DOI: 10.18454/PMI.2017.1.3

UDC 553.212:551.24

PLUME TECTONICS – MYTH OR REALITY?

Yurii I. DARAGAN-SUSHCHOV
VNIIOkeangeologia named after I.S.Gramberg, Saint-Petersburg, Russia

The paper is dedicated to the role of mantle plumes in the formation of large igneous provinces. From different regions of the world facts are mentioned that contradict key points of plume tectonics. Closer attention is paid to classical volcanic provinces on Hawaiian islands and in Iceland, as well as to Siberian and Deccan Traps, oceanic plateau Ontong Java, Central Atlantic magmatic province, Alfa and Mendeleev Ridges in the Arctic Ocean. A conclusion is drawn that plumes are a special case of mantle-lithospheric flows, which according to deep geophysics are often located horizontally which leaves out their plume origin. Heated masses of mantle substance under young volcanic regions or rift zones of mid-ocean ridges do not emerge from the depth in the form of a straight column, but rather have arbitrary shapes, skewing to the sides and having outgrowths, offshoots, spherical bulges. Vertically rising flows of hot magma (plumes) are not a cause, but an effect of a lithospheric split and rise of magmatic substance due to decompression. A conclusion is made that it is unproductive to exaggerate the shapes and sizes of plumes and use them to explain all the diversity of endogenous processes.

***Key words*:** plume tectonics, mantle-lithospheric flows, Hawaiian islands, Iceland, large igneous provinces

***How to cite this atricle*:** Daragan-Sushchov Yu.I. Plume Tectonics – Myth or Reality? Zapiski Gornogo instituta. 2017. Vol. 223, p. 3-8. DOI: 10.18454/PMI.2017.1.3

Introduction. Plume tectonics originated half a century ago in the framework of a plate-tectonic hypothesis in the efforts to explain the mechanism of areal magmatism of oceanic islands and intraplate flood basalt provinces. A gold standard of plume tectonics is a chain of volcanic islands located in the north-western part of the Pacific Ocean, from undersea Emperor Ridge to the Hawaiian archipelago, which is characterized by renewal of volcanic activity in the direction from north to south. This fact is explained by the passing of the plate above a stationary hot spot or a mantle plume (J.Wilson, 1963 and W.Morgan, 1972). By virtue of researchers, today the sphere of influence of deep-earth magmatic processes on tectonic phenomena like mantle plumes and super-plumes has extended. It is considered that plumes are responsible for powerful volcanic processes on the Earth surface and formation of large igneous provinces. Plumes are regarded as the main driving force of tectonic plates, the cause of continental rifting, continent split, spreading, destruction of continental crust and its transformation into oceanic one. A special surge of interest in plume-tectonic concept occurred in 90s years of the 20th century with the progress in seismic tomography, that discovered mantle heterogeneities in different regions of the Earth. For the time being the number of detected plumes of different sizes exceeds 5 thousand.

Problem statement. As any concept, plume tectonics is founded on several experimentally verifiable suggestions, the main of them [11] are the following:

- a mature mantle plume consists of a large disc-shaped head with a diameter up to 2-2.5 thousand km and a tail from 10 to 200 km in diameter;
- temperature of plume head is 200-250 °C higher than surrounding mantle, which causes the floating of the plume, i.e. active plumes must have a heightened heat flow above them;
- due to enormous sizes, plumes stay overheated for a significant period of time, from 100 to 300 million years;
- areal volcanism must be preceded by a rise of territory above the plume with an amplitude of up to 1 km at epicenter, following the shape of a mantle dome;
- initially, at the epicenter of a hot plume there must be a melting of picrite magmas, the amount of which decreases from the center out.

Despite the fact that current interpretation accepts different variations in plume structure, their temperature, size and depth of formations, it still does not explain either a huge variety of surface volcanic products, or specifics of their tectonic position. You get the impression that lack of proof

DOI: 10.18454/PMI.2017.1.3

in detecting hot plumes in the subsurface is comparable to the lack of doubts in their existence. Plume concept is especially popular among Russian geologists regardless of their adherence to mobilist or fixist paradigms. Plume tectonics or mantle upwelling are used to explain every more or less large-scale magmatic occurrence, even if there is no geophysical evidence of mantle heterogeneities.

