Global Na8-Fe8 Systematics of MORBs: Implications for Mantle Heterogeneity, Temperature, and Plumes

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In a global examination of Na8-Fe8-axial depth variations of mid-ocean ridge basalt (MORB) glass compositions from the Smithsonian database, we find that modeling of MORBs as the product of large variations in potential temperaure (Klein and Langmuir, 1987, JGR, 92, 8089) is not supported by Na8-Fe8-depth data for any ridge segment of any length. However, the observed inverse and positive Na8-Fe8 variations are in excellent agreement with the systematics of solidus melts in the plagioclase/spinel lherzolite transition in the CaO-MgO-Al_2O_3-SiO_2-Na_2O-FeO system at 0.93-1.5 GPa, and 1240-1260°C (Presnall *et al.*, 2002, GCA, 66, 2073). This system contains all the main mantle mineral phases in this pressure range (ol, opx, cpx, pl, sp) and 99% of both the extracted melts and the source. Thus, chemical systematics of melts at the solidus provide very strong constraints on the major-element chemistry of melting processes. On the surface that defines solidus melt compositions in the pl/sp lherzolite transition interval, contours of constant pressure are nearly parallel to contours of constant MgO, but are at a high angle to contours of Na_2O. An inverse Na8-Fe8 correlation occurs for melting at constant pressure. In contrast, positive Na8-Fe8 correlations occur when short diapirs progressively melt as they rise. Melts having the highest MgO/FeO are extracted last from the tops of these diapirs. In this modeling, we find that the southern Atlantic mantle from Bouvet to about 26°N is relatively homogeneous, whereas the Atlantic mantle north of about 26°N shows significant long-range heterogeneity. The mantle between the Charlie Gibbs and Jan Mayen fracture zones is strongly enriched in FeO/MgO, perhaps by a trapped fragment of basaltic crust in a Caledonian suture (Foulger *et al.*, 2005, Spec. Paper 388, 595). The strongly enhanced melt productivity at Iceland is explained as the product of this enrichment, not a hot plume. The East Pacific Rise and Galapagos Ridge sample mantle that is heterogeneous over short distances. The mantle beneath the northern part of the Indian Ocean is fairly homogeneous and is depleted in FeO/MgO relative to the mantle beneath the Red Sea. Our model replaces plumes and large variations in potential temperature with mantle heterogeneity and uniformly low temperatures of MORB generation.

Intraplate volcanism due to small-scale convection -a 3D numerical study

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Some volcanic chains in the south pacific show fast and unsteady age progressions towards the East Pacific Rise (300 mm/yr) inconsistent with the plume hypothesis. They have yet been attributed to plate processes (cracking due to extension [Sandwell et al. 1995] or thermal contraction [Sandwell and Fialko 2004]) and dynamic mantle processes (return flow [Conder et al. 2002] or small-scale convective instabilities [Buck and Parmentier 1986]). The latter is supported by recent gravity studies [Harmon et al. 2006]. In the Earth's uppermost mantle small-scale convection (SSC) is likely to develop due to instabilities of the thickened thermal boundary layer below mature oceanic lithosphere (usually 70 Ma).

They are characterized by convective rolls aligning with plate motion, whose onset is earlier for higher Rayleigh numbers (e.g. hot or wet mantle) and adjacent to lateral inhomogeneities, such as fracture zones or hotspot tracks. Beneath hence young (< 40 Ma) and thin lithosphere partial melt is potentially emerging in the upwellings of SSC. Melting changes particularly the compositional buoyancy by melt retention and additional depletion of the residue, and therefore promotes upwelling and allows for further melting (buoyant decompression melting (BDM) [Raddick et al. 2002]). These processes allow only for a few percent of partial melting. Here we present results of a fully thermo-chemical 3D-numerical mantle flow study on the interaction of SSC and BDM with a realistic, temperature-dependent rheology. We explore depth, duration, degree and amount of melting and melt extraction of the BDM, and study the 3D-geometry of SSC and melting. We vary parameters such as mantle temperature, plate speed, thermal and compositional Rayleigh numbers and melt extraction scheme. We compare patterns of SSC and melting with purely thermal cases. This study reveals, that 3D-patterns (and onset) of melting due to SSC are mainly controlled by thermal buoyancies. They are slightly modified by compositional buoyancies, latent heat of melt and melt extraction scheme. Moreover, we put constraints on the SSC hypothesis for intraplate volcanism. Positive thermal anomalies (> 100 K) would be required to trigger off-ridge melting in a static mantle (no SSC). However, we find, that a few percent of partial melt are emerging due to SSC for low mantle viscosities ($5x10^{18}$ Pas)

and ambient temperatures. We postulate small lateral thermal or compositional anomalies to obtain early onset of SSC locally yielding the observed patterns of volcanism (i.e. chains).

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Testing the volcanic record for evidence of broad hotspot melting anomalies

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The notion of a mantle plume has long been that of a mushroom-like 'head' and thin 'tail' structure rising from a deep thermal boundary layer, generally depicted as the core-mantle boundary. Drifting of tectonic plates over the narrow, presumably fixed, hotspots created by such plume 'tails' has long provided an elegant explanation for time-progressive lines of islands, seamounts and ridges. But a major problem cited for this 'standard' plume model is a lack of evidence in the volcanic record for head-andtail upwellings.

However, recent thermo-chemical numerical modeling is exploring scenarios where upwelling structures are more irregular in shape and behaviour compared to a classic thermal plume 'head-tail' (Farnetani and Samuel, 2006). Furthermore, possible entrainment of a deep chemical boundary can vary greatly with strongly temperature-dependent viscosity from nearly stagnant large plumes in the lower mantle to fast episodic pulsations travelling up the pre-existing plume conduit (Lin and van Keken, 2005, 2006). Thus, the classic 'head-tail' may not be the only possible upwelling structure.

New age data show that the Galapagos Volcanic Province developed via the progression of broad regions of concurrent dispersed volcanism that we link to a correspondingly broad mantle melting anomaly (O'Connor et al., submitted, 2007). Thus, evidence from direct dating of the oceanic hotspot record is also suggesting that hotspot melting anomalies might be much broader than commonly inferred from the 'headtail' plume model and the dimensions of individual seamount chains and aseismic ridges.

New strategies are therefore needed for investigating the hotspot volcanic record in order to better test the plume hypothesis. To this end we have recently sampled multiple seamount chains and ridges scattered across a broad region of the southern South Atlantic. Our focus is on investigating multiple hotspot chains stretching across a very broad region of the South Atlantic seafloor as a potentially useful way of testing 1) the new thinking that plume upwellings may differ from the classic ‘head-tail’ structure and 2) our evolving hypothesis that hotspot melting anomalies are much broader than suggested by regions of active volcanism marking the young ends of individual hotspot trails.

Formation of the North Atlantic Igneous Province: what is the role of the Iceland mantle anomaly?

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Several studies have recently challenged the arrival of the Iceland mantle plume around breakup time as an explanation for North Atlantic Igneous Province formation, as some unexplained aspects remain. Alternative processes have been suggested for the wide-spread and excessive magmatism, including delamination, small-scale or edge driven convection, and chemical mantle heterogeneities. We review available datasets and compare them with predictions from the mantle plume and alternative models.

We find that none of the existing models provides a complete explanation of all aspects of North Atlantic breakup-related magmatism at this point. Additional most of the observed geochemical variations are ambiguous and can either be explained to reflect intrinsic variations of deep-mantle sources (mantle plume) or contaminations from the non-convective mantle and/or continental crust. Even the strongest radiogeninc isotopic mantle plume “fingerprint”, high He ratios, is currently being challenged, as a prove of a deep mantle source.

Based on this modelling (numerical and analogue), geophysical and geochemical available datasets we suggest a new model for the formation of the North Atlantic Igneous Province. In this model, dynamic processes related to rifting that are predicted now by many models play a dominant role in the model for volcanic margin formation. Small-scale convection can enhance melt production during rifting and may be responsible for widespread uplift, also post-break-up. We suggest that the onset of magmatism along the NAIP is first only due to dynamic rift processes which may have triggered the later phase. In the second phase of the hybrid model, which is not related to the continental break-up. The Icelandic mantle anomaly dominates the NAIP formation.

