News & Views

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Testing the mantle plume hypothesis: An IODP effort to drill into the Kamchatka-Okhotsk Sea system

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The great mantle plume debate (GPD) has been going on for ~ 15 years [1-7], centered on whether mantle plumes exist as a result of Earth's cooling or whether their existence is purely required for convenience in explaining certain Earth phenomena [3]. Despite the mounting evidence that many of the so-called plumes may be localized melting anomalies, the debate is likely to continue. We recognize that the slow progress of the debate results from communication difficulties. Many debaters may not truly appreciate (1) what the mantle plume hypothesis actually is, and (2) none of the petrological, geochemical and geophysical methods widely used can actually provide smoking-gun evidence for or against mantle plume hypothesis. In this short paper, we clarify these issues, and elaborate a geologically effective approach to test the hypothesis. According to the mantle plume hypothesis, a thermal mantle plume must originate from the thermal boundary layer at the core-mantle boundary (CMB), and a large mantle plume head is required to carry the material from the deep mantle to the surface. The plume head product in ocean basins is the oceanic plateau, which is a lithospheric terrane that is large (1000's km across), thick (> 200 km), shallow (2-4 km high above the surrounding seafloors), buoyant (~ 1% less dense than the surrounding lithosphere), and thus must be preserved in the surface geology [8]. The Hawaiian volcanism has been considered as the surface expression of a type mantle plume, but it does not seem to have a (known) plume head product. If this is true, the Hawaiian mantle plume in particular and the mantle plume hypothesis in general must be questioned. Therefore, whether there is an oceanic plateau-like product for the Hawaiian volcanism is key to testing the mantle plume hypothesis, and the Kamchatka-Okhotsk Sea system is the best candidate to find out if it is indeed the Hawaiian mantle plume head product or not [8,9].

The plate tectonics theory established ~ 50 years ago has formed a solid framework for understanding how the Earth works on all scales with great success. One of the primary assumptions in this theory is that the surface plates are rigid and do not deform internally, but they can move relative to one another along plate boundaries. Therefore, the plate tectonics theory can readily explain all the Earth processes (e.g., magmatism, metamorphism and earthquakes) along plate boundaries, but cannot explain within-plate geological phenomena. The mantle plume concept was thus put forward to explain within-plate phenomena such as the active Hawaiian volcanism and the Hawaiian-Emperor seamount chains with age progression within the interior of the vast Pacific plate. Wilson [10] called the within-plate volcanoes like Hawaii as "hotspots" with a relatively fixed deep source, deeper than and thus unaffected by the moving Pacific plate. Morgan [11] proposed further that the hotspots are surface expressions of deep-rooted thermal mantle plumes coming from the core-mantle boundary (CMB). The current view is that cooling of the mantle leads to plate tectonics while cooling of the core is responsible for mantle plumes [12-14]. The plate tectonics theory and mantle plume concept thus complement each other to explain much of the totality of Earth processes and phenomena.

The plate tectonics is well expressed by the plate motion and plate boundary zone processes, and has been repeatedly tested to be a mature theory with the efficacies being far more powerful than perceived at present [15]. On the other hand, despite some persuasive arguments in favor of mantle plume derivation from a deep mantle thermal boundary layer like the CMB [12,14,16] and its convenience to explain the origin of large igneous provinces (LIPs) since the late Paleozoic [17-20] (Fig. 1), the mantle plume concept remains a hypothesis (vs. theory) because mantle plumes cannot yet be detected with confidence [2,5,21,22] despite seismological attempts [23,24]. This difficulty, the confusing usage of "mantle plumes" and numerous alternative ideas proposed to explain within-plate magmatism [see reviews of refs 22, 25] altogether have led to the great debate on whether mantle plumes exist or not [3]. This debate has been rather heated [1-7], and is one of the greatest in the history of the solid Earth Science [3].

Can the mantle plume debate be resolved?

Scientific debates are healthy and useful if the proposed hypotheses can be tested whether they are proven to be correct or invalidated. The current mantle plume debate lacks hypothesis testing or the methods used for testing are ineffective. For example, it is common to read in the literature the statement like "*geochemical evidence for mantle plumes*". Such apparently acceptable statement is actually in error because it ignores the *assumption* that we know the geochemistry of mantle plume source materials, which we actually do not, and which we *assume* to come from the deep mantle that is *assumed* to be geochemically more enriched than the shallow mantle that is geochemically depleted as *inferred* from the global ocean ridge basalts. The obvious error of the statement comes from the use of assumption-based assumptions as evidence. It is logical to treat these assumptions as hypotheses, which again require testing before they can be considered as valid evidence or not. To make this point even clearer, let us consider two straightforward examples. (1) It has been widely accepted that mantle plumes come from recycled oceanic crust, but the latter is compositionally too depleted to be the source of intra-plate ocean island basalts of mantle plume origin like Hawaiian tholeiites (not even to mention the alkaline varieties). (2) the Cenozoic intra-plate basalts in eastern continental China are well-constrained to have derived from the upper mantle and have nothing to do with deep-mantle plumes, yet they are compositionally enriched and much more so than Hawaiian tholeiites of mantle plume origin. Hence, the existing geochemical approach to test mantle plume hypothesis is circular and has no way out. Petrology has been widely used to identify mantle plumes by using basalt-based thermometry, but this method is also questionable [26].