Curiously enough, it is in the western world, where the concept first emerged, that in the latest decade numerous well-reasoned publications doubt universality of plume mechanism or even reject it altogether. So, a renowned American physicist D.Anderson, one of the founders of seismic tomography and authors of the plume concept, expressed his doubts in the real existence of plumes, supposing that for the time being there is not enough seismic data to detect them. A quick look at the extensive literature shows that regions of plume generation can be located at any depth, plumes are stationary or dynamic, have a long or a short lifespan, rise upward or move at an angle, are local-sized or large-scales, have no head, have one or many heads, produce a stable or variable heat flow, have high or low ratio of helium isotopes. A natural question follows: how can mutually exclusive data attest to the existence or non-existence of plumes? The answer is evident - they cannot. In such case plume tectonics is not a hypothesis but a speculative priori assumption. Considering such diversity of facts, plume tectonics does not explain anything, but on the contrary, distorts an already unclear and complicated picture of Earth's interior structure.

Despite all the diversity of tomographic algorithms, geophysical data clearly point to heterogeneities in upper mantle. This viewpoint is also supported by geochemists investigating xenoliths. Low-velocity zones do not form a single layer, as it was supposed when the plume concept has been created, i.e. upper mantle is heterogeneous. Neither is asthenosphere a single layer. Modern seismography has demonstrated that continents have deep roots underneath them, reaching 400-600 km, and no asthenosphere. Alternating of low-velocity (hot) and high-velocity (cool) zones in the upper mantle implies that thermal and thermochemical conventions take place. The share of the latter probably prevails, as high pressure at such depths weakens thermal expansion and chemical influence on the floating heated substance exceeds thermal effect. Mantle lenses and streams heated to various extents have peculiar shapes and are often located horizontally, which rules out their plume origin. Cold and hot streams of mantle substance form intricate patterns in horizontal and vertical planes, but there is no full conformity between their underlying extensions and surface shapes. Heated masses of mantle substance underneath young volcanic regions or rift zones of mid-ocean ridges do not emerge from the depth in the form of a straight column, but rather have arbitrary shapes, skewing to the sides and having outgrowths, offshoots, spherical bulges. Today many researchers think that plumes are not responsible (or responsible to a very small extent) for the motion of tectonic plates. Identified morphology of mantle heterogeneities limits the role of plumes to formation of large igneous provinces and ocean islands with a heavy basalt layer, i.e. returns to the initial concept of hotspots.

Role of plumes in formation of large igneous provinces. Classical examples of modern volcanic provinces, supporting plume tectonic concept, are Hawaiian islands and Iceland. In the north-western part of the Pacific Ocean and in the Hawaiian archipelago itself plume tectonic concept in any of its modifications contradicts geophysical and petrogeochemical materials. For instance, there is an mismatch between supposed trajectory of the Pacific plate above Hawaiian hotspot, calculated using distribution of linear magnetic anomalies, and the actual direction and age of volcanoes of the Emperor and Hawaiian Ridges, especially in the point of their elbow-like junction [22]. Volcanoes are not stretched out in one line, instead they are distributed in space. The elevation level along Hawaiian islands does not decrease with distance from the moving plate, which would have been expected according to plume theory. For the Emperor Ridge no elevation has been detected whatsoever [21]. Seismography did not show any connection between low-velocity anomaly in the mantle and surface volcanism [24]. The archipelago itself is located above cold high-velocity mantle, while heated low-velocity extensions in the mantle were detected at a significant distance to the south-west from Hawaii. Volcanoes in the south of Hawaiian archipelago form two parallel linear geo-

 DOI: 10.18454/PMI.2017.1.3

chemical series located only 40 km from one another [15]. In one of them the composition of volcanic products changes with the age of the volcano, whereas in the other one no such change occurs. Inability of plume tectonics to explain these peculiarities of Hawaiian islands force scientists to search for other solutions.

One of them revives a mid-19th century concept of lithospheric stress, which causes abrupt magma eruptions from small-depth reservoirs. The modern version of this hypothesis is represented by a theory of lithospheric split, according to which progradation of a lithospheric fracture above the drifting plate leads to consecutive eruptions of cascade volcano chains. At the same time, hypotheses of small-scale mantle convection and compensatory lithospheric bending are being developed.