R.M. supported by BFR05/133 (Luxembourg)

Global kinematics in the deep vs shallow hotspot reference frames

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Plume tracks at the Earth's surface probably have various origins such as wet spots, simple rifts and shear heating. Since plate boundaries move relative to one another and relative to the mantle, plumes located on or close to them cannot be considered as reliable for a reference frame. Using only relatively fixed intraplate Pacific hotspots, plate motions in two different absolute reference frames, one fed from below the asthenosphere, and one fed by the asthenosphere itself, provide different kinematic results, stimulating opposite dynamic speculations. Plates move faster relative to the mantle if the source of hotspots is taken to be the middle-upper asthenosphere because hotspot tracks would not then record the entire decoupling occurring in the low velocity zone. A shallow intra-asthenospheric origin for hotspots would raise the Pacific deep-fed velocity from a value of 10 cm yr_^{1} to a faster hypothetical velocity of about 20 cmyr_^{1}. In this setting, the net rotation of the lithosphere relative to the mesosphere would increase from a value of 0.4359 _ Ma_^{1} (deep-fed hotspots) to 1.4901 _ Ma_^{1} (shallow-fed hotspots). In this framework, all plates move westward along an undulated sinusoidal stream, and plate rotation poles are largely located in a restricted area at a mean latitude of 58_S. This reference frame seems more consistent with the persistent geological asymmetry that suggests a global tuning of plate motions related to Earth's rotation. Another significant result is that along E-or NE-directed subduction zones, slabs move relative to the mantle in the direction opposed to the subduction, casting doubts on slab pull as the first order driving mechanism of plate dynamics.

Successful and failing plumes: the Icelandic case

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Reconstructions suggest that the Icelandic melting anomaly has been active for at least 100 Myr. However its characteristics are not constant in time. Volcanic episodes with moderate temperature from Ellesmere Island to Greenland predate the major episode of mafic magma emplacement containing picrite (˜60Ma), while present Iceland shows again a moderate temperature anomaly. These observations cannot be explained by the classical model of mushroom-shaped plume out of a localized heat. We have systematically studied the more realistic case of thermochemical convective instabilities (TCIs) developing in a heterogeneous mantle. Fluid mechanics results show that: (1) TCIs of large extent (˜1000km) are expected to develop from the bottom of the mantle with a characteristic spacing of 3000-4000km. (2) They should be hotter than purely thermal convective instabilities since their temperature-derived density anomaly must be sufficient to counterbalance the stabilizing chemical density anomaly. (3) Upon reaching the 660km transition zone, a hot TCI could pond long enough to generate moderately hot (˜100C) thermal plumes in the upper mantle. (4) The TCI could eventually cross the 660 interface and reach the surface, producing hot traps (˜300C) on a wide area. (5) The TCI material would also cool down, until its thermal buoyancy is not sufficient to counterbalance its compositional anomaly, and sink back into the mantle. But, since this "failing plume" is still hotter than the ambient mantle, it will generate moderately hot thermal plumes. (6) The thermal plumes sample primarily the bulk (or upper) mantle and entrain only thin filaments of the TCI material. This sequence could explain the Icelandic observations, namely the hot traps as well as the mild temperature anomalies pre-and post-traps, the upper mantle component in the present-day Iceland lavas as well as its rare gas anomaly, and the apparent disconnection between slow seismic anomalies in the upper and lower mantle. More generally, this study shows that a) all slow seismic anomalies are not upwellings, b) convective features in the mantle are strongly time-dependent, and c) we need to include time in the models.

Geology and Geophysics of the Bermuda Volcanic Edifice and Bermuda Rise: Synthesis and Current Research

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Deep-sea drilling of ocean floor during DSDP Leg 43 and on Bermuda itself, together with geophysical data (anomalies in basement depth, geoid and possibly heat flow) and modeling, suggest that volcanism and uplift forming the Bermuda Rise and four volcanoes began during the early to middle part of the Midde Eocene (47-40 Ma). Some authors also attribute 65 Ma igneous activity in Mississippi and 115 Ma activity in Kansas to a "Bermuda hotspot" or plume fixed in the mantle below a moving North America plate. However, such a hotspot/plume would have had tomanifest itself episodically, turning off for up to 25 million years at a time, and/or be heavily influenced by lithospheric structure. Moreover, Cretaceous igneous activity in Texas and Eocene intrusions in Virginia then require separate mantle "blobs".

Bathymetric and magnetic data show the elongation of both the Bermuda volcanoes and Rise along crustal isochrons, and the Bermuda Rise is located mostly within a belt of rougher, thinner crust and seismically "slower" upper mantle—implying possible retention of gabbroic melts at the ancient MAR axis and suggesting the involvement of mantle lithosphere. The Bermuda Rise is also seismically more active than the surrounding crust, possibly reflecting weaker upper mantle. These observations are consistent with numerical models, constrained by available geophysical data, which attribute the Bermuda Rise to some combination of lithospheric re-heating and dynamic uplift. While the relative contributions of these processes remain unknown, three features of the Bermuda Rise and volcanic edifices clearly distinguish them from archetype seamount chains such as Hawaii: 1) the Bermuda edifices and Rise are elongated at right angles to the direction of plate motion; 2) there has been little or no subsidence of the Rise and volcanic edifice since its formation—in fact, it appears that Rise uplift continued from the late Middle Eocene into the Miocene; and 3) the small volume of magma, estimated from the size of the volcanic edifices, is inconsistent with the effects of a long-lived mantle plume. However, geochemical studies of over 1000 units of lava flows and intrusive rocks recovered from the Dalhousie University Deep Drill 1972 indicate the presence of a wide compositional gap between shield-building tholeiitic lava flows and strongly undersaturated melilite nephelinites intruded as dykes, similar to what is observed on some "hotspot"-generated seamounts and islands, e.g. Hawaii.

We infer that the Bermuda Rise and other Atlantic mid-plate rises are supported by anomalous asthenosphere, upwelling or not, that penetrates the thermal boundary layer and travels with the overlying North America plate. New CO2 laser ^{40}Ar-^{39}Ar age data for lava flows and intrusive units recovered from the 1972 borehole provide a test of this hypothesis. We speculate that the "Bermuda event" is linked to a global plate kinematic reorganization, triggered by the closing of the Tethys and the associated gravitational collapse into the lower mantle of subducted slabs which had been temporarily stagnant near the 660 km mantle discontinuity. The widespread onset of sinking slabs required simultaneous upwelling for mass balance. The global plate reorganization was accompanied by increased stress in some plate interiors, favoring magma ascent along pre-existing fractures. This model implies that the Bermuda event and concomitant igneous activity in e.g., Virginia, West Antarctica, and Africa were among such upwellings, but structurally influenced by the lithosphere.

Future geophysical surveys and drilling of a transect of boreholes across and along the Bermuda Rise— elucidating turbidite offlap during rise formation— might discriminate between a widely distributed mantle source and a narrow plume whose head (or melt root) spreads out radially over time, generating an upward and outward expanding swell.

Long term stability in Deep Mantle structure: Evidence from the ~ 300 Ma Skagerrak-Centered Large Igneous Province (the SCLIP)

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Igneous rocks of intra-continental rifts are generated by decompression melting in response to extension but magmas generated by deep-seated mantle plumes may also find their way into intra-continental rifts by 'upside down drainage'. Consequently it can be hard to be confident that a particular set of igneous rocks in a rift is plume related. Uncertainty of this kind has long plagued research on the Oslo graben in SE Norway. We have addressed that problem within the broader framework of Permo-Carboniferous magmatism and rifting in NW Europe, and show on the basis of (i) huge volume ($>0.5 * 10^6$ km^3), (ii) large areal extent and (iii) brevity of eruption interval (± 4 My), that the flare-up of igneous activity at 297 Ma in NW Europe which generated a Skagerrak-Centered Large Igneous Province (SCLIP) is the product of a deep-seated mantle plume: the Skagerrak Mantle plume. We confirm our location for the Skagerrak plume and show its derivation from the core-mantle-boundary (CMB) by restoring it, using a new reference frame, to its ~ 300 Ma position. That position (ca. 11°N, 16°E, south of Lake Chad, Central Africa) lies vertically above the edge of the African Large Low Velocity Province (LLVP). We have previously shown that eruption locations vertically above the edge of one or other of the Earth's two LLVPs at the CMB characterize nearly all the LIPs erupted since 200 Ma. Recognition of the SCLIP plume source enables us to show that the edge of the African LLVP at the CMB has not moved significantly with respect to the spin axis of the Earth during the past 300 My which is a 30% longer duration for the stability of a deep mantle structure than we have previously been able to demonstrate.

Mantle plumes and the Pacific superswell

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We present a model based on mantle plumes that could explain many of the anomalous features of the superswell region. First, long-time subduction around the rim of the Pacific would drive flow in D" toward the center of the 'rim of fire'. This continuous supply of D" would promote the concentration of plumes into the superswell region (and also on the other side of the earth in the African superplume region). This is independent of migration of the subduction zones as the Pacific closes in pace with the opening of the Atlantic and Indian oceans. Second, longterm outward conduction of heat from the plume pipes would heat the mantle between the pipes (it would heat outward˜100 km in 100 m.y.;˜200 km in 400 m.y.). This heating of the ’background’ mantle up to plume temperatures would change the geotherm of the superswell region compared to ’normal’ regions -this hotter geotherm could disturb the equilibrium of the 660-400 km region of the mantle from its normal pattern. This would lead to many short-term instabilities, which could provide an explanation for the many short-lived features of this region.