Mantle tomography is a useful means to show mantle seismic velocity structures on various scales [23,24]. The velocity variation, if detected to be resolved within error, could be caused by mantle temperature variation or compositional heterogeneity or both in combination. Some studies show that many of the accepted present-day mantle plumes do have reduced seismic velocity from near-surface all the way down to deep mantle or even close to the core-mantle boundary, proving the presence of hot thermal mantle plumes and their deep mantle origin [23,24]. These results are, however, debatable as we do not yet at present have adequate seismic resolution to reach those conclusions [2,4,5,21,22], which explains why the plume debate persists. Importantly, seismology has limited use about geological histories on any useful scale.

The above clarifies some fundamental difficulties in current thinking on mantle plume debate. This debate cannot be resolved unless we take an objective and geological approach as discussed below.

Is the mantle plume hypothesis geologically testable?

Despite the above, the mantle plume hypothesis is geologically testable and we can carry out the testing if we genuinely understand this hypothesis, including our agreement on (1) what thermal mantle plumes are, (2) where they come from, (3) how they behave, and (4) what consequential observations may be predicted. Campbell [6] concisely summarized the key elements of the mantle plume hypothesis as follows:

> *"Mantle plumes are columns of hot, solid material that originate deep in the mantle, probably at the core–mantle boundary. Laboratory and numerical models replicating conditions appropriate to the mantle show that mantle plumes have a regular and predictable shape that allows a number of testable predictions to be made. New mantle plumes are predicted to consist of a large head, 1000 km in diameter, followed by a narrower tail. Initial eruption of basalt from a plume head should be preceded by ~1000 m of domal uplift. High-temperature magmas are expected to dominate the first eruptive products of a new plume and should be concentrated near the centre of the volcanic province. All of these predictions are confirmed by observations."* (Fig. 2a-c)

With these definitions and characteristics of mantle plumes kept in mind, we can proceed to carry out geological testing by avoiding, to any degree, controversial elements (such as petrological, geochemical and seismological interpretations as discussed above), but emphasizing geologically characteristic products of the hypothesized mantle plumes.

Two identified and generally agreed-on mantle plume products

(1) *Large igneous provinces* (LIPs [17-20]), which are termed continental flood basalts (CFBs; e.g., Siberian Trap, Deccan Trap, Columbia River, and Emeishan basalt provinces) on land and oceanic plateau basalts (OPBs; Ontong Java Plateau, Kerulen Plateau, and Caribbean basalt provinces) in ocean basins, representing decompression melting products of the *mantle plume heads* when approaching or upon reaching the base of the lithosphere (continental and oceanic) (Fig. 1a). The LIPs are characterized by varying large volumes (0.1 ~ 10 x10^6 km^3) with great areal extents (0.1 ~ 10 x10^6 km^2) erupted in short periods (< 10 Myrs) [22].
(2) *Age progression volcanic chains* such as the H-ESMC, which are made of basaltic seamounts representing decompression melting products of *plume tails* (Fig. 1a,b). These chains could be short-lived, but can be long-lived such as the Iceland (~ 60 Myrs) and Hawaiian (> 85 Myrs) volcanism. The plume tail volcanism must occur and is volumetrically less significant, but the age-progression trails may or may not be well developed depending on the longevity of a plume and how fast the LIP-carrying plate moves relative to the "fixed" source of the plume. For example, the lack of age-progression volcanic trail for the ~ Siberian LIP is consistent with the slow motion of the giant Eurasian continent in the Triassic, and the prominent H-ESMC (Fig. 1) resulted from rapid motion of the Pacific plate and its reorientation at ~ 43 Ma although the Hawaiian mantle plume source may not be fixed (see refs. 8,9).

Physical foundation of the mantle plume hypothesis

(1) *Mantle plumes must initiate at a hot thermal boundary layer* (TBL), across which a large temperature contrast exists. The CMB is arguably the only such a hot TBL in the Earth because there is no convective mass exchange between the core and mantle due to the huge density contrast. As a result, the heat transfer between the two is through the rather inefficient conduction, hence the CMB (or the seismic D") region is the hot TBL (Fig. 2d). The heat conduction from the core to the base of the mantle can cause localized instability (or Rayleigh-Taylor instability) at the base of the mantle, leading to the initiation of mantle diapirs/plumes (Fig. 2e & f) and their rise because of the thermal buoyancy. Thermal plumes cannot develop elsewhere in the mantle because where the thermal gradient is adiabatic ($dT/dP = \Delta V/\Delta S$; temperature change due only to material molar volume change in response to pressure/depth change) and there is no excess heat or temperature. This is the physical footing of the mantle plume derivation from the CMB [see ref 3]. There are three conceptual confusions that need clarification. (a) Some