Another widely recognized example of a contemporary hotspot is Iceland. It is a large island in the North Atlantic, located at the intersection of Mid-Atlantic Ridge (MAR) with Faroe-Greenland plateau, connecting North America with Great Britain and Scandinavia. Visible part of Iceland's crust is practically fully composed of volcanic rocks, represented by 90 % of tholeiitic basalts and a smaller fraction of olivine ones. Remaining 10 % are intermediate and felsic volcanic rocks: andesite, dacite, rhyolite, trachyte. Lavas are followed by pyroclasts and hyaloclastites of the same composition. Sediment rocks are very rare, they are represented by interfacial lenses of river and lake deposits and tillites and certainly are volcanomictous.

From the viewpoint of plume tectonics, formation of Iceland, Greenland-Iceland and Iceland-Faroe Ridges and other geological structures of that region is explained by Iceland plume located in low-velocity mantle zone [20]. As a result of fragmentation of North Atlantic land mass in late Mesozoic era, a separation of North-American and Eurasian plates took place. In Paleocene age a plume penetrated underneath this territory, which lead to seafloor spreading and gravitational rise of the lithospheric region. Greenland-Iceland and Iceland-Faroe Ridges, Jan Mayen Ridge and other elevation in this region are an ancient trace of tectonic plates drifting beneath Iceland plume or its lateral flows [23]. The main arguments for the existence of Iceland plume is abnormal thickness of the earth crust below the center of the island (up to 40 km) and high seismic pressure waves greater than or equal to 7 km/s. Excess thickness of the earth crust underneath Iceland, compared to other MAR regions, is explained by the drift of oceanic plate over a stationary hotspot. Plume penetration implies an increased geothermal regime of the entire Icelandic region.

However, the latest measurements of heat flow in Iceland demonstrated that it does not differ from other MAR regions, especially from the side of the North-American plate. On the contrary, it is even lower for the North-American plate than for the Eurasian one, though the situation has to be the opposite according to plume concept. The crust beneath Iceland is colder than the one at similar depths near the East Pacific Rise [18]. Unlike in Hawaii, in Iceland no age migration of the hotspot trace has been detected. Thus, a classical Hawaiian model of a tectonic plate migrating above a deeply fixed plume is incapable of explaining huge amounts of volcanism in North Atlantic (British Arctic) Igneous Province and in Inceland, in particular. Seismic and thermal anisotropy, characteristic of Iceland, is hard to ascribe to stationary plumes. Picrite lavas as an indicator of high mantle temperatures are altogether absent in Iceland. On the contrary, recent drift valleys are often dominated by icelandite (iron rich andesite) and felsic lavas. Seismic tomography has not shown any plume-like structure in the lower mantle underneath Iceland. Below the point of 250 km low-velocity anomaly takes an oblong shape, complimentary to MAR. Such weak anomalies in the lower mantle have been detected under the shields in Canada and Scandinavia, but no one assumes the presence of mantle plumes there.

Contradictions in factual evidence of the plume concept encourages alternative versions of Iceland anomaly. From the positions of plate tectonics, there is a hypothesis about MAR intersection with Caledonian suture, which marks an ancient subduction zone. Excessive amounts of basalts, melted from the subsurface of Iceland compared to adjacent MAR regions, can result from existence of ancient subduction slabs that up until today remained in the nearby mantle regions [14]. Considering actual heterogeneity of the mantle, specific subsurface structure of Iceland can be as-

DOI: 10.18454/PMI.2017.1.3

cribed to multi-scale convection [16] or long-lasting decompression zones in the lithosphere [13]. To explain the origin of trapping mechanism, including Icelandic region, a concept of whirls in nonlinear geophysical environment has been suggested [2]. It is supposed that the difficulties in interpreting Icelandic phenomenon from the positions of plume tectonics are caused not only by insufficient seismic experiments, but also by speculative handling of geophysical data separately from geological tests. It is geological data that showed how in early Tertiary times Iceland had already been a part of a giant land bridge between America and Europe, which in Miocene period submerged in North Atlantic. The reasons for such dip can be different – spreading or basification, but the fact itself, that in late Mesozoic era there was land in place of today's North Atlantic, was discovered by geology.

