Fundamentals of the Plates vs. Plumes Debate

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The “plumes debate” concerns whether anomalous volcanic areas result from a) leakage of melt from the mantle, permitted by lithospheric extension (the Plate hypothesis), or b) the delivery of high-temperature material from the core-mantle boundary by thermally buoyant, deep-mantle plumes (the Plume hypothesis). This debate does not merely involve igneous petrology and mantle convection. It is extraordinarily cross-disciplinary and almost every branch of geology and geophysics is relevant. It is fundamental to how the Earth works, from the core to the surface.
The Plate hypothesis predicts that magmatism is driven, either directly or indirectly, by plate tectonics [http://www.mantleplumes.org/]. Magmatism is envisaged to be a passive reaction to lithospheric extension. Its quantity and chemistry are predicted to reflect source fusibility and composition. Thus, where “anomalous” magmatism occurs, lithospheric extension is expected to be observed, e.g., an extensional plate boundary, a back-arc basin, distributed intraplate extension or a continental rift zone. It is a common misunderstanding that the mere existence of melt in the mantle is sufficient to explain surface eruptions–that the lithosphere is passive and melt in the mantle can pass through it unimpeded as light passes through a glass window. This is not the Plate hypothesis, which predicts that lithospheric extension is required for melt to escape to the surface. The Plate hypothesis views surface volcanism as mapping lithospheric extension, not the existence of melt in the mantle. Where melt volumes are large, the chemical fingerprints of high source fusibility are predicted.
The Plume hypothesis predicts a) surface uplift tens of millions of years before flood volcanism, b) flood volcanism lasting a few tens of millions of years, c) a “plume tail” extending from the surface to the core-mantle boundary, d) a time-progressive volcanic chain, and e) high source temperatures. These predictions are rarely confirmed with confidence and have never all been confirmed at a single “anomalous” volcanic province. The Plume hypothesis has survived for the last four decades only because it has been extensively modified in ad hoc ways to accommodate unpredicted observations. Modifications include proposals that plumes can arise from almost any depth, that plume material can flow sideways for thousands of kilometres, that plumes may have a wide range of geochemical compositions, and that where a predicted characteristic has not been observed, even in the face of extensive searching, it may be assumed that the characteristic exists. The plume model has become the default explanation for anomalous volcanism because it can be adapted to explain anything, the absence of anything, and the inverse of anything. It has evolved into a model that cannot be falsified, no matter what is observed or not observed.
The scientific method involves testing predictions against observations in an attempt to falsify an hypothesis. In the case of the origin of anomalous volcanism, science has strayed from this path. In my presentation I shall outline the fundamental issues underpinning the “plumes debate”, I shall describe the challenges scientists face in resolving the issue, and I shall suggest research approaches that can potentially resolve this fundamental question.

Keywords: plate hypothsis, plume hypothesis, scientific method

Plume, superplume, plate tectonics, and Earth system

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The Earth is composed of solid planetary system of plate tectonics, plume, superplume tectonics, and growth tectonics in the core with averaged speed of cm-scale per year, except the outer core. The surface of the Solid Earth is covered by thin atmosphere of only 1 bar which is driven by Sun with extremely high-speed hydrological process, indicating the operation of separate system from the solid Earth. Dynamic convection of liquid outer core causes strong bi-polar geomagnetism to protect living organisms on this planet from solar winds and galactic cosmic rays.
Mantle convection in the spherical planets follow the 3D shape as plumes and superplumes from the depth, but it shows platy mode on or near the surface. When the surface is covered by liquid water which plays a critical role to decrease frictional intensity, hence causes the operation of plate tectonics. Plate tectonics provides a mild surface environment on the rocky planet. The three-fold coupling of tectonics, superficial plate tectonics, plume and superplume tectonics in the middle depth, and core tectonics in the deepest place is the cause of the characteristics of habitable planet. One more additional feature for habitability could be a small amount of water on the Earth, by which huge landmass can appear above sea-level.
Superplume operates probably only after 1.0Ga after the formation of the Earth, because of the extensive amounts of slab graveyards can generated and form a supercontinent. Those slab graveyard partially melted to form buoyant restites and sinks of
partial melt enriched in FeO to grow anti-crust above CMB.