consider the 660-km seismic discontinuity (i.e., 600-D), which is the lower-upper mantle boundary, as a TBL for thermal plume derivation. We consider this to be unlikely because heat transfer (or thermal "homogenization") across the 660-D is effectively accomplished through "convective" processes as evidenced globally by penetration of many subducting slabs into the lower mantle; mass-balance requires the same amount of material rising into the upper mantle accordingly. Hence the 660-D is not a TBL for thermal plume derivation. (b) Slab stagnation in the mantle transition zone (above the 660-D) can happen because of fast trench retreat such as beneath eastern China, but the stagnated slab is not a TBL in a global context and if anything, it is cold and is a heat sink, not heat source [15]. (c) Enriched (e.g., high heat-producing elements K-U-Th) mantle compositional heterogeneity can cause non-adiabatic thermal gradient in the mantle (Fig. 2d) and may cause "chemical" plumes, but these are, if any, volumetrically insignificant relative to thermal plumes derived from the CMB [3].

(2) *Mantle plume heads are required for volumetrically significant lower-to-upper mantle mass transfer.* This is simulated numerically (Fig. 2e) and experimentally (Fig. 2f), and is straightforward in terms basic physics as described by the stokes-law [12]:

$$U = \frac{a^2 g \left(\rho_m - \rho_p\right)}{3\mu_m}$$

where U is the terminal ascending velocity of a plume head (or diapir), a is the radius of the diapir, ρ_p is the density of the hot plume rock, ρ_m and μ_m are respectively the density and viscosity of the surrounding mantle rocks, and g is the acceleration due to gravity. Clearly, in addition to enhanced thermal buoyancy of the plume ($[\rho_m\text{-}\rho_p] >> 0$) and overcoming the viscus resistance of the surrounding mantle (μ_m), the rising velocity is proportional to the size (a^2) of the diapir. The continued material supply maintains the growth of the plume head (Fig. 2e,f), and the growing plume head would ascend faster with increasing size (a^2), making it possible to transport volumetrically significant lower mantle material to the shallow mantle, whose decompression melting produces LIPs. Hence, there would be no mantle plumes if there were no LIP-producing plume heads.

(3) *Oceanic plateaus (LIPs) of mantle plume head origin are compositionally buoyant and unsubductable*. Large mantle plume heads must undergo decompression melting when reaching the solidus at shallow mantle or upon touching the base of the lithosphere. High extent of partial melting of the hot plume heads would produce voluminous melt and form thick basaltic crust upon solidification overlaying the thickened harzburgitic residue with a total lithospheric thickness of > 200 km (vs. mature oceanic lithosphere of ~ 90 km). Both the crust and melting residue are less dense and the whole package is ~ 1% ($\Delta\rho$ %= $[\rho_{PL}-\rho_{NL}]/\rho_{NL}$x100 ≈ - 1%; $_{PL}$ = plateau lithosphere, and $_{NL}$ = normal oceanic lithosphere) less dense and thus more buoyant than the surrounding lithosphere [8], giving rise to the plateau nature of 1000's km across, ~ 2 km below sea level and ~ 3-4 km shallower than the surrounding seafloors. The buoyant and unsubductable nature of the oceanic plateau is manifested by the

subduction of the Atlantic seafloor beneath the Caribbean plate, which is thought to be the Galapagos mantle plume head, and by the subduction of the Solomon plate beneath the giant Ontong Java plateau in the southwest Pacific. The unsubductable nature of oceanic plateaus is better appreciated through two basic illustrations: (1) geometrically and volumetrically, a buoyant and giant (~ 1000 km across and ~ 200 km thick ≈ $1.5x10^8$ km^3) oceanic plateau lithosphere with high elevation will jam the "small" (e.g., an upside-down triangle of 200 km across by 8 km deep) trench rather than subduct; (2) the relative buoyancy force increases with increasing volume of the body of interest (i.e., an oceanic plateau lithosphere), which is easy to understand for a ball, $B = - Vg[\rho_{PL} - \rho_{NL}]$ (B is the buoyancy force, V is the volume of a plateau lithosphere, and g is the acceleration due to gravity). Note that active ridges and aseismic ridges are subductable because they are *small bumps* atop the normal oceanic lithosphere, but oceanic plateaus are not because they are giant and twice as thick as normal oceanic lithosphere (see above) [8]. Oceanic plateaus of mantle plume head origin in the geological history must be accreted to existing continents and preserved in the surface geology of orogenic belts, often modified by subduction-zone magmatism [8,9,20,27-29].

Where is the unsubductable oceanic plateau of Hawaiian mantle plume head origin?