A compelling evidence of correcting role of geological tests is offered by results of drilling and dredging on marginal plateaus Voring, Rockall and other intra-oceanic rises of North Atlantic. Continental type of crust on the major part of Voring and Rockall plateaus has been proven only due to deep-hole drilling, which intersected Pre-Cambrian granulites and granitoids in the foundation of both structures. Earlier it was thought that their foundations are represented by basic magmatic rocks of the third layer of oceanic crust. In the Norwegian Basin, which according to geophysical data consists of oceanic crust, deep oil wells and dredging operations helped to discover numerous blocks of continental crust. Here in the walls of large splits and on local elevations typical continental rocks were found, represented by terrigenous varieties of arkosic types, quartz rocks, greenstone slates, epidote amphibolites and migmatite-granites, analogous to the ones discovered on Hatton Rockall and Faroes elevations, similar to potassium migmamtites in the continental framing of North Atlantic. Even the slopes of Reykjanes Ridge and Iceland-Faroe Channel contain granulites and charnokites typical for Pre-Cambrian shields [6].

At the same time none of the co-existing theories can explain why the amount of melted magmatic substance beneath Iceland is 2-3 times higher than in other MAR regions, whereas the temperature in Iceland subsurface is relatively low. Besides, identified surface volcanism should be linked to geochemistry of basalt, which are very close to basalts from oceanic islands and MAR. It remains unclear, how significant amounts of intermediate and felsic magmatites appeared in the active rift zone of Iceland and why picrite lavas are completely absent, when other MAR regions are characterized by the prevalence of basalts and ultrabasites.

Inconsistencies between the main suggestions of plume tectonics and actual geologic and petrologic tests have also been observed in other large igneous provinces. Continental flood basalts, like Deccan traps in India [19], Tungus syneclise in Siberia [1, 12] and oceanic plateau Ontong Java [9], are characterized by a low heat flow, comparable to other cratons, and the absence of elevation above the plume, preceding areal volcanism. Notably, core of the wells drilled on Ontong Java plateau contained pyroclastic rocks (tuffs), which points to subaerial character of eruption. Judging by argon isotope ratios for Ontong Java, two brief large-scale eruptions took place with an interval of 30 million years.

Neither is there evidence for the existence of elevation above the plume in the large Central Atlantic magmatic province. Besides, here were also identified two magmatic events with an interval of 70 million years [17]. The earlier event happened geologically instantly in early Jurassic period, practically simultaneously with Pangaea split, which resulted in the formation of the giant Central Atlantic magmatic province, represented by tholeitic low-potassium basalts. Starting from early Cretaceous and through Cenozoic period the province experienced eruptions of alkali olivine basalts from numerous (more than a hundred) volcanoes, stretched out in a range of undersea mountains located chaotically, independently of spreading centers. Alkali olivine lavas and plutons of similar composition have been detected on both shores of Central Atlantic in the East America and West Africa. Two episodes of magmatism cannot be attributed to a single superplume. Alkali olivine basalts are clearly younger than intruded tholeitic ones, moreover, magmatic melts for both of them originate from different depths.

Non-critical interest towards plume tectonics, which, according to many scientists, is the main cause of large-scale migration of mantle substance and plays a central role in the split and drifting of land masses, is especially common for underexplored territories, e.g. the Arctic [7]. Insufficient information is compensated by a priori guesses.

Even today many researchers of Arctic believe that undersea Alfa Ridge and adjacent Mendeleev Ridge, located in Transarctic elevation zone of the Arctic Ocean, are an oceanic plateau formed as a result of a mantle plume affecting an ancient spreading center, similar to Icelandic one. Their argumentation is quite trivial: abnormal crust thickness (30-40 km) with high «basaltic» seismic velocities, relatively homogenous upper crust and sporadic findings of modified alkali basalts in tuff matrix. The logic is clear: if seismic characteristics of the crust of Alfa and Mendeleev Ridges are close to seismic characteristics of the crusts of Iceland, plateau Ontong Java and Kerguelen elevation, which are a priori regarded as oceanic, then Alfa Ridge is also a result of mantle plume influencing the oceanic crust. Such position of the majority is accepted by the UN Commission on the limits of the continental shelf (New York) and formalized in Article 76 of the Convention on the Law of the Sea (1982), where it is stated that ridges of the deep ocean bed, formed as a result of seafloor spreading, or ridges, formed as a result of active volcanism, related to eruption of abnormally hot mantle, are regarded by the Commission as oceanic structures. However, in the latest years appear publications that leave open the possibility of continental origin of Alfa and Mendeleev Ridges, taking into account ambiguous interpretation of velocity models [10] and dredging results for Mendeleev Ridge [3]. High seismic velocities in the crust are common not only for basalts of the second oceanic layer, but also for carbonates and Pre-Cambrian metamorphic rocks, which is strongly indicated by Vøring plateau drilling. Furthermore, alkali basalts are more characteristic of surface intraplate structures or oceanic plateaus (of disputable genesis) and are never encountered in mid-oceanic ridges and abyssal basins.