Experimental constraints on the origin of OIBs

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The trace-element and isotopic ratios of mafic alkaline magmas (e.g., basanites and alkali basalts) from oceanic islands and continental alkaline massifs are often explained by the presence of subducted/recycled oceanic crust in their sources. Alternatively, these ratios could reflect oceanic or continental lithosphere-bearing sources into which amphibole- and/or pyroxene-rich metasomatic veins have been emplaced. The major-element compositions of alkaline magmas provide important tests of these hypotheses and constraints on possible source compositions and their petrologic evolution. To date, high-pressure melting experiments on peridotites, eclogites, and peridotite/eclogite mixtures have not fully reproduced the major-and trace-element compositions of basanites and the spectrum of composition from basanite to alkali basalt observed in alkaline massifs worldwide.

Here we present the results of high-pressure melting experiments (1.5 GPa, 11501350˚C) on natural hornblendite and clinopyroxene hornblendite lithologies that occur as metasomatic veins in the French Pyrenees. All experiments were run in Pt+graphite capsules. The compositions of low-degree melts in experiments on both lithologies are controlled by kaersutite breakdown and the quenched glasses are strongly *ne*-normative (*Ne*+*Le*>18 wt%) and silica-poor (SiO_2 <42 wt%). K_2O/Na_2O, Al_2O_3/TiO_2, and CaO/Al_2O_3 ratios in the experimental partial melts do not vary significantly from 1165 to 1275˚C and are similar to silica-poor basanites that occur on oceanic islands and in continental alkaline massifs. Moreover, the incompatible trace-element patterns of the quenched glasses overlap those of silica-poor OIBs. These trace-element patterns reflect primarily the enriched trace-element patterns of the hydrous veins used as starting materials; this enriched character is a universally observed feature of such hydrous veins.

A second set of experiments was done using a layer of hornblendite sandwiched between layers of moderately depleted peridotite at 1.5 GPa and 1225-1325˚C in order to simulate interaction between melting hornblendite and adjacent mantle. At the same temperature, the SiO2 contents of partial melts produced in the sandwich runs are up to 4-5 wt% higher than liquids from the hornblendite-only and clinopyrenehonblendite-only experiments (although some are still *ne* normative). This difference reflects the dissolution of orthopyroxene in the peridotite layers in the sandwich runs. For both major and trace elements, the compositional trends from glasses from the hornblendite-only and clinopyroxene-hornblendite-only melting experiments to glasses from the sandwich experiments are similar to trends observed in natural basanite alkali basalt suites.

Our results show that partial melting of metasomatized lithosphere (i.e,. peridotite + amphibole-bearing veins) could generate liquids similar to alkaline lavas in continental settings and that recycling (e.g., via subduction or/and delamination) and partial melting of such veined lithosphere could likewise contribute to the compositional characteristics of oceanic alkaline lavas. The same source types could also explain compositional trends from basanite to alkali basalt observed in both oceanic island and continental massif settings provided that reaction occurs between basanitic liquids and the surrounding peridotite (most likely during the melting process, but perhaps during transport to the surface). Furthermore, the isotopic characteristics of alkaline HIMU and EM-type OIBs are consistent with models of amphibole-bearing vein formation and resultant element fractionations [1]. Our results are thus consistent with the hypothesis that alkaline OIBs are dominantly produced by large degrees of melting of small volumes of trace-element-rich and volatile-rich material (e.g., originally metasomatic veins) present within the upper mantle rather than less enriched but volumetrically more abundant recycled oceanic crust. We conclude that partial melting of amphibole-bearing veins in metasomatized lithosphere can account for the major-element, trace–element, and isotopic compositions of alkaline OIBs and should be considered a testable alternative to more widely accepted models of their formation that invoke recycling of oceanic crust sediments.

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[1] Pilet et al. (2005) EPSL 236, 148-166

The seismic low velocity of Iceland's mantle. The shape of a thermal and melt anomaly

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The most dramatic landscape in the seismic velocity structure is in the top 200 km under Iceland. Analysis of near distance and regional surface waves (Love and Rayleigh in the ICEMELT dataset) in the period range 5-100 s, makes it possible to define variation in absolute velocity and anisotropy with fine vertical details in 6 different 1-D models distributed laterally over 500 km distance. There is a large asymmetry in the thickness of the lithosphere across the ridge system. Under similar aged surface geology (10-15 Ma) a 60 km thick lithosphere is under northwest Iceland and at least 100 km thick under east Iceland. Hypothesis of a buried continental fragment under east Iceland have been proposed. More likely explanation is an un-conformal upbuild of thick crust (30-35 km) on top of 30-40 Ma old oceanic lithosphere, due to repeated rift jumps to the east. Another factor in the east-west lithosphere asymmetry, though not quantified, is the predominant west and northwest mantle flow in the asthenosphere inferred from anisotropy, thus supplying greater transport of heat under the American plate. However, not all aspect of the anisotropy structure fits a preconceived plume model: So far there is no convincing evidence of a large scale vertical mantle flow in the top 200 km. A major characteristic is a low shear velocity in the shallow asthenosphere under central Iceland and the rift zones. The absolute SV velocity in the depth range 30-120 km is 8.2% lower on average than the PREM model, with 200 km diameter. Kreutzmann et al. (2004) have with geodynamical methods modeled the Iceland seismic plume signature (LVZ) as a combination of thermal and melt anomaly. Bjarnason and Schmeling (2007) continue to model Iceland's LVZ as a combination of thermal and melt anomaly, although with higher partial melt 3% in the shallowest asthenosphere at 30 km depth, while Kreutzmann et al. (2004) modeled 1% overall partial melt in the depth range 30-120 km. Whether this means that the plume exists is a matter for a lively debate with red wine in hand or from the podium.

Several plume 'paradoxes' can be resolved by a plume-fed asthenosphere

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Both Fitton's 'OIB paradox' and Anderson's 'Helium-paradoxes' have simple resolutions if the Mid-Ocean Ridge Basalt (MORB) source is in fact plume-fed asthenosphere. Fitton's Ocean Island Basalt (OIB) paradox can be restated as the observation that typically EMORB (Enriched-MORB) have OIB (e.g. plumelike) chemical fingerprints, often without an obvious nearby plume source. This 'paradox' can be resolved if the OIB fingerprints are due to preferential melting of lower-solidus components that are typically present as lithologic layers in all mantle upwelling in plumes and whose incompatible elements are typically extracted by deep plume melting. If the the asthenosphere is plume-fed, those lower-solidus components that survive plume upwelling without melting to form OIB (for example, by upwelling in the cooler rim of a plume) can then migrate horizontally to ascend beneath a mid-ocean ridge, where they melt to produce E-MORB flavors as discussed in Phipps Morgan and Morgan (1999).

Compilations of the ratios of rare gas abundances in OIB and MORB show complementary ratios of helium relative to the heavier noble gases -ratios in OIB of He/Ne, He/Ar, He/Kr, and He/Xe are consistently lower than ratios in MORB which has a relative surplus of helium. This is evident in observations of 3He/22Ne (both stable, primordial isotopes) and 4He/21Ne (both produced by the decay of U and Th) and also 3He/36Ar (stable) and 4He/40Ar (radiogenic). This evidence conflicts with mantle evolution models that invoke isolated, distinct, long-lived reservoirs as the sources of OIB and MORB but not with our proposed model. A mechanism to preferentially retain helium in residues of OIB melt-extraction (which later melts to produce MORB) is as follows. The mantle has He-rich components that at both extremes of the mantle He-isotope spectrum (Highest 4He/3He in incompatible-element-rich lumps; Lowest 4He/3He in He-poor depleted residues of previous cycles *an*d He-rich streaks of the most 'primordial' mantle) and mantle components are typically layered at a fine-enough (< 1 km) scale where He-diffusion between components can be an important transport mechanism over Ga mantle residence times. Helium diffuses orders of magnitude faster than the heavier noble gases. During mantle stirring and plume ascent helium (both 3He and 4He) partially diffuse from the 'lumps' of primordial or highly enriched material (high in U and Th among other LIL's) into the more refractory material surrounding these lumps whereas the heavier noble gases do not. When the easier-to-melt lumps melt to make OIB, their gases have a deficiency of helium because this has diffused out. During more extensive melting at mid-ocean ridges, some refractory material into which helium but not heavier gases of the enriched-low solidus lumps had diffused melt to produce an excess of helium in MORB. Furthermore, correlations between helium and other radiogenic isotopes at Iceland and the Galapagos imply that the mantle upwelling and melting at plumes is more incompatible element-rich and 4He/3He-low than the typical asthenospheric leftovers to plume melt-extraction when they melt a second time beneath a mid-ocean ridge.

