

Mantle plumes and dynamics of the Earth interior — towards a new model

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Abstract. Seismic tomography provides reconstructions of thermal-density structure of the Earth's mantle as deep as the mantle/core boundary (CMB). For the first time, a direct image of dynamic processes, occurring inside the globe, was obtained. Existing plate-tectonic models of modern geodynamics lead to a number of discrepancies. Most important are: stationary position of mantle plumes as the assumption of the convection process in the Earth's mantle, mantle convection versus data on both its viscosity and the existence of global seismic discontinuities, possibility of horizontal displacements of lithospheric plates above the discontinuous LVZ zone which disappears under deep-seated continental "roots", the model of radially growing distance between mid-oceanic ridges and Africa (also Antarctica), the growing separation between hot spots occur in neighbouring plates with time, geophysical data indicative of considerable input of energy and material from the Earth's core into the mantle, uncompensated by any exchange between the lower and upper mantle. New models (multi-layered convection or a plate-tectonic hybrid convection model) intend to explain tomographic image with taking into consideration geochemical data but with miserable results. The nature of mantle convection still remains controversial. The phenomenon of stationarity of hot spots relative to the accepted plate movements and the absence of evidence indicating deformations of mantle plumes by the convection system are also unclear and controversial. The presented model of the expanding Earth's offers a reasonable solution to these discrepancies and paradoxes.

Key words: mantle, seismic tomography, convection, hot spots, geodynamic models, expanding Earth

Geological structure and dynamics of the Earth have been of increasing concern of geologists and geophysicists over the last years, partly because modern seismic methods have been developed: reflection seismic surveys and tomographic experiments. The former method, applied at prolonged recording time, enables obtaining reliable images of tectonic structure of the Earth's crust and upper mantle, especially in continental areas (see Cwojdzinski, 2003). The latter method, permanently improved, provides reconstructions of distribution of areas with different seismic wave velocities at various levels of the entire Earth's mantle. Areas of anomalously low velocities are believed to be associated with those parts of the mantle which show higher temperatures and lower density as compared with cooler and rheologically more rigid surroundings (e.g., Dziewonski & Anderson, 1984; Anderson et al., 1992). For the first time, an analysis of thermal-density structure of the Earth's mantle could be performed as deep as the mantle/core boundary. And also for the first time, a direct image of dynamic processes, occurring inside the globe, was obtained. This image has triggered heated discussions, as it disturbs previous ideas about the dynamic processes that take place inside the globe, which control the geological processes within the near-surface zone. The debate has also resulted in a website, www.mantleplumes.org, where different ideas and discussions are presented.

The inner structure of the Earth

The inner structure of the Earth has been examined by investigative methods estimating seismic wave velocity in individual geospheres. Curves of seismic velocities of longitudinal (compressional — P) and transverse (shear — S)

waves show step-like rapid changes at discontinuity surfaces. These surfaces are believed, as inferred from experimental studies, to be represented by thermal and density boundaries, and also boundaries separating individual geospheres of different viscosity (Fig. 1). The two major

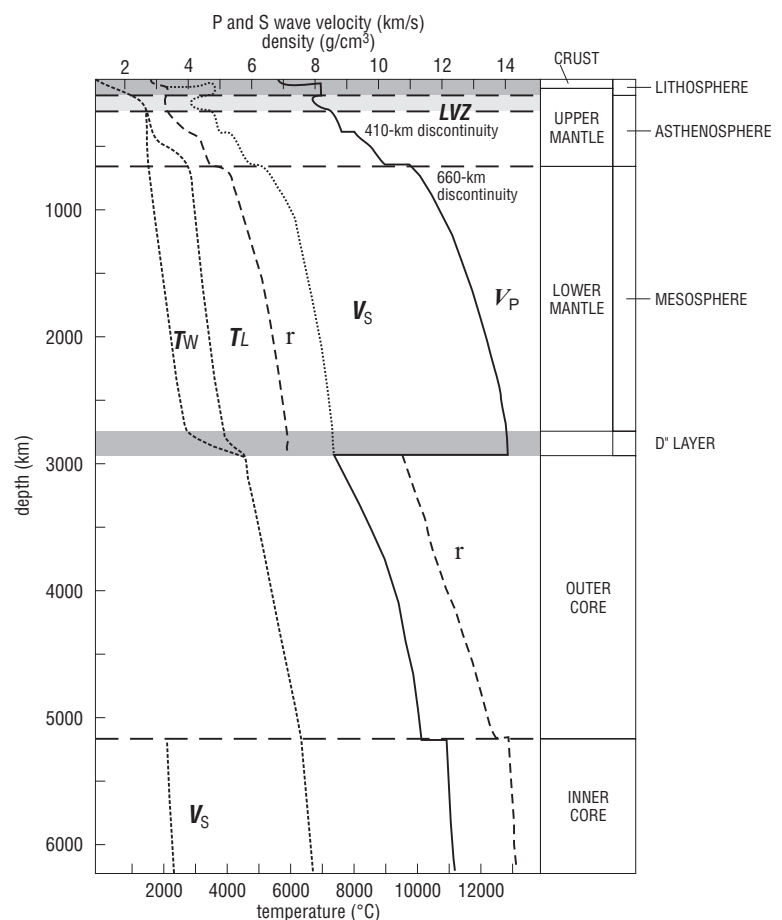


Fig. 1. Internal structure of the Earth based on compressional (P wave) and shear (S wave) waves velocity. Also calculated density (ρ) and temperatures for two mantle convection models: T_w (whole mantle convection — one-layered model) and T_l (two-layered convection) are shown. Main seismic discontinuities and basic internal division of the globe are presented. After Condie (1997) — supplemented and modified

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discontinuity surfaces, so-called first order seismic boundaries, are represented by the Mohorovicic (Moho) discontinuity at the average depth of 40 km, separating the Earth's crust (3–70 km thick) from the mantle, and the Gutenberg discontinuity at a depth of 2900 km, separating the Earth's mantle from the core. The core, in turn, is composed of the outer core (2900–5200 km below surface) and the inner core (5200–6360 km).

Second order seismic boundaries are observed within the mantle. They separate the lithosphere (a discontinuity at variable depths of 50 to 300 or 400 km), asthenosphere and mesosphere, i.e., the lower mantle (a discontinuity at a depth of 660 km). Such a concentric-layer structure of the inside of the Earth has long been well-known and accepted (see Dadelez & Jaroszewski, 1994). However, more recent studies (Condie, 1997) indicate that continental lithosphere (tectosphere) is up to 300 km thick (some of tomographic data suggest even 450 km, beneath old Precambrian continental basement). The tectosphere, revealing complex geological history and multi-phase evolution, formed as a result of various mechanisms; Precambrian basal accretion (up to 2.5 Ga) due to differentiation of the Earth's mantle (Taylor & McLennan, 1985; Condie, 2001) seems to be the major mechanism. The plate tectonic theory also suggests the involvement of typical plate tectonic processes such as subduction and collision, and accretion of island arcs and terranes (amalgamation) etc.

Parts of the tectosphere are separated by the young (180 Ma to recent) oceanic lithosphere which actually constitutes the asthenosphere transformed by a cooling in rift zones.

