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# Non-hotspot volcano chains from small-scale sublithospheric convection (a 3D-numerical study)

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Although most of the intraplate volcanism in ocean basins is expressed in linear chains, not all of these can be attributed to a stationary hotspot. Many ridges do not show a linear age-distance relationship predicted by the hotspot hypothesis - such as the Cook-Austal, Magellan or Line Islands, and Pukapuka ridges. Small-scale sublithospheric convection (SSC) has been proposed to account for the volcanism at Pukapuka [Buck and Parmentier, 1986] and may also explain enigmatic geochronology at other intraplate ridges.

In the Earth's uppermost mantle SSC is likely to develop due to instabilities of the thickened thermal boundary layer below mature oceanic lithosphere. It is characterized by convective rolls aligning plate motion. Their onset is earlier (i.e. beneath younger and thinner lithosphere) for lower mantle viscosities (e.g. for hot or wet mantle) or adjacent to lateral thermal or compositional heterogeneity. In these cases, partial melt potentially emerges in the upwelling limbs of SSC. Partial melting changes the compositional buoyancy owing to melt retention and additional depletion of the residue. Therefore, it promotes upwelling and allows for further melting. This self-energizing mechanism is able to sustain melt production in a once partially molten layer for a couple of million years [Raddick et al., 2002].

In this study [Ballmer et al., 2007], we take the step towards fully thermo-chemical 3D-numerical models of SSC (using the FEM-Code CITCOM) with a realistic, temperature- and depth-dependent rheology in order to quantitatively test the SSC-hypothesis on intraplate volcanism. We explore the 3D-patterns of melting associated with SSC, the age of seafloor over which it occurs, and the rates of melt generation by varying the key parameters mantle viscosity, temperature $T_m$, and water content. We also investigate the effect of lateral heterogeneity that locally reduces the onset age of SSC, and of a rheology dependent on composition (water and melt content).

Melting due to SSC is predicted to emerge in elongated features ($\sim$1000 km) parallel to plate motion and not just at a fixed spot. Thus, irregular age-distance relationships of the associated volcanism are predicted - contrary to the hotspot model. The seafloor age over which volcanism occurs is sensitive to $T_m$. For moderate $T_m$ (1350 $^\circ$C), volcanism develops beneath a relatively young lithosphere ($\sim$30 Myr), and higher $T_m$ retards the onset of SSC and volcanism because of the stabilizing influence of a thicker residue from previous mid-ocean ridge melting (e. g., $\sim$50 Myr for $T_m$=1410 $^\circ$C). Higher water contents have a similar effect as higher $T_m$. Mantle viscosity controls the rate of melt production with decreasing viscosities leading to more vigorous convection and volcanism. Effective viscosity required to obtain km-high seamounts is smaller than $\sim 2\cdot 10^{19}$ Pa·, or significantly lower if stiffening due to exhaustion of water is considered. Our calculations predict many of the key observations of the Pukapuka ridges, and the volcano groups associated with the Cook-Austral, Line and Marshall Islands.

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# Plume head-lithosphere interactions (PLI) near intra-continental plate boundaries and heterogeneities: a model based on thermo-mechanically and thermo-dynamically realistic formulation for the lithosphere and mantle

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In continental domain, plume-Lithosphere Interactions (PLI) have complex topographic and magmatic signatures and are often identified near boundaries between lithospheric blocks and plates of contrasting age and structure (e.g., young orogenic plates and cratons). These boundaries represent important geometrical, thermal and rheological barriers that interact with the mechanisms of emplacement of the plume head (e.g., Archean West Africa, East Africa, Pannonian - Carpathian system). The observable PLI signatures are conditioned by plume dynamics but also by complex rheology and structure of lithosphere that may include old blocks embedded in younger settings. We address this problem by considering a free-surface thermo-mechanical numerical model of PLI with 2 or 3 stratified elasto-viscous-plastic (EVP) continental plates of contrasting age, thickness and structure. In addition to our previous models, this new formulation is fully thermo-dynamically coupled and takes into account mineralogical phase changes within major compositional units: plume head material, normal lithosphere mantle and crust, cratonic mantle, asthenosphere, and the convective upper mantle. The model confirms our previous results, in particular showing that (1) surface deformation due to PLI is poly-harmonic; it leads to alternating or simultaneous compression-extensional “tectonic-like" events at surface, and is dominated by basin-scale uplifts and subsidences preferentially located at cratonic margins; this

deformation is characterized by much smaller wavelengths (50-500 km) than that, which are commonly expected for PLI ($>1000$ km); (2) plume head flattening is asymmetric below intra-plate boundaries, which leads to mechanical decoupling of crust from mantle lithosphere, and to localized faulting at the cratonic margin; (3) in presence of several cratonic blocks, plume head material may be trapped in between provoking major localised magmatic events, faulting and surface deformation. The results show that gradual density variations associated with progressive (above 440 km depth) phase changes reduce gravitational instabilities at the base of the plume-lithosphere mantle boundary that were predicted by previous models. Specifically, cratons “become” more stable. However, Negative Rayleigh-Taylor instabilities in the lithosphere above the plume head are important and provide a mechanism for crustal delamination. In case of several cratonic blocks, the combined effect of subsidence and lithospheric thinning at cratons edges, while plume head material is being stocked in between the cratons, favours major magmatic events at cratonic margins. Field evidence (West Africa, Western Australia) underline the trapping effect of cratonic margins for formation of (e.g.) orogenic gold deposits, which require particular extreme P-T conditions. Location of gemstones deposits is also associated with cratonic margins, as demonstrated by the Tanzanian Ruby belt. Their formation depend on particularly fast isothermal deepening processes, which can be reproduced by slab-like instabilities induced by plume head-cratonic margin interaction. On the other hand, absence of magmatic events should not be interpreted as evidence for the absence of plume, as the PLI may induce strong crustal melting that may overprint deeper signatures since crustal melts are generated at lower temperatures than mantle melts, and produce light low-viscous rapidly ascending magmas. Drip-like down-sagging of the lithospheric mantle and metamorphic lower crustal material inside the plume head may contaminate the latter and also alter the geochemical signature of related magmas.

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# A primordial, solar-like He and Ne signature in Michigan Basin brines - basic two-layered mantle convection model assumptions revisited

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Noble gases have historically been used as a cornerstone of the two-layered mantle convection model with a lower, primordial, largely undegassed reservoir from which ocean island basalts (OIBs) originate via deep mantle plumes, and a degassed upper mantle of which mid-ocean ridge basalts (MORBs) are representative. Among these core arguments was the so-called “mantle He-heat imbalance” or “He-heat paradox” with low He/heat flux ratios in the proximity of mid-ocean ridges which required a lower, undegassed mantle from which He removal would be impeded. Such low flux ratios were thought to result from a He deficit in the original upper mantle reservoir based on the assumption that both He and heat are in steady-state and have similar transport properties in the crust. The legitimacy of these earlier assumptions was recently assessed and proven unsound, leading to the invalidation of one of the oldest cornerstone assumptions of the two-layered mantle convection model (Castro et al., 2005). Central to this mantle convection view has also been the reported primordial He and Ne signatures in OIBs that have been systematically associated with the occurrence of deep mantle plumes and thus, the existence of a lower, undegassed mantle reservoir. Primordial He and Ne signatures became the “mantle plume fingerprint”.

Here, I report new He and Ne data from deep brines in the Michigan Basin that clearly reveal the presence of a primordial, solar-like component. While the existence of this component is unequivocal, its connection to a lower, largely undegassed reservoir in this stable continental region via a mantle plume is highly unlikely. Indeed, no hotspot

tracks are known in the region and significant mantle activity was last recorded at ~1.1Ga during the emplacement of the Mid-Continent Rift (MCR) system. I argue that such primordial signature can be accounted by a shallow noble gas reservoir in the subcontinental lithospheric mantle (SCLM) beneath the Michigan Basin, possibly created by a mechanism similar to that proposed by Anderson (1998) for oceanic regions. The Michigan Basin, which is located within the ancient North American craton (~1.1 - >2.5 Ga), lies on a very thick, U-Th-K depleted SCLM, which is refractory and buoyant relative to the asthenosphere, thus, possibly allowing preservation of a primordial, residual, depleted mantle reservoir at shallow depths, just beneath the continental crust. Alternatively, diffusion of solar-like He and Ne isotopes from primitive material into a residual refractory reservoir such as dunites during the Earth's early history as recently proposed by Albarede (in press) might have occurred.

