Mantle plumes: effect rather than cause of lithospheric breakup

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In 1971, Morgan suggested a concept of mantle plumes. The model is widely but not unequivocally accepted as the cause for flood basalt provinces. However, scientists familiar with volcanic activities or flood basalts, both time and regions, puzzled over how the mantle plume concept accorded with the observations. Many researchers argue that lithosphere breakup and associated volcanic or flood basaltic outbreaks and hotspots are controlled, top-down, by shallow processes, rather than by rising mantle plumes. Anderson has formalized this opposing view as the Plate paradigm. This paradigm includes concepts related to crack propagation, internal plate deformation, volcanic activities, recycled subducted slabs, and lithospheric breakup. Although both Plume hypothesis and Plate hypothesis relate to the thermal effect, few studies have been found to attempt to explain how the initial thermal instability forms or why the source of magma for volcanisms and LIPs might be maintained. In Plume hypothesis, they always assumed that such thermal instabilities are formed mostly at the core-mantle boundary and that the plume conduits remain for millions of years, as implied by the persistence of hotspots. White and McKenzie have developed a detailed formulation of the more passive and uniformitarian rifting model, providing an different explanation for the presence of huge basalt accumulations along rifted continental margins. However, they placed little emphasis on how mantle plumes begin and reach the base of the lithosphere.

In this paper, I combine the failure dynamic studies with inferences drawn from a three-dimensional modeling of surface cracking under thermal expansion induced extension and the results of geological observations to consider the dynamics of the putative link between mantle plume, flood basalts, and lithospheric breakup. I will show a numerical modeling result of a surface failure pattern occurred on a spherical shell loaded from inside with an internal pressure in a displacement control manner, resembling the behavior of thermal expansion, from which I derive an intuitive physical model of the process of surface cracking as a self-organized phenomena. It is shown that deep mantle plume is not required as the prerequisite for such a process. A new hypothesis for no-root mantle plume, starting from the top of the asthenosphere in a top-down pattern is then proposed, which implies that the mantle plumes should then be regarded as the effect rather than the cause of lithospheric breakup.

Based on the model, a LIP event can be considered as a positive feedback loop of a process that the response to its change amplifies the change. During a LIP event, heat accumulation in the mantle may cause continental uplift in the ways of thermal expansion and volume increase during the phase change. The lithospheric uplift may trigger rift in global scale with a pattern of polygonal fractures. This shallow-based lithospheric process can locally release stresses, thus promoting local de-compressive melting. Extra volume increase of the magma (during phase change from solid to liquid) may serve as the driving force for eruption, which in turn should result in new cracking and associated sudden pressure drop. The process will become unstable, providing the coupling between pressure and temperature within the mantle satisfy certain conditions for phase change. No deep mantle plume is needed to for such a LIP. This mechanism furthers our understanding of global cooling events: the gradual accumulation of heat within the earth may result in large igneous provinces, which may cause abrupt loss of heat during large volcano eruptions or huge flood basalts. This abrupt loss of Earth’ s heat makes the warming cycle to an end and a new start of the cooling cycle initiates, with glaciations as the extreme results.

Keywords: Mantle plume, rift, de-compressive melting, thermal expansion

Subduction Zones and Mantle Plumes

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In its simplest form, the plate-tectonic hypothesis expects volcano chains to lie behind subduction zones, *e.g.*, the circum-Pacific belt and the Alpine-Himalaya continent-continent collision zone. Nevertheless, volcanism associated with subduction is considerably more diverse than this. In this paper I argue that this diverse volcanism reflects the real, complex stress fields associated with subduction zones. Specifically, where the lithosphere is in extension, permissive volcanism occurs. Volcanism that is more diverse and widespread than predicted by the simple, textbook model of subduction zones is thus an expected feature of real geological cases.

Back-arc extension was not originally part of plate tectonic theory. Nevertheless, when it was discovered, it fit naturally into the model. It did not violate predictions of plate tectonics and radical revision of the theory was not required. Sinking slabs lie down in the mantle at their depth of neutral buoyancy and their surface hinges thus retreat. This process results in extension as the lithosphere ahead of hinges is pulled apart and volcanism occurs as a result. In some cases this deformation and volcanism takes the form of spreading and the development of oceanic crust. In other cases, distributed volcanism occurs, time-progressions may be observed, and small flood basalts may erupt. Examples include:

* spreading in the Sea of Japan;
* the Manus back-arc basin;
* volcanic activity in eastern China;
* the Columbia River flood basalt in the states of Washington and Oregon, U.S.A.;
* volcanism in the Basin-Range province in the western U.S.A.;
* volcanism in Italy, behind the Alpine subduction zone;
* distributed, time-progressive volcanism in eastern Anatolia, Turkey; and
* time-progressive volcanism in Mexico.