Possible Proof for genetic Link between the mafic Ferrar LIP and the silicic Antarctic Peninsula Volcanic Group identified in the Transantarctic Mountains

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The Mid-Jurassic Ferrar Large Igneous Province (LIP) extends along the cratonic margin of East Antarctica. The effusive section is underlain by fluvial and lacustrine sediments, known as Beacon Group throughout the Transantarctic Mountains, which itself covers crystalline basement. In Northern Victoria Land, Antarctica, the sediment succession consists of (1) a lower formation of approximately 250m thickness, dominated by medium to coarse grained, trough cross-bedded quartz sandstones (known as Section Peak Formation, SPF) grading into (2) an upper, about 50m thick newly defined formation of ripple cross-laminated, fine grained sandstones to siltstones consisting almost exclusively of a reworked, well sorted, rhyolitic, distal fall-out assemblage of shards, angular quartz, and feldspar (informally called Shafer Peak Formation, SHF). The biostratigraphic ages given by a *Dicroidium*-flora in the SPF, and a flora dominanted by cycadophytes and dipterid ferns (lacking *Dicroidium*) in the SHF, can preliminarily be deduced as Rhätoliassic (most likely Late Triassic) and Lower Jurassic, respectively. On lithological grounds we propose that the SHF can be correlated stratigraphically with the Hanson Formation in the Beardmore Glacier Region, Central Transantarctic Mountains.

The succession of both formations, SPF and SHF, is intruded by sills that are several 10m to a few hundred meters in thickness and of andesitic Low-Ti Ferrar magma type composition. While the quartz sandstones of the SPF behaved brittle during sill intrusion, the younger tuffaceous sandstones (SHF) exhibit soft sediment deformation, fluidization and peperite formation, indicating that the sills intruded these rhyolitic ashes in still unconsolidated wet conditions. The sills must thus be considered to be coeval with the SHF.

The formation of SHF-type distal fall-out ashes can be traced for over 1000 km without major differences in grain size, from Northern Victoria Land to the Beardmore Glacier Region, Central Transantarctic Mountains. This excludes a proximal origin for the rhyolitic ashes and favors a generation by distal large volume (ultraplinian), caldera-type eruptions. The closest exposed rhyolitic volcanic province of Lower Jurassic age is the Mt. Poster Formation (MPF), Ellsworth Mountain Volcanic Group, in the southern Antarctic Peninsula, today 3000 km away from Northern Victoria Land. A reduction by only 400km is given if the Cenozoic spreading between E-and W-Antarctica is considered.

Whole rock geochemical analyses indicate comparable chemical compositions with respect to incompatible immobile elements for the S-type rhyolitic low-Ti ignimbrites of the MPF and the reworked ashes of the SHF. This could imply a common origin. As would be expected, the distal fall out ashes are Si-enriched compared to tephra closer to the eruption center. The apparently coeval emplacement of rhyolitic SHF/MPF magmas and the first shallow intrusive phase of mafic Ferrar LIP magmatism may indicate a possible genetic link between both. The genesis of the S-type crustal melts being generated in a back-arc environment by underplating of large volumes of Ferrar LIP magmas uprising from the enriched subcontinental lithospheric mantle along the cratonic margin of E-Antarctica will be discussed.

Complexities of the Upper-Lower Mantle Transition Zone Beneath Hotspots

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Hotspots observed at the Earth's surface are frequently associated with hot thermal plumes within the earth. Over the past few years, improved seismic imaging techniques such as high-resolution tomography and migration have significantly increased the constraints on the existence and dimensions of thermal anomalies beneath hotspots. Still, questions remain regarding the depth extension of hotspots, for example, whether they are continuous across the upper-lower mantle transition zone (350 –1000 km) in the presence of two major mineral phase changes.

In this study we introduce a novel approach to analyze underside reflected waves and determine the shear velocity structure within and below the transition zone at major hotspot locations. Rather than relying on traditional time-domain travel time and amplitude information, we apply Least-squares Radon Transform that simultaneously recovers time shifts and ray parameters. While the time shifts of SdS waves (d for a discontinuity) are sensitive to discontinuity depths, ray parameters directly reflect the seismic structure beneath the discontinuity. We observe a negative relationship between the perturbations of ray parameter and shear velocity within and below the transition zone. The ray parameters are generally greater than their respective reference values, and hence suggest the presence of low-velocity anomalies; the depressed 410-km discontinuity is further evidence for such thermal variations. The topography of the 660-km discontinuity reflects both olivine and majorite-garnet phase transitions, and is therefore much more difficult to interpret. Furthermore, the presence of major thermal perturbations is not evident from global tomographic models, nor is it reflected in the differential times of SdS waves beneath the hotspot locations. Even in the absence of compositional variations, accurate identification of a mantle plume beneath a hotspot is a challenge task that requires the knowledge of ray parameter/velocity, topography of the 410-km discontinuity, as well as the presence/absence of mid-mantle reflectors.

A review of carbonatitic magmatism in the Paran‡-Angola-Etendeka system

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Early and Late Cretaceous carbonatitic complexes from southern Brazil occur along the main tectonic lineaments of the South America platform. A similar situation is recognized for the Angolan and Namibian occurrences in Africa. In general, the alkaline-carbonatite complexes show intrusive/subintrusive, subcircular or oval shaped structures and are indicative of high upwelling energy. However, lava flows, single dykes and dyke networks may be also found. Processes of liquid immiscibility from trachytic-phonolitic liquids, starting from parental alkaline mafic magmas are believed to have generated carbonatitic liquids, as suggested by field relationships and geochemical characteristics. Ca-, Mg-and Fe-carbonatites are widespread even in the same complex. The remarkable scatters of the incompatible elements is mainly due to 1) the control of accessory phases, e.g. apatite, pyrochlore, fluorcarbonates and fluorite, and 2) the repeated overprinting of hydrothermal over magmatic processes.

Geochemical characteristics have been systematically determined for carbonatite samples from selected outcrops in Paraguay, Brazil, Angola and Namibia (Eastern Paraguay: Rio Apa, Amambay, Sapucai; Southern Brazil: Alto Paranaíba, i.e. Catal„o, Salitre, Tapira, etc.; Ponta Grossa Arch, i.e. Barra do Itapirapu„, Jacupiranga, Juqui·, Mato Preto, etc.; Lages and Anitpolis; Angola: Bailundo, Langonjo, Lupungola„

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Sulima and Tchivira-Bonga; Namibia: Dicker Willem, Kalkfeld, Ondurakorume, Okurusu, Osongombo and Otjisazu). The occurrences comprise three main chronogroups,

i.e. 1) Early Cretaceous (Eastern Paraguay; Brazil, Ponta Grossa Arch and Anitpolis;

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Angola and Namibia); 2) Late Cretaceous (Brazil, Ponta Grossa Arch, Lages and Alto Paranaíba; Namibia); 3) Paleogene, Brazil and Namibia . Two principal types of associated alkaline rocks are represented, i.e. plagioleucitites l.s. (Eastern Paraguay; Brazil: Ponta Grossa Arch; Angola and Namibia) and kamafugites l.s. (Brazil: Alto Paranaíba and Lages; Namibia).

Significant variations in O-C isotope compositions are found in primary carbonates, the variations being mainly due to isotope exchange between carbonates and H2OCO2-rich fluids, whereas magmatic processes, i.e. fractional crystallization or liquid immiscibility, probably affect the (18O and (13C values by not more than 2â. The isotope exchange model implies that the most significant isotopic variations took place in a hydrothermal environment, e.g. in the range 400-80∞C, involving fluids with CO2/H2O ratio ranging from 0.8 to 1. Two main paths of (18O-(13C fractionation are originated by subvolcanic and surface conditions, respectively. Weathering and groundwater fluids, therefore, appear to be important, as well as meteoric water, which yielded samples strongly enriched in light carbon owing to contamination by a biogenic component. The behaviour of trace elements (e.g. Sr and REE) is consistent with the above conclusions.

Sr-Nd-Pb systematics highlight heterogeneous mixtures between HIMU and EMI mantle components, likewise to the associate alkaline rocks and the flood tholeiites of the Paraná-Angola-Namibia Province. This is also consistent with Re-Os systematics on selected mafic samples from the Alto Paranaíba alkaline-carbonatite province.

The data relative to the noble gases suggest that the source(s) are similar to other mantle derived magmas (e.g. HIMU and MORB) and that the carbon of carbonatites is unlikely to be subduction-related carbon, and support a C-O fractionation model starting from mantle-derived sources.

The bulk of the geochemical data shows that mostly of the occurrences contain an enriched isotopic signature. In general, Sr-Nd-Pb-Os isotopes and trace elements data from potassic rocks suggest that the associated carbonatites and primary carbonates reflect the composition of the source mantle. In particular, the combined O-Sr systematics and Sr-Nd-Pb-Os isotopic data indicate that the carbonatite system is dominated by mantle component(s) without appreciable crustal contamination. Thus, in spite of the great variation shown by C-O isotopes, Sr-Nd-Pb-Os isotopic systematics could be related to an isotopically enriched source where the chemical heterogeneities reflect a depleted mantle "metasomatized" by small-volume melts and fluids rich in incompatible elements. These fluids are expected to have promoted crystallization in the mantle of K-rich phases that gave rise to a veined network variously enriched in LILE and LREE. The newly formed veins (enriched component) and peridotite matrix (depleted component) underwent a different isotopic evolution with time as reflected by the carbonatitic rocks.