Overall, the primordial solar-like He and Ne signatures present in the Michigan Basin brines strongly suggest that a deep primordial mantle reservoir is not required to explain the presence of such components, an observation that disrupts yet another core argument of the two-layered mantle convection model. The notion that primordial He and Ne are fingerprints of mantle plumes should be revised, as these new data clearly suggests this is not necessarily the case. The SCLM underneath ancient cratons is a great candidate for hosting primitive ancient mantle noble gas reservoirs. This study provides a strong observational case for long-term primordial lithospheric storage of noble gases.

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# Collision-derived Late Cenozoic Dynamics of a Melting Anomaly beneath Central Mongolia: magmatic and tectonic Evidence

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Spatial–temporal pattern of Late Cenozoic volcanic activity in Central Mongolia has been interpreted as surface expression of melting zones temporally transformed to melting lenses. The former are exhibited by loci of coeval volcanic fields extended up to 500 km, the latter are marked by isometric volcanic areas with diameter up to 200 km. Activity of the melting zones is constrained in time intervals of 23.4–9.7, 9.6–2.6 and $<$1.9 Ma respectively activity of the melting lenses is recognized at two latter time intervals. Based on seismic images, the magmatic processes are attributed to depth 80–200 km. Correlation of volcanic events in Central Mongolia and Tibetan Plateau demonstrates a common connection of mantle processes beneath both areas with tectonic stress derived from Indo-Asian collision zone (Rasskazov et al., 2007, in press).

In this presentation, the model is developed on basis of new geochronological and geochemical evidence on spatial–temporal change of mantle magmatic sources beneath Central Mongolia. Volcanic rocks from this area are alkaline basalts with K- and K-Na affinities. In terms of Sr and Nd isotope compositions, we distinguish three end-members of mantle sources for volcanic rocks: 1) slightly enriched (EM', $^{87}$Sr/$^{86}$Sr $\sim$0.7047, $^{143}$Nd/$^{144}$Nd $\sim$0.51229), 2) depleted (DM, $^{87}$Sr/$^{86}$Sr $\sim$0.7039, $^{143}$Nd/$^{144}$Nd $\sim$0.51259), and 3) more enriched (EM, $^{87}$Sr/$^{86}$Sr 0.7049–0.7059, $^{143}$Nd/$^{144}$Nd 0.51207–0.51232). In time interval of 23–10 Ma, K-rich and K-Na series were produced by separate mantle sources dominated by the first and second components, respectively. Subsequent K-rich liquids were produced from the DM source and mixed with K-Na ones, derived from the EM' source. Eruptions of liquids with the EM signature marked structural reorganizations and temporally changed to those with the EM' characteristics (Chuvashova et al., 2007).

High activity of potassium in the mantle is defined by occurrence of K-bearing clinopyroxenes in the deep mantle at pressures of 5–7 GPa (Tsuruta & Takahashi, 1998; Safonov et al., 2005), i.e. at depth of 120–180 km. Decreasing potassium activity in the shallow mantle presumes transition from K-rich to K-Na liquids. The sources of K-rich lavas are referred to depth 120–200 km and K-Na ones to the relatively shallow mantle. K-rich liquids indicate strongly mobile high temperature mantle loci where the melts are generated due to adiabatic decompression and are capable to escape to surface from relatively deep level, K-Na compositions show shallow melting processes, required less heat, and exhibit spatial transition to an energetically weaker part of a melting zone or lens.

Local eruptions of K-Na lavas at 23.0–15.5 Ma demonstrated exclusively shallow initial melting. Subsequent K-rich lavas were indicative for pronounced collision-derived stress, resulted in sin-kinematical decompressional melting of the deep mantle. Firstly, at 15.5–14.3 Ma, a locus of volcanic rocks with K-affinity was stretched north-northeast, at direction of collision-caused compression, and spatially coincided with the eastern boundary of East Hangay. Afterwards, at 14.3–10.4 Ma, eruptions K-rich lavas were aligned west-north-westerly, in orthogonal direction. Structural reorganization at ca. 10 Ma was expressed by concentration of tectonic stress and related K-rich and K-Na magmatism along the eastern boundary of Central Hangay.

Magmatic evolution beneath Central Mongolia showed transition from spatially separated deep and shallow mantle sources in a lattice of melting zones operated between 23 and 10 Ma to partly coalescent ones occurred after the major structural reorganization responsible for origin of the new magmatic pattern during the past 10 Ma.

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# Non-plume generation of large-scale melting beneath supercontinents

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Supercontinents promote mantle warming and associated large-scale magmatism. Mechanisms for this feedback include the clustering of mantle plumes and lithospheric forcing of convective length scales. Modeling studies show that long-wavelength convection inherent to an internally heated mantle with no active plumes and a supercontinent produces mantle temperature anomalies of +100 °C. Such global mantle warming could have sourced the Central Atlantic Magmatic Province during the breakup of Pangea. Here we use 3D spherical mantle convection models with continents to investigate the temperature beneath continents, changing the total continental area and distribution. We show that in the presence of plumes, warming is enhanced leading to a temperature excess of 200 °C. We also find that significant broadly distributed heating occurs beneath diminutive supercontinents appropriate to the Archean, even in purely internally heated models. This result could help to explain the pulse in continental growth at 2.7 Ga.

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# New ages and geochemical data for Gorgona Island, Colombia: Indication of a ∼30 Ma long history of heterogeneous mantle melting in the formation of the Caribbean Large Igneous Province

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The huge Caribbean Large Igneous Province (CLIP) is the remnant of one or more oceanic melting anomalies active during the late Cretaceous in the Pacific realm. The CLIP has been traditionally ascribed to the initial outburst of the Galapagos plume in Late Cretaceous. However, plate reconstruction as well as geologic and geodynamic arguments exclude the Galapagos hotspot from being the source of the CLIP (Pindell et al., 2006, Geologica Acta) and also cast doubt on the genesis of the province as a result of a mantle plume. In an alternative model the CLIP would be related to the opening a large slab window beneath the Great Caribbean Arc where it intersected the proto-Caribbean ridge in Turonian to Campanian times (Pindell et al., 2006).

Here we present new geochronologic and geochemical data on Gorgona Island, located 50 km west of the Pacific coast of Colombia. The island is formed by an igneous complex which includes komatiites, peridotites, gabbros, picritic basalts and breccias, affected by reverse and oblique faulting with a general E to NE vergence. Previous datings on basalts yielded ages of 88.9±1.2 Ma (Ar-Ar) and petrologic studies showed a large spread in radiogenic isotopes and incompatible trace element ratios. Gorgona was interpreted as the product of a mantle plume with different reservoirs and whose present expression would be either the Galapagos or the Salas y Gomez hotspot. Using Ar-Ar laser step heating we obtained reliable plateau and/or isochron ages which fall within those reported for rocks sampled in situ in the Caribbean large igneous

province (CLIP) ($\sim$92-65 Ma). Only one basaltic sample yielded an age comparable with those reported in the literature. Two basalts intercalated with komatiites and a gabbro yielded younger ages ($\sim$75 – 62 Ma), similar to those of rocks exposed along the western coast of Colombia. Our high quality trace element data for Gorgona show substantial differences with respect to the Sala y Gómez hot spot but overlap those from the more primitive rocks of the CLIP. Considering our new ages, the Gorgona suite displays a secular variation from more enriched to more depleted terms. We propose that Gorgona represents a piece of the CLIP accreted to the Colombian margin and that the suite was produced by several pulses of magmatism with progressively higher grades of mantle melting in a $\sim$27 Ma interval. Our results do not agree with the formation of the CLIP as the product of the initial activity of a mantle plume but seems to be better explained by a progressive opening of a slab window in an oceanic subduction system.

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# Challenges to Plume and Plate – Telling it like it is

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The modern quest for alternatives to the mantle plume hypothesis arose shortly following the turn of the 21st century. It offers the exciting prospect of a new generation of theories, models and viewpoints. However, progress will quicken if there is more widespread acceptance of a number of basic, fundamental truths that are not new. Most damaging is the problem of the definition of a mantle plume. A theory cannot be tested if there is no agreement about what it is. This problem has been highlighted repeatedly over the last few years, but as yet no resolution has been reached. “Definitions” range from an excess of $CO_2$ in the lithosphere, to “any flow driven by thermal buoyancy”, to a hot, cylindrical, mushroom-like upwelling from the core-mantle boundary.

The most fundamental observation at melting anomalies is amounts of magma perceived to be unusually large. Both the quantity and composition of this melt need to be explained. Melting anomalies usually have ocean-island-basalt (OIB) geochemical signatures, which almost certainly results from the presence of recycled near-surface material in the source. The OIB geochemical signature does not require a lower-mantle, or plume origin. This fact has not been universally taken on board, however, and failure to do so continues to impede progress. It is also commonly assumed that high helium isotope ratios (high $^3He/^4He$) uniquely require a lower-mantle origin, despite strong evidence to the contrary. Continuing to cling to unsafe assumptions amounts to ignoring fundamental problems instead of addressing them.

