

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 neighbourhood 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

東北アジア地域のプレート内部火山の深部構造と起源

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

Chen, C., D. Zhao, Y. Tian, S. Wu, A. Hasegawa, J. Lei, J. Park, I. Kang (2017) Mantle transition zone, stagnant slab and intraplate volcanism in Northeast Asia. *Geophys. J. Inter.* **209**, 68-85.

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Keywords: Northeast Asia, Intraplate volcanism, Mantle transition zone

新生代北東アジアテクトニクスはスタグナント太平洋プレートのマントル深部脱水作用を必要とするか？

Does Cenozoic tectonics in NE Asia need the deep dehydration of the stagnant Pacific Plate?

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マントル遷移層のスタグナント太平洋プレート由来の流体成分が、北東アジアの新生代テクトニクスに重要な役割を果たしているというモデルが提案されている。しかし、鉱物学、岩石学、地質学的見地から、このマントル深部脱水モデルには多くの重大な見落としがある。

スラブ脱水反応によって放出されたH₂Oによって蛇紋岩化マントルがマントルウェッジ最下部に形成されると考えられている。H₂Oが深部マントルにもたらされるには、蛇紋岩化マントルが高密度含水ケイ酸塩鉱物が安定な6GPaまでスラブと共に沈み込む必要がある。しかし、蛇紋岩化マントルの主要構成鉱物である蛇紋石の物性は、蛇紋岩化マントル沈み込みが困難であることを示している。蛇紋石の密度はカンラン石の密度より著しく小さく、蛇紋岩化マントルは自らの浮力のため沈み込むことができない。蛇紋岩化マントルを沈み込ませるには、沈み込むスラブからの引きずりが必要である。しかし、蛇紋石の機械強度はカンラン石よりも小さいため、蛇紋岩化マントルはスラブ引きずりに対して滑り面として働くと考えられる。従って、スラブ引きずりは蛇紋岩化マントルに有効に働かないと考えられる。

太平洋プレートの最も古い部分と、若いフィリピン海プレートが二重沈み込みを行う中部日本は、蛇紋岩化マントルが6Gaまで沈み込める場所と考えられている。しかし、この場所で太平洋プレートの海溝系はNNE-SSW方向からNS方向に向きを変える。このようなスラブジオメトリの転換点では、走行平行張力によってスラブウィンドが開くと考えられる。スラブウィンドウを通じて、マントルウェッジはサブスラブマントルと相互作用を起こし、温度を上昇させると考えられる。中部日本における火山フロントの海溝側への移動は、伊豆一小笠原弧の衝突による地質構造の屈曲が原因であると考えられる。

西南日本山陰玄武岩のNb負異常は、マントル深部脱水作用の重要な証拠と見なされている。しかし、見積もられている含水量(1.5%)はハワイなどのOIBと同程度である。西南日本は付加体コンプレックスから形成されており、山陰玄武岩の地球化学的特徴は島弧リソスフェアの関与によって説明可能である。九州で観察される火山岩の地球化学的特徴と九州-パラオ海嶺の関係は、島弧火山岩類の地球学的特徴がスラブ由来流体ではなく、島弧リソスフェアの関与によって説明されることを示している。

深部脱水作用によって付加されたH₂Oによるリソスフェア脆弱化が、北東アジアのリソスフェア薄化をもたらしたと考えられている。北東アジアにはタン・ルー断層など多数の横ずれ断層が発達する。横ずれ剪断による鉱物粒子の細粒化はリソスフェア脆弱化をもたらす。伸張テクトニクスを原因とする反応も鉱物粒子を細粒化させリソスフェアを脆弱化させる。剪断駆動溶融作用はマントル上昇流をリソスフェアの脆弱部に集中させ、さらなる脆弱化と薄化をもたらすと考えられる。

鉱物学、岩石学、地質学的見地から、上述のようにスタグナント太平洋プレートのマントル深部脱水作用を主張する研究には多数の重大な見落としがある。北東アジアから得られる証拠の束とそれらに基づく複眼的考察は、北東アジアで観察される地質事象は横ずれ伸張テクトニクスなどの浅所マントルの作用によって説明さ