These conclusions may be extended to the whole Paraná-Angola-Etendeka system, where isotopically distinct parent magmas were generated following two main enrichment events of the subcontinental lithospheric mantle at 2.0-1.4 and 1.0-0.5 Ga, respectively, as also supported by Re-Os systematics. The mantle sources preserved the isotopic heterogeneities over a long time, suggesting a non-convective lithospheric mantle beneath different cratons or intercratonic regions. The area distribution shows that the time-integrated isotopic enrichment of the carbonatites and associated alkaline rocks decreases from West (Eastern Paraguay) to East (Angola and Namibia), and it is related to age decrease of the alkaline magmatism, i.e. from Early Cretaceous to Paleogene.

Overall the data indicate that the alkaline-carbonatitic magmatism originated from a significant but small scale heterogeneous subcontinental mantle. In this scenario, the Tristan da Cunha, Walvis Ridge-Rio Grande Rise and Victória-Trindade hotspot tracks might reflect the accomodation of stresses in the lithosphere during rifting, rather than continuous magmatic activity induced by mantle plumes beneath the moving lithosphere.

Notably, these conclusions are consistents also with the tholeiitic magmatism from the South American Platform (SAP), where all the data indicate that mantle source heterogeneity was well establiished at leat since Late Archean times, as documented by the Precambrian and Mesozoic SAP tholeiites which have similar compoxsitional featutres, particularly the tholeiites cropping out on the same craton. The concentration of the Precambrian and Mesozoic SAP tholeiitic magmatism towards cratonic/mobile belt boundaries suggests that an important role in its genesesis was played by upper mantle "edge drive convection" geodynamics. In particular, it is notable that the mantle "netasomatic' processes might be related to ancient subduction-related processes (e;g; Trajsamazonian and Brasiliano events).

The "Plate" model for the genesis of melting anomalies

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The Plate Tectonic Processes, or "Plate" model for the genesis of melting anomalies ("hot spots") attributes them to shallow-sourced phenomena related to plate tectonics. It postulates that volcanism occurs where the lithosphere is in extension, and that the volume of melt produced is related primarily to the fertility of the source material tapped. This model is supported in general by the observation that most present-day "hot spots" erupt either on or near spreading ridges or in continental rift zones and intraplate regions observed or predicted to be extending. Ocean-island-basaltlike geochemistry is evidence for source fertility at productive melting anomalies. The melting anomalies that have been classified as "hot spots" and "hot spot tracks" exhibit extreme variability. This suggests that a "one size fits all" model to explain them, such as the classical Plume model, is inappropriate, and that local context is important. Associated vertical motion may comprise precursory-, contemporaneous-or post-emplacement uplift or subsidence. The total volume erupted ranges from trivial in the case of minor seamount chains to ~10^8 km^3 for the proposed composite Ontong Java–Manihiki–Hikurangi Plateau. Time progressions along chains ranges from extremely regular to absent. Several avenues of testing of the hypothesis are underway and are stimulating an unprecedented and healthy degree of critical debate regarding the results. Determining seismologically the physical conditions beneath melting anomalies are challenging because of problems of resolution and interpretation of velocity anomalies in terms of medium properties. Petrological approaches to determining source temperature and composition are controversial and still under development. Modeling the heat budget at large igneous provinces requires knowledge of the volume and time-scale of emplacement, which are often unclear. Although ocean-islandbasalt-type geochemistry is generally agreed to be derived from recycled near-surface materials, the specifics are not yet agreed. The subject is currently at an ongoing stage of development, and poses a rich array of crucial but challenging questions that need to be addressed.

Regional stresses before, during and following Large Igneous Province magmatism

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The actual stress field acting before, during and after Large Igneous Province (LIP) magmatism has never been thoroughly investigated from a large combination of fault field data. Evaluating stress orientation from seismic reflection surveys showing offshore deformed sediments or/and lavas is subject to major uncertainties. Dyke swarms considered as sets of mode-I fractures only provide information on the orientation of the minimum and maximum horizontal stresses active during their emplacement ; no information is given on the stress regimes and stress fields predating and postdating dyke emplacement. However, considering the inherent fractal organization of fractures in the crust, it is possible to infer the whole stress evolution of a LIP at a regional scale from a statistical study of local stress tensors inverted from populations of small-scale faults. This work is partly achieved at the scale of the North-Atlantic Province including data from W-and E-Greenland, Scotland, Ireland, Faeroe Islands and Iceland. We thus characterise a major transient stress field instability at the scale of the LIP during the main magmatic activity of the Early Cenozoic. We discuss the origin of the stress fields and their time/space evolution in light of the different theories for LIP generation (mantle plumes, lithosphere delamination, etc.).

Crustal Assimilation versus Mantle Melts in Lavas from Banks Peninsula, NZ

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Intraplate volcanism was active continuously throughout the Cenozoic on the South Island of New Zealand producing two volcanic end members: 1) widely dispersed volcanic fields and 2) shield volcanoes. The Banks Peninsula represents the latter consisting of 2500 km^2 lavas erupted at two composite shield volcanoes – the older Lyttelton and the younger Akaroa volcano. Volcanic activity on Banks Peninsula persists 6 Ma and can be divided into four different phases. The first eruption of the Lyttelton volcano took place 12 Ma ago. Volcanic activity at the Lyttelton volcano proceeds until 10 Ma ago. Afterwards the center of volcanism shifts towards the SE by erupting the lavas of the Mount Herbert volcanic group, which gave two ^{40}Ar/^{39}Ar ages of 9.1 and 8.3 Ma. These ages overlap with volcanic activity at the Akaroa volcano 8.8 Ma ago, which was preceded by another shift of the main volcanic activity to the SE. The Diamond Harbour Volcanic Group occurring mainly at the outer flanks of the Lyttelton Volcano represents late stage volcanism (7.6 – 6.8 Ma). Mafic volcanic rocks sampled (MgO > 4 wt%) range from basanites trough alkali basalts to tholeiites and can be divided by their silica content into a low silica group having SiO2 < 48.5 wt% and a high silica group with SiO2 concentration > 48.5 wt%. Trace element pattern of the volcanic rocks analyzed are akin to those of ocean islands basalts. Volcanic rocks of the low silica group show more pronounced peaks in Nb and Ta and troughs for Pb and K on a multi-element diagram, which becomes less pronounced in the high silica group. This is accompanied by increased ratios of fluid to less fluid mobile elements (e.g. Pb/Ce, U/Nb, Ba/La etc.) and lower concentrations of incompatible elements, like Rb, Ba, Nb, La etc. in the high silica group compared to the low silica group. Isotope ratios measured on mafic volcanic rocks are enriched with the low silica group having higher ^{206}Pb/^{204}Pb, ^{143}Nd/^{144}Nd and ^{176}Hf/^{177}Hf ratios and lower ^{87}Sr/^{86}Sr, _ 7/4 and ∂^{18}O values reflecting a HIMU-type source and a EMII-type source for the high silica group. Therefore, there are apparently two different types of sources beneath Banks Peninsula volcanoes 1) HIMU-type and 2) EMII-type source that could either imply mantle heterogeneity or the EM-type signature being created by crustal assimilation. Energy-constraint assimilation-fractional crystallization (ECAFC) calculations require 8 % of crustal material to be assimilated into uncontaminated the HIMU-type samples to generate a similar EM-type signature as observed in our samples, which is plausible and underlined by trace element modelling. But how are the melts generated? In context of melt generation on the New Zealand micro continent, revealing no morphologic or geophysical indication of a thermal anomaly and/or extensional tectonism beneath Banks Peninsula an alternative process has to be introduced to trigger melting. A possible mechanism to produce melts stationary over 6 Ma is lithospheric detachment.

