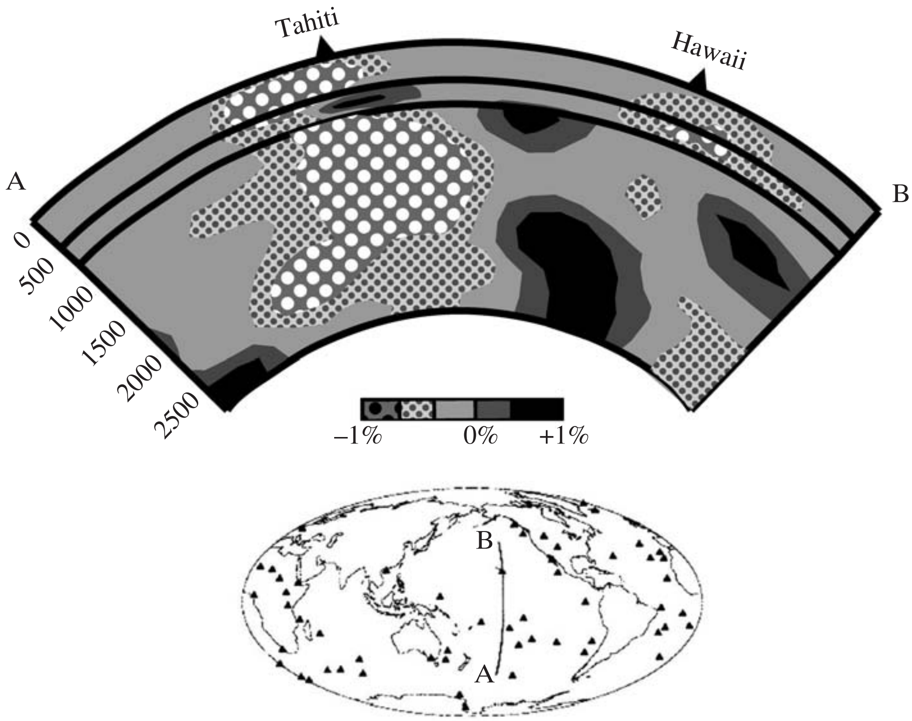

Fig. 3. Vertical section of anomalies of P-wave velocities along the Hawaii–South Pacific Superswell line. The scale of deviation from the average value and the location of the section are shown below. The position of the Hawaii and Tahiti hot spots [75] is noted by triangles.

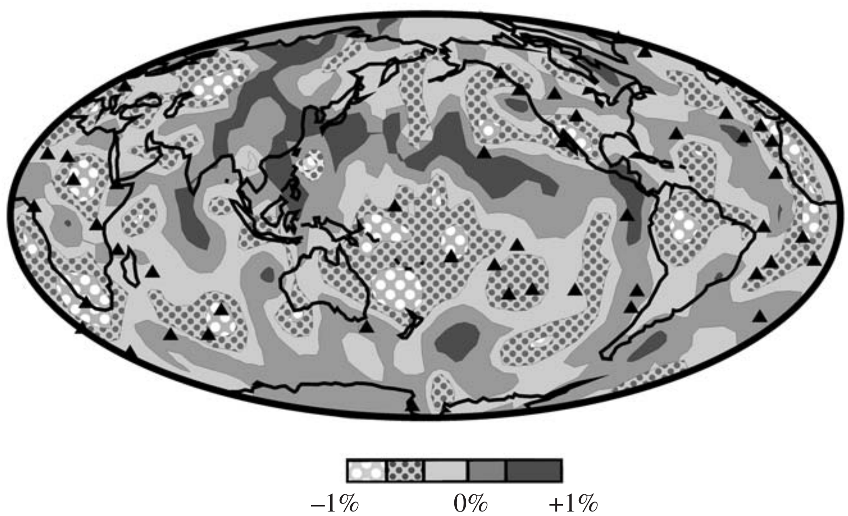

Fig. 4. Anomalies of P-wave velocities near the mantle–core interface at a depth of 2730 km. The scale of velocities is given below. Hot spots on the Earth's surface are noted by triangles [75].

depleted, secondary enriched (refertilized), and recycled domains are described in such figurative terms as marble cake, spaghetti, plum cake, etc. Some authors assume that mantle domains of different types can undergo He-isotope exchange over long intervals of geological time [14].

(2) Doubts appear in real images of plumes based on seismic tomographic results, up to the assertion that the detected seismic anomalies correspond to the noise level [44]. Indeed, by no means all plumes are traceable down to the core, although the plume tail may be thinner than the wavelength used, and thus undetectable.

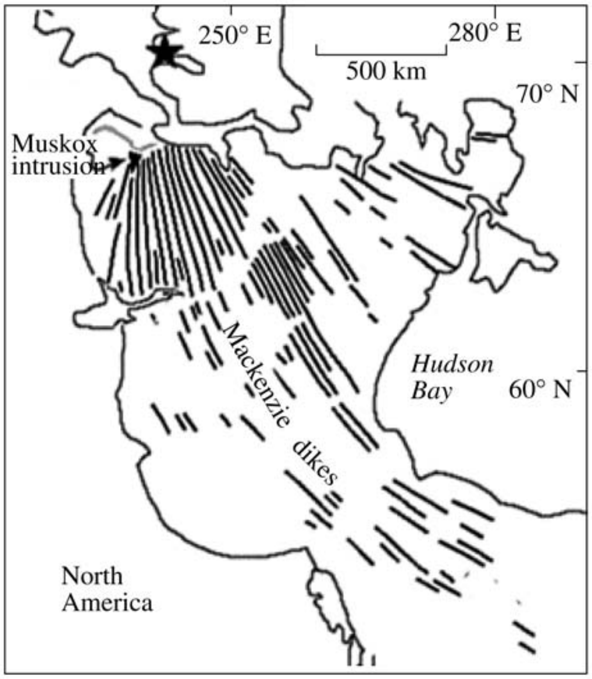

Fig. 5. The system of radiate dikes, sills, and layered intrusions 1270 Ma in age in the Mackenzie Province; an example of a deeply eroded Proterozoic LIP with exposed plumbing system [32, 34].

The mushroomlike morphology of plumes is also not supported. Nevertheless, despite all the imperfections, seismic tomography reveals many important things. The section along the Mid-Atlantic Ridge (Fig. 7) demonstrates hot and cold zones, and even the zone of dry spreading in the Central Atlantic. The root of Iceland pierces the entire upper mantle.