Explaining the volume of magma at melting anomalies, in particular high-volume tholeiitic provinces such as Hawaii, is clearly the single most important challenge in front of us. Despite oft-repeated assumptions to the contrary, mantle plumes cannot explain the eruption rates and volumes observed at many localities, unless the lithosphere is assumed to have been thinned and the temperature raised much more than is observed. Alternatives have been suggested, e.g., long-term ponding of melt followed by rapid release, and fluxing of fertile source material by volatiles. However, few tests have been done and these theories remain speculative and unquantified. Explaining the melt volumes is the most important thing that needs to be done, but few people are working on it.

Closely linked to volume is the issue of temperature. Are melting anomalies hot or not? The most direct approach to determining the temperature of the source is using petrology. However, it is still highly controversial what is and what is not a valid approach. Similar data have been used to obtain wildly different results, depending on the a priori assumptions. For example, high-MgO basalts from melting anomalies and mid-ocean ridges have been variously interpreted to indicate source temperature differences of up to hundreds of degrees, a difference of zero, or as being incapable of indicating temperature. It is urgent to sort these problems out.

It is commonly assumed that seismology is essentially the only way of determining the depth of origin of a melting anomaly. However, in truth it is not at all clear whether traditional seismological approaches can be of much help. The fundamental problems are a) resolution, b) ambiguity of interpretation, and c) poor data coverage. Problem c) may one day be solved, but problems a) and b) are likely to remain. Seismic tomography is very unlikely to ever be able to attain the resolution required to detect objects with the narrow dimensions suggested for deep mantle plumes. Phase (including liquid/solid), composition and temperature all affect seismic wave speeds and these cannot normally be separated out. Red does not necessary mean hot and rising, and indeed this may be the least likely interpretation.

Seismology is powerful to provide information about the interior of Earth, but what it can and cannot do need to be understood and it needs to be used to do what it can and not what it can’t. This simply homily urges an adjustment of attitude that could be applied to all areas of endeavour within the subject and would set the entire subject on a more conservative and safer course.

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# Origin of pyroxenite component in the source of the Canary shield stage magmas constrained from olivine phenocryst - radiogenic isotope relationships

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One of the major geochemical challenges in understanding dynamics of mantle history is to identify the nature and quantification of components involved in partial melting. Recycled oceanic crust is commonly suspected but the role of other mechanisms such as delamination of subcontinental lithosphere is still debated. The main goal of the present study is understanding the genetic link between Ni and Mn concentrations in olivine phenocrysts and whole rock isotopic composition with the aim to constrain origin, amount and isotopic composition of components involved in partial melting of the Canary mantle source due to recycling of subducted oceanic crust and/or delaminated African subcontinental lithosphere. Our approach is based on the coherent variations of Ni and Mn concentrations in olivine phenocrysts as a function of relative contribution of the recycled component to the ascending mantle plume [1,2]. We demonstrate that the concentrations of Ni and Mn in olivine phenocrysts from the most primitive picritic to basaltic lavas from Gran Canaria, Tenerife, La Gomera, La Palma and El Hierro shield stages, as well as from submarine basaltic hyaloclastites drilled during ODP Leg 157 in the submarine clastic apron of Gran Canaria strongly correlate with whole rock Sr, Nd and Pb isotope ratios of their host lavas. Our data set allows to estimate Sr-Nd-Pb isotopic composition of at least two components involved in the partial melting: the first is a “peridotitic” component which is isotopically very similar to the low-velocity component of the upwelling mantle proposed in [3], while the second is more likely represented by “reaction pyroxenite” whose origin requires involvement of physically and chemically complex material resembling mixture of the recycled oceanic crust and/or delaminated subcontinental lithosphere, both went through the “subduction factory”; the last is supported by recent geophysical studies arguing for the presence of active subduction beneath Gibraltar [4] and the 300 km seismic discontinuity generated by $SiO_2$-stishovite formation in eclogitic assemblages [5].

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# Evidence for True Polar Wander since mid-Cenozoic time: A Paleomagnetic Investigation of the Skewness of Magnetic Anomaly 12r (32 Ma) Between the Galapagos and Clarion Fracture Zones on the Pacific Plate

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In recent years, some researchers have asserted that there has been no motion of the Pacific hotspots relative to the spin axis since the age (ca. 47 Ma) of the elbow in the Hawaiian-Emperor chain (e.g., Tarduno et al. 2003). In contrast, the apparent polar wander of the Indo-Atlantic hotspots shows distinct motion of the hotspots relative to the spin axis over the same time interval (e.g., Morgan 1981; Besse and Courtillot 2002). If this latter shift is due to true polar wander, one would expect to see a similar shift of Pacific hotspots relative to the spin axis. Here we present critical new data and analyses to test these distinctly different hypotheses.

Specifically, we present results of an investigation of the skewness of magnetic anomaly crossings of anomaly 12r between the Galapagos and Clipperton and between the Clipperton and fracture zones on the Pacific plate. We chose to focus on this region for three reasons. First, numerical experiments showed that these crossings, of all those available from the Pacific plate, should contain the most information about the location of the 32 Ma paleomagnetic pole for the Pacific plate. Second, many of the available crossings are from vector aeromagnetic profiles, which have superior signal to noise ratios (Horner-Johnson and Gordon, 2003). Third, the rate of seafloor spreading recorded in these crossings exceeds the threshold (half rate of 50 mm/yr) above which no anomalous skewness occurs. Moreover, for the first time, we combine uncertainties in plate-hotspot rotations (Andrews et al. 2005) with paleomagnetic uncertainties to obtain the total uncertainties of our new paleomagnetic pole recon-

structed into the Pacific hotspot frame of reference.

The results show significant and unambiguous motion of Pacific hotspots relative to the spin axis since 32 Ma. Moreover, when the 32 Ma Pacific plate paleomagnetic pole is reconstructed into the Pacific hotspot reference frame, it is consistent with the paleomagnetic pole of the Indo-Atlantic hotspots. We conclude that the global set of hotspots have moved in unison relative to the spin axis since 32 Ma, which is most simply interpreted as true polar wander.

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# What is the role of subduction in the flood basalt origin?: Siberian Traps case study

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Experimental data combined with numerical calculations suggest that fast subducting slabs are cold enough to carry into the deep mantle a significant portion of the water in antigorite, which transforms with increasing depth to phase A and then to phase E and/or wadsleyite by solid-solid phase transition. Ice VII and clathrate hydrates are also stable at PT conditions of cold slabs and represent other potential phases for water transport into the deep mantle. Some cold slabs are expected to deflect while crossing the 410 km and stagnate in transition zone being unable to penetrate through 660 km discontinuity. In this way slabs can move a long way beneath continents after long-lived subduction. With time, the stagnant slabs are heated to the temperature of the ambient transition zone and release free H2O-bearing fluid. Combining with transition zone water filter model this may cause voluminous melting of overlying upper mantle rocks. If such process operates in nature, magmas geochemically similar to island-arc magmas are expected to appear in places relatively remote from active arcs at the time of their emplacement. Dolerites of the south-eastern margin of the Siberian flood basalt province, located about 700 km from suggested trench, were probably associated with fast (cold) subduction of the Mongolia-Okhotsk slab and originated by dehydration of the stagnant slab in the transition zone. We show that influence of the subduction-related deep water cycle on Siberian flood basalt magmatism gradually reduced with increasing distance from the subduction zone. Supported by RFBR 08-05-00642 and 08-05-98104.

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# Was depth of magma generation in the Baikal rift controlled by extension?