Curves of P wave velocity beneath different geostructural units within the upper mantle (Fig. 2) indicate the presence of a low velocity zone (LVZ) of variable thickness ranging from 50 to 100 km. This zone occurs at the top of the upper mantle (sometimes the term asthenosphere is restricted to LVZ). The characteristic features of this zone, such as low seismic wave velocities, strong energy dispersion of the waves, and large electric conductivity indicate that it is composed of the upper mantle material (garnet

herzolites = pyrolites) with 1 to 5% of intergranular melt. The lower boundary of LVZ (Lehmann discontinuity) is associated both with a waning of fluid fraction and with a considerable increase in the upper mantle viscosity. In the classical plate tectonic interpretations, LVZ was a “sliding layer” which enabled a horizontal movement of the rigid lithospheric plates. However, detailed seismic analyses indicate that the existence and thickness of LVZ depend on the geothermal gradient, and thus this is a discontinuous layer. In oceanic ridge zones, beneath some of the active continental rifts and under intra-montane basins, its thickness ranges from 100 to 200 km. Under continental platforms, LVZ is poorly developed, and beneath Precambrian cratons it is completely absent. Geoisotherms do not intersect here the upper mantle rocks solidus.

Various seismic tomography data, heat flow and electric conductivity analyses, and results of mantle xenolites investigations confirm the occurrence of continental roots beneath Precambrian cratons, reaching depths of even 400–450 km.

Thus, an essential question arises: what do the lithospheric plates glide over, if LVZ is discontinuous? The original, simple movement model of lithospheric plates must be revised.

The global seismic discontinuity occurs in the asthenosphere at a depth of 410 km (Fig. 2). It is conspicuous by a rapid change in P and S wave velocities over a distance of 10 km, at velocity difference of about 1 km/s. Experimental data of high pressure investigations prove that the discontinuity formed as a result of phase transformations olivine → wadsleyite (density greater by 6%), and clino- and orthopyroxenes → garnet. Another boundary of phase transitions is not manifested seismically — it should occur at depths of 500–550 km, where wadsleyite is transformed into magnesium spinel, and the density increases by approximately 2%.

The upper mantle, i.e., the so-called transition layer, is bounded at the bottom by a seismic discontinuity occurring at a depth of 660 km. This discontinuity is considered to represent the upper/lower mantle boundary. This is a very important, global seismic boundary. A rapid increase in seismic wave velocity by 5–7%, and in density by 8%, takes place at this boundary (Figs. 1, 2). This boundary zone is up to 5 km thick, its top surface is uneven, and location may change by 20 km over a distance of hundreds or thousands km. Experimental data from high-pressure investigations (at $p = 23$ GPa) indicates phase transformation of magnesium spinel to perovskite and magnesiowüstite as responsible for the step-like increase in seismic wave velocity. As emphasized by Condie (2001), this type of phase transformation impedes the sinking of cool lithospheric slabs (subduction slabs) in the lower mantle. Therefore, some of geophysicists (e.g., Tackley et al., 1994) are of the opinion that cumulation of the sinking lithospheric slabs should occur just at the 660 km boundary. Seismic tomography seems to confirm that the sinking upper mantle slabs reach as deep as the core/mantle boundary.

This extremely important problem gives rise to a question about the nature of the mantle convection process commonly accepted by the plate tectonic theory: is there possible a convection involving the entire Earth's mantle (whole-mantle convection), or is there two-layered convection, separate for the upper and lower mantle?

As evidenced by petrological data, the lower mantle (mesosphere) is composed of Mg-perovskite, with the

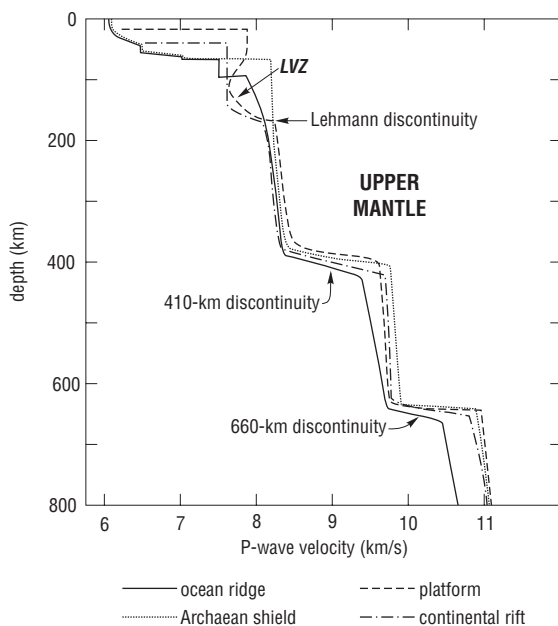


Fig. 2. P wave velocity distribution in the upper mantle beneath different geostructures. Low velocity zone, Lehmann, 410 km and 660 km discontinuities are shown. After Condie (1997) — supplemented

Fe/Mg ratio greater than in the upper mantle. Density of Fe-perovskite is greater than density of Mg-perovskite. Isostatic and gravity data indicate that mantle viscosity increases with depth by two orders of magnitude. The gravitational sinking of subduction slabs in the lower mantle is then practically very difficult. The concept of the so-called post-subduction slabs avalanches is an attempt to overcome this difficulty (Brunet & Machetel, 1998). According to this theory, the cool lithospheric slabs, gravity-sinking in the upper mantle, cumulate at the 660 km boundary and, subsequently, episodically “breaking through” the boundary, they submerge towards the core/mantle boundary (CMB). High viscosity of the lower mantle, confirmed, among others, both by the existence of two major elevations at the CMB and by geochemical isolation of domains in the lower mantle (durability of the order of 10^9 years), as supposedly evidenced by geochemical studies of magmatic rocks and hot spots (Condie, 2001), allows to ask a question whether any cell convection is at all possible within the lower mantle.

Another mineralogical and thermal boundary, recently discovered at a depth of 2800–2900 km, is the so-called transition layer D" which accompanies the core/mantle boundary. The layer shows an average thickness of 200–250 km within a depth range from 100 to 500 km, and therefore its top surface is bulbously deformed. In layer D", its density diminishes, the increase of wave velocity slowly decelerates, and a rapid change of these parameters is observed at the boundary with the core, i.e., at the base of layer D" (Fig. 1). This zone is strongly heterogenous in terms of its lateral extent, and has a very complex composition (Condie, 2001; Panning & Romanowicz, 2004). Seismic studies found the occurrence of the so-called “fuzzy” zone at the boundary with the core, which probably corresponds to an area of strong chemical and physical interaction between the core and siliceous Earth’s mantle. However, layer D" temperatures are not sufficiently high to cause a melting of perovskite and Mg-wustite.

Another interesting feature of layer D" is the fact that horizontally polarized shear waves (S) velocities are by about 1% faster here than vertically polarized S waves velocities — it indicates, according to Panning and Romanowicz (2004), that a horizontal shear is dominant here. Layer D" is a zone where two large planetary features are formed: the so-called superplumes (Breger & Romanowicz, 1998; Condie, 2001; Romanowicz & Gung, 2002). These features are today represented by 2 domal bulges on the top of layer D": under the Pacific Ocean and under Africa (Fig. 3A). P and S wave velocities for these giant upwellings are lower than for the ambient space, indicating their higher temperatures and lower viscosity.