In addition, volcanism has been observed behind subduction hinges, for example as “petit spots”, attributed to permissive volcanism through cracks in the lithosphere as it approaches subduction zones and bends [Hirano *et al.*, 2006]. Volcanism at Samoa is likely also associated with cracking of the Pacific plate as it approaches the Tonga trench [Natland & Winterer, 2004].

Despite the obvious association of volcanism and lithospheric extension in the neighbourhood of subduction zones, in many cases this volcanism has been attributed to deep mantle plumes. In this paper I argue instead that the diverse volcanism that occurs in the wider neigbourhood of subduction zones can be explained naturally by expected lithospheric extension of various kinds. This provides a simpler explanation of volcanism in subduction environments than appealing to two separate and independent processes–plate tectonics and mantle plumes.

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Keywords: mantle plumes, subduction zones, plate hypothesis

Geodynamic consequences of slab retreat: Implications for the orogenic development in the Circum-Pacific and Mediterranean-Carpathian regions

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Geodynamic reconstructions in both (south) western Pacific and the Mediterranean regions exemplify features of trench migration, back-arc extension, and transient pattern of surface subsidence-uplift those are characteristic for slab retreat/roll back tectonics. The development of these processes is usually followed by plate collision and tectonic displacements are mainly controlled by vertical forcings (e.g slab pull, mantle upwelling) rather than horizontal plate convergence. In this work, geodynamic modeling results of sub-crustal slab retreat (delamination) are used to infer the pattern and the amount of of surface uplift-subsidence, shortening-extension, trench migration. Model parameters are varied to test the influence lower crustal thickness/density, density of sinking slab, lithospheric thickness. Subsequently, a comparison between the model results are made against the; 1) last 12 Myrs tectonic evolution of the western North island in new Zealand, 2) Eocene-Oligocene evolution of New-Caledonia, Lord Howe regions 3) the last 10 Myrs post-orogenic lithospheric evolution of the Southeast Carpathians. Model results are in good agreement with the southward migration of the 1.2 km of uplift and 2 km of subsidence in the east of Taranaki basin in central island, 2 km of subsidence of the New Caledonia trough and 1-2 km of uplift of the Lord Howe rise, ˜ 1 km of uplift in the southeast Carpathians-Transylvania and up to 6 km of subsidence in the Focsani basin. The retreating slab induces subsidence on the surface while pulling down the crust. The zone of slab removal results in the surface uplift and this is controlled by isostatic and dynamic response to the mantle uprising under the crust.

Keywords: Slab retreat, western Pacific, Mediterranean

Mantle transition zone, stagnant slab and intraplate volcanism in Northeast Asia

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Three-dimensional P and S wave velocity structures of the mantle down to a depth of 800 km beneath NE Asia are investigated using ~981,000 high-quality arrival-time data of local earthquakes and teleseismic events recorded at 2388 stations of permanent and portable seismic networks deployed in NE China, Japan and South Korea. Our results do not support the existence of a gap (or a hole) in the stagnant slab under the Changbai volcano, which was proposed by a previous study of teleseismic tomography. In this work we conducted joint inversions of both local-earthquake arrival times and teleseismic relative travel-time residuals, leading to a robust tomography of the upper mantle and the mantle transition zone (MTZ) beneath NE Asia. Our joint inversion results reveal clearly the subducting Pacific slab beneath the Japan Islands and the Japan Sea, as well as the stagnant slab in the MTZ beneath the Korean Peninsula and NE China. A big mantle wedge (BMW) has formed in the upper mantle and the upper part of the MTZ above the stagnant slab. Localized low-velocity anomalies are revealed clearly in the crust and the BMW directly beneath the active Changbai and Ulleung volcanoes, indicating that the intraplate volcanism is caused by hot and wet upwelling in the BMW associated with corner flows in the BMW and deep slab dehydration as well.