Discussion. Progress in Earth sciences leads to a conclusion that it is not plumes that lead to lithospheric split and magma eruptions, but the other way around – splits in the lithosphere cause mantle substance to melt and rise due to decompression [8]. Mantle plumes have been modeled experimentally, but they have never been detected in the nature in their pure form. For the time being only mantle heterogeneity has been proven by means of seismic tomography. It still is unclear why splits sporadically happen in the lithosphere and what spatial and temporal relations control their occurrence. It should be noted that, due to the convergence of phenomena in nature, geology does not necessarily need a beautiful theory of everything, explaining all the diversity of processes happening on Earth. Every theory reflects only limited aspects of development. Polarity of viewpoints at different stages in the history of geology is well known: plutonism-neptunism, catastrophism-evolutionism, fixism-mobilism. History of geology has shown that simple explanations of complicated multifactor processes do not withstand the test of time. Efforts to find a universal mechanism of tectonic processes is similar to an attractive but fruitless idea of creating «an eternal engine».

Plumes as a hot mantle stream move regardless of convective flows of heterogeneous mantle. Even if plumes exist – they are only a particular case of mantle-lithospheric flows. Hence it is unproductive to exaggerate the shapes and sizes of plumes and use them to explain all the diversity of endogenous processes. Any modern Earth theory has to take into account rotational and cosmic factors that to a great extent define magmatism and tectonics of different regions [4, 5].

Conclusions

1. Mantle plumes are not the main cause of formation of large igneous provinces on the continents and in the oceans. Even more so, they cannot be a universal reason of planet's tectonic processes: spreading, continental rifting, motion of tectonic plates.

2. Plumes and superplumes are only a particular case of mantle-lithospheric flows.

3. When searching for causes of tectonic processes on Earth, it is essential to take into account rotational and cosmic factors.

DOI: 10.18454/PMI.2017.1.3

REFERENCE

1. Daragan-Sushchov Yu.I. Early Triassic Lakes of Tungus Syneclise. Istoriya ozer pozdnego paleozoya i rannego mezozoya. Leningrad: Nauka. 1987, p. 249-257 (in Russian).

2. Mirlin E.G., Kononov M.V., Mironov Yu.V. Possible Nature of Trap Magmatism (on the Basis of Concepts of Whirls in Tectonosphere and the Nonlinear Geophysical Environment). *Vestnik KRAUNTs*. *Nauki o Zemle*. 2008. N 2. Iss. 12, p. 28-41 (in Russian).

3. Kaban'kov V.Ya., Andreeva I.A., Ivanov V.N., Petrova V.I. Geotectonic Nature of the Central Arctic Morphostructures and Geological Implications of Bottom Sediments for Its Interpretation. *Geotektonika*. 2004. N 6, p. 33-48 (in Russian).

4. Pogrebitskii Yu.E. Geological Nature of the Arctic. Arktika na poroge tret'ego tysyacheletiya (resursnyi potentsial i problemy ekologii). St. Petersburg: Nauka, 2000, p. 91-104 (in Russian).

5. Pogrebitskii Yu.E., Neizvestnov Ya.V. Newest Dynamics of Lithosphere. Geologo-geofizicheskie kharakteristiki litosfery Arkticheskogo regiona. St. Petersburg: VNIIOkeangeologiya, 2004. Iss. 5, p. 36-52 (in Russian).