Geophysical investigations of Panning and Romanowicz (2004), based, among others, on S wave polarization anisotropy, show that a vertical flow of matter dominates within these structures. The different temperatures in layer D" probably result both from a heat generated by the Earth’s core and from a mixing of melted Fe (from the core) with a high-pressure silica phase (from the mantle — FeO, FeSi, Mg-perovskite).

Tomographic images confirm the fact that both these global superplumes, gradually narrowing, rise above layer D" into the mantle, and then they spread aside under the lithosphere (Romanowicz & Gung, 2002). Bunge et al. (1998) emphasize that these global intra-mantle structures,

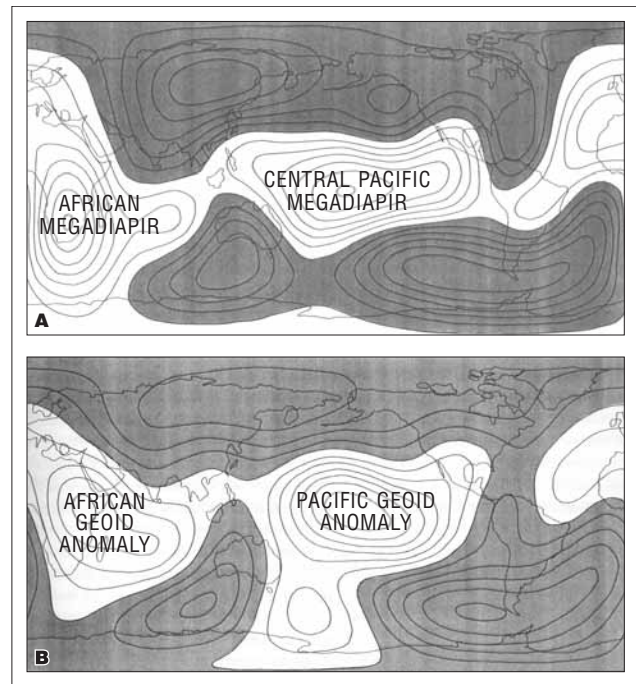


Fig. 3. A — Calculated topography of the core — mantle boundary (CMB); B — The Earth geoid anomaly. Both after Hager et al. (1985). Two upwellings of the CMB boundary coincide with two major geoid anomalies: beneath Africa and Central Pacific

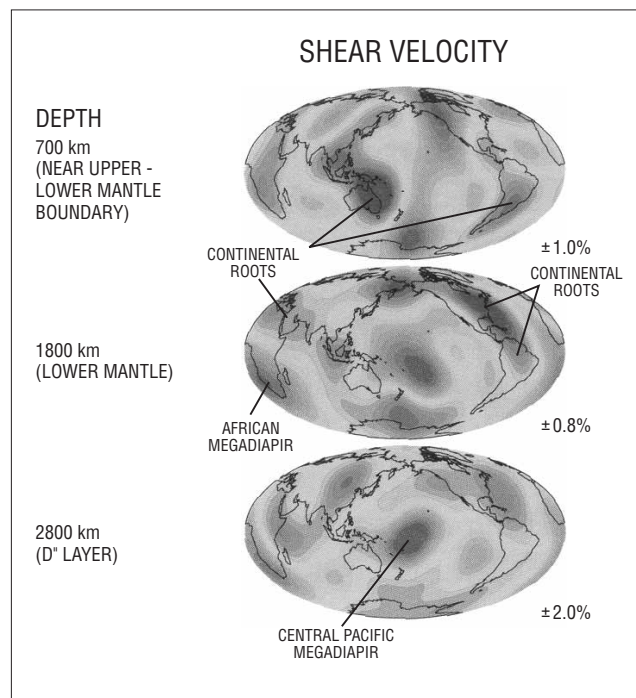


Fig. 4. Tomographic image based on shear wave velocity for three depths in the mantle: 700 km, 1800 km and 2800 km (Condie, 2001). Cold and rigid continental roots beneath Australia and South America are seen at the depth of 700 and 1800 km in the lower mantle. African and Central Pacific megadiapirs are born in the D" layer near CMB and are evident near the 660 km seismic discontinuity. Even in the D" layer portions with anomalously lower and higher shear waves velocity are shown

rising up from the core/mantle boundary, cannot be predicted by current tectonic plate models.

The term “superplume”, used by many authors (op. cit.) for both the mushroom-like upwellings (Pacific and Afri-

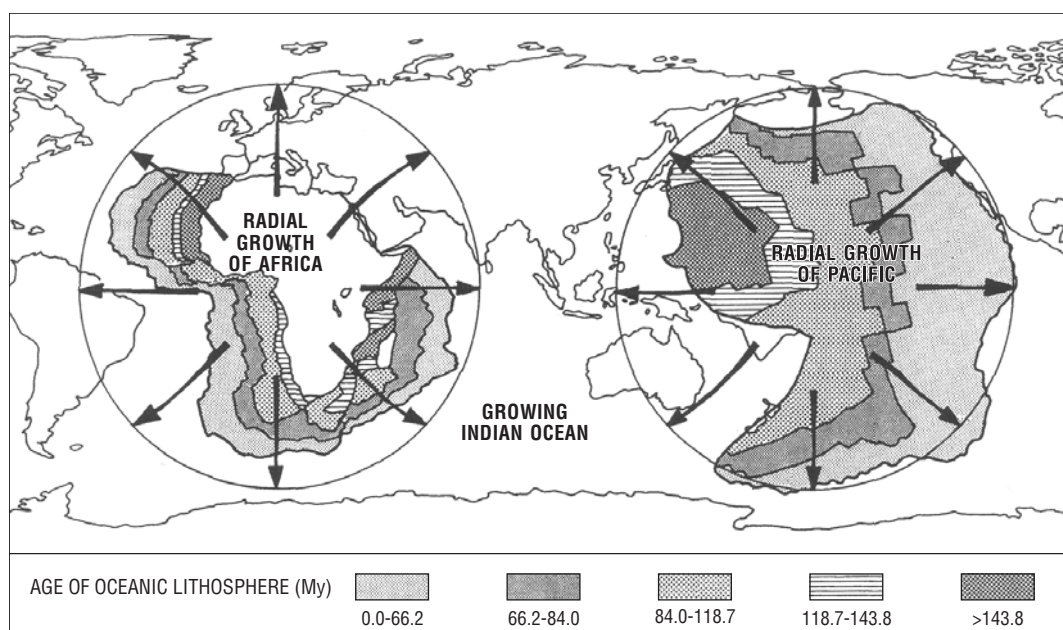


Fig. 5. Simultaneous radial growth of the African and Pacific plates in the last 180 Ma centered over the two main mantle upwellings (megadiapirs) (Condie, 2001). Note that the Indian Ocean is growing at the same time

can), seems to be somewhat inadequate. Both the size and shape of these structure entitle me to propose for them either a term “megaundation”, introduced to the literature by van Bemmelen (1972), or a term “megadiapir”.