The above analysis with geological illustrations states explicitly that oceanic plateaus of mantle plume head origin must exist and be preserved in the surface geology. The concepts of *hotspots* and *mantle plumes* came into being because of the very intra-plate Hawaiian volcanism, and the Hawaiian volcanism has been unquestionably regarded as representing the classic mantle plume derived from the CMB with the H-ESMC as the product of the narrow plume tail melting (see above). It is surprisingly paradoxical, however, that we do not even ask the obvious question: *where is the LIP of Hawaiian mantle plume head origin* on the global LIP map (Fig. 1a)? This *scientific negligence* has left us with two possibilities, both of which require serious geological investigations on whether the LIP exists or not:

(1) Mantle plumes do not exist because the Hawaiian plume, which is the very foundation case for the plume concept, becomes skeptical without the predicted LIP of plume head origin. Before denying the plume concept, we must investigate to prove where the LIP exists or not, rather than to accept the absence from the map (Fig. 1a) as the fact to refute the mantle plume concept. This requires that we expend geological effort in search of the potential LIP beyond the Kuril-Kamchatka and western Aleutian trenches [8,9].
(2) Mantle plumes do exist and the Hawaiian volcanism with the H-ESMC, as unquestionably accepted, is simply the surface expressions of deep-rooted Hawaiian mantle plume. The compositionally buoyant and physically unsubductable oceanic plateau (LIP) of the Hawaiian mantle plume head origin must have been kept on the surface. But where is it on the global LIP map (Fig. 1a)? The senior author put forward the very question to Ian Campbell (1989 in Hawaii) who was advertising the tank-syrup experiment for mantle plumes (Fig. 2f) prior to the publication of [13]. The same question remains unanswered some 28 years later despite the potentially testable hypothesis put forward [8,9]. Again, this requires that we endeavor to search for the potential LIP beyond the Kuril-Kamchatka and western Aleutian trenches [8,9].

Niu and co-authors [8,9] offered independent lines of evidence to hypothesize that the best candidate for the Hawaiian mantle plume head LIP must be in the Kamchatka-Okhotsk sea system with the materials including the basement of the Kamchatka arc and the shallow seabed of the Okhotsk Sea. This hypothesis remains most logical and reasonable because it can be tested by means of IODP effort with the assistance of further geological and geophysical studies. Fig. 3 is self-explanatory, and illustrates why and how the oceanic plateau of Hawaiian mantle plume head origin is there represented by the basement of the Kamchatka Arc and Okhotsk Sea. The clue comes from the 43 Ma Bend along the H-ESMC (Figs. 1-4), whose origin was reviewed with an insightful analysis given in [9]. Some recent work suggests an older age of ~ 47 Ma for the Bend (vs. ~ 43 Ma in the vast literature), but before the new age is fully verified we here choose to use ~ 43 Ma to be consistent with the H-ESMC age data and with the geological observations in discussion (Fig. 4a inset); the exact age for the Bend does not affect the hypothesis testing. Some recent studies also show that the Hawaiian hotspot may not be fixed, but experienced southward drift [see ref 9], which is probably true, but the ~ 60° orientation change from 349.7°NNW of the ESMC to 292.5° NWW of the HSMC is best explained as the result of the Pacific plate reorientation because other age-progression trails on the Pacific plate show the same or similar [see ref 9; Fig. 1].

A topographically prominent feature in the far-east northeast Asia is the Mesozoic Okhotsk-Chukotka Andean-type continental margin with a well-developed magmatic belt (Fig. 4a), to which the ESMC is essentially perpendicular, which is consistent with the NNW Pacific plate motion and its subduction beneath the Okhotsk-Chukotka continental margin until ~ 43 Ma. At ~ 43Ma, collision of the oceanic plateau of the Hawaiian plume head origin jammed the trench (see Fig. 3b) and caused the Pacific plate to have changed its course of motion represented by the HSMC. The new subduction was thus then initiated at the compositional buoyancy contrast at the plateau edge of the younger seafloor (see Fig. 3b), leaving the oceanic plateau of the Hawaiian mantle plume head origin on the northwest side of the present-day Kuril-Kamchatka trench (Figs. 3c, 4a). The basement of the Kamchatka-Okhotsk Sea is the very mass of the Hawaiian plume head product [8,9].

The strong line of supporting evidence is given in Fig. 4b with details given in [8,9]. The volcanic zircons sourced from the otherwise Mesozoic Okhotsk-Chukotka magmatic belt and preserved in the forearc Ukelayet flysch (Fig. 4a) in fact have continuous magmatic ages from ~ 90 to ~ 44 Ma (Fig. 4b). The minimum magmatic age of ~ 44 Ma is significant because it is statistically the same as the ~ 43 Ma Bend of the H-ESMC (Fig. 4a,c). The straightforward explanation is that this age indicates the timing of the collision of the Hawaiian plume head plateau with the Okhotsk-Chukotka arc, which jammed the trench, stopped the arc magmatism (no younger than ~ 44 Ma volcanism), and caused the Pacific plate reorientation towards the NNW course represented by the HSMC since ~ 43Ma [8,9].