れることを示している。

キーワード：リソスフィア加水脆弱化、スタグナントスラブ、蛇紋岩ダイアピル、H₂Oチョークポイント、横ずれテクトニクス、鉱物粒子細粒化

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

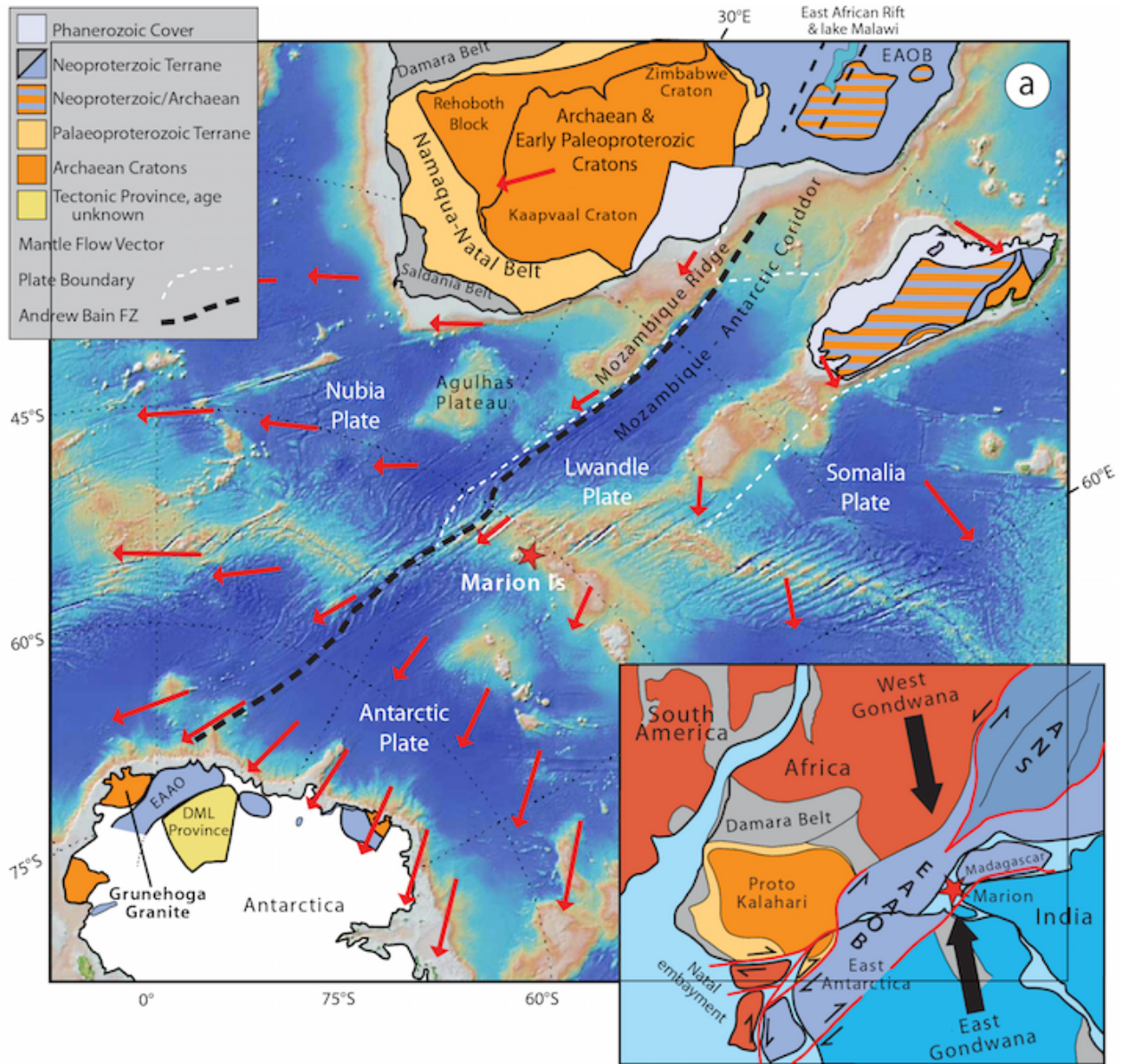
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The SW Indian ridge Marion Rise and the Icelandic Rise are the two largest oceanic rises. Whereas Iceland is supported in large part by thickened crust, sampling shows SWIR crust is generally thin and discontinuous, even over the rise. Thus, in the 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_3 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



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 $\sim 45^\circ$ 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 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 v_{perp} , the rate of hotspot motion perpendicular to the direction of absolute plate motion, there is no significant dependence on absolute plate speed. Moreover, v_{perp} 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 $|v_{\text{perp}}|$ 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 (\geq 0.15 wt.%), illustrating a sequential 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 lherzolite. 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.

キーワード：ピクライト、背弧海盆、低CaOカンラン石、小木玄武岩、見島火山岩類、高Mg安山岩

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