The Pacific megadiapir (megaundation) is tomographically traced (Breger & Romanowicz, 1998; Courtillot et al., 2003; Romanowicz & Gung, 2002) down to layer D" as deep as the base of the lithosphere (LVZ). In the upper mantle, this structure splits into two shallow diapirs of the South Pacific and NE Pacific. The latter one approaches to western North America (Fig. 4). The African megadiapir is generated under SW Africa (Fig. 4), in the lower mantle it widens under the whole southern Africa and adjacent Atlantic areas. The African continent located in the centre of the mantle megadiapir is encircled by the spreading centres of the Atlantic and Indian Oceans, and by numerous hot spots connected with topographic swells. This area is characterized by a relief of basins and swells and a system of rift valleys. According to Pavoni (vide Condie, 2001, p. 52) geotectonic bipolarity of the Earth, i.e., simultaneous radial spreading of the African and Pacific plates during the last 180 Ma, is genetically related to both the mantle megadiapirs (Fig. 5).

On the Earth's surface, these upwellings correspond to negative anomalies of the geoid (Fig. 3B). One of them is located under the Afar region in East Africa, the other one is situated symmetrically with its centre beneath the central and southern Pacific. These structures are associated with a number of mantle plumes reaching up to the surface where they form the so-called hot spots.

Mantle plumes

According to the current definitions, a mantle plume is a bubble of hot material from the mantle, showing lower density and viscosity relative to the surrounding matter, and rising to the surface due to the effect of isostatic buoyancy (Fig. 6). When reaching the Earth's surface, this heat column results in the following features: a domal morphological swell with an average diameter of about 2000 km,

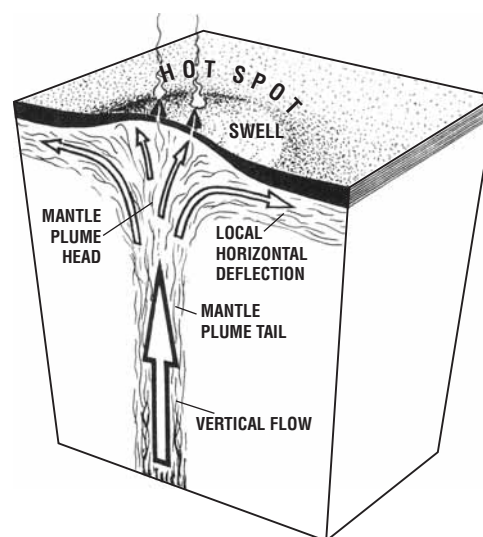


Fig. 6. Schematic model of a typical mantle plume and corresponding hot spot

an area of increased heat flow, and a series of magmatic phenomena including intraplate volcanism, sometimes so intense that it leads to the formation of plateau basalts.

Already Wilson (1963) interpreted the linear chain of Hawaii islands and submarine volcanoes to be a result of the Pacific plate movement above a stationary mantle plume. Morgan (1971, 1972) was the first author who found that mantle plumes originate from the core/mantle boundary, and they are stationary relative to one another. A number of laboratory experiments (e.g., Whiethead & Luther, 1975; Kumagai, 2002) have shown that the shape of mantle plumes depends on their viscosity; if viscosity of the matter inside the plume is lower than viscosity of the surroundings, the mantle plume consists mostly of a head (over 1000 km in diameter) and a narrow tail (about 100 km in diameter). The basic research methods applied for mantle plume investigations include surface observations: studies of heat flow, geochemistry and age of volcanic rocks (espe-

cially plateau basalts and island intraplate basalts), as well as investigations of the deep Earth structure with the use of seismic methods, including seismic tomography. It should be taken into account that the small thickness of mantle plume tails so far makes it impossible to trace directly their location in the Earth's mantle by tomographic methods (except of largest among them, e.g., Iceland (Fig. 7) and Afar — Ritsema et al., 1999). As emphasized by Condie (2001), the principal theory of mantle plumes is currently well supported, but many features of these structures are

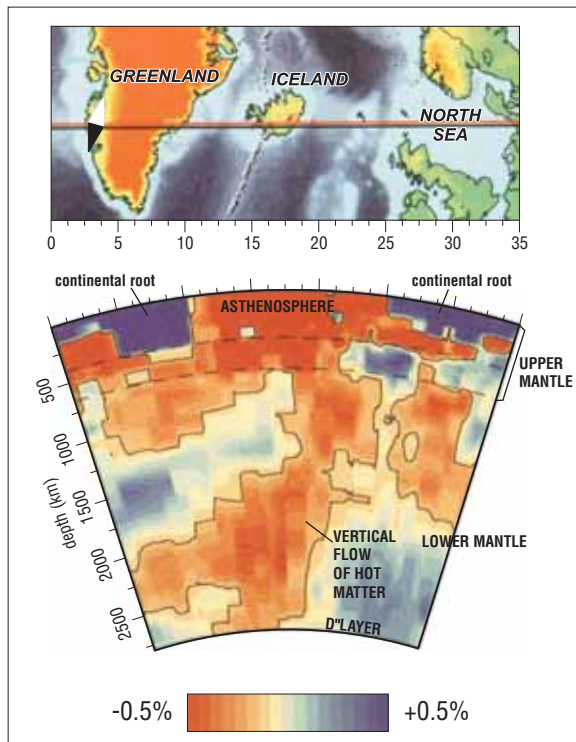


Fig. 7. Tomographic cross section through North Atlantic between Greenland and N. Germany showing distribution of zones with slow (red) and fast (blue) S-wave velocities for upper and lower mantle. Continental roots reaching 400 km deep beneath Greenland and Europe, irregular masses of hot and buoyant mantle matter at different levels, asthenospheric (LVZ) pillow beneath Iceland and its vicinity and almost vertical mantle plume feeding the LVZ are shown

unclear and controversial.

During the last 1 Ma, 49 hot spots have been active (Courtilot et al., 2003). There are a total number of 150 such hot spots of variable age, well-known and described. Most of them are no longer active. Not all of them necessarily correspond to mantle plumes originating from basal parts of the Earth's mantle. In recent years, there has been much discussion on the criteria for distinguishing plumes of deep, mantle origin.

According to the paper cited (Courtilot et al., 2003), deep-seated mantle plumes are conspicuous by a set of features distinguishing them from shallower structures generated in the upper mantle. Hot spots corresponding to these structures can be associated with long-lived volcanic track commencing with plateau-basalts (traps) (e.g., Afar, Canary Islands, Iceland, Louisville and Reunion hot spots), although it is not a *sine qua non*. The famous Hawaiian hot spot (Wilson, 1963), does not have an equivalent in plateau-basalts. An important criterion is high buoyancy of mat-

ter derived from deep mantle, which is manifested by the formation of a domal topographic swell in the hot spot area (e.g., Afar, Canary Islands, Hawaii, Iceland, Pitcairn), as well as of anomalously high $^3\text{He}/^4\text{He}$ and $^{21}\text{Ne}/^{22}\text{Ne}$ rates in volcanic rocks. Farley and Neroda (1998) are of the opinion that such geochemical anomalies indicate a rising of magma from long-isolated and very primitive magma reservoirs. The high ratio of the above-mentioned noble gases isotopes is the characteristic feature of magmas from Afar, Azores, Bouvet, Cape Verde Islands, Easter Island, Galapagos, Hawaii, Iceland, Juan Fernandez, Kerguelen, Reunion, Samoa, Pitcairn and Yellowstone (Courtilot et al., 2003).

Attempts to correlate surficial hot spots with tomographic images from different depths have also been undertaken recently. Zones of anomalously low S waves velocity indicate the presence of anomalously warm and lighter mantle matter flows under hot spots. The deep rooting, at least at a depth of 500 km, is typical, among others, of hot spots from Afar, Bowie, Canary Islands, Easter Islands, Hawaii, Iceland, Juan de Fuca, Samoa and Tasman (Fig. 8).