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A puzzling thing with the origin of the Baikal rift is the relationship between extension and volcanism. Extension started in the Late Eocene and volcanism initiated at some 25 to 14 Ma in different parts of the rift system. This favors a passive rifting and decompression origin of the volcanism. However, two major rift basins occupied by the Baikal Lake are amagmatic, a fact which casts doubt on the decompression melting model. Recently, recycling of fertile material via stagnant Pacific slab subduction was suggested as a cause of plumes (diapirs), melting, and active rifting. In the northeastern part of the rift there are two volcanic fields smaller than 100 km in diameter; the Udokan and Vitim. The Udokan volcanic field is located at the southern shoulder of the Chara basin at the termination of the rift. The Vitim volcanic field buries small basins outside the rift axis in the central part of the rift. In the southeastern part volcanic rocks are spread over a region about 300 by 500 km forming a number of distinct volcanic fields (Tunka, Hamar-Daban, Dzhida, Khubsugul, Oka and Tuva) within basins, on their shoulders, and in regions without surface expression of extension. We calculated the depth of origin of the primary basaltic melt for these fields based on rock chemistry. It appears that the depth of melting linearly decreases from the Udokan (94+-17 km) to Tuva (67+-10 km) and can be described by the equation: Depth(km)=95-0.02L ($r = 0.94$, $n = 6$), where L is the distance in km from the Udokan along the rift. Gravity-based crustal extension data for 4 profiles across the rift yields the equation: Extension(km)=0.018L+0.5 ($r = 0.96$, $n = 4$). Thus, the greater the crustal extension, the shallower the depth of melting. However, the dry-mantle-xenolith-based geotherm for Oka shows that passive melting of the mantle is impossible at the estimated depth. Extension did not cause melting, it increased melt

production of asthenosphere fed by fertile material. Supported by RFBR 08-05-98100.

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# Impact volcanism and upper mantle melting; megamelting

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It is now widely accepted that large-scale mantle melting initiated by energetic bolide impacts must have been a common event during the early history of the Earth, and igneous petrology can be used to address the fate of these mega-melts. In other words, the same 1000 km scale impact craters seen on the Moon did not form on Earth, but instead are envisaged to have formed gigantic melt-filled basins, of the order of $>25$ to $\sim 100$ km thick, which almost certainly differentiated during slow cooling, and may have helped to initiate the crustal dichotomy between sialic and basaltic terrains (Therriault, Grieve et al LPSI 2001). Different physical models for large impacts processes differ in detail, but converge on this result that for impact events above some critical size ($\sim$few hundred kilometres effective crater diameter), the volume of impact melt exceeds the transient crater volume. In addition, the contribution to substantially increasing volumes of impact melting ($>$ 10e6 km3; Jones et al EPSL 2002) derived from decompression of the underlying mantle remains an important but largely unexplored concept.

The Sudbury impact melt sheet serves as a newly recognised example of differentiation from super-liquidus melts of re-melted sialic crust, but what about similar events in purely basaltic or peridotitic terrains (ie oceanic)? Igneous petrology provides the philosophical criteria for predicting how such processes as immiscible liquid fractionation and subliquidus phase fractionation will occur during thermodynamic crystallisation over the pressure range of what are effectively discrete small magma oceans. However, there is a huge gap in our knowledge of the high temperature data required, which extends well above the liquidus for silicates ($>>$ 1900 K) at relatively low

pressures ($< 5$ GPa). Hence, a new era of experimental igneous petrology is urgently required to understand these superheated events in the Earth's ancient mantle. To put this into context, we can imagine the instantaneous formation of a gigantic superheated melt disc whose vertical height surpasses the total depth of even the thickest crust. How did such a superhot lid influence the underlying mantle? Lastly, such non-plume ideas (impact volcanism) need not be confined to the time period of the early Earth, and have been proposed to operate during the Mesozoic (Ontong Java Plateau; Jones Elements 2005) and on other planets, including Venus (Hansen JGR 2006).

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# Proterozoic to Jurassic LIP mantle source evolution: example from the 180Ma-Karoo and 1.1Ga-Umkondo provinces, Africa.

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Most of the studies focus on the Phanerozoic large igneous provinces (LIPs) and in particular those related to the disruption of Pangea (e.g. CAMP, Parana-Etendeka,) while Precambrian LIPs (e.g. Ventersdorpf, Fortescue) remain less studied. Although the investigation of Precambrian CFBs is difficult because of their poorly preserved character, their study, in parallel with younger overlapping LIP, is fundamental for monitoring the evolution of the mantle composition through time. Such a study has been previously successfully carried out on superimposed LIPs from the South American platform [1] but has not been documented so far for LIPs in Southern Africa.

Recent $^{40}$Ar/$^{39}$Ar geochronological studies of the Okavango giant dyke swarm (and related sill satellites) showed that $\sim$ 88% of the dykes were emplaced at 179 $\pm$ 1 Ma and belong to the Karoo large igneous province [2] whereas $\sim$12% of dykes (plus sills) yielded Proterozoic ages ($\sim$1-1.1 Ga; [3]). Here, we provide new preliminary major, trace and Rare Rarth element analyses of the Low-Ti Proterozoic dykes that suggest, combined with age data, a cognate origin with the 1.1 Ga Umkondo large igneous province [4].

The geochemical characteristics of the Proterozoic basalts are comparable to the overlapping low-Ti Karoo basalts and suggest that both LIPs were derived from similar enriched mantle sources. A mantle plume origin for these LIPs is not easily reconciled with our data as (1) a mantle plume signature is not recognized in the Proterozoic dyke dataset, neither is it convincingly established for Karoo basalts which bear a dominant lithospheric mantle signature [5], (2) drifting of the African plate during ∼900 Ma implies that Umkondo and Karoo magmatism would have tapped different mantle plume reservoirs (with different signatures) and (3) two different mantle plumes should have been chemically modified in a different way during their ascent through a heterogeneous mantle. Rather, we propose that the Karoo and Umkondo provinces monitored the slight evolution of a shallow enriched (lithospheric?) mantle through time. To probe the Southern African mantle further in time, the Archaean Palabora dyke swarm is under investigation.

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[2] Jourdan et al. (2004), EPSL 222, 989-1006

[3] Jourdan et al. (2006), EPSL 241, 307-322

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# Giant dyke swarms and triple junctions do not necessarily define a mantle plume signature

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Giant dyke swarms and triple junction define geometries that are generally inferred to mark the response of the crust to mantle plume head impact. Poor consideration is generally given to the possible role of structural inheritance of the basement fabric in the emplacement of these swarms. Cases of inheritance can easily be addressed using geochronology and structural observations. Here, we review in detail selected case examples of multi-generation dyke swarms that are related with large igneous provinces and subduction settings and that do not require mantle plume impact to explain their patterns.

(1) The 700km-long Independence dyke swarm (California) is beyond any doubt a subduction-related feature. It was intruded in several major magmatic episodes over more than 100 Ma. Interestingly, despite major changes in the orientation of plate convergence, the direction of dyke emplacements remains constant [1]. (2) The 1700-km-long Red Sea dyke system include both Neoproterozoic and Cenozoic (24-21 Ma) dykes [2] suggesting that the dyking event associated with the Red Sea opening followed an ancient Proterozoic direction. So, this arm of the Afar triple junction was not initiated by the Afar plume (3) The 180 Ma Karoo giant radiating dykes swarms include Jurassic, Proterozoic (± archaean) dykes. Dyke orientations are largely controlled by pre-existing structures that also controlled emplacement of Precambrian dykes [3]. (3) The trend of several 200-Ma CAMP dyke swarms follows Pan-African and Hercynian directions and South American dyke swarms include both Proterozoic and Jurassic dykes [4]. (4) The Senneterre ($\sim$2.21 Ga), Biscotasing ($\sim$2.17 Ga) and

Abitibi (∼1.14 Ga) southern Canada dyke swarms [5] are geographically superposed, suggesting strong structural inheritance and a multi-reactivated weakened crustal pathway. Finally, we note that two of the 65-Ma-Deccan dyke swarms follow the western limit of the Indian craton and the third branch follows the Central Indian Tectonic Zone suggesting structural control. However, no Precambrian dykes have been identified yet. Other concise examples are addressed.

Although our observations do not rule out a mantle plume origin for most of these dyke swarms (which is well-established in some cases), they cast some doubt about the significance of dyke swarms and other triple junctions in the mantle plume model.