It should be noted that seismic tomography is a rather specialized kind of research, and the final word must belong to the experts. It is from the experts themselves, however, that we continue to obtain new and more detailed information each year [47, 60, 66, 72, etc.], with the effect of multiplying, rather than reducing, the number of known seismotomographic interpretations (and this pertains not only to plumes but also to subduction zones). Before seismotomographic evidence, subduction zones were traced down to 700 km on the basis of deep-sourced earthquakes. Seismic tomography traces cold lithospheric slabs deeply in the lower mantle (Fig. 8). One must have great courage to contest these data, as Foulger has done [35], without being a seismologist.

(3) The statement that all plumes are predated by uplift of the Earth's surface has been shown to be not fully valid. For example, the Siberian flood basalt province, the submarine Ontong Java Plateau, and the Deccan traps are exceptions [35–65]. However, the Siberian example, the most familiar one for me, does not give an unequivocal answer. As has been emphasized many times, in this case, we deal with the much greater Ural–Siberian superplume, which arose in the Early Triassic, when the Urals and western Siberia underwent substantial uplifting. As concerns the Ontong Java LIP, this volcanic plateau initially arose on the deep oceanic bottom, so that the uplift may have proceeded unnoticed. In addition, it was shown in [23] that the effect of a plume on complexly built layered lithosphere may result in equivocal surface manifestation, e.g., as spatial alternation of elevated and subsided blocks.

(4) The suggestion that plumes are an absolute reference frame for permanently moving lithospheric plates has also proven incorrect. Displacements of the upper portions of plumes relative to their lower parts have been described [40, 73, 75, etc.]. Paleomagnetic studies have also revealed displacements of plume trails, which should most likely be regarded as floating anchors rather than fixed reference points [31]. The substantial shift of mantle sources for some volcanic chains is supported by paleomagnetic evidence as well [21, 55]. Nevertheless, these data do not impel us to discard the idea of plumes because the scale of such offsets is by an order of magnitude less than the displacement of the volcanic trail on the plate surface. Comparison of the paths of apparent polar wander established from paleomagnetic data and the motion of hot spots shows their good consistency over the last 49 Ma and increasing discrepancy in older epochs [62]. Moreover, comparison of the position of hot spots in the Pacific Ocean relative to the plumes in the Atlantic and Indian oceans has confirmed their mutual deviations and correlation within these groups [53, 59]. Three hot-spot families—Pacific, Indo-Atlantic, and Icelandic—have been suggested [53]. As has been shown, the hot spots of the former two families have remained relatively fixed during the last 80 Ma.

(5) The existence of anomalously high temperatures (up to 300–400°C above the background values) in the mantle, which is a necessary condition for melting under dry conditions [11], has been cast into doubt. Such temperatures should be expressed in a corresponding increase in heat flow above the active plume, but actually this is not observed (see below).

(6) Finally, attempts (in my opinion, clearly unsuccessful) have been made to find an alternative explanation for the regular variation in age of volcanoes in the submarine and on-land mountain ridges pertaining to plume activity. Now it is impossible to dispute the existence of a great number of such ridges; up-to-date information about them was used in the compilation of Fig. 2. The necessity to explain this fact, which is inconvenient for opponents of plumes, has sparked renewed interest in the hypothesis of crack propagation as proposed by J. Dana [35, 69]. Seemingly, the most adequate approach to the verification of this hypothesis is consideration of the forces that drive lithospheric plates and deform them. It would have to be shown that a combination of forces or their transformation gives rise to extension across the inferred fracture and the

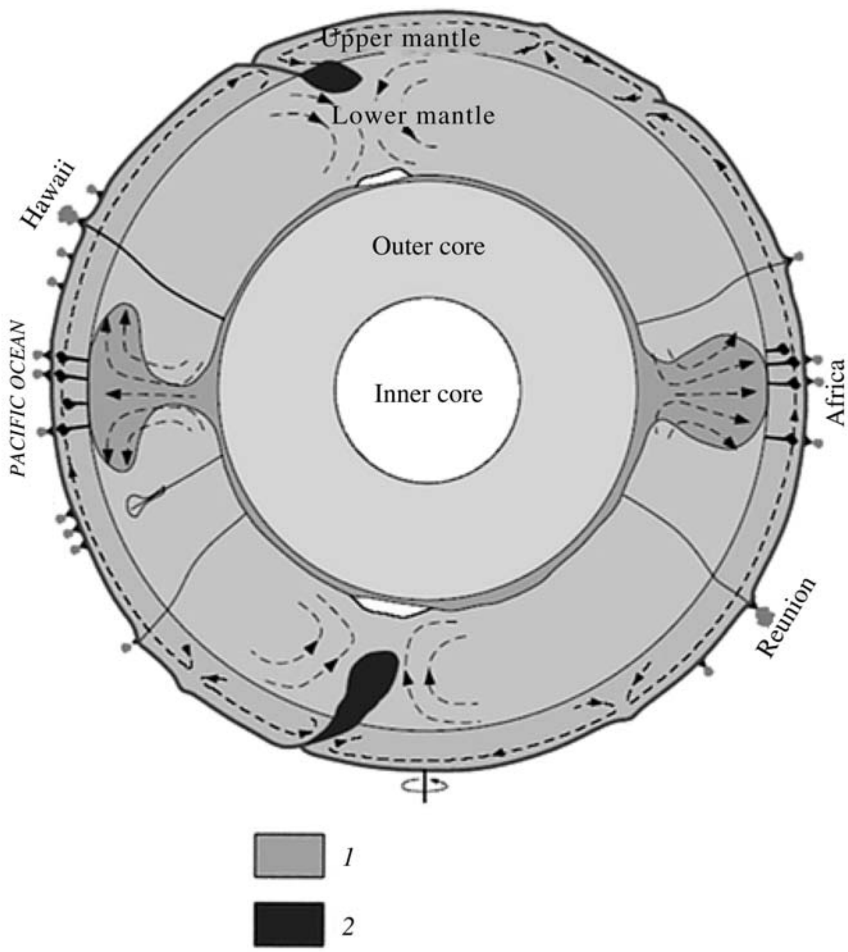

Fig. 6. A model of the relationships between plate and plume tectonics [29]. (*1*) Superplume, (*2*) plunging lithospheric slabs.

volcanic chain. However, in the most obvious case of the Hawaiian–Emperor and similar ridges, the subduction slab pull and rollback, mantle drag, and ridge push do not correspond to the tensile stress. As was shown in [77], the maximum horizontal stress is commonly oriented nearly parallel to the absolute direction of plate motion, indicating that the driving force controls the stress distribution within the plate as well. Unfortunately, in the recently published substantiation of the crack propagation mechanism [69], this reasoning was not taken into account. The thermoelastic stress was estimated for cooling of the Pacific Plate, considered as a spherical shell. Having omitted the powerful forces of the plate-moving mechanism, the authors obtained the desired tensile stress providing fracture formation. It is common in physics to simplify a problem by omitting secondary factors; in this case, however, it is a major force that has been neglected.