One may argue that the plume head plateau may be in the Bering Sea region, which is possible for some peripheral material if any, but is unlikely to be the primary target because plateaus of buoyant materials must have thickened lithosphere with shallow seafloor (see above). This is not the case for the Bering Sea especially for its western Commander Basin ("CB" in white; on average 3500 m below sea level with a sediment-buried 1.5 m layer of MORB-like basalts recovered from Hole 190 of DSDP 19) and heavily sedimented Aleutian Basin ("AB" in white; on average > 3800 m deep) (Fig. 1a,4a). The local topographic highs such as the Shirshov Ridge ("S" in red) and Bowers Ridge ("B" in red) (Fig. 4a) are tectonically separated same structure of 90 – 30 Ma age). In contrast, the Kamchatka Arc-Okhotsk Sea system has all the characteristics of an oceanic plateau:

(a) The Kamchatka Arc-Okhotsk Sea system is of exotic origin that collided with the Andean-type Okhotsk-Chukotka continental margin at ~ 44 Ma (Fig. 4;[8,9]); it has even been considered as "Okhotsk" plate in the literature.

(b) It is conspicuously broad (> 1000 km across) and shallow (see Fig. 1a), reflecting thickened and buoyant plateau lithosphere.

(c) Much of the Okhotsk Sea bed is rather shallow, from a few 100's m to no deeper than 1600 m at the deepest Deryugin Basin, which could be ascribed to sedimentation, but it should be noted that there is no major river input into this sea. Furthermore, there is no systematic depth increase from costal localities into the interiors of the Sea. In fact, the deepest point (~ 1600 m) in the Deryugin Basin is deeper than the southern slope (~ 1100 m deep) just north of the Kuril Basin ("KB" in white). That is, while sedimentation could be important, the first-order elevation/topography of the Okhotsk Sea is largely controlled by the basement elevation and topography.

(d) The high elevation of the Kamchatka arc (volcanic ridge of 500 – 1500 m above sea level) reflects significant magmatic productivity, but may owe much, or partly, to the physical (buoyancy) effect of the subducting Obruchev Rise (OR; Fig. 4a) and its melting contribution, This is to be further investigated.

(e) The new (Kuril-Kamchatka) subduction zone must have initiated at the edge of the plateau with the arc basement being the plateau mass [8,9].

(f) The Kuril Basin (KB; Fig. 4) is recently developed back-arc trough in response to slab rollback and trench retreat.

Drilling into the basement of the Kamchatka Arc-Okhotsk Sea

From the foregoing discussion, it is explicit that (1) the mantle plume concept widely invoked in the solid Earth science research has been challenged; (2) the challenge results from indiscriminate use of the concept and from the fact that this concept remains a hypothesis to be tested; (3) previous and current hypothesis testing has proved to be ineffective; (4) an effective geological approach to test the hypothesis is possible only if we fully understand the mantle plume concept, its basic physics and all the built-in assumptions, including plume *origination* from a hot TBL (e.g., the CMB) and *rising* through a growing plume head; (5) regarded as the classic mantle plume derived from the CMB, the Hawaiian mantle plume, if it is indeed one, must have its plume-head product (oceanic plateau type LIP) preserved in the surface geology; and (6) the basement of the Kamchatka Arc-Okhotsk Sea is identified to be the best candidate for the plume head LIP [8,9].

An IODP effort to drill into the basement of the Kamchatka Arc-Okhotsk Sea is predicted to be revealing. If the drilling is properly and adequately done, we may be convinced that the Hawaiian mantle plume has no plume head, it is not a thermal mantle plume derived from the CMB or mantle plume hypothesis needs reconsideration. However, the basement of the Kamchatka Arc-Okhotsk Sea may indeed be the Hawaiian mantle plume head product and thermal mantle plumes do exist. We may suggest the following actions:

(1) Some historical (1950's-1960's) seismic sounding data exist as reported recently,

especially in the Russian literature, whose interpretations may need reconsideration, but can be valuable guidance for planning new geophysical surveys. It is worth to mention that a recent study [30] prefers the studied locality of South-Okhotsk Basin as being of “continental in nature, rather than previously accepted oceanic crust”, with the thinner-than-expected crustal thickness as being “caused by Cenozoic mantle plume activity”. This is a very local study and the new interpretation is largely unfounded. It needs ground-truthing by means of drilling on ideal sites.

(2) A field study on adjacent land sites is needed to provide a geological context for all the possible geological events taking place prior to ~ 44 Ma, especially the Okhotsk-Chukotka volcanic belt (Fig. 4) as well as the coastal geology of the western Kamchatka.

(3) On the basis of re-evaluating the existing geological and geophysical data, a well-informed and coordinated international program should be initiated for geophysical investigations using seismic and gravity methods with the aim of identifying ideal drilling sites.

(4) Initial geophysical investigations may be focused on the Kuril Basin region and its northern slope (KB in Fig. 4a; ~ 2-3 km below sea level) as it is inferred to be recently developed back-arc basin in response to the slab rollback and trench retreat, and thus must have thinned plateau lithosphere with basement better exposed or easily accessed for drilling into.