The use of such criteria to all of the modern 49 hot spots has led Courtilot et al. (2003) to a conclusion that only 9 hot spots meet at least 3 of the 5 criteria. However, analysis of their data indicates that the opinion is too cautious. Cri-

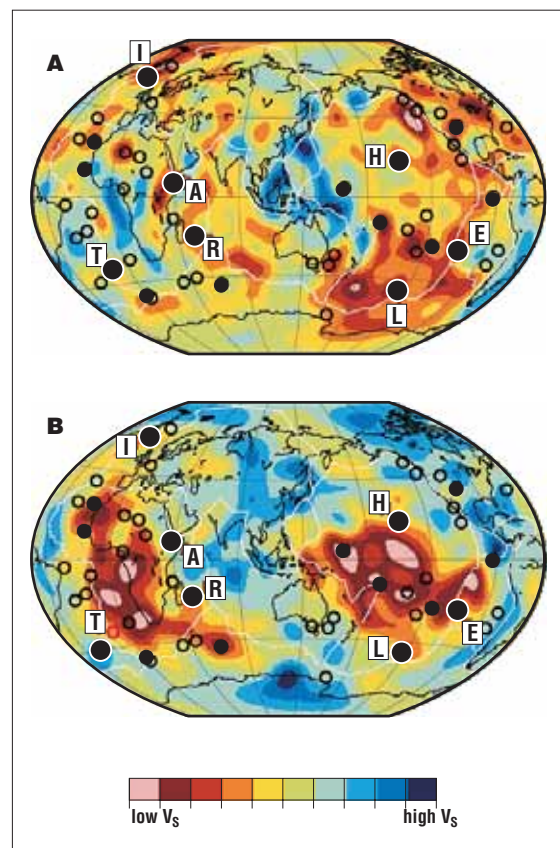


Fig. 8. Distribution of the 49 hot spots on the background of tomographic images at 500 (upper mantle) and 2850 km (D'' layer) depth. Tomographic image after Ritsema et al. (1999). Scale of colours from -2% to +2% — beneath the maps. Primary hot-spots (according to Courtilot et al., 2003) are shown as bigger black spots: I — Iceland, T — Tristan, A — Afar, R — Reunion, H — Hawaii, E — Easter, L — Louisville; suspected hot spots of very deep origin (on the base of Courtilot et al. (op. cit) data) are shown as smaller black dots, other hot spots as black circles

teria resulting from the existence of a volcanic track, commencing with plateau-basalts, seem to be artificial; many distinct hot spots are not associated with traps (e.g., Hawaii, Bowie, Canary, Cape Verde, Juan Fernandez, Galapagos). The isotopic criteria are in turn ambiguous due to lack of data for many of the modern hot spots, and as many as 18 hot spots are characterized by the high He/Ne ratio in volcanites. There are equally many hot spots that meet the topographic criterion. Nevertheless, the existing geophysical and geochemical data indicate that there are different forms of the upward rise of matter in the Earth's mantle: megadiapirs (megaundations, superplumes), primary plumes, secondary plumes and mantle diapirs. What is extremely important is that the major primary hot spots are not spatially associated with megadiapirs, but they are independent structures.

In conclusion, the so-called primary mantle plumes (Courtilot et al., 2003) are generated at thermal boundaries inside the globe, most probably in layer D". Most of hot spots do not correlate with any specific structure of lithospheric plates — mantle plumes and the plates are not related to each other. However, it seems that most of mantle plumes are correlated with the two anomalies of the geoid: the Atlantic-African and South Pacific anomalies (Duncan & Richards, 1991). These anomalies are at least in part associated with mantle megadiapirs (Fig. 8).

Convection in the Earth's mantle and mantle plumes

Convection in the liquid is driven by buoyancy forces produced by the density (temperature) variations. Cell convection is a process in which the upward-rising flow of hot matter and the sinking flow make up a closed convection cell. The dynamic thermal system of the Earth is characterized by the transfer of heat from the core to layer D". The heat is subsequently transferred from the surface by thermal conductivity. This system is obviously disturbed by radiogenic heat sources in the Earth's mantle. For a long time, geophysicists have been intrigued by the question whether there is any convection between these two surfaces.

Traditionally convection currents are considered a driving force stimulating lithospheric plate movement (see Dadlez & Jaroszewski, 1994). Mantle convection was already mentioned by Dietz (1961) and Hess (1962) in works which later became the basis for the plate tectonic theory. Since then, most of geotectonicians have taken it for granted that the oceanic lithosphere, being cooled from the surface downwards, is getting denser to exceed the asthenosphere density, and then is sinking in the Earth's mantle. The lithosphere is replaced along the mid-ocean ridges and rift zones by the rising hot asthenosphere closing the convection cells.

In the whole-mantle convection model, cited by Hess (1962), the convection process refers to the whole Earth's mantle (Fig. 9A) as deep as the CMB. Ascending currents occur here under rift zones, while descending currents are crucial for the subduction process. This model is very simple and clearly explains cyclic circulation of matter within