A somewhat different approach to explanation of time-progressive volcanic chains was demonstrated in [67], where the formation of such chains is referred to the rearrangement of plate boundaries accompanied by extension. However, this concept is also based on the idea of crack propagation.

It should be added that, in contrast to the plume model, this conjecture does not give satisfactory explanations of a number of phenomena. First, the strong anisotropy of oceanic, transitional, and marginal continental crust crossed by volcanic chains does not affect their morphology. Second, the orientation of time-progressive volcanic chains strikingly corresponds to the vectors of motion of lithospheric plates (Figs. 2, 9). For example, the volcanic chains located on different slopes of the East Pacific Rise are distinguished by opposite trends of age progression, as can be seen in Fig. 9. The volcanic edifices located on the mid-ocean ridges (Iceland, Azores, Galapagos) are split. The Reunion and Kerguelen volcanic chains cross the active Carlsberg mid-ocean ridge and extend further over the next plate because the ridge itself drifts in the northeastern direction. The Kodiak–Bowie and Cobb volcanic chains, on the one side, and Yellowstone, on the other side of the

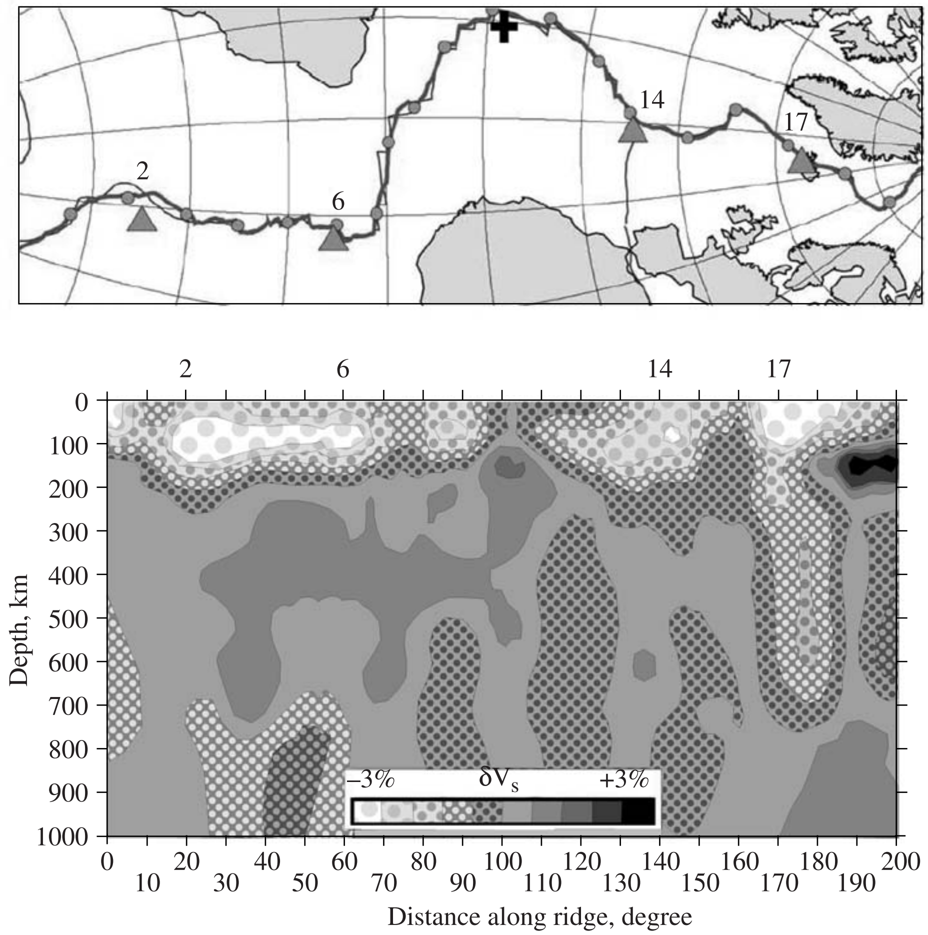

Fig. 7. Tomographic section along the Mid-Atlantic Ridge, modified after [61]. The geographic position of the section is shown in the upper panel. The solid line is the ridge axis; the gray circles are stakes spaced at 10° by latitude. The triangles are hot spots (stakes 2, 6, 14, and 17: Tristan da Cunha, Asuncion, Azores, and Iceland, respectively). The cross, added by the author, indicates a region of dry spreading with insignificant melting. The tomogram shown below demonstrates anomalies of S-wave velocity. Among hot spots, only Iceland is underlain by a deep (down to the transitional layer) column of low-density material, which does not reveal visible relations to the lower mantle but nevertheless extends deep into the mesosphere, indicating that Iceland may be regarded as a plume. The tomogram does not bear information on the nature of other hot spots.

plate boundary are oriented strictly along the motion vectors of host plates. Finally, the oblique northeastern orientation of the St. Helena and Tristan da Cunha chains exactly fits the direction of motion of the corresponding plate. The active or recently extinct volcanoes of almost all chains are localized above superswells close to their margins (Fig. 2).

The latter fact is also supported by paleomagnetic data [21, 22]. It has been shown that LIPs arising over the last 300 Ma, i.e., since the formation and breakdown of Pangea, are situated exactly above the 1% contour line of S-wave attenuation surrounding the African and Pacific provinces of low S-wave velocities at the mantle–core interface. The Siberian and Columbian LIPs surround swells of smaller dimensions. The location of the 24 most active volcanic hot spots coincides with the same boundaries, thus corresponding to zones of plume generation. The vertical projection of these zones fits the +10-m contour of the geoid. The low-velocity regions that occupy about 2 wt % of the total mantle probably differ from the remainder in composition [1, 38]. Because LIPs arose on the Earth's surface during the last 2.5 Ga, it may be suggested that superswells with surrounding zones of plume generation have existed as long as LIPs.