Reference

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Keywords: Northeast Asia, Intraplate volcanism, Mantle transition zone

Does Cenozoic tectonics in NE Asia need the deep dehydraiton of the stagnat Pacific Plate?

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It is considered that hydrous components derived from the stagnant Pacific Plate at the mantle transition zone would play significant roles in the Cenozoic tectonics of East Asia. From the viewpoint of mineralogy, petrology and geology, the deep dehydration model has numbers of critical oversights.

The serpentinized mantle would be formed by additions of H_2O from the subducting slab at the base of the mantle wedge. In order to bring H_2O into the deep mantle, the serpentinized mantle should subduct with the slab to 6 GPa where dense hydrous silicate minerals are stable. Properties of serpentinite, a main mineral of serpentine, indicate the difficulty of the serpentinized mantle subduction. The density of serpentinite is significantly lower than that of olivine. The serpentinized mantle therefore could not subduct because of its buoyancy. The slab drag is required to subduct the serpentinized mantle. Mechanical strength of serpentinite, however, is weaker than olivine, which indicates that the serpentinite mantle would behave as a slip plain to the slab drag. The slab drag therefore would not effectively act on the serpentinized mantle.

Central Japan, where the oldest part of the Pacific plate and the young Philippine Sea plate doubly subduct, is regarded as the place where serpentinized mantle could subduct to 6 GPa. The trench orientation of the Pacific Plate, however, turns from NNE-SSW to N-S there, which indicates that a slab window would be opened by the strike-parallel tensional stress there. A slab window enables penetration of sub-slab mantle into the mantle wedge to increase its temperature. The retreat of the volcanic front to the back-arc side there would be the result of the bending of geological structures by the collision of the Izu-Bonin Arc to Central Japan.

Geochemical characteristics, such as the negative Nb anomaly, of the San' in basalts from SW Japan are considered as definite evidence for the deep dehydration. The estimated H_2O content (1.5 wt. %) for the basalt, however, is similar to that in OIB-type basalt such as Hawaii. The geochemical feature could also be explained by involvement of sub-arc lithosphere into the source mantle, since SW Japan is essentially composed of accreted oceanic materials. The relationship between the geochemistry of volcanic rocks and the Kyushu-Palau Ridge in Kyushu indicates that geochemistry is essentially controlled by arc lithosphere rather than hydrous components derived from the slab.

Lithospheric weakening by the deep dehydration is considered to have caused lithospheric thinning in Northeastern Asia. Numbers of strike-slip faults, such as Tan-Lu, however, strike there. These strike-slip faults already existed before than the start of the lithospheric thinning. The grain size reduction by strike-slip shear would weaken the strength of the lithosphere. Reactions induced by horizontal extension would also reduce grain size to weaken the lithosphere. Shear-driven melting would concentrate mantle upwelling to the lithospheric weak zone, which would cause further weakening and thinning of the lithosphere.

As pointed above, researches proposing the deep dehydration model have numbers of critical oversights in mineralogy, petrology and geology. The body of evidence obtained from East Asia and interdisciplinary considerations indicate that geological phenomena observed there would be explained by shallow mantle processes such as transtensional tectonics.

Keywords: hydration weakening of lithosphere, stagnant slab, serpentine diapir, choke point of H2O, strike-slip tectonics, grain size reduction