(5) The Kamchatka island is capped with arc magmatic rocks and it will prove difficult to drill into the basement. It is important to note, however, that compared to the rest of the Kuril arc to the south, the Kamchatka island has high elevation with central ridge varying from ~ 500 m to 1500 m above sea level, which is apparently consistent with thickened crust with greater extents of melting and melt extraction. We infer that the high elevation of the Kamchatka Island arc may result from the subducting Obruchev Rise (OR in Fig. 4a) in two complement ways: (a) its buoyancy and (b) its melting for greater melt/crust contribution.

(6) There are no geological and physical reasons that the Hawaiian plume head materials would be in the Bering Sea, but we cannot rule out some dispersed materials in the Commander Basin, especially in its west regain adjacent to Kamchatka. Hence, some geophysical and geological work in this region will be useful. We should note that the objective is to test whether the Kamchatka Arc-Okhotsk Sea system basement is the Hawaiian plume head plateau, Hence, to focus on petrological/geochemical interpretations of individual samples without spatial coverage should be avoided as this will be misleading.

(7) An IODP effort for drilling with in situ bore-hole analysis and a comprehensive program to study the lithological properties, geochronology, petrology and geochemistry of the drill-core samples will provide a definite test as stated in the title of this paper.

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Figure captions

Fig. 1. Top, showing global large igneous provinces (LIPs, red) since 250 Ma (adapted from [19]). Bottom, showing global distribution of hotspots and their age-progression trails recorded on the moving plates [17-20] (summarized in *Plate Tectonics* by Frisch W, Meschede M, Blakey R, 2011, Springer), some of which are genetically related to LIPs in the top panel. Note that nowhere is there LIP associated with the Hawaiian mantle plume recognized in the top panel.

Fig. 2. (a-c; adapted from *Tasa Graphic Arts, Inc*:), illustrating the mantle plume hypothesis: plume initiation at the core-mantle boundary, rise of the plume with the head being fed by the plume tail, decompression melting of the head producing a LIP (flood basalts on land as "CFB" or on seafloor as "OPB"), and an age-progression volcanic trail (a seamount chain) left on the LIP-carrying moving plate. (**d**, simplified from [3]), emphasizing that thermal plumes must come from a hot thermal boundary layer (TBL) across which a large thermal contrast exists; the core-mantle boundary (CMB, or the seismic D" region) is inferred to be the most likely location of such hot TBL in the earth. (**e**, adapted from [4]), showing theoretical simulation of thermal mantle plume development at the CMB, its rise/growth and the timeframe of ~ 100 Myrs required to reach the lithosphere. (**f**, from [6,13]), showing tank-syrup simulation of thermal plume development.

Fig. 3. Cartoons illustrating the consequences when a buoyant oceanic plateau of mantle plume head origin reaches a trench (adapted from [8,9]). (**a**) the accretion, thickening and subduction of an oceanic lithosphere. Initiation and rise of a mantle plume from the basal thermal boundary layer (TBL) at the core-mantle boundary (CMB) (1), development of plume head (2), and formation of oceanic plateau (3) by decompression melting of the plume head. (**b**) The plateau moves with the plate leaving a hotspot trail on the younger sea floor. This plateau, when reaching the trench, has important consequences as indicated. If the trench jam leads to the cessation of the subduction, the subducting plate will reorient its motion to where subduction is likely. A large compositional buoyancy contrast at the plateau edge becomes the focus of the stress within the plate in favor of the initiation of a new subduction zone [8,9] (**c**) Initiation and subduction of the dense oceanic lithosphere soon leads to dehydration-induced mantle wedge melting for arc magmatism, but the basement of the very arc is the oceanic plateau [8,9]. Note that (**c**) is meant to illustrate the concept, which is simplified and exaggerated to schematically describe the present-day Hawaii-Emperor Seamount Chains (H-ESMC), Kamchatka arc, Okhotsk Sea and abandoned Andean-type Okhotsk-Chukotka continental arc (see Fig. 4).

Fig. 4. (a) Portion of the world map showing the Hawaiian-Emperor Seamount Chains (H-E SMC) in the context of the northwest Pacific region with information given as indicated (from [9]). The inset gives the ages of the seamounts along the chains from the literature

(summarized in [9]). The Okhotsk-Chukotka volcanic belt outlined in white is thought to be a Mesozoic Andean-type continental margin with abundant granitoids. The Ukelayat flysch outlined in white dashes is thought to be part of the preserved fore-arc basin with flysch strata. S and B (in red) stand for Shirshov and Bowers ridges respectively in the Bering Sea, and are thought to be tectonically separated same structure of ~ 90-30 Ma age. CB and AB (in white) stand for the Commander and Aleutian Basins in the western Bering Sea. KB (in white) is the Kuril Basin. OR (light blue) with the red arrow indicates the NW-striking Obruchev Rise on which the > 82 Ma Meiji seamount stands, and is being subducted beneath the Kamchatka arc. (**b**, adapted from [9] summarized from the literature), showing magmatic zircons in the Ukelayat flysch sourced from the Okhotsk-Chukotka magmatism actually have continues ages from ~ 90 to ~ 44 Ma, i.e., the magmatism stopped at ~ 44 Ma. (**c**, adapted from [8,9]), showing that the age of the H-E bend (~ 43 Ma) is essentially the same as the ending time of the Okhotsk-Chukotka magmatism [9].