In contrast to the plume concept, neither the hypothesis of crack propagation nor other alternative conjectures (see below) explain the aforementioned phenomena. Given this fact, we should remember the principle "Leave well alone," or as Ockham's razor states *entia non sunt multiplicanda praeter necessitatem* ("Entities must not be multiplied beyond necessity")!

However, other alternatives should be mentioned for the sake of completeness. In particular, attempts have been and continue to be made to explain the origin of regular volcanic chains by specially organized sublithospheric convection, e.g., related to the cooling effect of

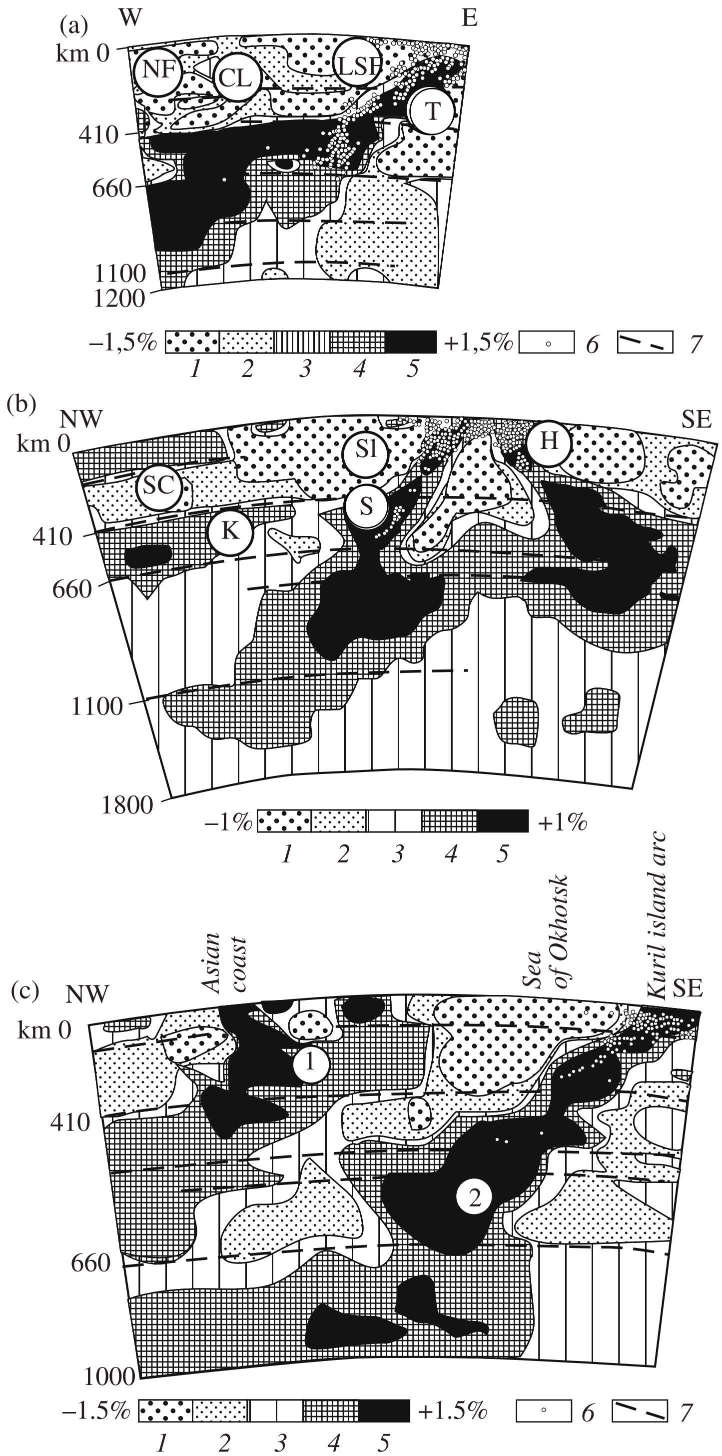

Fig. 8. Structure of the mantle beneath the active zone of continent–ocean transition, after the data of deep seismic tomography (P-waves), modified after [20] and adapted after [8]: (a, b) sections of the West Pacific island-arc system: (a) Tonga island arc, (b) Sangihe and Halmahera. (*1–5*) Mantle domain with varying seismic velocities: (*1, 2*) slow; (*3*) medium; (*4, 5*) fast; (*6*) earthquake source; (*7*) inferred deep detachment. Subduction zones (letters in circles): T, Tonga; S, Sangihe; H, Halmahera; fragments of abandoned subduction zones: CL, Colville–Lau (?) of Miocene age; K, Kalimantan of Cretaceous age; backarc basins: LSF, Lau and South Fiji; NF, North Fiji; Sl, Sulu; SC, South China; (c) deep structure of (1) ancient and (2) present-day subduction zones in the Kuril–Okhotsk region.