Remelting the Gondwanan Mantle - Older and Younger

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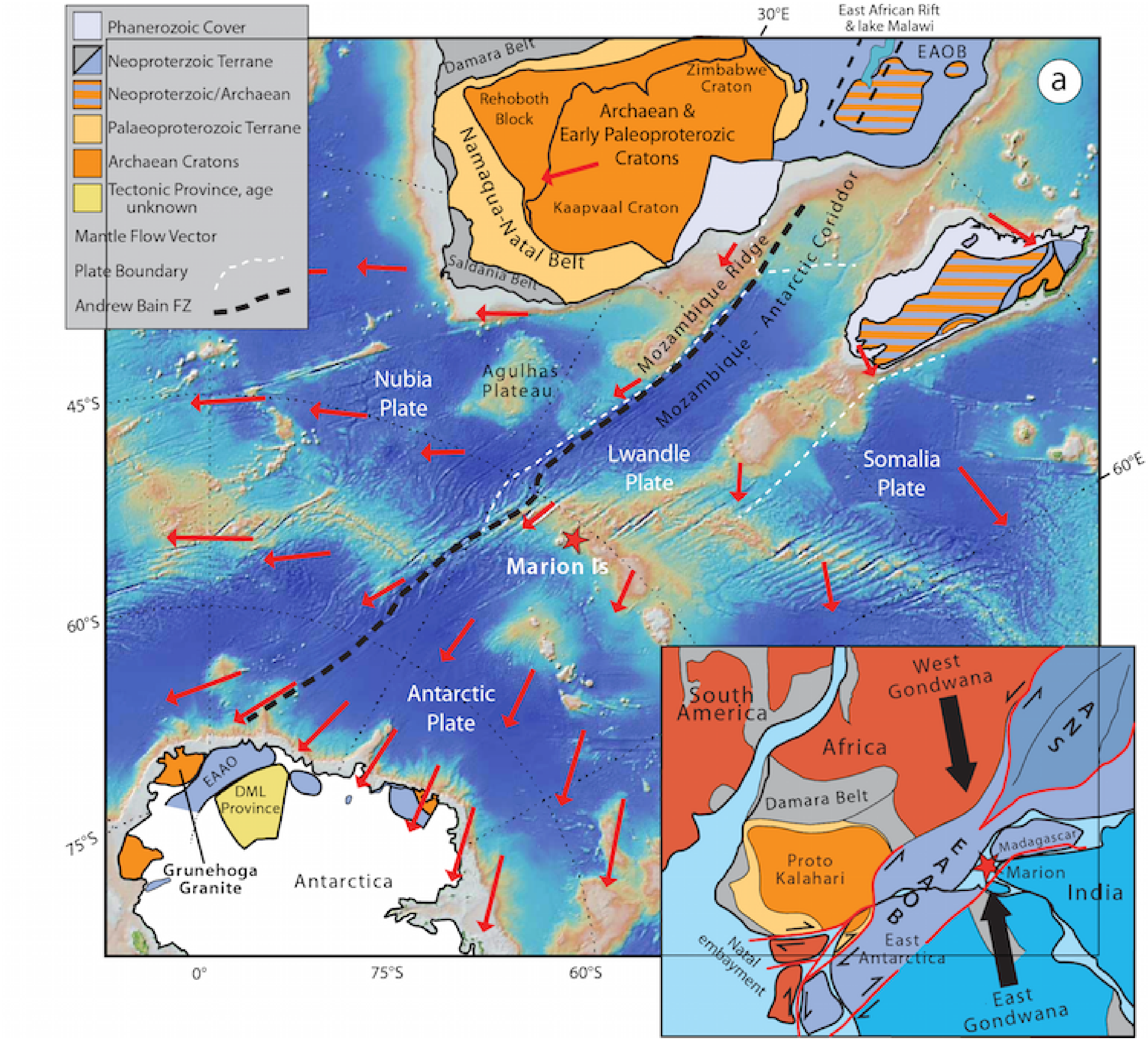
The SW Indian ridge Marion Rise and the Icelandic Rise are the two largest oceanic rises. Whereas Iceland is supported in large part by thickened crust, sampling shows SWIR crust is generally thin and discontinuous, even over the rise. Thus, in the absence of thickened crust, the Marion Swell at the top of the rise should be supported by previously melted buoyant depleted mantle. Though basalts and peridotites are more refractory up the rise, the degree of melting inferred from peridotite Cr spinel and basalt Na_8 is only moderate. The peridotites, however, have substantially lower bulk alumina than those sampled to the east and west. Thus, the Marion platform mantle source must be garnet-poor and highly buoyant. This requires removal of high silica melts during the earlier melting, causing excess pyroxene depletion, consistent with a hydrous back-arc or arc environment.

Plate reconstructions shows the Marion Swell corresponds to mantle pulled from beneath the Pan-African Orogenic Belt, during breakup of Gondwana, while SWIR mantle to the east and west originated beneath Archean cratonic lithosphere. The Pan-African Orogenic belt is a 650 to 500 Ma ~1000-km wide terrain consisting of accreted micro-continental fragments and juvenile island arcs formed by subduction and closure of the Mozambique Ocean. Notably missing from the belt is any evidence of the old Mozambique Ocean Crust itself. The major suture zones bounding the belt are strike-slip zones due to southward-directed escape tectonics. These were re-occupied during Gondwana rifting, one of which now bounds the Marion Swell as the Andrew Bain Fracture Zones. Thus, the Marion Rise is likely the product of delamination of old arc-related lithosphere along with the Marion, Crozet, and Reunion Hotspots swept up in the radial mantle flow triggered by the emplacement of the Karoo Plume. The Karoo Plume itself is likely the product of the subduction of Mozambique Ocean crust, due to its greater density than old arc lithosphere, beneath the transition zone, up to ~560 Ma. This then eventually triggered the plume, initiating the breakup of Gondwana.