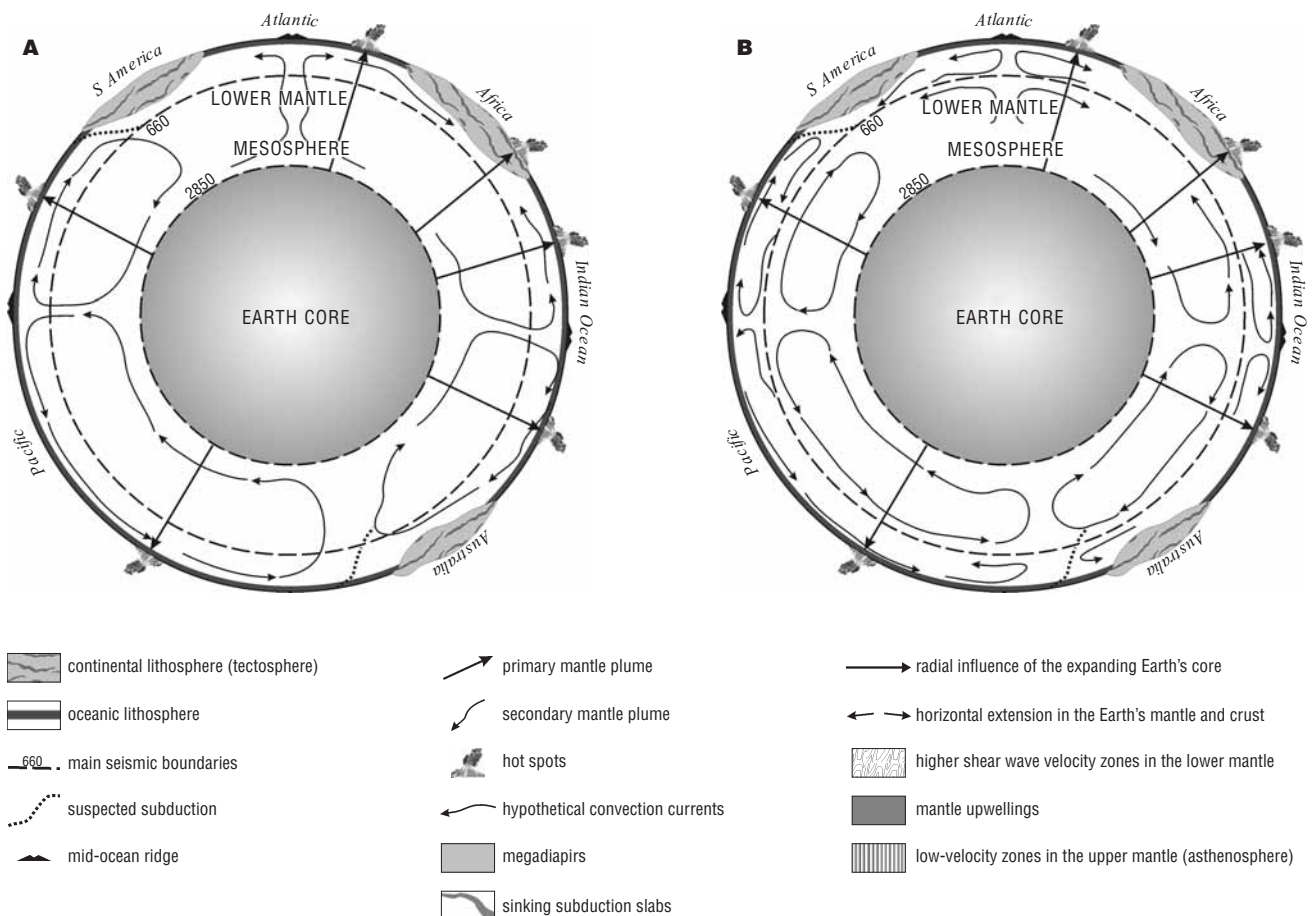


Fig. 9. The internal structure of the Earth and classical models of geodynamics: A — whole-mantle (one-layered) convection model, B — two-layered convection model. The relative position of continents is maintained

the Earth's mantle. This simple model is contradicted by the existence of an outstanding zone of discontinuity in density, viscosity and thermal properties, that occur at the 660 km boundary. The zone is an important barrier for free circulation of matter between the upper and lower mantle. The convection process described in this way would have to be very slow, what makes it impossible to explain the complex and fast movement of plates, microplates and terranes that is widely accepted by geologists.

The two-layered convection model (Fig. 9B) assumes that the convection process occurs in two geospheres separated by the 660-km depth discontinuity. Upper mantle convection is believed to directly control the lithospheric plate motion, whereas the lower mantle convection governs the distribution of matter and heat in the mesosphere. This model is supported by arguments indicating geochemical distinctions of the lower mantle, and also suggesting its high viscosity quickly increasing with depth. Such a model also facilitates explanation of relatively rapid changes in movement of lithospheric plates and microplates. On the other hand, both the discontinuity, associated with the LVZ zone, and the tomographically confirmed existence of continental roots down to depths of 250 to 450 km suggest that the two-layered convection model seems to be rather unlikely.

In the classical tectonic-plate convection model, the ascending current appears under rift zones, whereas the descending current — in subduction zones. The well known contradiction between such an image and the situation found around Africa and Antarctica which are surrounded by oceanic ridges with active spreading, caused that it has been recognised that oceanic ridges are shallowly rooted structures and, together with the oceanic lithosphere, they are moved away from these continents. However,

such interpretation creates plenty of difficulties. How to reconcile the asymmetric movement of an active spreading zone with the symmetric structure of the oceanic lithosphere and the symmetric distribution of hot spots on both sides of the mid-oceanic ridge (in the Atlantic). If the "driving force" of plate motion is so shallow, how can it manage to move continents so deeply rooted in the upper mantle? Where, at last, is the permanent and effective heat for rift magmatism derived from?

But if convection currents operate in the Earth's mantle — why do not they disturb the mantle plumes formed at the core/mantle boundary?

Mantle plumes — hot spots

A stationary mantle plume, rooted in layer D" and exerting a vertical force on a moving lithospheric plate, should result in the formation of the so-called hot spot track or volcanic tracks on the plate (Morgan, 1971, 1972). The most well-known and recently active structures of this type are Hawaiian–Emperor Sea Mts. (Wilson, 1963), Tuamotu, Easter, Louisville, Tasman Sea Mts. in the Pacific Ocean, Rio Grande Walvis and New England in the Atlantic, Reunion in the Indian Ocean (Fig. 10). These tracks are conspicuous by a gradual rejuvenating of the age of volcanism along them however it is not a common phenomenon. The basic Hawaiian model seldom operates in nature, and deviations from the rule are frequent: multi-phase eruptions and eruptions that follow the existing weakness zones (e.g., transforming faults and other fault zones) appear along the tracks. Also a linear age arrangement of volcanoes is frequently disturbed. Within the framework of plate tectonic theory, special models are being worked out, explaining the occurrence of such phenomena on a litho-

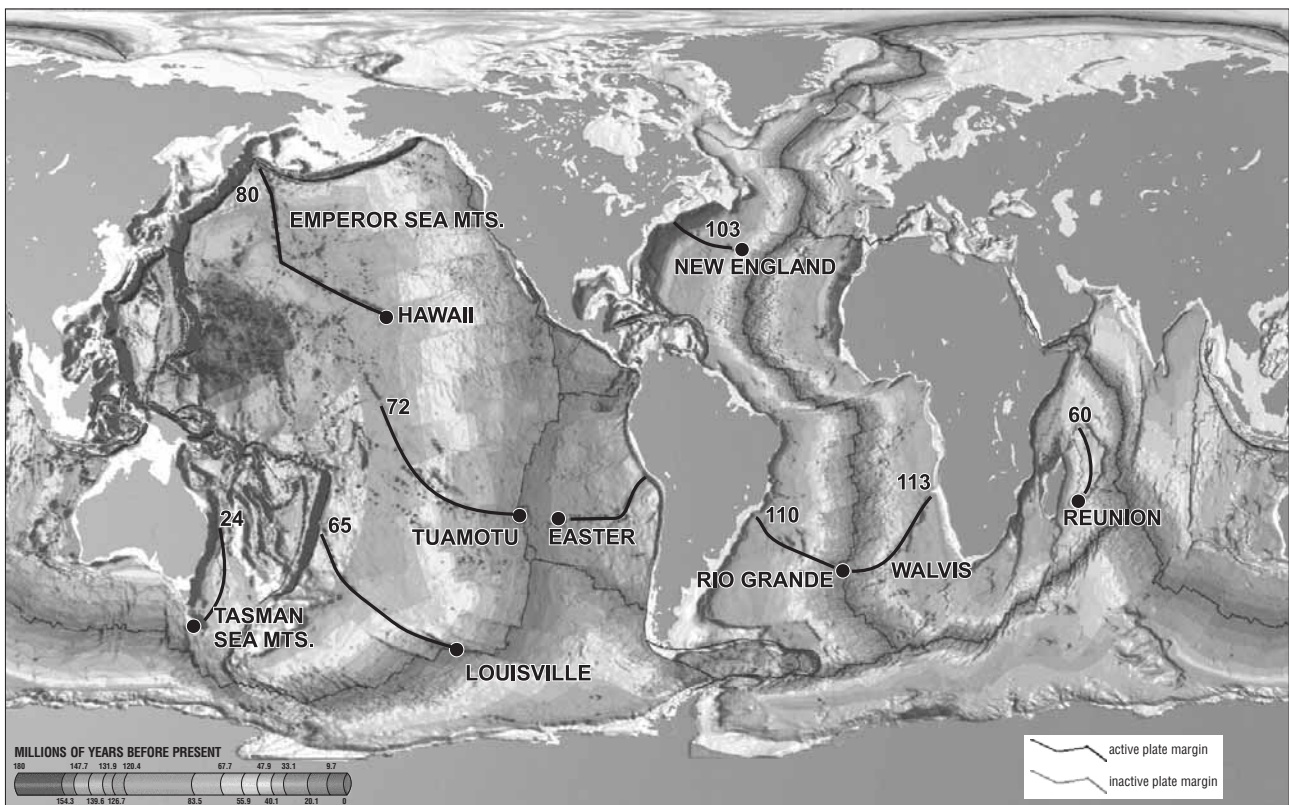
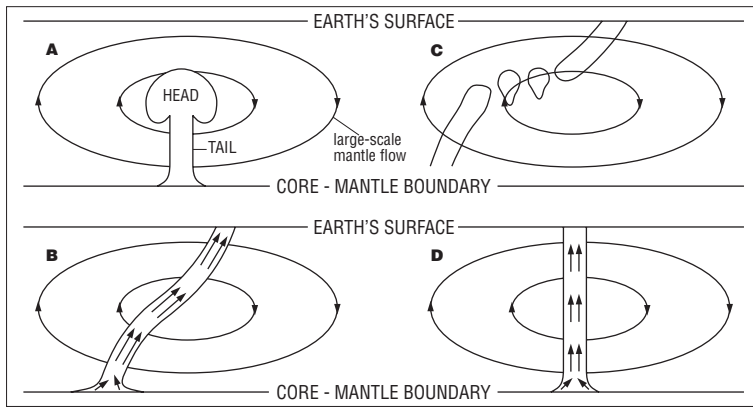