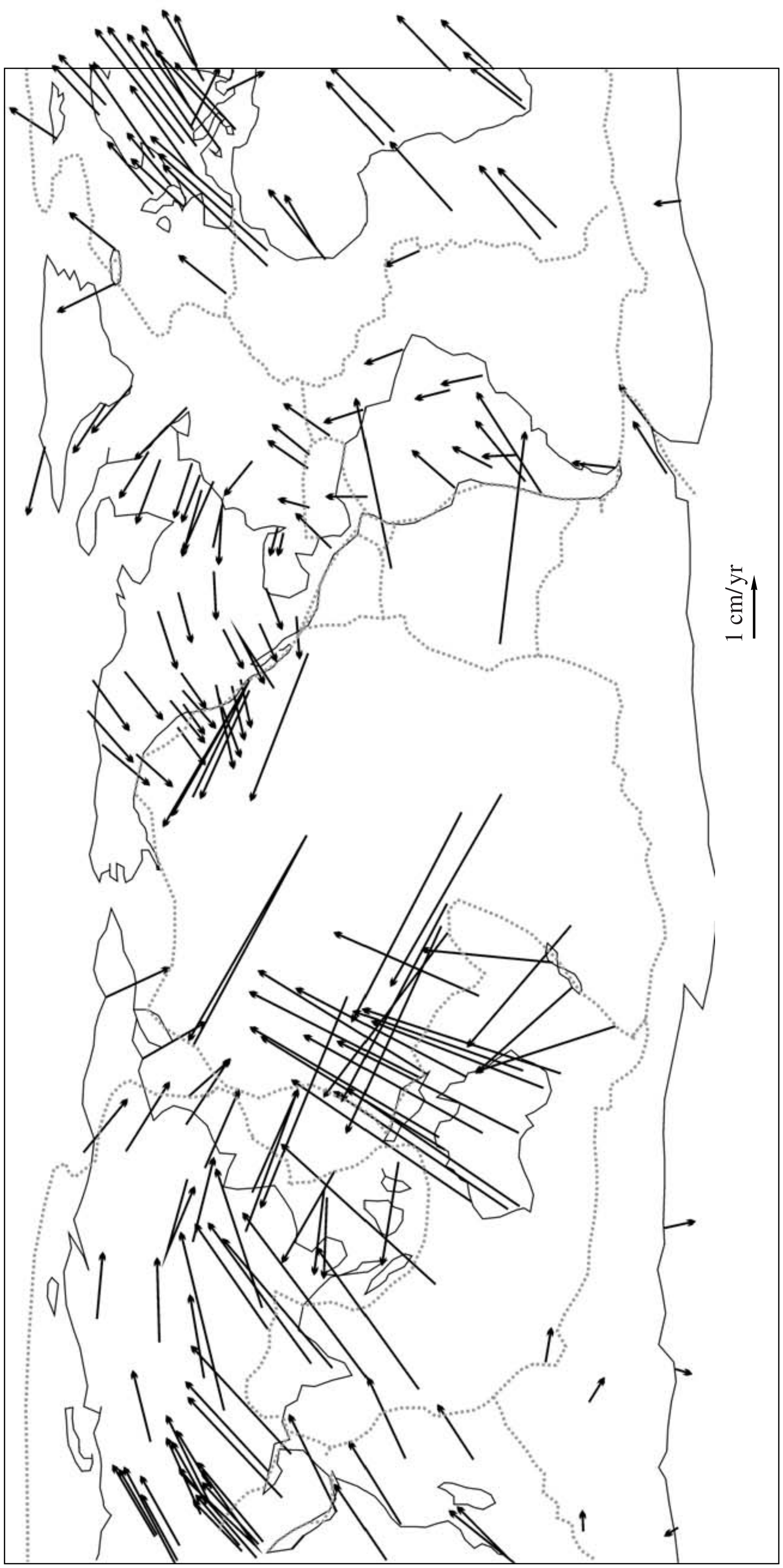

Fig. 9. Vectors of lithospheric plate motion in ITRF 2005 (http://itrf.ensg.ign.fr). Plate boundaries are shown by dotted lines.

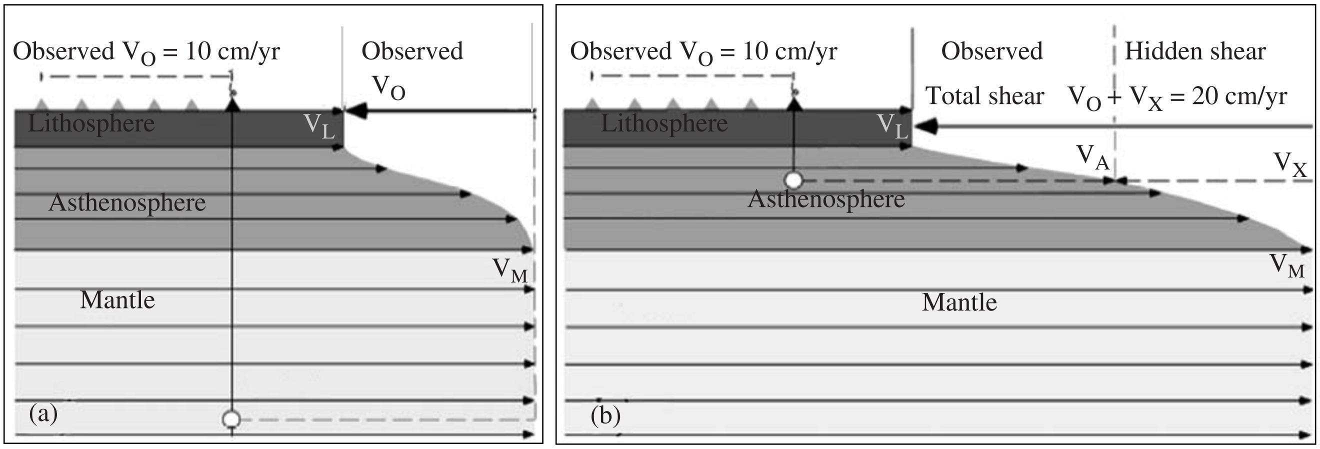

Fig. 10. An attempt to explain the time progression of volcanoes along the Hawaiian–Emperor Ridge. The Hawaiian volcanic trail indicates that the connection between the magma source and the lithosphere is destroyed. The lithosphere moves to the west-north-west. Two alternatives are possible: (a) source is located beneath the asthenosphere; i.e, in the subasthenospheric mantle the total shear between the lithosphere and the mantle is recorded in the volcanic trail; (b) the source of the Hawaiian hot spot is situated in the asthenosphere; i.e., the total shear between the lithosphere and subasthenospheric mantle is not recorded in the volcanic trail because a part of this shear occurs beneath the source (deep, hidden shear) [Doglioni et al., 2005] (cited after [30]).

the continental margin [45]. A hypothesis of small-scale roll convection with elongated cells parallel to the plate motion was proposed in [18]. The authors of this model acknowledge that it fits for specific chains only and, as the preceding one, does not pretend to universality.

Don Anderson [15, 16], another opponent of the plume concept, put forward the hypothesis of drifting melting source (easily melting eclogite blob) in the asthenosphere, whose velocity is higher than the velocity of crust motion but lower than the velocity of the underlying mantle. A similar model was presented in [31] in graphic form (Fig. 10).

This interpretation turned out even worse than the idea of crack propagation. The hypothesis was worked out ad hoc for the Hawaiian–Emperor Ridge and is suitable for explanation of other chains, where seamounts become older westward. However, all of the hot spots in the Indian Ocean and the eastern Atlantic become older in quite the opposite direction: to the northeast and east rather than to the southwest (Figs. 11, 12; cf. Fig. 2). This hypothesis was considered in more detail in [10], in my presentation at the EGU General Assembly 2008 [57, 58], and in discussion on the website http:www.mantleplumes.org. This discussion turned out somewhat strange: my opponents said nothing about the striking consistency in the vectors of plate motion and orientation of time-progressive volcanic chains and the coincident position of young volcanoes and superswell boundaries (see above), although this is the main point. The probability of the random character of such coincidences is vanishingly small.