Keywords: Mantle Plumes, Ocean Ridge, Lithospheric Delamination


Phanerozoic Cover
Neoproterzoic Terrane
Neoproterzoic/Archaean
Palaeoproterozoic Terrane
Archaean Cratons
Tectonic Province, age unknown
Mantle Flow Vector
Plate Boundary
Andrew Bain FZ
30°E
East African Rift & lake Malawi
EAOB
a
Damara Belt
Rehoboth Block
Zimbabwe Craton
Archaean & Early Paleoproterozic Cratons
Kaapvaal Craton
Namaqua-Natal Belt
Saldania Belt
Mozambique Ridge
Mozambique - Antarctic Coridor
Nubia Plate
Agulhas Plateau
Lwandle Plate
Somalia Plate
60°E
45°S
Marion Is
60°S
Antarctic Plate
EAAO
DML Province
75°S
Grunehoga Granite
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Proto Kalahari
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Marion
India
East Antarctica
Natal embayment
East Gondwana

Plume Flux, Spreading Rate, and Obliquity of Seafloor Spreading

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Most of Earth’s surface is created by seafloor spreading, a fundamental global tectonic process. While most seafloor spreading is orthogonal, i.e., the strike of mid-ocean ridge (MOR) segments is perpendicular to transform faults, obliquity of up to ~45° occurs. Here, building on the work of DeMets et al. [2010] we investigate the global relationship between obliquity of seafloor spreading, spreading rates, and the flux of nearby plumes. While we confirm the well-known tendency for obliquity to decrease with increasing spreading rate [Atwater and Macdonald, 1977], we find exceptions at both intermediate (up to 18°) and ultra-fast (up to 12°) rates of spreading. Thus, factors other than the minimization of power dissipation across mid-ocean ridges and transform faults [Stein, 1978] may influence the amount of obliquity.

Abelson & Agnon [1997] modeled spreading centers as fluid-filled cracks and found that the variation of segment orientation depends on the ratio of the magma overpressure to the remote tectonic tension that drives plate separation. A high ratio promotes oblique spreading and a low ratio promotes segmentation that results in orthogonal spreading. They further argued that if a hotspot lies near a MOR segment, the hotspot contributes to magma overpressure along the segment. We quantify their argument as follows: (1) that magma overpressure increases with increasing flux of a plume. (2) that effective magma overpressure decreases with increasing distance between a MOR segment and a plume. From this we estimate the effective plume flux delivered to each mid-ocean ridge using published plume flux estimates.

Not only does obliquity tend to decrease with increasing spreading rate, but also it tends to increase with increasing effective plume flux delivered to a MOR segment. Many exceptions occur, however. Along slow spreading centers, many segments are less oblique than along the Reykjanes Ridge and western Gulf of Aden despite having higher effective plume flux. Similarly, along intermediate spreading centers, some ridge segments are less oblique than along the western Galapagos spreading center, despite having greater effective plume flux. We conclude that neither the minimum power dissipation model nor the hotspot proximity model fully explain the globally observed variations of oblique spreading.

Keywords: Plume Flux, Obliquity of Seafloor Spreading

Dispersion of hotspot trends: A tool for estimating motion between groups of hotspotsDispersion of hotspot trends: A tool for estimating motion between groups of hotspots