6. Silant'ev S.A. Metamorphic Rocks of Atlantic Ocean Seafloor. Moscow: Nauka, 1984, p. 103 (in Russian).

7. Filatova N.I., Khain V.E. Structures of central Arctic and Their Connections to Mesozoic Arctic Plume. *Geotektonika*. 2009. N 6, p. 24-51 (in Russian).

8. Anderson D.L. Lithosphere, Aesthenosphere, and Perisphere. *Rev. Geophys*. 1995. Vol. 33, p. 125-149.

9. Tejada M.L.G., Mahoney J.J., Neal C.R., Duncan R.A., Petterson M.G. Basement Geochemistry and Geochronology of Central Malaita, Solomon Islands, with Implications for the Origin and Evolution of the Ontong Java Plateau. *Journal of Petrology*. 2002. Vol. 43, p. 449-484.

10. Dove D., Coakley B., Hooper J., Kristofferson Y. Bathymetry, Controlled Source Seismic and Gravity Observations of the Mendeleev Ridge; Implications for Ridge Structure, Origin, and Regional Tectonics. *Geophys. Journal Int*. 2010. Vol. 183. N 2, p. 481-502.

11. Campbell I.H. Large Igneous Provinces and the Mantle Plume Hypothesis. *Elements*. 2006. N 1, p. 265-269.

12. Czamanske G.K., Gurevich A.B., Fedorenko V., Simonov O. Demise of the Siberian Plume: Paleogeographic and Paleotectonic Reconstruction from the Prevolcanic and Volcanic Records, North-Central Siberia. *Int. Geol. Rev*., 1998. N 40, p. 95-115.

13. Gernigon L., Ringenbach J.C., Planke S., Le Gall B. Deep Structures and Breakup along Volcanic Rifted Margins: Insights from Integrated Studies along the Outer Voring Basin (Norway). *Marine and Petroleum Geology*, 2004. Vol. 21. N 3, p. 363-372.

14. Foulger G.R., Anderson D.L. A Cool Model for the Icelandhotspot. *Journal of Volcanology and Geothermal Research*. 2005. N 141, p. 1-22.

15. Ihinger P.D. Mantle Flow Beneath the Pacific Plate: Evidence from Seamount Segments in the Hawaiian-Emperor Chain. *American Journal of Science*. 1995. Vol. 295, p. 1035-1057.

16. Korenaga J. Mantle Mixing and Continental Breakup Magmatism. *Earth Planet. Sci. Lett.,* 2004. Vol. 218, p. 463-473.

17. McHone J.G. Non-Plume Magmatism and Rifting During the Opening of the Central Atlantic Ocean. *Tectonophysics*. 2000. Vol. 316, p. 287-296.

18. Menke W., Levin V. Cold Crust in a Hot Spot. *Geophys. Res. Lett*. 1994. Vol. 21. N 18, p. 1967-1970.

19. Sheth H.C. Were the Deccan Flood Basalts Derived in Part from Ancient Oceanic Crust within the Indian Continental Lithosphere? *Gond. Res*., 2005. N 8, p. 109-127.

20. Shilling J.G. Iceland Mantle Plume. *Nature*. 1973. Vol. 242. N 54, p. 565-571.

21. Smith A.D., Lewis Ch. The Planet Beyond the Plume Hypothesis. *Earth-Science Reviews*.1999. Vol. 48, p. 135-182.

22. Stuart W.D., Foulger G.R., Barall M. Propagation of the Hawaiian-Emperor Volcano Chain by Pacific Plate Cooling Stress. *Geological Society of America Special Paper 430*. Ed. by G.R.Foulger and D.M.Jurdy. 2007, p. 497-506.

23. White R.S., McKenzie D. Mantle Plume and Flood Basalts. *J. Geophys. Res*. 1995. Vol. 100. N B9, p. 17543-17585.

24. *Zhao D*. Global Tomographic Images of Mantle Plumes and Subducting Slabs: Insight into Deep Earth Dynamics. *Physics of the Earth and Planetary Interiors*. 2004. Vol. 146, p. 3-34.

Author **Yurii I. Daragan-Sushchov,** *Candidate of Geological and Mineral Sciences*, *Leading Researcher*, *daragan-sushchov.iury@yandex.ru* (*VNIIOkeangeologia named after I.S.Gramberg*, *Saint-Petersburg*, *Russia*)

The paper was accepted for publication on 16 November, *2016*.