Keywords: plate tectonics, superplume, Earth system

Change in mantle potential temperature through Earth time: Hotspots versus Ridges

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Mantle potential temperature is the key parameter that determines rolls of mantle upwelling in mid ocean ridges (MORs) and hotspots including large igneous provinces (LIPs). We calculated mantle potential temperature (Tp), degree of partial melting (F), depth of melting column (Pmt), and source mantle depletion (expressed by fractions of DM and PM components) for MORB-like and some hotspot basalts of various ages using a forward trace element mass balance and heat balance calculation model named Ocean Basalt Simulator ver. 1 (OBS1). The samples examined include Cenozoic, Cretaceous, Jurassic, neo-Proterozoic, Proterozoic, and Archean basalts over 3.5 Gyrs covering the entire geological records available on the earth. Primary MORB-like basalt trace element compositions changed with time from unfractionated (flat relative to PM) with low abundances (3.45–2.70 Gyr), to flat with higher abundances (1.90–0.81 Gyr), to LREE-depleted with even higher HREE abundances (0.15–0.07 Gyr), to modern LREE-depleted N- and D-MORB (0 Myr). These temporal changes require an increasingly depleted mantle source and a decreasing degree of mantle melting through time and with decreasing mantle potential temperature. Our results using trace elements are similar to those using major elements by Herzberg et al. (2010), with the highest T_p ~1650 °C in the Archean and early Proterozoic (3.5 to 1.7 Gyr), some ancient basalts have T_p down to ~1400 °C but not lower. Our results suggest T_p maxima at around 2.7 and 1.7 Gyr, although we have few basalts between those ages. After 1.7 Gyr, T_p decreased linearly to T_p ~1300–1400 °C today. This long-term change is consistent with models of the Earth’s thermal history that use a low Urey ratio in the convecting mantle. OBS1 models for non-MORB-like komatiites and picrites from large igneous provinces (LIPS) and hotspots have higher T_p up to ~1780 °C in the Archean to Paleoproterozoic, 1600 °C in the Jurassic, and 1500 °C today. These rocks may have formed from deep plumes. In contrast, the decreasing temperatures with time in MORB-like basalts reflect the cooling history of the upper mantle.

Keywords: Mantle potential temperature, MORB, Hotspot OIB

Seismic imaging of the mantle structure beneath intraplate volcanoes

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We have used high-resolution seismic tomography to study the 3-D seismic velocity structure of the mantle or upper mantle beneath several intraplate volcanoes, including Erebus (Gupta et al., 2009), Yellowstone (Tian and Zhao, 2002), Cape Verde (Liu and Zhao, 2014), Tengchong (Lei et al., 2009; Wei et al., 2012), Hainan (Wei et al., 2012), as well as Changbai, Ulleung and Jeju in NE Asia (Zhao et al., 2009; Zhao and Tian, 2013; Wei et al., 2015). Beneath Erebus and Cape Verde, prominent low-velocity (low-V) anomalies are revealed in the upper mantle down to 500-600 km depths, whereas the structure in the lower mantle is not imaged because of the small aperture of the portable arrays deployed around each of the volcanoes. A significant low-V anomaly from the surface down to a depth of about 1000 km is revealed clearly beneath Yellowstone using abundant data recorded by the dense and large-aperture USArray. Beneath the Changbai, Ulleung and Jeju volcanoes, low-V zones are revealed in the crust and upper mantle down to about 400 km depth, whereas a high-velocity (high-V) zone is visible in the mantle transition zone (MTZ), suggesting that these intraplate volcanoes in NE Asia are caused by hot and wet upwelling flows in the big mantle wedge (BMW) above the stagnant Pacific slab in the MTZ. A similar feature is found for the Tengchong volcano in SW China, which may be caused by hot and wet upwelling in the BMW above the subducting Indian plate (or the Burma microplate). Beneath Hainan, a low-V zone exists in the upper mantle, which seems to extend down to at least 1000 km depth. These results indicate a great variety of the mantle structure and origin of the intraplate volcanoes.