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Figure 1 (Niu et al., 2017, SB N&V)

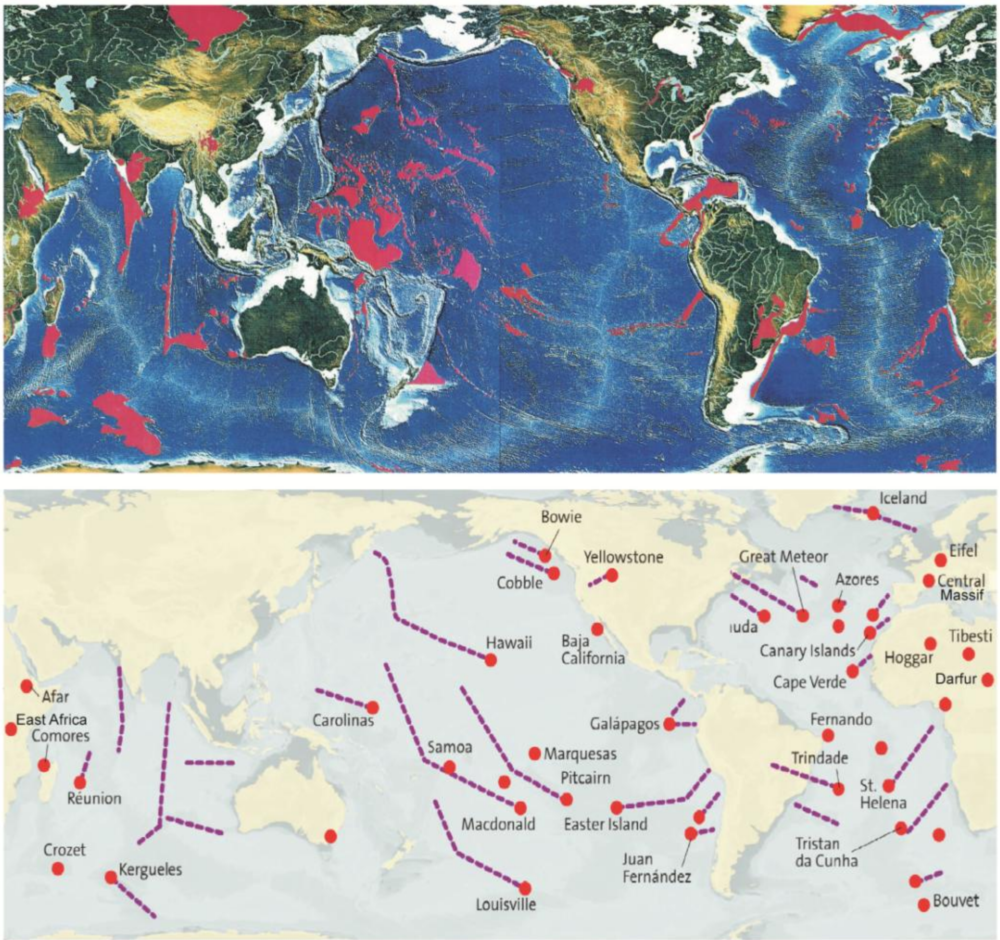

Figure 2 (Niu et al., 2017, SB N&V)