Origin of WPB-Type Magmas in Rear Volcanic Belt of Kamchatka as a Result of Melting of the Kula Paleoslab

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The within-plate-basalt-type (WPB) volcanism occurred in the rear volcanic belt of Kamchatka (Sredinny Ridge) during two separate episodes (40Ar/39Ar ages of 2 1.3 Ma and 0.08-0 Ma) with background of island-arc-basalt-type (IAB) volcanism. WPB volcanism of the initial stage is characterized by Ba/Nb of 25-10, Nb/Yb of 14.0-7.3 and DUPAL isotopic features (206/204Pb 18.058-18.095, delta8/4Pb 50-64, 87/86Sr 0.7036-0.7040, 143/144Nd 0.51295-0.51297). Modern WPB volcanism is characterized by two distinct subtypes, one of which is similar to IAB (206/204Pb 18.201-18.270, delta8/4Pb 6-18, 87/86Sr 0.7032-0.7034, 143/144Nd 0.51300-0.51312) differing from that by less prominent depletion in HFSE (Ba/Nb 96-39, Nb/Yb 6.7-2.7). Another subtype takes intermediate position between DUPAL and IAB (206/204Pb 18.154-18.212, delta8/4Pb 22-30, 87/86Sr 0.7032-0.7035, 143/144Nd 0.51302-0.51305, Ba/Nb 37-27 and Nb/Yb 10.5-5.4). We suggest that DUPAL WPB were derived from remelting of the Kula paleoslab MORB crust (eclogites). The Kula paleoslab is located in transition zone of mantle beneath the Sredinny Ridge. The eclogites were brought to the sublithosphere by composite diapirs (plumes). Initiation of the Pacific slab subduction stopped WPB volcanism until Pacific slab interacted with the Kula slab at depth. This process was responsible for the modern pulse of volcanism with typical IAB volcanism derived from the metasomatised mantle wedge, WPB-volcanism of eclogite-bearing diapirs and IAB-WPB-hybrid volcanism. (The work is supported by SB RAS 6.9, RFBR 05-05-64477 and RFBR 07-05-00959).

Plume head -lithosphere interactions near intra-continental plate boundaries.

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In continents, Plume-Lithosphere Interactions (PLI) are often identified near boundaries between younger plates (e.g., orogenic) and old stable plates (e.g., cratons), which represent important geometrical, thermal and rheological barriers that interact with the 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 lithosphere rheology and structure. We address the latter problem by considering a free-surface numerical model of PLI with two stratified elasto-viscous-plastic (EVP) continental plates, one of which is older and thicker than another. The results show that: (1) plume head flattening is asymmetric, it is blocked from one side by the cold vertical boundary of the older plate, which leads to the mechanical decoupling of the crust from the mantle lithosphere, and to localized faulting at the cratonic margin; (2) the return flow from the plume head results in sub-vertical down-thrusting (delamination) of the lithosphere at the margin, producing sharp vertical cold boundary down to the 400 km depth; (3) plume head flattening and migration towards the younger plate results in concurrent surface extension above the centre of the plume and in compression (pushing), down-thrusting and magmatic events at the cratonic margin (down-thrusting is also produced at the opposite border of the

younger plate); these processes may result in continental growth at the “craton side”; (4) topographic signatures of PLI show basin-scale uplifts and subsidences preferentially located at cratonic margins. Negative Rayleigh-Taylor instabilities in the lithosphere above the plume head provide a mechanism for crustal delamination. Inferred consequences of PLI near intra-continental plate boundaries, such as faulting at cratonic edges and enhanced magmatic activity, could explain plume-related metallogenic crises, as suggested for West Africa and Australia. This study suggests that the plume impact may have complex consequences for surface evolution. In particular, absence of magmatic events should not be interpreted as evidence for the absence of plume events. If some melts/magmatic events are observed at the surface, they will not necessary have unambiguous deep geochemical signatures, as the hot source plume material stalls below Moho and forms a long-lasting (10 to 100 Myr) sub-Moho reservoir. This should induce strong crustal melting that may overprint deeper signatures since crustal melts are generated at much lower temperatures than mantle, and produce light low-viscous rapidly ascending magmas. In addition, drip-like down-sagging of the lithospheric mantle and metamorphic lower crustal material inside the plume head may contaminate the latter and thus alter the geochemical signature of plume-related magmas.

K-T magmatism of northwestern Indian shield: A result of fragmenting continent

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Cretaceous-Tertiary (K-T) boundary marks magmatism at Mer-Mundwara, Sarnu-Dandali and Tavidar in western Rajasthan, northwestern Indian shield. The magmatism is located at the Barmer-Sanchor-Cambay rift margin. Alkaline and associated magmatism, Cambay-Sanchor-Barmer rift basin, Deccan volcanism and separation of the Seychelles micro-continent from India have been interpreted to be the products of Reunion plume activity during K-T period in northwestern India. The Mundwara and Sarnu Igneous complex (68.53-0.16 Ma) are interpreted as pre-outburst plume activity and the main plume outburst phase is described as Deccan volcanism (65.5 0.5 Ma).

The separation of Indian landmass from Eastern Gondwana during Jurassic resulted Rift basins in Kutch (Gujarat) and Jaisalmer (Rajasthan) region and no plume was hypnotized for this. This fragmentation caused alkaline magmatism at 120 Ma in Sarnu region. This date is not within 65 to 68 Ma time framework and excluded from Reunion Plume activity. The geodynamic changes in northwestern Indian shield from Jurassic to K-T boundary were in repose of fragmenting continents rather than Plume interactions. The Gondwana break up during K-T period caused extensional tectonic regime resulting separation of Seychelles from India, origin of Arabian Sea, Deccan volcanism, Cambay-Sanchor-Barmer rift basin and associated magmatism. The presence of ultra-basic circular plutons, carbonatite and lamprophyre dykes at Mer-Mundwara and Sarnu-Dandali signify development of deep crustal fractures. This initiated decompressional melting in northwestern Indian shield under extensional tectonic regime during K-T time rather than any Plume activity.

Plumes in a convecting mantle

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Plumes originate as convective instabilities from thermal boundary layers within the Earth's mantle. The most prominent boundary layers are the 670km discontinuity and the Core-mantle boundary at 2900 km depth. The fluid dynamics of plumes, i.e. their spatiotemporal evolution and their transport properties are only understood under conditions which are oversimplified,as compared to the mantle. Laboratory experiments can hardly take into account features which can critically influence the formation and evolution of plumes. Mantle convection is likely to be partially powered by internal radioactive heat sources. Further, the viscosity of the mantle material is known to strongly depend on temperature and pressure. Also there is clear evidence for a decrease of the coefficient of thermal expansivity with increasing pressure throughout the mantle. All those effects have an effect on the generation and the evolution of plumes. By means of numerical experiments we investigate the plume evolution in different mantle-relevant scenarios. It is demonstrated that plumes do not exist in purely internally heated convection. as long as constant material properties are assumed. A viscosity, increasing with pressure and/or a coefficient of thermal expansion decreasing with pressure have been proposed ti suppress the formation of plumes. We show that these effects lead to a focusing of buoyancy into a few strong plumes. Such, even in internally heated systems, plume instabilities do evolve and the Core-mantle boundary seems a likely location for

plumes to nucleate. A strong temperature dependence of the viscosity leads to episodic plumes. Initially a massive plume heads develops and travels upwards. Subsequently pulses of hot material can rise through the established low viscosity channel. Plumes evolving selfconsistenly from a thermal boundary layer, do hardly entrain material during their ascent. Instead they transport mostly material from the boundary layer.

Trace Element and Sr-Nd Isotope Inference on Source of the Late Cenozoic Alkaline Basalts in the Western Khubsugul Area

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Alkaline basaltic volcanism in the western Khubsugul area (Northern Mongolia) took place during two distinct the Early and Late Miocene episodes. Volcanic rocks of different age are distinguished through K-Ar and Ar/Ar dating and their location in relief. Despite the age difference the volcanic rocks are similar in major and trace element compositions, spanning between two end-member types. One type of the basalts is similar to the OIB and is best explained by 1-3 % partial melting of garnet-bearing asthenospheric mantle. Another type of the basalts shows crustal signatures such as depletion of Nb relative K, enrichment of Sr and Pb relative Ce and Pr. In Sr-Ndisotope and trace element combined diagrams, the Early and Late Miocene basalts show different trends. The Late Miocene OIB-type and crustal-signature-type basalts have moderately depleted and enriched Sr-Nd-isotope features, respectively (eNd +3, 87Sr/86Sr 0.7041 and eNd -2, 87Sr/86Sr 0.70495, respectively). 87Sr/86Sr and 1/Sr ratios are positively correlating. However, the Early Miocene OIB-type and crustal-signature-type basalts show enriched and depleted isotope signatures, respectively, opposite to that of the Late Miocene basalts. In 87Sr/86Sr vs 1/Sr the Early Miocene basalts are negatively correlating. The reason for the crustal trace element signatures in the western Khubsugul basalts is not clear. It could be explained by in situ crustal contamination for the Late Miocene basalts, but recycled origin of these signatures related to Pacific slab subduction in the Early Miocene basalts is more likely. (Study is supported by RFBR 05-05-64477 and MK-1588.206.5).

The Deccan-Reunion hotspot history: hotspot-ridge interaction for the last 60 Ma

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The history of the Deccan-Reunion hotspot is often described as the smooth and continuous building of the Deccan traps, Laccadives, Maldives, Chagos, Nazareth, Cargados Carajos, and Soudan Banks, and finally Mauritius and Reunion Islands, as the Indian and African plates were moving northward. The Deccan-Reunion hotspot is therefore envisioned as a typical intraplate hotspot during most of its history, except when the Central Indian Ridge (CIR) crossed the hotspot track at about 35 Ma -without much consequence on both of them.