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# Age and origin of magmatism at the Marie Byrd Seamounts (Amundsen Sea)

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The Marie Byrd Seamounts (MBS) form a large intraplate volcanic province aligned sub-parallel to the northern shelf of Marie Byrd Land (West Antarctica). This seamount cluster spans over 800 km in E-W direction and consists of 8 large volcanoes and 30 minor volcanic structures. The seamounts are located in 3.5 to 4 km water depth and have an areal coverage of up to 75x50 km at their base and reach a height of 3 km above the surrounding seafloor. So far, knowledge of the age and origins of this enigmatic seamount province is very limited, and their existence is difficult to explain by classical hotspot models. R/V Polarstern cruise ANT-XXIII/4 collected new bathymetric and geophysical data as well as igneous rocks for the first time. This data and samples are used to acquire formation ages and to decipher petrogenesis and magma sources in order to obtain a spatiotemporal evolution of the MBS. In connection with geophysical data and plate reconstruction models, these investigations contribute to the reconstruction of the tectonic evolution of the SW Pacific and to the ongoing discussions on the origin of intraplate volcanism. The bathymetry of the largest ones of the MBS reveals a guyot-like morphology indicating that they once formed ocean island volcanoes that eroded at sea level and subsequently subsided 1.6 km in the western and 2.4 km in the eastern part of the province. Uneroded small cones on the flanks and on the erosional platform of the seamounts represent late stage or post-erosional, post-subsidence phases of volcanism, respectively. $^{39}$Ar/$^{40}$Ar age dating of the dredged samples exhibit Cenozoic ages ranging from ca. 65 Ma (Paleogene) in the western to ca. 52 Ma (Eocene) in the eastern part of the seamount chain. The ages clearly show that the voluminous MBS formed well after the full development of the Pacific-Antarctic-Ridge and the break-up of New Zealand from West Antarctica. The relatively short time span of magmatism coincides with a phase of major plate reorganization in the Bellinghausen and Amundsen Sea (Eagles et al., G-cubed 5,7, 2004), possibly causing volcanism induced by plate fracturing. First geochemical results show that the obtained samples mostly consist of relatively evolved volcanic rocks of the alkaline differentiation series. Sr-Nd and in particular Pb isotopes display a two component mixing array of depleted upper mantle and an enriched (EM) mantle component. The presence of EM could either reflect shallow recycling of lithospheric sources during continental break up or contamination by continental crust, which -based on new seismic refraction data - seems to extent much farther north of the shelf break than previously thought (Gohl, USGS OFR, in press). However, primitive basaltic glass from a recent lava flow dredged at the base of PeterI Island, located on ocean crust of the Bellinghausen Sea, define the EM mixing endmember and thus seem to exclude extensive assimilation processes for the evolved MBS lavas. In conclusion, shallow recycling of fertile continental lithosphere into the upper mantle during the final breakup of Gondwana followed by plate fracturing and upwelling of the fusible material most likely explain the origin of the enriched MBS component. However, lithospheric delamination as suggested for the conjugate New Zealand margin (Hoernle et al., EPSL 248, 2006) also deserves consideration.

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# Two-stage melting and noble gases

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The AGU Fall 2007 meeting had several papers on diffusion of noble gases under mantle conditions (e.g., Hart et al. - U21B-0407, Watson et al. - U21B-0410, Albarede - V43F-07). Here we show how diffusion combined with our plume-based model of a plum-pudding mantle, a plume-fed asthenosphere, and two-stage melting (first to make OIBs above a rising plume and second to make MORBs by melting asthenosphere which is the residue from the first-stage of melting) can explain the rare gas patterns seen in OIB and MORB. In this abstract, we focus on the observation that the ratios of 3He/22Ne and 4He/21Ne are higher in MORBs than in OIBs. [3He and 22 Ne are both stable, primodial isotopes. 4He and 21Ne are both produced by the decay of uranium and thorium; 4He is directly produced by this decay, 21Ne is produced by an occasional alpha particle reaction 18O(a,n)21Ne. In mantle silicates, the production ratio is one 21Ne for every 2.2x10ˆ7 4He.] So how can there be more 3He/22Ne in MORB than OIB, and similarly more 4He/21Ne in MORB than OIB? We think diffusion of helium between neighboring components in the plum-pudding mantle is the simplest physical mechanism to explain this. The primordial 'plums' contain more 3He, 20Ne, 22Ne, 36Ar; but the helium (and not the larger neon, argon, and heavier noble gases) diffuses out from the concentrated plums into neighboring components. Thus in the first-stage melting at a rising plume, the easy-to-melt but small-volume fraction components that melt to produce OIB contain less He than the heavier noble gases (because some He has diffused away into neighboring more barren components). In the second, more-extensive melting that makes MORB, the more barren material will partially melt and release this helium, resulting in the MORB having relatively more He than the heavier, less diffusive noble gases. Similarly, in non-primordial components with enrichments of uranium, thorium and potassium (recycled continental crust, recycled oceanic crust), helium but not 21Ne or 40Ar, etc.

has diffused out from the concentrated lumps that melt in the first state, again resulting in lower-than-the-average He in OIB but higher-than-the-average He in MORB. Other aspects of this model will be presented.

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# Dynamics of mid-Paleocene North Atlantic and African plate boundaries linked by European intra-plate deformations

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The process of continental break-up provides a large-scale experiment that can be used to test causal relations between plate tectonics and the dynamics of the Earth's deep mantle. Detailed diagnostic information on the timing and dynamics of events, which are not resolved by plate kinematic reconstructions, can be obtained from the response of the interior of adjacent continental plates to stress changes generated by the plate boundary processes. Here we demonstrate a causal relationship between North Atlantic continental rifting at ˜62 Ma and an abrupt change of the intra-plate deformation style in the adjacent European continent. The rifting involved a left-lateral displacement between the N American-Greenland plate and Eurasia, which initiated the observed pause in the relative convergence of Europe and Africa. The associated stress change in the European continent was significant and explains the sudden termination of ˜20 Myr of Late Cretaceous to earliest Paleocene contractional intra-plate deformation within Europe to be replaced by low-amplitude intra-plate stress-relaxation features. The pre-rupture tectonic stress was large enough to have been responsible for precipitating continental break-up, without the necessity of invoking a thermal mantle plume as a driving mechanism. The model explains the simultaneity of a number of diverse geological events and how the intra-continental stratigraphic record can reveal accurate details about the timing and dynamics of processes causing stress changes not resolved by reconstructions based only on plate kinematics.

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# A broad Galápagos hotspot melting anomaly linked to disturbance of the underlying core-mantle boundary?

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New evidence from direct isotopic dating of the oceanic hotspot record is suggesting that hotspot melting anomalies might be much broader than commonly inferred from the dimensions of individual seamount chains and aseismic ridges and their associated active 'volcanic' hotspots. Such an inference is supported by recent thermo-chemical numerical modelling exploring scenarios where upwelling structures are more irregular in shape and behaviour compared to a classic thermal plume 'head-tail' (*e.g., Farnetani and Samuel, 2006*). New age data from the Galápagos Volcanic Province suggest that it developed via the progression of broad regions of widespread, long-lived and possibly concurrent volcanism resulting from tectonic plate motion over a broad Galápagos hotspot melting anomaly (*O'Connor et al., 2007*).

Seismic imaging of the core-mantle boundary under the Cocos plate shows a 100-km vertical step occurring in an otherwise flat D" shear velocity discontinuity (Thomas et al., 2004, Hutko et al., 2006, Kito et al., 2007). One possible explanation is that folding and piling of a cold subducted slab on reaching the core-mantle boundary might account for this lateral variation in terms of a post-perovskite phase change (*Thomas et al., 2004, Hutko et al., 2006, Kito et al., 2007*). Low velocities inferred at the edge of this proposed slab material may result from the lateral displacement of a thin hot thermal boundary layer leading to upwelling at the tip of the slab, (*Thomas et al., 2004, Hutko et al., 2006, Kito et al., 2007*), which in turn might possible be connected to our inferred broad hotspot melting anomaly. The combination of the recent imaging of an anomaly at the D"-discontinuity and the inference of a broad

overlying Galápagos hotspot melting anomaly suggest that the Galápagos region is an ideal natural-laboratory for studying the possibility of interaction between the core-mantle boundary and overlying lithosphere.

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# Thick plates and a two-layer mantle: basis for a single model of mantle magmagenesis, all the way from MORB to OIB to flood basalts to kimberlite

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Magmagenesis within the mantle has long presented problems. These include:- Magma chambers would collapse: How can the depth of segregation change systematically? Percolation can be too slow: How are end-member compositions brought together, often from different segregation depths? How are deep xenoliths entrained? These problems arise in the context of a heavy reliance, of which the plume concept is an example, upon mantle mobility, unconstrained heat sources and thermodynamic equilibration.

Recent demonstration [1] from several examples of plate dynamical behaviour in the past 150Ma that we have both a 2-layer mantle and that cratons have keels that nearly reach the 660, demands appraisal of how this radical change reflects upon the genesis and understanding of mantle-derived magmas. So that is the task here, bearing in mind that the thick-plate perpective extends (but not so deeply) all the way to MORs [2]. We will show that, contrary to traditional perspectives in which thin plates are thought necessary for magmas to reach surface, a thick-plate version of the plate tectonics paradigm leads to exciting illumination of mantle magmagenesis and its significance.