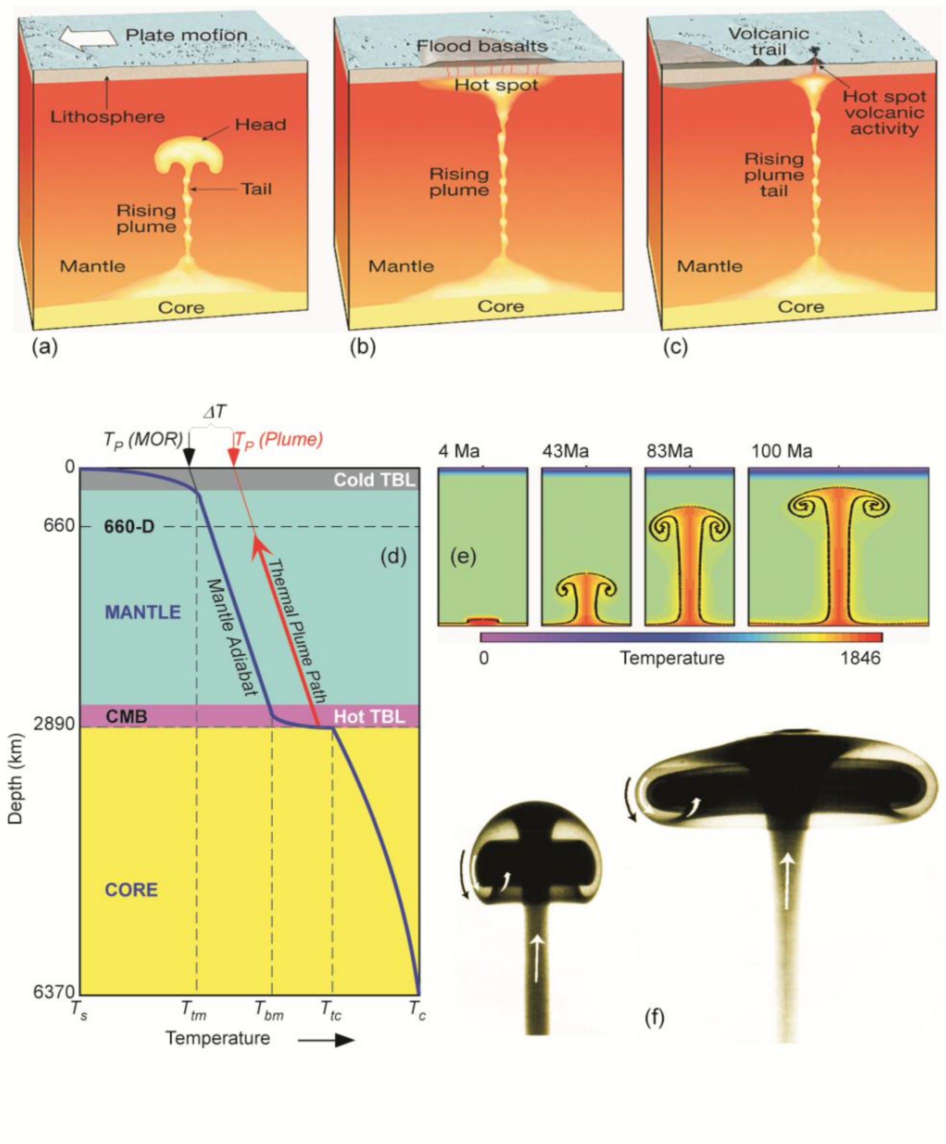

Figure 3 (Niu et al., 2017, SB N&V)

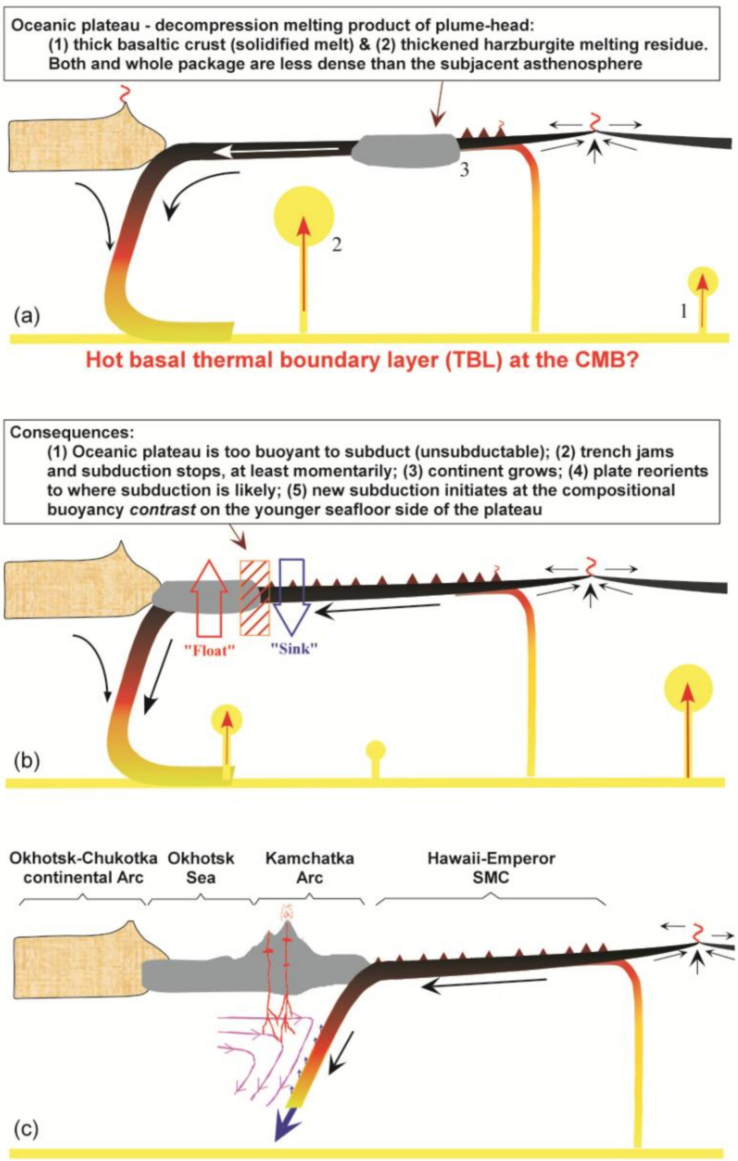

Figure 4 (Niu et al., 2017, SB N&V)