Conversely, the geochemical enrichment, peculiar morphology and geophysics of the CIR at 19_S support some kind of recent hotspot-ridge interaction. Ar-Ar dating of dredged samples from Rodrigues Ridge, a 600-km long volcanic structure, suggests a rapid emplacement of this ridge at 7-11 Ma, whereas Sr, Nd and Pb isotopes show gradual fading of the Reunion hotspot influence with distance. Signs of a more recent activity are Rodrigues Island, dated about 1 Ma, and a set of recently discovered en-echelon volcanic ridges, Three Magi and Gasitao Ridges, which extend Rodrigues Ridge up to the CIR axis. These sigmoid ridges, aligned along an E-W direction, provided K-Ar ages of 0.4 and 1.8 Ma, and their isotopic compositions are intermediate between those of Rodrigues Ridge and the CIR axis.

The observation of such an interaction while the CIR and Reunion Island are 1000 km away from each other suggests that the Deccan-Reunion hotspot had a long history of interaction with the Carlsberg Ridge (CR) and the CIR in previous stages of its history. This interaction started as early as the hotspot inception by the Indian plate, triggering rifting between India and the Seychelles Block and the opening of the CR between A29r and A27 (65-61 Ma). The geometrical configuration of the CR-CIR and the hotspot suggests that, between A26 and A20 (58-43 Ma), the CR was close to the hotspot. At a large scale, the observation of systematic ridge propagation in the Arabian and Eastern Somali Basin between A26 and A21r has been interpreted as reflecting interaction between the CR and the Deccan-Reunion hotspot. Conversely, interaction with the CIR was limited due to the long offset of the Mauritius-Chagos FZ. A significant part of Chagos, Nazareth, and Cargados Carajos Banks may have been formed on the African plate, as a conjugate of Maldives and southern Laccadives Banks, in agreement with their physiography and the ages provided by drilling sites. Once reconstructed, the conjugate tracks are symmetrical; they narrow and deepen with younger age, suggesting a decrease in the hotspot strength. The saddle between Maldives and Chagos Banks, located at a bend in the general trend of the structure, would correspond to a fossil ridge dated ˜A20 (43 Ma). The good fit between Chagos Bank and the Mascarene Plateau suggests rifting and break up of pre-existing structures between 43 and 35 Ma, instead of a mid-ocean ridge passing over a hotspot.

The hotspot would have been quiescent between 45-10 Ma, possibly inhibited by the thick northeastern Mascarene plateau created in earlier stages of its evolution. The cause for its rejuvenation in two pulses at 11-7 Ma (Mauritius Island, Soudan Bank, and Rodrigues Ridge) and the last 2 Ma (Reunion and Rodrigues Island, Three Magi and Gasitao Ridges) is unclear and may be related to internal deformations of the African plate.

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Magmatic dynamics of the Sayan-Mongolian late Cenozoic low-velocity mantle domain, Central Asia

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A 3D tomographic image of Asia based on records of surface S-waves (Yanovskaya & Kozhevnikov, 2003) revealed the Transbaikal and Sayan-Mongolian low-velocity domains at the mantle levels of 200-350 and 50-200 km, respectively. A study of magmatic expression of the former domain demonstrated long-term processes related to Mesozoic through Cenozoic plate subduction beneath East Asia. Origin of the latter domain remained unclear in terms of spatial-temporal relation between the low-velocity region and magmatism (Rasskazov et al., 2004; Rasskazov & Taniguchi, 2006). In this presentation, we consider new tomographic evidence on limits and inner structure of the Sayan-Mongolian domain and also demonstrate new geochronological and geochemical data on volcanic rocks to show a temporal sequence of magmatic processes. The domain is subdivided into southern (Gobi), central (Hangai) and northern (Sayan) parts. Magmatism remained active during the Late Mesozoic through Cenozoic in the former area, but it was not characteristic for two other parts of the domain between ca. 260 and 22 Ma. A late Cenozoic magmatic reactivation of the Sayan and Hangai areas took place at 22-17 and 17-10 Ma, respectively. Records of SV-waves during new teleseismic experiment MOBAL_2003 of a cooperative Russian-French-Mongolian project (Modvinova et al., 2005) show evidence on spatial transition of mantle processes from delamination beneath Hangai to upwelling beneath Sayan. A foot of the Sayan-Mongolian low-velocity domain corresponds in depth to the cratonic Lehman Discontinuity (depth of about 210 km beneath the Siberian Craton). We suggest that the late Cenozoic magmatic dynamics in the central and northern parts of the Sayan-Mongolian low-velocity mantle domain reflected temporal variations of a collision-derived tectonic stress between thick lithospheric keels of the Indian indenter and Siberian craton.

Slab-steepening & breakoff: an alternative shallow-plate tectonic model for the genesis of plume-like melting anomalies in continental intraplate settings

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The classical plume model requires a set of prerequisite criteria to be fulfilled in order to be able to distinguish a region as a plume-related setting: a precursory domal uplift followed by the eruption of large volumes of volcanic material, the weakening of the magmatism in time in response to the disappearance of the plume head, the fixity of that particular area relative to other hot spots and the emplacement of hot and fertile asthenospheric mantle at shallow depths. The area including the Eastern Anatolian -Iranian High Plateau (EAIHP) and Lesser Caucasus (LC), located almost in the middle of the Alpine-Himalayan collision zone, accomplishes all of these criteria. Results of recent geological and geochemical studies revealed that the EAIHP & LC were subjected to a regional domal uplift around 12 Ma before the initiation of a widespread volcanism at around 11 Ma. This domal structure, which is comparable to that of the Ethiopian High Plateau (i.e. 1000 km in diameter with 2 km height) except for its north-south shortened asymmetrical shape, is currently being supported by the asthenosphere emplaced in exceptionally shallow depths (40-50 km). The volcanic activity produced great volumes of volcanic material, covering almost half of the EAIHP & LC in a number of countries including Turkey, Russia, Georgia, Azerbaijan, Armenia and Iran. The aforementioned volcanism, although still active, weakened in time across the region.

By virtue of these features, the EAIHP & LC can be regarded as the site of a "melting anomaly" or "hotspot" resembling the setting proposed for mantle plumes. In spite of the presence of these parameters, recent geologic, geophysical and geochemical data provide evidence against a plume origin across the EAIHP & LC. Results of these findings coupled with experimental studies support the view that both domal uplift and extensive magma generation can be linked to the mechanical removal of a portion or the whole thickness of the mantle lithosphere, accompanied by passive upwelling of normal-temperature asthenospheric mantle to a depth as shallow as 40-50 km. Mechanical removal of the mantle lithosphere might be controlled by delamination in the north (beneath the Erzurum-Kars Plateau in NE Turkey), while it was linked to slab-steepening and breakoff beneath a subduction-accretion complex in the south, in the north of the Bitlis-Pötürge-Zagros suture zone. Therefore, magma generation beneath the EAIHP may have been controlled by adiabatic decompression of the asthenosphere. The mantle source region possibly owed its exceptional fertility either to a subduction component inherited from a previous subduction event (i.e. Pontide subduction), to the oceanic crustal material previously subducted beneath the region, or to a combination of both. Delamination of lithospheric fragments might also have created a similar effect, by dewatering themselves as they sank and turning into fertile eclogite-rich ultrabasic blobs which are relatively fusible (i.e. the Eclogite Engine of D.L. Anderson). The EAIHP & LC example is important in showing that shallow plate tectonic processes (e.g. slab breakoff) have the potential to generate regional domal structures in the Earth's lithosphere as well as large volumes of magma in continental intraplate settings.

Age and petrogenesis of the EM I magma source beneath Öraefajökull, Iceland

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It is known that Öraefajökull has several geochemical signatures that are characteristic of EM I-type mantle, such as enriched Sr and Pb ratios that are not yet recognized elsewhere in Iceland. This has been attributed to an enriched end member of the Iceland mantle plume (1, 2).

An enriched mantle plume end member is not essential in producing the EM source, however it can explain it. EM magmas can also be produced by re-melting older trapped continental crust within Icelandic crust (3) or by melting decoupled continental lithospheric mantle beneath Öraefajökull, SE Iceland.

The seismological crust is 30 km thick under eastern Iceland and 34 km to the MOHO with 26-30 km to base of lower crust beneath Öraefajökull. Thus, Icelandic lower crust probably displays amphibolite to granulite metamorphic facies (4). Melts generated here may interact with the trapped continental crust to produce EM magmas.