Fig. 10. Most important recent hotspot tracks shown on the background of the ocean-floor map. The age of volcanoes at the beginning of each track is seen. Age data from Condie (2001)



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Fig. 11. Hypothetical stages in the evolution of a mantle plume rising through convective mantle: A — first stage: mantle plume head rises vertically, B — first stage of deformation by convection currents, C — last stage — splitting of a tail, D — non-deformed plume-tail rises through the mantle. After Steinberger & O’Connell (1998)

spheric plate constantly moving above hot spots (Condie, 2001).

The behaviour of a mantle plume, rising through the convection mantle, has been modelled for many years (Steinberger, O’Connell, 1998). Theoretically, hot matter rising from the CMB (Fig. 11A) should undergo a gradual deformation (Fig. 11B) and even dismembering (Fig. 11C). The evidence that mantle plumes are tilted from the vertical is being sought today in tomographic images, however with miserable results so far.

As found by Condie (2001), hot spots producing the major volcanic ridges on the Pacific Ocean seem to occupy a stationary position in relation to the mantle. They do not undergo deformations by convection currents (Fig. 11D). This is the general discrepancy in tectonic-plate interpretations.

Plate tectonicians ask themselves a question whether hot spots are static, or else they change their position with time. There is no doubt that hot spots located in a single plate and close to one another, also show stationary positions relative to one another, as evidenced for the Pacific Ocean (Morgan, 1971; Steinberger & O’Connell, 1998).

Position of hot spots, considered in relation to hot spots which are far away from one another, seems to change with time. For example, the Hawaii–Emperor Sea Mts. volcanic

chain is displaced relative to the position calculated with an assumption that the hot spot remains in a constant position relative to the Atlantic and Indian Ocean hot spots. Such calculations were made by Di Venere and Kent (1999).

Because the cited observations are not coherent — the tectonic-plate interpretations are full of frustration and misunderstanding of the phenomenon.

Towards a new model?

Summing up, it must be emphasized that the plate-tectonic interpretation of data concerning modern dynamics of the Earth’s interior leads to a number of discrepancies (see Condie, 2001; Courtillot et al., 2003). Most important are:

- stationary position of mantle plumes at the assumption of the convection process in the Earth’s mantle;
- mantle convection versus data on both viscosity of mantle matter and the existence of seismic discontinuities;
- possibility of horizontal displacements of lithospheric plates above the LZV zone which is a discontinuous layer disappearing under deep-seated continental “roots”;
- the model of radially growing distance between mid-oceanic ridges and Africa (also Antarctica), and its incompatibility with geological data;

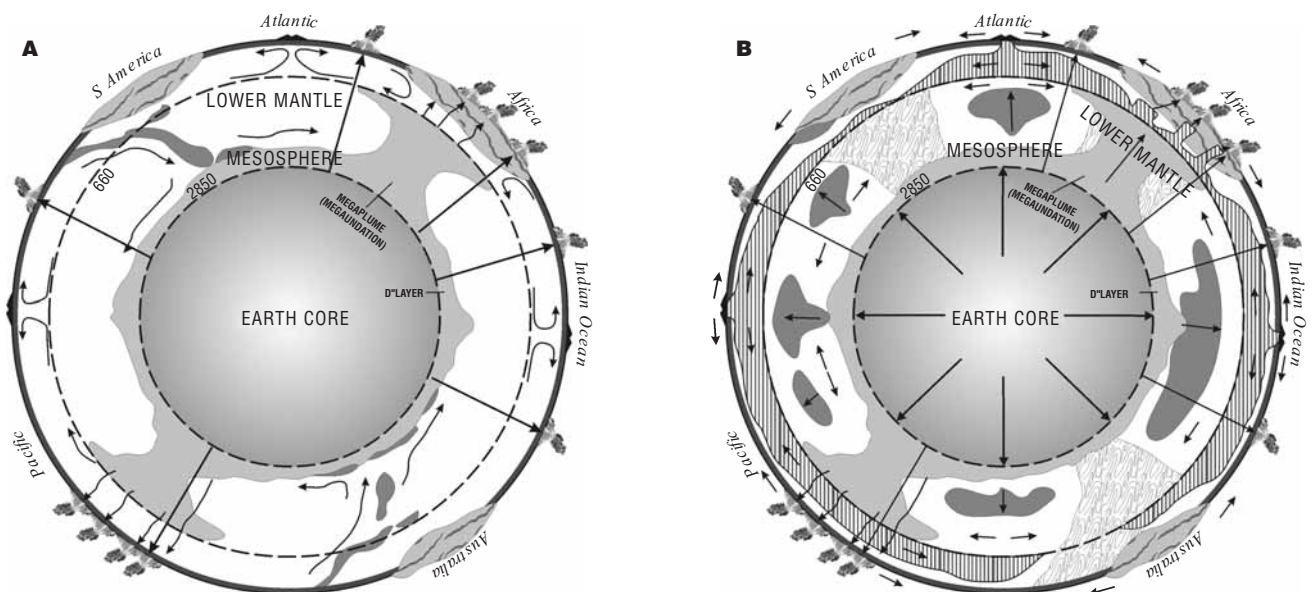


Fig. 12. The internal structure of the Earth and new models of geodynamics: A — contemporary plate-tectonic model of the internal Earth’s dynamics (plate-tectonic model of hybridic convection); B — proposed model of the expanding Earth’s geodynamics. For explanations see Fig. 9

— the growing separation between hot spots occur in neighbouring plates with time;

— geophysical data indicative of considerable input of energy and material from the Earth's core into the mantle, uncompensated by any exchange between the lower and upper mantle.