(7) These "disclosures," although readily refuted in many respects, manage to highlight the weak points in the model of plume tectonics, specifically the absolutized attributes of plumes and the infinite expanding of the term *plume*. This term is now used for any anomalous or seemingly anomalous (relative to classic plate tectonics) manifestation of igneous activity, whether deep- or shallow-seated. A certain portion of criticism of the plume concept is added by advocates of passive rifting. This mechanism may be regarded as a partial alternative to plume tectonics, which explains shallow-seated magmatism related to decompression. The rifts of East Africa or the Baikal Rift are examples.

ALTERNATIVES TO PLUME TECTONICS PROPOSED BY ITS OPPONENTS

Returning to the basic paper by Foulger [35], we note that this publication declares the passive extension of the lithosphere, decompression, and local enriched domains of the mantle and crust as universal conditions of all anomalies of melting. In other words, it proposes a model of passive rifting caused by plate-tectonic driving forces within intraplate space. This antiplume concept is called the "plate" model for the genesis of melting anomalies [35], and is regarded as a universal mechanism. Only the all-embracing approach provokes objection; the remainder is quite sensible. The model of passive rifting has been repeatedly and fruitfully discussed in Russian literature [6]. At the same time, its positioning as an absolute alternative to the model of active intraplate volcanism is hardly reasonable.

The papers by Foulger (both cited and preceding) are consonant with the aforementioned publications by Anderson [15, 16]. According to his statements, the domains of enriched mantle, which do not require extremely high temperature for melting (see the section "Antiplume lobby," paragraph 5), are composed largely

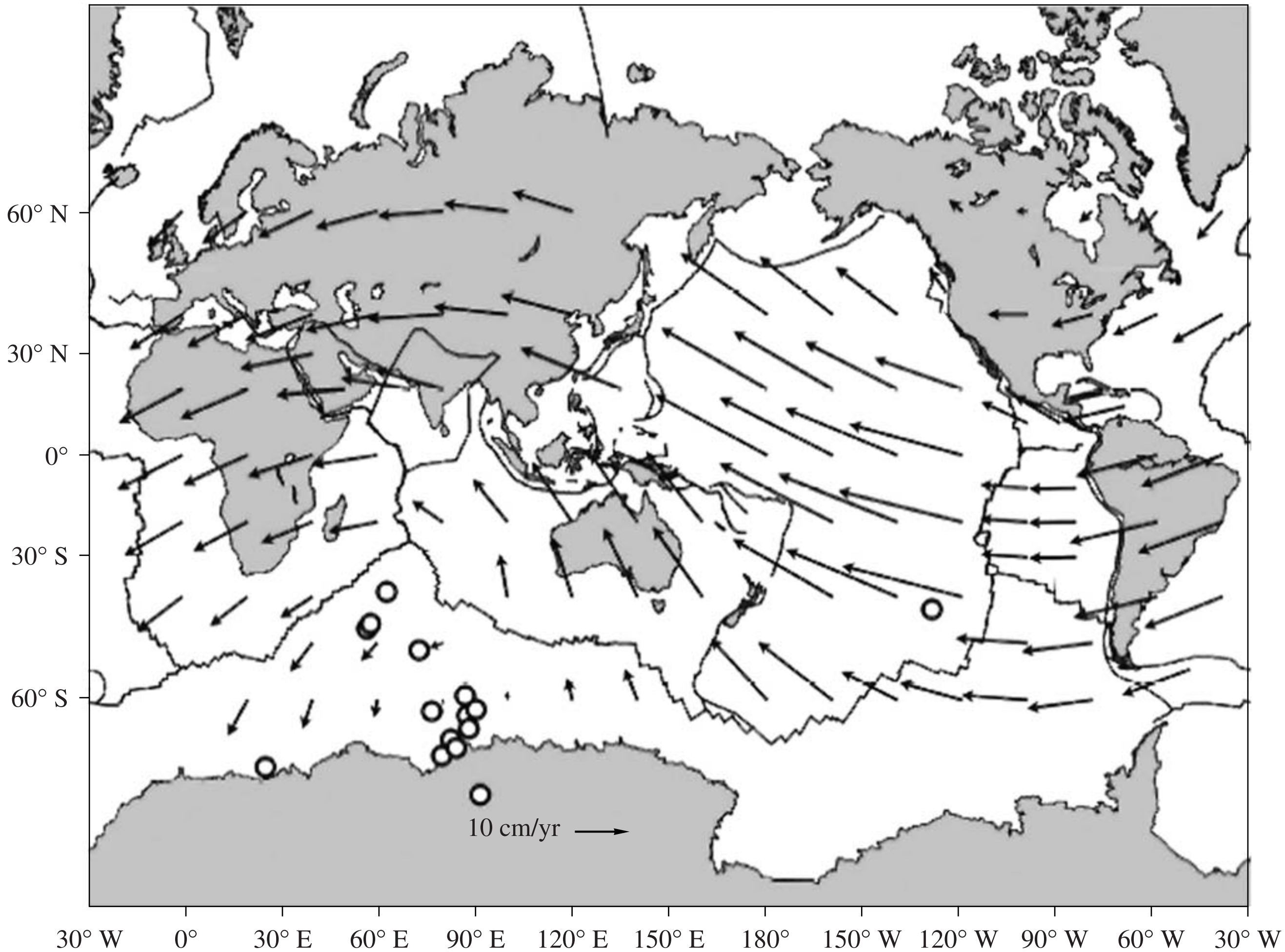

Fig. 11. Present-day plate velocities recalculated from the NUVELIA model of relative plate motions [De-Mets et al., 1990, 1994] under conditions that shallow-seated hot spots are taken as a reference frame. Note that in this system all plates move to the east. Rotation poles are denoted by circles (cited after [30]).

of eclogite formed as a result of delamination of thickened continental crust. The temperature of the mantle below 100 km is lower than the melting temperature of dry peridotite but higher than the melting temperature of basaltic or eclogitic components as products of earlier recycling (Fig. 13).