The basic model is that of an induced diapir in a deep, narrow, mantle crack, first presented at Goldschmidt 2005 [3], but needing thick plates to be fully applicable. This has three main features:- (a) Being an induced diapir (for which plate tectonic mechanisms exist), the degree of melting increases as it rises, but then decreases as wall cooling asserts an influence, the solids, enlarged by cumulate intergrowths, then forming a 'log-jam' in the crack (a phenomenon well-known to engineers), through which the melt is then forced. This not only controls the primary segregation depth, which thereby depends on thermal factors such as wall temperature and crack opening rate, but also constitutes a source of xenoliths when ruptured. (b) Reduced pressure is characteristic of the bottom of any diapir. In this case, incipient melting of low-melting mantle accessories provides a source not only of their often-rich trace element contents but also melt pathways along which gases will diffuse, with resulting light-isotope enhancement. At MORs, continuity promotes self-cancelling of this effect. (c) Eruptivity control, and more, arises from the presence, at some level in the walls, of the sp-gt peridotite phase change. Upon heating by an eruption, this increases volume $>40$ times more than thermal expansivity, and may close the crack, prising it apart elsewhere. At MORs this now constitutes the main ridge-push force. In the OIB case, it may prolong volcanic chains.

The two mechanisms (a) and (b) provide, in effect, 2 different kinds of segregation, and at 2 different depths, thus offering an apparently 2-source-component final composition, there having been insufficient time (narrow crack, fast flow) for mutual equilibration at the log-jam level.

Four simple variants of this basic model will be presented, adapted to each of the four kinds of magmatism named in the title. Source compositions are still important but processing is central and thick plates provide the space to do it in. So local differences of source composition are far less significant but a major one occurs in the presence of lower mantle composition in the TZ, due to seepage across the 660 [4].

If time allows, the talk will begin with two dynamical examples from Ref [1] that support our initial proposition and conclude by outlining how the Earth's changeover from whole-mantle convection is documented by events leading to the rise in atmospheric oxygen at $\sim$2.25Ga, so we are a product of that changeover.

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# Mantle plume and the formation of marginal sea depressions

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Kuno (1968) proposed and idea on systematic distribution of different types of *basalts series* across of islands arcs: tholeites formed in the fore arc portions of the arcs while high-aluminum and then more high-temperature alkali basalts formed in back arcs portions. This is because of the shift with pressure of the liquidus boundaries involving olivine, pyroxene and silica minerals in the mantle wedge. Later on this effect has been experimentally proven by I. Kushiro (1975). While the systematic in the distribution of tholeitic and alkali basalts across an island arc reflect distribution of temperatures with depth, metamorphic complexes show mainly lateral change of temperatures, which increase toward the continent.

Towards the continent, the trench-arc system gives a place to marginal sea floors that has never contain new metamorphic rocks but still preserve relict continental crust at borderlands. Bottoms of the marginal sea floors are composed of young tholeitic basalts related to the extremely high heat flow. In this portion of the system *trench–island arcs–marginal sea floor–continental margin* (TIMC) heat transfer increases dramatically resulting in the back arc zone direct interaction ultramafic magma with lower crust and in the formation of mixed magmas whose composition is intermediate between mantle peridotite and upper crust acid material, i.e. Mg-rich andesites and boninites (Bindeman & Perchuk, 1993). This conclusion follows from the systematic change with time deepwater volcanism in the marginal sea floors from rhyolites via andesites to basalts (e.g., Perchuk, 1987; Frolova et al., 1992), and replacement of lower crust island arcs by ultramafic magmas (Kushiro, 1983; Tatsumi, 2001, 2006). Thus, temperature increases while the depth of magma generation decreases across the TIMC system reflecting in the formation of the following metamorphic-magmatic zonation: HP-LT metamorphic terrenes => LP-UHT metamorphic belts => intense acid magmatism => intense tholeitic magmatism. This supports a model for geodynamic evolution of active continental margins due to the interaction of a mantle plume with the crustal rocks (Frolova et al., 1992). Recent treatment of seismic data (Zhao, 2001, 2004) reproduces this model in terms of distribution of P-anomalies. Thus, evolution of both the magmatic and metamorphic complexes in the Western Pacific type continental margins reflects evolution of mantle derived plume. The intensity of the interaction, i.e. tectonic extension and magmatic replacement of continental crust that increases from the Okhotsk Sea on North via the Japan Sea to the Philippine Sea on South.

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# Origin of alkaline OIBs: constraints from experimental petrology and melting behavior

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The interpretation of melting anomalies beneath oceanic islands (thermal or compositional) is directly linked to the nature of the source material that melts. Trace-element and isotopic characteristics of basaltic magmas from ocean islands suggest the presence of “enriched” components in their sources. These components have been interpreted as being derived from recycled oceanic crust ± sediment. An alternative is that the enriched components are metesomatic veins present within the lithosphere or metasomatized lithosphere that has been incorporated into the convecting mantle. These two interpretations (oceanic crust vs. metasomatic veins/lithosphere) are generally considerate as being antagonistic. However, the large petrological and chemical variability observed in OIBs (from *ne*-normative to *hy*- and *qtz*-normative magmas), suggests that both components may be important, e.g., oceanic crust may be important in the generation of tholeiitic magmas from large oceanic islands and continental lava flows [1]. The fact that partial melts of oceanic crust are silica oversaturated makes it difficult to envision a significant role for them in the generation of alkaline (i.e., *ne*-normative) magmas.

Partial melting experiments at 1.5 and 2.5 GPa on natural amphibole-rich veins and on their dehydrated equivalents demonstrate that key features of the major and trace element compositions of alkaline basalts from both oceanic and continental settings can be explained by moderate to high degrees of melting of metasomatic veins “in situ” or after having been recycled within the convecting mantle. However, this interpretation of the origin of alkaline basalt is not unique and the melting of silica-deficient garnet pyroxenite (formed by the extraction of silica-rich fluids during subduction from initial silica-oversaturated oceanic crust) could also explain, in some respects, the formation of *ne*-normative basalts [2, 3].

A critical aspect of partial melting in the context of upwelling mantle is the melting behavior of the different lithologies within the upwelling mantle (i.e., metasomatic veins /recycled oceanic crust + enclosing peridotite). If low-solidus vein material melts during adiabatic decompression but is chemically isolated from but in thermal equilibrium with the adjacent peridotite, the degree of melting of the veins will be enhanced relative to the amount of melting that only vein material would undergo, meanwhile the enclosing peridotite will be "refrigerated" by the melting of the veins, and thus will melt at lower pressure and to lower degrees than if the veins were not present. Thus, low-solidus vein material in upwelling mantle should melt to much high degrees relative to the accompanying peridotite [4]. Stracke et al. [5] indicate that the degree of melting of subducted oceanic crust would have to be very low ($\leq 1\%$) in order to explain the high trace-element contents of alkaline OIBs. Given that oceanic crust has a lower melting temperature than peridotite [6], such low degrees of melting is inconsistent with the above analysis [see 4]. Our experiments on the other hand show that metasomatic veins can melt to a large degree and still satisfy the trace element contents of alkaline basalts. We conclude that melting of amphibole-bearing lithospheric veins (or their dehydrated equivalents after recycling within the convecting mantle) plays a role in the petrogenesis of alkaline lavas and we suggest that recycled components in the sources of islands characterized by tholeiitic magmas (i.e., Hawaii or Iceland) and in the sources of islands where *ne*-normative compositions are dominant (i.e., Polynesia, island in the Atlantic Ocean, etc.) are distinct.

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# Plumeless Oceanic Volcanism Challenges Whole-Mantle Convection

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Here we apply petrological constraints that test the existence of hot mantle plumes and whole mantle convection. Model-system phase relations show that if basaltic melts are extracted from a lherzolitic source at high P and T ($>\sim$ 1.5 GPa, 1280˚C), they are picritic. Fractional crystallization of these magmas in a crustal magma chamber at low pressures would show an initial trend of olivine-controlled crystallization. In a global compilation of 6,937 MORB glass analyses (389 from Iceland), mainly from the petDB database, we find no indication of such a trend. Therefore, despite claims of extensive olivine-controlled crystallization of MORBs based on hypothetical olivine-addition calculations, we find that observed MORB glasses, including those from Iceland, show no evidence of extraction from the mantle at P $>\sim$1.5 GPa, 1280˚C (Presnall *et al.*, 2002, *Geochim. Cosmochim. Acta*, 66, 2073; Presnall and Gudfinnsson, *J. Petrol.*, in press). We conclude that no hot plumes (Jan Mayen, Iceland, Azores, St. Helena, Tristan, Bouvet, Easter, Galapagos, Afar) exist along or near oceanic ridges. The strong olivine-controlled crystallization trend at Hawaii indicates a much higher temperature of melt extraction, and this might seem to support the existence of a plume at Hawaii. However, model-system phase relations and the existence of diamonds show that the pressure of melt-extraction at Hawaii must also be much higher than that of MORBs. Thus, the Hawaiian picritic magmas are consistent with melt extraction from a greater depth along a geotherm similar to that beneath oceanic ridges, and the existence of hot plumes in the ocean basins has no support even at Hawaii. As hot plumes are the dominant component of return flow from the deep mantle in a whole-mantle convection model, their total absence severely challenges the existence of whole-mantle convection. We replace hot mantle plumes with fracturing of the oceanic seismic lithosphere in response to stresses imposed by continental plates (Presnall and Gudfinnsson, *J. Petrol.*, in press). These fractures induce explosive escape of $CO_2$ vapor from the slightly melted seismic low-velocity zone, which assists the transport of MORB melts to the surface and explains the constant association of strombolian and effusive eruptions at oceanic ridges (Clague *et al*., 2003, *AGU Mon.* 140, 111). Shifting stress fields over time cause the birth, propagation, and death of spreading ridges.