We will constrain the age of the EM source using a traverse east from Öraefajökull by sampling two extinct volcanic centers and exposed plutons, 30 and 80 km east of Öraefajökull respectfully. Due to Iceland having a, generally, E-W rifting direction these centers would have been central volcanoes in SE Iceland during their activity and may demonstrate an Öraefajökull-like EM signature. We are able to date some of the rocks from these centers using fresh biotite phenocrysts, to make the age constraint more accurate. The extinct centre 80 km from Öraefajökull contains several silicic units, both eruptives and plutons, which will allow constraints to be placed on crustal interaction. This work uses detailed, high quality Sr-Nd-Pb-O isotope data all acquired at Royal Holloway, University of London, as well as numerical trace element modeling and physical modeling to test the enriched plume model verses a lithospheric source model in producing the EM I signature observed at Öraefajökull, SE Iceland.

1 Prestvik et al., 2004. EPSL, 190, 211-220
2 Manning et al., Unpublished
3 Foulger et al., 2006. Geophys. J.Int. 165, 672–676
4 Foulger et al., 2003. Geophys. J. Int. 155, 567–590

Alkaline basaltic volcanism in Central Mongolia and Northeast China for the past 15 Ka: decompressional and delayed fluid melting of the mantle

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Compilation of ^{14}C dating results on volcanic eruptions of the past 15 ka demonstrates the earlier activity in Central Mongolia than in Northeast China. Cessation of volcanism in the former area and its initiation in the latter one occurred at ca. 8780-8740 years B.P. (calibrated ages by tree rings). In both cases, volcanism might be triggered by a strong tectonic impulse occurred in the Indo-Asian collision zone. Geochemical study of volcanic rocks showed that this delay was accompanied by a change of magma generation in the mantle from adiabatic decompression to fluid style. Source heterogeneities of volcanic rocks were studied by means of trace-element modeling. It was inferred that firstly, decompression-derived small (1.5-3 %) liquid fractions from a metasomatized source with 5 % of garnet were exhibited along the west–eastern volcanic line in the Taryat basin of Central Mongolia, the subsequent melt fractions (up to 5 %) from a source region with garnet content as low as 3 % were manifested along the north–north-eastern line. Compositionally similar alkaline basalts were produced in Jingpohu of Northeast China at time interval of 5430–4400 years B.P. (Zhang et al., 2002). Initial partial melts of ca. 2 % beneath the Frog Pool volcanic center and those of ca. 5 % beneath the Crater Forest volcanic line (with 8 and 5 % of garnet, respectively) were followed by varied melt fractions beneath the latter area with final portions of ca. 5 % produced at source region with garnet contents from 8 to 3 %. Unlike volcanic rocks from Central Mongolia, those from Northeast China were isotopically heterogeneous and depleted by high field strength elements (Nb, Ta, and Hf). Volcanic activity in Central Mongolia appeared to be a direct response to processes in Indo-Asian collision zone, the one in Northeast China might be caused by a delayed influence of isotopically depleted fluids related to the stagnated Pacific slab.

Phantom plumes in Europe and the circum-Mediterranean region

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Anorogenic magmatism of the circum-Mediterranean area (Tyrrhenian Sea, Sardinia, Sicily Channel and Middle East) and of continental Europe (French Massif Central, Eifel, Bohemian Massif and Pannonian Basin) has been proposed to be related to the presence of one or more mantle plumes. Such conclusions based on geochemical data and seismic tomography are not fully justified because: 1)a given chemical and isotopic composition of a magma can be explained by different petrogenetic models; 2)a given petrogenetic process can produce magmas with different chemical and isotopic composition; 3)tomographic studies do not furnish unique results (i.e., different models give different results); 4)the commonly adopted interpretation of seismic wave velocity anomalies exclusively in terms of temperature is not unique – velocities are dependent also on other parameters such as composition, melting, anisotropy and anelasticity. Tomography and geochemistry are powerful tools but must be used in an interdisciplinary way, in combination with geodynamics and structural geology. Alone they cannot provide conclusive evidence for or against the existence of mantle plumes.

The existence of large and/or extensive thermal anomalies under Europe is considered unnecessary, because other models, based on the existence of upper mantle heterogeneity, can explain the major, trace-element, and isotopic variability of the magmas. Volcanism in central Europe (the French Massif Central, Germany and the Bohemian Massif) is concentrated in Cenozoic rifted areas and is here interpreted as the result of passive asthenosphere upwelling driven by decompression. Similarly, anorogenic magmatism in Sardinia, the Tyrrhenian Sea and the Pannonian Basin is explained as the result lithospheric stretching in a back-arc geodynamic setting. The most important factors determining the locus and, in part, the geochemical characteristics of magmatic activity are the Moho and the lithosphere/asthenosphere boundary depths. Where both are shallowed by tectonic processes (e.g., in rift zones or back-arc basins) passive upwelling of asthenospheric mantle can explain the magmatic activity.

Geochemistry of Dominant Low-Ti Basalts of the Siberian Traps and Subduction-Related Model of Their Origin

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Siberian Traps is one of the most voluminous volcanic provinces on Earth (˜4*10ˆ6 kmˆ3, covering ˜7*10ˆ6 kmˆ2). It was formed between the Late Permian and the Late Triassic, at a time when the Pangea supercontinent was surrounded by subduction zones. The dominant erupted rocks are low-Ti basalts, which make up to 80 % by volume of the classical Noril'sk lava sequence. In the Angara-Taseevskaya Syncline, West Siberian Basin and Maymecha-Kotuy area the low-Ti basalts make up to about 100 %, 99 % and 50 % by volume, respectively. The low-Ti basalts despite their wide spatial distribution and temporal variations within Late Permian -Late Triassic are characterized by uniform geochemical features similar to that of island-arc basalts. In conventional plume model, this is explained by high-degree lithospheric (either mantle or lower crust) contamination of primary plume melts. However, taking into account the size of the Siberian Traps and heterogeneous nature of underlying lithosphere, the contamination is unlikely to yield uniform composition of erupted magma. Thus, sublithospheric origin of the low-Ti magmas is suggested. The sublithospheric upper mantle attained 'subduction-like' trace element features shortly before the Siberian Traps volcanism because of Permian subduction. New model includes water recycling through fast subduction, slab stagnation in transition zone of mantle, water-saturation of the bottom-part upper mantle peridotite and its upwelling to sublithospheric depth and, finally, voluminous melting. The model is supported by (1) tectonic position of the Siberian Traps in a back-arc setting of Permian subduction systems, (2) island-arc-basalt-like trace element patterns for the majority of the erupted basalts, (3) experimental data on the high water capacity of the mantle transition zone, its recharging via the subduction process and (4) significant volume expansion of olivine as a result of water saturation. (Study is supported by RFBR 05-05-64477)

The amount of recycled crust in sources of mantle-derived melts

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Plate tectonic processes introduce basaltic crust (as eclogite) into the peridotitic mantle. The proportions of these two sources in mantle melts are poorly understood. Silica-rich melts formed from eclogite react with peridotite converting it to olivine-free pyroxenite. Partial melts of this hybrid pyroxenite are higher in Ni and Si, but poorer in Mn, Ca and Mg than melts of peridotite. Olivine phenocrysts compositions record these differences and were used to quantify the contributions of pyroxenite-derived melts in mid-ocean ridge basalts (10-30%), ocean island and continental basalts (many>60%) and komatiites (20-30%). This implies involvement of 2-20% (up to 28%) of recycled crust in mantle melting.

To understand the role of crustal material in creating compositional heterogeneities in the mantle and to evaluate the geodynamical consequences of this contribution, one must quantify the crustal input to the mantle sources of common, mantle-derived magmas in mid-oceanic ridges (MORB), ocean islands (OIB) and large igneous provinces (LIP). Here we use an approach based on a combination of major elements and compatible trace elements in parental melts, because these are more uniform in the mantle and are strongly controlled by the residual phases in equilibrium with partial melts. Our method is based on the experimental and theoretical prediction that high pressure (P> 3.0 GPa) melting of typical recycled oceanic crust (in the form of eclogite with a separate SiO_2 phase), and reaction of this melt with peridotite, produces olivine-free pyroxenite. We show that further melting of this hybrid lithology in the absence of residual olivine is more voluminous than the melting of peridotite (at a given pressure and temperature), and pyroxenite-derived melts are characteristically enriched in Si and Ni, but depleted in Mg, Ca and Mn compared to their peridotite-derived counterparts. This difference arises because olivine principally controls the composition of melt produced in peridotite, whereas pyroxene mainly controls the composition of melt from olivine-free hybrid pyroxenite. Experimental data predict that, as such pyroxenite-derived melts raise towards the surface, the decrease in pressure causes their saturation in olivine. This olivine is unusually Ni rich, and Mn and Ca poor. Using a new, large dataset of high-precision analyses of olivine phenocrysts from OIB, LIP, MORB, and komatiites, we show that hybrid pyroxenite is a common source in upwelling mantle and a major contributor to tholeiitic (silica saturated) and transitional (moderately silica undersaturated) magmas of OIB and LIP emplaced on thick oceanic or continental lithosphere.

A. V. Sobolev *et al.*, *Science Express*, 29 March 2007 (10.1126/science.1138113).