The advantage of such an approach for explanation of the geochemical features of the Hawaiian volcanics was recently demonstrated in [68]. A model of progressive melting in the mantle has been proposed. At a depth of ~150 km, in the low-velocity zone (asthenosphere?) lying within a depth interval of 130–170 km, eclogite as a product of lithosphere recycling starts to melt in the center of plume. The percolating liquid reacts with overlying peridotite to form secondary enriched pyroxenite. In the course of further ascent of plume, pyroxenite and then peridotite are involved in melting. The incomplete magma mixing is expressed in the geochemical variations of erupting volcanics. The single but very important difference from the Anderson's model consists in its operation in the ascending flow of convecting mantle, i.e., in a plume. Moreover, without such a flow, eclogite cannot hang in the asthenosphere for tens of million years, as is accepted in the model of time-progressive volcanic chains [30] (see above). The densities of gabbro, peridotite, and eclogite in the crust and the upper mantle are 2.87, 3.30, and 3.45 g/cm^3, respectively. At a depth of ~150 km eclogite must sink in the asthenosphere, whereas at a depth of less than 50 km it is transformed into gabbro and floats to the roof of the athenosphere.

Subjecting the opponents of plumes to criticism, we must keep in mind that the idea of recycled mafic igneous and probably sedimentary rocks as possible enriched sources of mantle melting are very advantageous. As has been shown, they not only open the way to recognition of magma sources of volcanic rocks pertaining to plumes and superplumes [68, 74], but in

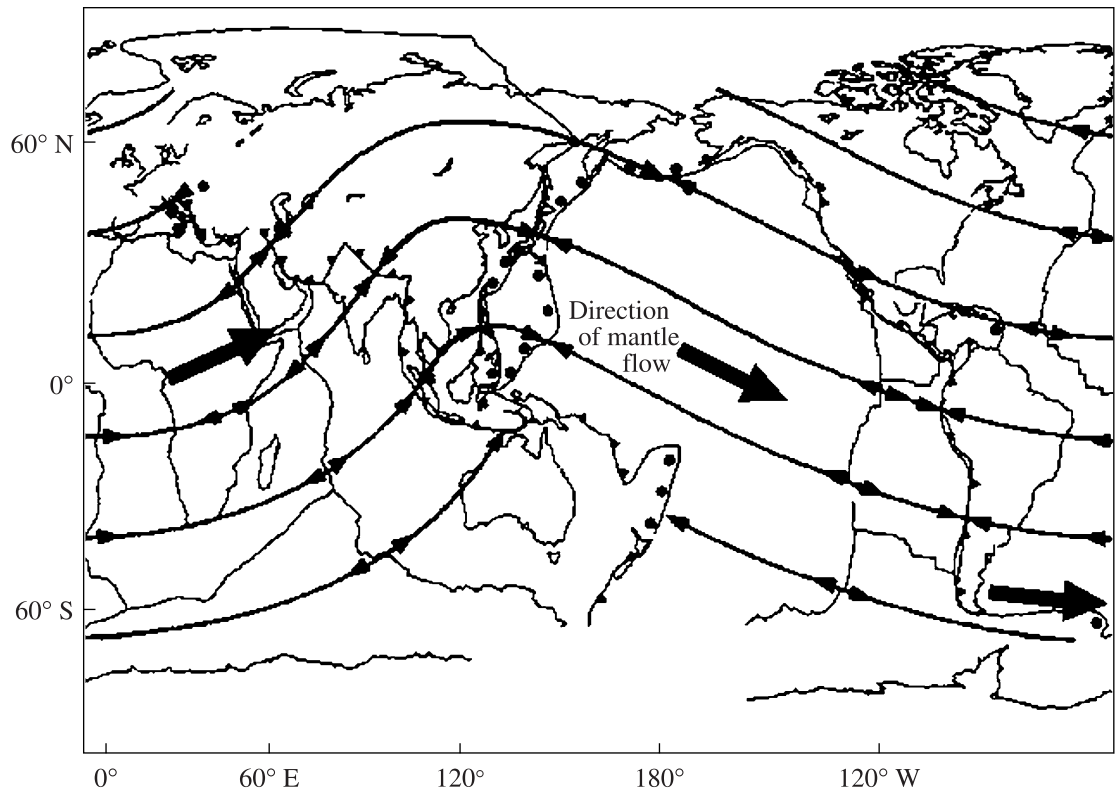

Fig. 12. Correlating the directions of absolute plate motions that issue from the position of large rift zones 40 Ma ago, we obtain the field of coherent sinusoidal flow, along which the plates move with different relative velocities in the system of geographic coordinates [Doglioni, 1993] (cited after [30]).

some cases allow us to manage without plumes at all, replacing them with quite plausible plate-tectonic models, e.g., in the case of passive rifting. However, it should be emphasized that passive rifting is unable to explain melting in the midst of the asthenosphere or in the subasthenospheric layer, because decompression and melting begin as soon as a fracture in the lithosphere attains the asthenosphere, and this fracture cannot penetrate deeper, whether 30 or 300 km.

Passive rifting is not the only non-plume mechanism of the formation of volcanic provinces. The vast province of the Baikal region, Mongolia, Northeast China, and Central Japan is an example of an alternative to the plume mechanism. A nearly horizontal lithospheric slab is currently detected beneath this province with seismic tomography [75, 78]. Due to its low density (?), this slab cannot sink below the phase boundary between the upper and lower mantle and slips along this interface, inducing melting of the overlying mantle like a common suprasubduction wedge (Fig. 14). This mechanism is posited by some authors as an explanation of ancient LIPs, including the Siberian LIP [42].

DISCUSSION AND CONCLUSIONS

Although criticisms of the plume concept contain many rational, ideas which must be taken into account in the further development of global geodynamics, absolute rejection of plume tectonics must be considered unacceptable. Opponents of plume tectonics have not managed to adduce convincing arguments against the two main pieces of evidence for the reality of plumes.

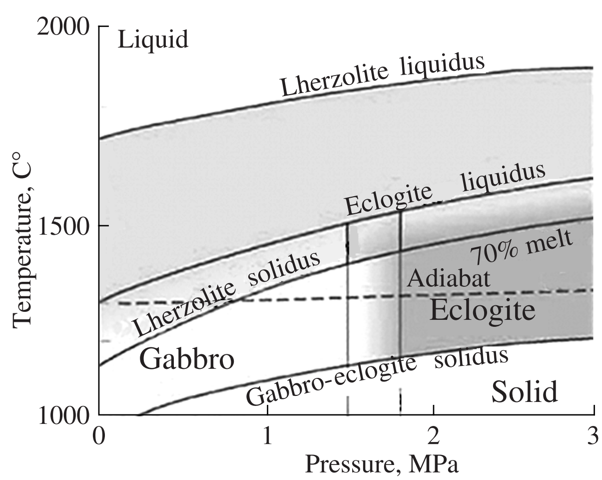

Fig. 13. Melting conditions of lherzolite, eclogite and gabbro in the mantle [16].