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# On alternative models for the origin of time-progressive volcanic chains

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The time-progressive character of some volcanic chains is well known for decades and is proven with a different degree of reliability for many of them. The recent overviews of the primary data can be found in the papers of O'Neil et al. (2005), Clouard and Bonneville (2005), enhanced by some additional information (e.g. Geldmacher et al., 2005). A couple of dozens of such chains is a real challenge for anyone who works at the problem of origin of melting anomalies.

One of explanations was suggested by T. Wilson (1963) as a hypothesis of "hot spots" – surficial manifestations of immovable deep mantle melting anomalies, the idea developed later by W. Morgan (1971) as a theory of plumes – convective upwelling streams of a light hot mantle substance coming from the core-mantle boundary. It was a smart explanation, and still is, though the idea of an absolute horizontal immobility of plumes is disproved now by paleomagnetic and geodetic data, and details of melting processes still need a lot of research and thinking.

The recent passionate, and in some important aspects, well-founded scepticism of many authors concerning the plume theory has brought back to life an almost forgotten theory of J. Dana, that of a propagating crack. Recently the idea has found its new adherents among adversaries of plume tectonics. It might seem that most evident approach to a propagating crack model is in a suggestion of an existence of a maximum horizontal tensile stress normal to the crack and ensuing volcano chain. But in the most evident example of Hawaii-Emperor and other likely chains of the Pacific, the ideas of classical plate tectonic forces and deformations (subduction slab pull and rollback, mantle drag and ridge push) can not explain the orientation of the corresponding cracks if any. It had been shown at a global scale (Zoback et al., 1989), that the maximum horizontal stress is usually subparallel to the direction of absolute plate motion, suggesting that the forces driving the plates also dominate the stress distribution in the plate interior. Probably because of it, a different approach was undertaken (Stuart et al., 2007). Plate tectonic forces were not taken into account at all, and "a thermoelastic stress rate for present-day cooling of the Pacific plate using a spherical shell finite element representation of the plate geometry" was calculated. A needed result had been obtained, at a price of ignoring of classical plate tectonic forces, a price probably too great to be acceptable. Over and above, still more questions must be answered by the crack propagation supporters before the hypothesis becomes a theory: 1. Why the propagation of time-progressive chains in all oceans is always oriented as predicted by plume-and-plate tectonics? 2. Why the crack propagation is not affected by the strongest anisotropy of oceanic, transitional and continental lithosphere, crossed by many chains? 3. Why the Reunion and Kerguelen time-progressive volcanic chains overrode the active MOR, if they are propagating cracks?

Another alternative model is that of easily melting magma sources (pyroxenite "blobs"), drifting in an asthenosphere (Anderson, 2007). The model, worked out in detail by M. Cuffaro and C. Doglioni (2007), suits the Pacific chains, but at a global scale it fails because it is contradicted by the behavior of time-progressive chains in the Eastern Atlantic and Indian oceans. On the other hand, the very idea of a pyroxenite "blob" (basic in composition) hanging in asthenosphere for many tens of Ma, conflicts with the nature of asthenosphere, the latter demonstrating readily the effects of the Archimedes law. When situated deeper than 50 km, the "blob" exists as an eclogite which is much denser that the ambient peridotite and must sink, if not supported by a plume upwelling. When situated higher than the phase transition zone, it turns into gabbro which is much lighter than the peridotite and therefore must finally strike the bottom of lithosphere.

By itself, the idea of pyroxenite as an easily melting component of the Earth's mantle seems to be very promising. It really can be of a great benefit for the plate tectonic approach in explanation of shallow, top-asthenospheric decompression-induced melting anomalies (Foulger, 2007; Anderson, 2007). But it can be also extremely useful for the real plume model as it became evident recently from an example of the deep-sourced Hawaiian magmas (Sobolev et al., 2005; Yaxley, Sobolev, 2007).

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# Cenozoic Magmatism in Asia: Geochemical Signatures of slab-related Processes

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Models of global seismic tomography and interpretation of geochemical data on oceanic basalts served as a basis for hypothesis on leading role in geodynamics of density differentiation in the Earth interior. The active down-going high-velocity and stagnated slabs coexist with upwelling low-velocity anomalies in the mantle. Structural reorganizations led to spatial redistribution of the density inhomogeneities. As a result, stagnated slabs and above-slab regions underwent repeatable melting which overlapped not only low-velocity regions but also high-velocity slabs. Mixing of high- and low-velocity constituents of the mantle could produce intermediate composition temporally dominated by involvement in melting of material derived from slab- or above-slab regions.

We demonstrate geochemical evidence on leading role of slab-related geodynamics beneath Asia using results of more than 2000 new ICP-MS analyses and recently published data on Cenozoic volcanic sequences. A diagram K/1000Ta vs. La/Ta has been applied for definition of complementary trends of liquids originated from slabs and above-slab regions in subduction and collision zones. The latter show specific trends for frontal and back-side areas. The recoded trends of volcanic rocks from different areas of Asia yield a common composition of K/1000Ta = $\sim$12 and La/Ta = $\sim$7. As compared to this composition, both ratios decrease with relative isotopic (Sr, Nd) depletion and increase with isotopic enrichment.

Subduction- and collision-related geochemical signatures are well expressed in volcanic rocks from Northeast and Southeast China, respectively. The frontal and back-side collision-governed signatures are attributed to volcanic rocks from the southern and northern Tibetan Plateau. Complementary slab-derived components with back-side and frontal collisional signatures were recognized to be temporally substituted by the above-slab one with frontal collisional values in a sequence of East Hangay, Central Mongolia. This evolution demonstrates temporally increasing role in deep dynamics of processes developed in Indo-Asian collision zone. Liquids from the above-slab sources with back-side collisional values were identified in the Middle-Amur Basin (Southeast Russia) at 14.8-7.4 Ma with subsequent change to those from the slab-derived sources at 5-4 Ma. This case is indicative for cessation of deep collision-driven dynamics. Similar temporal change of sources was found for volcanic sequence in the Orkhon-Selenga area of Central Mongolia.

Geochemical evolution of Cenozoic magmatism in Inner Asia is inferred to preserve a style of slab-related processes developed at convergent plate boundaries.

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# Melting anomalies and tectonic activity on “passive” margins

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Passive continental margins are created during the rift-drift transition stage of the oceanization process. These margins are commonly regarded as volcanic or non-volcanic according to the amount of igneous products emplaced during the break-up stage. In this respect, the Atlantic Ocean is acknowledged as a classic example of an ocean bounded by passive margins of both nature. In the north, volcanic margins were generated during the Paleocene. In the central part, non-volcanic margins were generated in the Jurassic-Cretaceous. However, in the central Atlantic, both western and eastern conjugated rifted margins are the site of melting anomalies giving way to small-volume magmatism much later than the rift-drift stage.

A prime example of this type of magmatism is found in Senegal, whose continental margin developed in Middle-Late Jurassic and is generally regarded as a monoclinal structure affected by normal faulting. Nevertheless, this margin is affected by post-rift magmatism of Cenozoic age (35-0.6 Ma). The igneous products are scattered over the Cap-Vert peninsula as alkaline lava flows and shallow level intrusions. Additional saucer-shaped sills have recently been detected in the Senegal offshore on the basis of integrated seismic, magnetic and gravimetric surveys. The occurrence of hydrothermal vents and forced folds related to sill intrusion allows to date the igneous event to the Miocene. The age of magmatism displays a minimum delay of 130 Ma with respect to rifting, with consequent decoupling of cause-effect link between rifting and magmatism.