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It is widely believed that groups of hotspots in different regions of the world are in relative motion at rates of 10 to 30 mm a^{-1} or more. Recent work on plate motions over the past ≈50 Ma indicate no significant motion between hotspots and place an upper bound on such motion of ≈10 mm a^{-1}. Here we present a new method for analyzing geologically current motion between groups of hotspots beneath different plates. In an inversion of 56 globally distributed, equally weighted hotspot trends, misfit magnitudes range from 0° to 86° (median= 9°; standard deviation =23°). The dispersion is dominated by differences in trend between different plates rather than dispersion within plates, lending support to the notion that groups of hotspots beneath different plates do indeed move relative to one another. The absolute value of mean angular difference for a given plate decreases significantly with increasing absolute plate speed. When these angular misfits are converted to vperp, the rate of hotspot motion perpendicular to the direction of absolute plate motion, there is no significant dependence on absolute plate speed. Moreover, vperp differs significantly from zero for only two of ten plates and then by no more than 1 mm a^{-1}. Thus, motion between groups of hotspots may be as low as 1 mm a^{-1} and perhaps even slower when considering plate non-rigidity and errors in relative plate motions. The upper bound on $|\,vperp|$ is 3.2 ±2.8 mm a^{-1}. Therefore, groups of hotspots move between 1 mm a^{-1} and 6 mm a^{-1} relative to the mean hotspot frame, substantially slower than found in some prior work.

Keywords: Hotspot fixity, Absolute plate velocity

Can Seismic Tomography See Mantle Plumes?

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Seismic tomography is often used to study the three-dimensional structure of the upper and lower mantle, and is the most powerful tool for imaging structure beneath “hot spots”. Tomography experiments have often found regions of low wave speed beneath hot spots (and elsewhere) that might be an effect of high temperatures such as thermal plumes, but such results are seldom reproducible from one study to another. The basic reason for this difficulty is the sparseness and unevenness of the sampling of the Earth by seismic waves, a consequence of the sparse geographical distribution of earthquakes and seismometers. An infinite number of three-dimensional models are consistent with any real data set. The common practice of inverting seismic data to derive one such model is thus not informative, since the results are so highly non-unique.

The North Atlantic Ocean provides a good illustration of these difficulties. This region is sampled relatively well by seismic waves, due to the abundance of seismometers in Europe and North America and on Iceland and other islands, and to a favorable distribution of seismicity (compared to the central Pacific Ocean, for example). Nevertheless, derived mantle models differ in seeing or not seeing features that can be interpreted as mantle plumes. The locations, orientations, etc. of these features also differ from study to study.

Despite the shortcomings of real data sets, however, they do usually contain useful information. Even though an infinite number of conceivable models are consistent with available data, even more models are inconsistent with the data. A useful way forward is to use data to test hypothetical models, seeking to rule out some of the competing hypotheses about the Earth, as suggested by Tarantola (2006).

Keywords: seismic tomography, plumes, resolution

Low CaO olivine phenocrysts in picritic rocks formed in back-arc area, Japan.

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Low-CaO core (<0.17 wt.%) of olivine phenocrysts are found from Miocene picritic rocks distributed in back-arc area, Japan Sea. Picritic dolerite of Ogi Basalt, Sado island, Japan, has MgO content ranging from 12 to 34 (wt.%), which is controlled by olivine accumulation. Based on c.a. 50 line profiles, the large phenocrysts show reverse zoning, and Fo content of the core varies grain by grain, in the range Fo 90 to 82, rimmed with normal-zoned rim (Fo90 to 87). Composition of high-Fo core has low-CaO contents (0.1-0.15 wt.%) and continue to that of low-Fo core with high-CaO contents (≥0.15 wt.%), illustrating a sequencial trend of composition. The compositional trend is similar to that of olivine phenocrysts crystallized from high-CaO boninitic magma. NiO contents of all the olivine phenocrysts are no more than 0.28 (wt.%). Xenocrystic origin of olivine core of the phenocrysts is suggested as captured from dunitic cumulate rather than from mantle lerzolite. High-CaO boninitic magma could be parental to form this dunitic cumulate body. Similar core of olivine phenocrysts can be found in picritic basalt of Miocene Mishima Volcanic Rocks, Mishima Island. Though any boninitic rocks has not been known in the back-arc area, boninitic magmatism could not be denied from these facts. Although high Mg andesite is not popular in back area, there are some adakitic dacite and high Mg andesite reported from the Japan Sea side in Neogene to Miocene age. Associated with back-arc spreading, boninitic magma could have been originated by decompressional melting of upwelled hot mantle, or by melting of depleted mantle source reacted with slab melts.

Keywords: picrite, back-arc basin, low-CaO olivine, Ogi Basalt, Mishima Volcanic Rocks, high Mg andesite