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Keywords: Intraplate volcano, mantle plume, seismic velocity structure

Where was the Permian Emeishan mantle plume in southwestern China?

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During the past two decades, extensive geological and geophysical studies have been conducted on the Permian Emeishan flood basalt province in southwestern China, which is interpreted as a large igneous province (LIP). Most previous studies proposed that the Emeishan LIP was sourced from a mantle plume, based on the following lines of evidence: (1) 1-km of domal uplift prior to large-scale basalt eruptions; (2) the spatial distribution of low-Ti and high-Ti basalts from the inner zone to the outer zone of the LIP; (3) the presence of picrite in basalt layers and elevated MgO contents, which suggest high temperatures; (4) rapid eruptions of basalt over a short period of less than 1 Myr; and (5) fluctuations in paleo-temperatures and the occurrence of a mass extinction event.

However, recent structural, petrological, sedimentological, and geochemical evidence, together with precise zircon U–Pb dating, does not support previous interpretations of a mantle plume beneath the Emeishan LIP. Recent data show that the apparent 1 km of domal uplift is an artifact of modeling multi-stage deformation. Furthermore, there is no distinct spatial pattern in Ti-enrichment, only with respect to lower (low-Ti) and upper (high-Ti) profile features. Additionally, the initial response of the lithosphere to mantle upwelling would have been a rift system. Rather than picrite lava, there are mafic–ultramafic intrusions and cumulative olivine phenocrysts with corrosion structures, which cannot be used as evidence of a high-temperature primitive magma. Precise U–Pb age data show that the basalts erupted over a period of 10–15 Myr, but large-scale eruptions occurred rapidly within a period of ca. 5 Myr. However, the record of paleobiological evolution shows that the mass extinction event did not coincide with the large-scale eruptions during the 5 m.y. interval.

The available evidence does not support the hypothesis of a mantle plume beneath the Permian Emeishan flood basalt province. As the Emeishan LIP formed during the assembly of the Pangea supercontinent, the large-scale upwelling of volcanic magma may be explained by horizontal flow of the asthenosphere and northward motion of the Yangtze plate.

Keywords: mantle Plume, Emeishan LIP, Permian

Insights from geochemistry and age of associated seamounts into the mantle source evolution of Shatsky and Hess Rises

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Shatsky Rise in the Northwest Pacific is the best example so far of an oceanic plateau with two potential hotspot tracks emanating from it: the linear Papanin volcanic ridge and the seamounts comprising Ojin Rise. Arguably, these hotspot tracks also project toward the direction of Hess Rise, located ~1200 km away, leading to speculations that the two plateaus are connected. New $^{40}Ar/^{39}Ar$ ages and trace element and Nd, Pb, and Hf isotopic data were obtained from dredged rocks recovered from the massifs and seamounts around Shatsky Rise in an effort to understand the relationship between these plateaus and associated seamounts. The similar initial source composition and geochemical evolution supports a plausible connection between Shatsky Rise and Hess Rise, with the latter probably representing either a resurgent plume head pulse and/or a triple junction-aided second LIP eruption. Each of these rises could have evolved from plateau-building stage composed of isotopically-depleted tholeiites forming the large massifs to post-plateau building stage consisting of isotopically-enriched trachytes forming the much smaller seamounts, e.g., Shatsky Rise to Cooperation-Earthwatch-Ojin seamount and Hess Rise to DSDP Site 465A seamount. Like Shatsky Rise's Ojin Rise, a short chain of seamounts of alkaline composition (Wentworth Seamount Chain) extending SE from southern Hess Rise, i.e. from DSDP Site 465, seems to show an age progression that is consistent with being a classical hotspot track associated with the Hess plateau. Although the results of this study cannot unequivocally provide a direct link between the plateaus and seamount volcanism, further investigation of these similar trends of mantle source variation, not only between Shatsky and Hess Rise but also Ontong Java, Manihiki, and Hikurangi plateaus could lead to a better understanding of the origin, evolution, and emplacement mode of most Pacific oceanic plateaus.

Keywords: Shatsky Rise, Hess Rise, seamounts