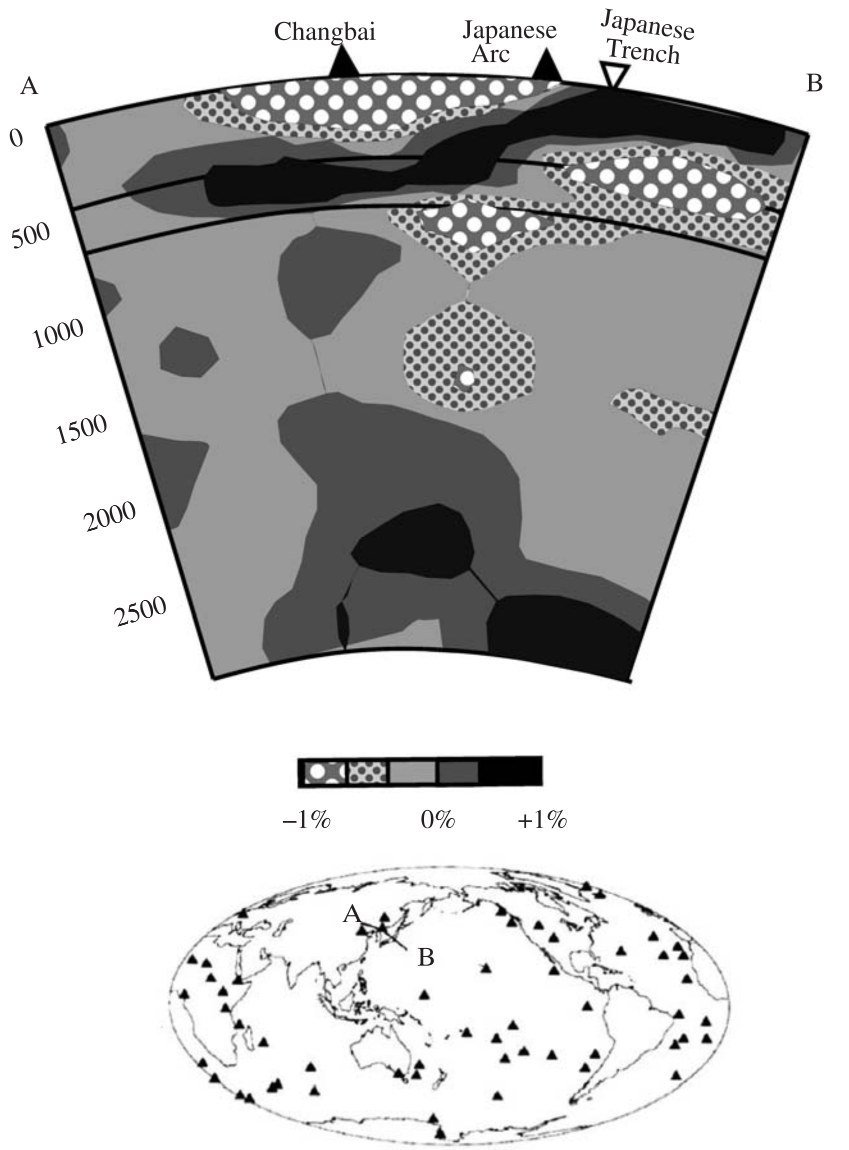

Fig. 14. Vertical section of P-wave velocities across Northeast China and Central Japan. The scale of deviations from average velocity and location of section are shown below [75].

(1) Alternative interpretations of time-progressive volcanic chains, e.g., crack propagation or specially organized sublithospheric convection with horizontal counter-flow in the asthenosphere and eclogitic body hanging for many tens of million years therein, cannot compete with the plume model, which explains not only the general behavior of volcanic chains but also many details related to plate motion in particular regions (see above).

(2) Seismic tomographic data indicate that the anomalies related to slab and hot spots extend into the mesosphere, i.e., beneath the asthenosphere (Figs. 3, 7, 8). This evidence contradicts the universal passive plate-tectonic mechanism (extension–decompression–melting of enriched mantle source), because this mechanism is limited by the lithosphere and the upper asthenosphere. By definition, the explanation of the LIP origin by anomalous behavior of subducted slabs, as applied to southeastern Asia (Fig. 14), cannot be universal, because the tomography of most slabs testifies to their extension into the lower mantle (Fig. 8) [43, 60, 75].

Thus, the results of seismic tomography, information on LIPs and time-progressive volcanic chains, as well as comparative analysis of the orientation of these chains and the direction of motion of lithospheric plates, not only support the existence of particular plumes but also show that they are tied up with one another and correlated with other global events. The relationships between epochs of LIP formation, magnetic superchrones, and global climatic changes are outlined in [30].

In fact, the results of seismic tomography do not always testify to the origin of plumes at the core–mantle interface; however, the resolution of this method is yet not sufficient.

As suggested by many researchers, mantle plumes may originate at different levels within the Earth and at least three plume varieties may be recognized: primary Morgan plumes ascending from the lowermost mantle, intermediate plumes that originate at the base of the transitional zone, and Anderson upper-mantle plumes, probably arising in the upper asthenosphere as a response to plate motions [28] (Fig. 6). The problem may be resolved in this way. However, the use of a single term for outwardly similar, but genetically different types of volcanism, is not an ideal solution and brings about additional criticism, sometimes causing people to "throw the baby out with the bathwater."

The aforesaid leads to the conclusion that the tectonic paradigm providing a consistent synthesis of plate and plume tectonics is still a work in progress. Modern geodynamics remains a rather controversial, continuously developing system of ideas, where researchers engage in active, and generally productive debate on the basis of new factual material and techniques. Irrespective of who is victorious in a particular debate, science will be the winner.

Despite all the controversies, the concept of convection in the asthenosphere and deeper levels of the mantle will remain the foundation of global geodynamic theory [4, 7, 9, 12, 13]. This statement follows from the results of seismic tomography and, in particular, from observation of the extending of slabs of the oceanic lithosphere into the lower mantle.

The convection models elaborated in modern geophysics reflect separate aspects of this process but do not embrace it in full, and therefore are distinct from one another. The future will show whether a comprehensive model can be created.

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