As increasingly more information has been provided, new models of internal dynamics of the Earth have lately been proposed. The modern models developed by Kellog et al. (1999) and Courtillot et al. (2003) can be termed multi-layered convection models of the Earth mantle or a tectonic-plate hybrid convection model. This model intends to explain tomographic image of the Earth's interior with taking into consideration geochemical data. The model presented in Fig. 12A is the synthesis of geophysical and geochemical data from the point of view of the plate tectonic theory. It is based both on the newest data on the two antipodal mantle superplumes (megaundations, megadiapirs) rising from layer D", and on two mantle plume types distinguished by Courtillot et al. (op. cit.): primary plumes formed at the core/mantle boundary and secondary plumes produced at much shallower depths at the top of the two superplumes (megaundations). This model considers the problem of mantle convection and the "driving force" for plate motions in a quite different manner. There is a lack of a uniform system of convection cells in this model to control the movement of lithospheric plates. Convection currents are local phenomena, they appear near the top of both the superplumes. Ascending currents are again placed under mid-ocean ridges. However, they do not form closed cells, but are carried by deeper movements of mantle material. Material exchange between the lower and upper mantle is believed to follow as a result of the so-called post-subduction avalanches, which reach to layer D" in this model (Brunet & Machetel, 1998). The concept that subduction plates reach as deep as the CMB is to explain energy and material balance in the lower mantle. The discussed model tries to reconcile geophysical data — in particular seismic tomographic images, with data about geochemistry and geological position of hot spots associated with mantle plumes. This approach to the convection process, different from the previous one, facilitates explanation of both the stationary position of hot spots and the lack of deformations, due to horizontal movements, of material stream rising from the core/mantle boundary. Despite that, the model still does not explain the phenomena such as horizontal movements of continents deeply rooted in the mantle, in particular if there is no continuous LVZ layer. Attempts to reconcile these observation with the hypothesis of horizontal plate movements are heading in two directions: a concept of slabs sliding down on the megapupwellings (Romanowicz & Gung, 2002), and a concept of anisotropic seismic structure of the asthenosphere under the oceans and within continental roots. The latter concept is related to the discovery (Gung et al., 2003) of the zone of horizontally polarized transverse S waves under most of cratons at depths of 250–400 km. Its topmost part is believed to be related (op. cit.) to the so-called Lehmann discontinuity. This discontinuity is supposed to facilitate horizontal movement of continental cratons if there is no continuous LVZ.

In conclusion it must be stressed that the modern tectonic-plate model of geodynamics of the Earth's interior shows many discrepancies.

The nature of mantle convection still remains controversial. Understanding of the convection process is the greatest challenge, as concluded by Condie (2001). Isotopic and geochemical data and the amount of heat production in the Earth's interior suggest that the lower mantle sources have maintained their geochemical identity for the last 2 billion years (op. cit.). It seems that the very most of the heat is produced by the lower mantle (Albarede, 1998), that denies the possibility of whole-mantle convection. On the other hand, tomographic data seems to confirm that the sinking lithospheric slabs can reach as deep as the CBM, i.e., to cross the 660 km discontinuity. Does it mean that the boundary is temporal only? Both the phenomenon of stationarity of hot spots relative to the accepted plate movements of and the absence of evidence indicating deformations of mantle plumes by the convection system are also unclear and controversial. In a conclusion to the model of the Earth's interior dynamics, Condie (2001) writes: *Whether this model will survive the test of rapidly accumulating new data remains to be seen. However, it appears that any model for mantle convection must be consistent with the existence of a compositionally distinct and gravitationally stabilized lower mantle.*

The solution is at hand

The paradox of our times is that the expanding Earth theory, today almost completely forgotten or scorned (Cwojdzinski, 2003), offers a reasonable solution to these discrepancies and paradoxes. The presented model of dynamics of the expanding Earth's interior (Fig. 12B) is based on currently available geophysical and geochemical data. Its basic characteristics are: 1) lithospheric plates are rooted in the Earth's mantle; 2) no cell convection operates in the mantle; 3) energy and material are transferred from the core/mantle boundary radially towards the planet surface; 4) upward-rising of material occurs at various depths and in different rocks as: megadiapirs (superplumes), primary and secondary mantle plumes, mantle diapirs of various types and other forms of vertical transfer of hot, less viscous and lighter masses of mantle material.

Such a model permits to explain the fundamental problems, raised by non-expanding Earth models, namely:

- 1) the "excess" of heat and material generated at the CBM,
- 2) the existence of seismic discontinuities related to a change in physical and chemical parameters (phase alterations, composition changes etc.) in the globe,
- 3) undisturbed vertical course of mantle plumes penetrating the entire Earth's mantle,
- 4) long-lasting geochemical isolation of layer D" and the lower mantle,
- 5) the occurrence of anomalously dense and cool mantle bodies with their equivalents even in layer D" (Condie, 2001),
- 6) ease of penetration of the lower and upper mantle as well as of the lithosphere by upward-rising streams and domes of mantle matter,
- 7) discontinuity of the LVZ (asthenosphere) and its variable thickness,
- 8) the occurrence of mantle roots under old Precambrian cratons,
- 9) symmetric pattern of mid-ocean ridges around Africa and Antarctica, and many others.

According to the theory of the expanding Earth, lithospheric plates are deeply rooted in the upper mantle and stationary relative to centre of the Earth. The asthenosphere (LVZ) forms at the top of the upper mantle due to rising hot, "floatable" masses of mantle material. For the expanding Earth, a balancing of mantle material is not necessary, the matter and energy are supplied from the core and radially influence the mantle. Megaupwellings (superplumes, mega-upwellings) are a result of constant flow of material and energy from the core to the mantle. The undisturbed course of mantle plumes is also a fairly natural phenomenon resulting from radial expansion of the Earth's interior. Volcanic tracks, the major evidence of the plate tectonic theory for lithospheric plate movement over a stationary mantle plume is explained by the expanding Earth theory as apparent plate motion resulting from stretching of the upper mantle basement over the mantle plume. On expanding Earth, stationarity of mantle plumes which form at the core/mantle boundary, relative to the Earth's centre, is a natural phenomenon. Similarly, it is natural that most of active hot spots show spatial relationship with regions which correspond to the Pacific and Atlantic mega-upwellings.

The entirely artificial tectonic-plate model, which is to explain the lack of spreading compensation around Africa, is being replaced on the expanding Earth by a natural process of radial growth of oceanic lithosphere around the continents (Fig. 5). Symmetrical position of mantle plume tracks in the Atlantic in relation to the mid-ocean ridge indicates that there is no lateral pushing away of the ridge from Africa. The increasing separation among hot spots was already explained by Stewart (1976) who showed that the great circle distance increase between different hot spot pairs is caused by growing dimension of the Earth.

The future will show what fate awaits the developing models. Undoubtedly, the common acceptance of the promising expansion model will require true scientific revolution and a change in the way of thinking of geologists and geophysicists. However, there are first signs of growing interest in this theory.

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