Additional examples of such delayed melting anomalies come from other central Atlantic passive margins. The North America margin of Newfoundland-Grand Banks is the site of several examples of alkaline igneous activity (dredged seamounts, lavas and sills drilled by OPD) with ages between 135 and 96 Ma, i.e. from coeval to c. 35 Ma later than the oldest oceanic magnetic anomaly. Seamounts dredged off the conjugate Iberian margin along the Tore-Madeira Rise have alkaline nature and ages between 104 and 80 Ma, that is magmatism has a delay of 25 to 50 Ma after rift-drift. Off the north-western margin of Africa, the Canary Islands are the result of long-lived igneous activity delayed of more than 100 Ma with respect to the rift-drift transition there. Further south, past the Senegal margin, the Cameroon line is the site of linear, long-lived alkaline magmatism showing no time progressive shift and active from 60 to 125 Ma after the rift-drift transition. In the south America margin, seismic surveys in the Sergipe-Alagoas-Jacuípe basins offshore north-eastern Brazil, indicate the occurrence of igneous bodies emplaced later than rift-drift stage.

These examples of “delayed” magmatism on passive margins cannot be explained by the activity of several “ad hoc” mantle plumes because of the small volume of magmatism and the absence of time-progressive tracks of igneous activity. Rather, onshore structural data from Senegal are evidence for magma emplacement on fault arrays conjugate with the geometric impact of oceanic fracture zones into the transitional-continental crust. Evidence for fracture zone reactivation is found also in offshore seismic sections. Moreover, gravity and magnetic modelling of location and shape of offshore sills show evidence for a geometric link with the belt of Atlantic fracture zones. Therefore we propose that the engine for the generation of these melting anomalies active on passive margins tens of Ma after the rift-drift transition is linked to the reactivation of oceanic fracture zones.

This mechanism is currently at work in the Antarctic rift. Here, the main rifting episode is of Late Cretaceous age, while alkaline magmatism is active since the Middle Eocene, some 50 Ma later. The igneous activity shows a tight genetic-geometric-geochronological link with the activity of a dextral strike-slip fault system affecting the continental crust and in turn linked to the Southern Ocean Fracture Zones.

The reported examples call for the inclusion in the inventory of passive margin types of a "new" type of margin: besides volcanic and non-volcanic margins, "delayed-volcanic" passive margin with alkaline magmatism should be accounted for.

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# Rodinia supercontinent break-up: Not a result of Superplume tectonics

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The formation of the Earth’s crust is a complex process, evolved over a long period. Upper mantle convection dynamics caused separation of low-density silicate minerals from the initial cooling melt. This resulted in the granitic continental part. These landmasses gradually accreted in the form of a supercontinent, which subsequently fragmented in the smaller continents.

The Rodinia supercontinent accreted between 1100 and 900 Ma. The history of supercontinent assembly and fragmentation is constrained through palaeomagnetic data from different landmasses along with other geological data. The assembly process caused development of orogens, melting anomalies and other thermal events under a compressional tectonic regime along continental margins. The formation of an insulative supercontinent changed the thermal pattern of the crust-mantle region. The change in upper-mantle thermal convection led to the breaking of the supercontinent at ca 750± 50 Ma along with decompressional melting through fractures resulting from extension. Large Igneous Provinces and other melting anomalies formed on the different landmasses at the time of Rodinia fragmentation.

Plate tectonics operated in response to thermal dynamics in the lithospheric part of Earth, and clearly explains the assembly and break-up of Rodinia during Neoproterozoic time. However, others have suggested a whole mantle thermal convection system from the core-mantle boundary, and the existence of a superplume at the time of Rodinia break-up. The superplume resulted mantle avalanches and ultimately continental rifting.

This superplume analogy does not explain the tectono-thermal energy required for the assembly of Rodinia; this can only be explained by plate dynamics. The same process accounts for break-up of the supercontinent under changed tectono-thermal conditions. There is an absence of widespread deep-seated Neoproterozoic ultramafic rocks in the Earth's crust, which should have arisen due to mantle avalanches. The Neoproterozoic melting anomalies constitute Large Igneous Provinces. Malani bimodal magmatism, with its dominant silicic component, shows the role of lithosphere rather than the core-mantle boundary region. Silicic magma is a low temperature melt and resulted from continental insulation heat build up and decompression on fragmenting continents.

The Neoproterozoic tectonothermal evolution of the crust during Rodinia assembly and fragmentation can only be explained by plate tectonic process. It does not have viable inputs from mantle avalanches and superplume tectonics.

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# Linking crustal recycling and osmium isotopes

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Recycling of subducted oceanic crust is widely thought to explain much of the chemical and isotopic heterogeneity of Earth's present-day mantle [1]. Geochemical tracers of recycled subducted ocean crust have included elevated 187Os/188Os in some studies [2,3] and high Ni and low Mn contents in others [4,5]. Here we link these tracers for the first time. For Iceland we observe strong positive correlation between amount of reacted recycled oceanic crust (estimated from Mn/Fe ratios of olivine phenocrysts after [5]) and 187Os/188Os ratio of bulk rocks. This result significantly strengthens the recycling model [1,6]. Furthermore it allows us to estimate the Os isotopic composition of both the recycled crust and the mantle peridotite, thereby constraining the model ages of end-members. We show that Icelandic lavas require ancient crustal component with model ages between 0.6 and 2 Ga and peridotitic end-member close to present-day mantle.

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# The case for a thermal origin of magmatism on the North Atlantic continental margin

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The cause of the magmatism on ‘volcanic’ continental margins is still disputed, specifically as to whether it is due to increased mantle temperatures. New seismic profiles across the Faroe and Hatton Bank volcanic margins in the NE Atlantic enabled us to constrain the seismic velocities and volumes of both the extruded and intruded melt. Near the Faroe Islands, for every 1 km along strike, 360–400 km$^3$ of basalt was extruded, while 540–600 km$^3$ was intruded into the continent-ocean transition (COT). Lower-crustal intrusions are focussed mainly into a narrow zone $\sim$50 km wide on the COT, whereas extruded basalts flow $>$100 km from the rift. Deep-penetration seismic profiles show that melt is intruded into the lower crust as sills which cross-cut the continental fabric, rather than as ‘underplate’ of 100% melt as has previously often been assumed. This means that measured lower-crustal velocities represent a mixture of continental crust and new igneous rock. Tomographic inversion of wide-angle traveltimes from 85 ocean bottom seismometers constrain average lower-crustal seismic velocities as 6.9–7.3 km/s under the COT, intermediate between the velocities of the continental crust and fully igneous oceanic crust on either side. By comparison with theoretical curves of igneous thickness versus seismic velocity (H–Vp), our observations are consistent with the dominant control on the melt production being elevated mantle temperatures, with no requirement for either significant active small-scale mantle convection under the rift or of the presence of fertile mantle at the time of continental breakup as suggested for the North Atlantic by other authors. The mantle temperature anomaly was c. 130–150 °C above normal at the time of continental

breakup, decreasing steadily by about 75˚C over the first 10 Ma of seafloor spreading.

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# Fluid streaming from the Transition Zone as a trigger for within-plate magmatism

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The distribution of Tertiary-Quaternary within-plate volcanic provinces throughout Europe is broadly anti-correlated with the location of a zone of high-velocity material within the Transition Zone at the base of the upper mantle (410-660 km depth), inferred to represent an accumulation of subducted slabs of oceanic lithosphere. Many of the major volcanic fields are located around the periphery of this velocity anomaly, coincident with the distribution of finger-like, slow velocity anomalies in the upper mantle, imaged by local seismic tomography experiments (e.g. Eifel, Massif Central). These anomalies have widely been considered to represent thermally anomalous "hotspots" or mantle plumes, some 100-150 ˚C hotter than the ambient upper mantle. However the absence of any evidence for a positive thermal anomaly at Transition Zone depths argues strongly against this. Indeed the Transition Zone is seismically fast – reflecting both the presence of high-velocity basaltic materials and, possibly, lower than ambient mantle temperatures.

An alternative explanation for these plume-like structures in the upper mantle is that they are the products of localised fluid streaming from the top of the Transition Zone. According to this model water is concentrated in the base of the upper mantle by subduction processes during the Africa-Eurasian collision and stored in high-pressure mineral phases. Periodic fluid release from the top of the Transition Zone (410 km), triggered by metamorphic break-down reactions, causes partial melting in the overlying mantle. Small degree partial melts of melilitic composition then rise towards the surface, causing further melting as they approach the base of the lithosphere. Localised extension within the lithosphere further enhances the degree of melting in some areas, producing the range of nephelinites, basanites and alkali basalts observed.