InterRidge Symposium and workshop:

RIDGE-HOTSPOT INTERACTION: Recent Progress and Prospects for Enhanced International Collaboration

8-10 September 2003
Brest, France

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Introduction

Hotspots cause many of the largest structural and chemical anomalies in Earth's ocean basins and influence crustal accretion along a significant portion of the global mid-ocean ridge system. One of the greatest challenges in hotspot-ridge studies is the integration of geological, geochemical/petrological, and geophysical data. Although there are several elegant models that describe mantle plume behaviour, often these appear to be at odds with the geochemistry/petrology information. Integrating geological constraints into dynamic models is an essential component of achieving greater understanding of this fundamental process of Earth evolution. This meeting will examine recent advances in this active research area, identify the most pressing questions and explore innovative ways to solve those problems that, by the very nature of their complexity and scale, will require concerted multi-disciplinary and international efforts. This meeting has the following specific objectives:

1) To review recent progress in geological, geophysical, geochemical, and theoretical studies of hotspots and their interaction with mid-ocean ridges on global ocean basins;

2) To identify key scientific issues that could be addressed in the coming years; and

3) To discuss a general plan for more focused international collaboration, especially multi-disciplinary experiments (including IODP) that can not be achieved by single nations alone.

The meeting will have two main components. The first half of the meeting is a symposium that combines oral presentations, posters, and discussion periods. The second half is a workshop that will produce, through alternating assembly and sub-group discussion sessions, a set of recommendations for the InterRidge Next Decade Initiative.

Acknowledgements. This meeting will not be possible without the support of several funding agencies and organizations. We are indebted to significant financial support from the US RIDGE-2000 Program, UK-ODP, and French CNRS-INSUE, which provided partial travel support for US, UK, and French participants, respectively. The InterRidge Program, Institut Universitaire Européen de la Mer (IUEM), Université de Bretagne Occidentale (UBO), Communauté Urbaine de Brest (CUB) and Conseil Général du Finistère (CG 29) provided additional financial support. We greatly appreciate Institut Universitaire Européen de la Mer, a component of Université de Bretagne Occidentale, for providing conference facilities for this meeting.

Meeting Program

Monday 8th - morning

08:30 Hotel pick up

09:00 Short meeting introduction

Oral session "Hotspot beneath a ridge: Iceland"

09:10 Christophe Hémond, Catherine Chauvel
Does the Icelandic plume really interact with the Mid-Atlantic Ridge? [24]*

09:40 Bram Murton
Plume-Ridge Interaction: a Geochemical Perspective from the Reykjanes Ridge [32]

10:10 M.F. Thirlwall, D. Mertz, R.N. Taylor, A. Friend, B.J. Murton
The effect of the Iceland plume on adjacent ridges: high precision Pb isotopic constraints [41]

10:40 Coffee Break

11:00 Yang Shen, Shu-Huei Hung
Seismological constraints on mantle flow and melt generation beneath the Iceland hotspot [38]

11:30 B. Brandsdottir
Plume-Ridge tectonics in Iceland [11]

12:00 R. Searle
Morphology of the Mid-Atlantic Ridge near the Iceland Hotspot [37]

12:30 Lunch

* Numbers in brackets indicate the page number of the abstract

Monday 8th - afternoon

Oral session "Hotspots near a ridge: Galapagos, Afar"

14:00 E. E.E. Hooft, D. R. Toomey, S.C. Solomon
Seismic imaging of the Galápagos plume and implications for plume-ridge interactions. [26]

14:30 Robert Reves-Sohn, Michael Braun
Melt migration in plume-ridge systems [12]

15:00 David Graham
Helium isotopes and mantle plume-spreading ridge interactions [22]

15:30 Coffee Break

15:50 K. Tamaki,
Hotspot-ridge interaction at the Gulf of Aden [40]

Poster session 1

16:20 Poster presentations (5 min each)

Emilie Hooft, Bryndis Brandsdottir, Rolf Mjelde, Heidiki Shimamura
Plume-ridge interaction north of Iceland: Kolbeinsey Ridge seismic experiment [25]

Olivier Bourgeois, Olivier Dauteuil
Rifting above a mantle plume: structural analysis of Iceland and analogue modelling [10]

Pascal Gente, Jérôme Dyment, Marcia Maia, Jean Goslin
Interactio between the Mid-Atlantic Ridge and the Azores hotspot during the last 85 Ma: Emplacement and rifting of the hotspot-derived plateaux [20]

Laure Dosso, Matthew Thirlwall
The Mid-Atlantic Ridge between 40 and 45°N: High precision Pb, Sr, Nd isotopic data [15]

G. Silvera
TBA

G.A. Cherkashov, G.P. Glasby
Submarine hydrothermal activity and mineralization at the Azores hotspot; interaction between a migrating plate and a static hotspot [TBA]

S.A.Silantyev
Variations in the geochemical and isotope characteristics of mantle peridotites along the Mid-Atlantic Ridge strike and their relationships with distribution of plume and spreading magmatic provinces [39]

M.D. Kurz, D. Fornari, D. Geist, K. Harpp
Hotspot influence at the Galapagos spreading center: inferences from Galapagos island seafloor morphology and geochemistry [28]

Dmitriev Leonid, S. Yu Sokolov
Spreading rate and geodynamic conditions of the mid-ocean ridge mantle magmatism [14]

~17:00 Poster viewing session

18:00 Pot d'accueil (poster viewing continues)

19:30 Back to hotels

Tuesday 9th - morning

08:30 Hotel pick up

Oral session "Hotspots approaching and migrating away from a ridge"

09:00 Marcia Maia, Christophe Hemond, Pascal Gente
The Foundation Hotspot-Pacific-Antarctic Ridge System: the case of a spreading ridge moving towards a hotspot [31]

09:30 Jian Lin, Jennifer Georgen, Henry Dick
Ridge-hotspot interactions at ultra-slow spreading conditions: Bouvet/Marion hotspots and the SW Indian Ridge [30]

10:00 Jérôme Dyment et al.
Interaction between the Deccan-Reunion hotspot and the Central Indian Ridge [16,17]

10:30 Coffee Break

Oral session "Modelling ridge-hotspot interaction"

11:00 Neil Ribe
Fluid mechanics of plume-plate and plume-ridge interactions [35]

11:30 Garrett Ito, J. Mahoney
Geochemical systematics of hotspots and mid-ocean ridges arising from melting and buoyant upwelling of a non-layered heterogeneous mantle [27]

12:00 Discussion – organizational matters for the Workshop

12:30 Lunch

Tuesday 9th - afternoon

Poster session 2

14:00 Poster presentations (5 min each)

Susan Fretzdorff for the German Ridge community
The resurrection of DeRidge: new German ridge activity in the Atlantic [18]

Susanne Fretzdorff, Karsten Haase, Nicole Stroncik, Peter Stoffers
Interactions of the Easter and Foundation plumes with the East Pacific Rise: a comparison [19]

David F. Naar, Sarah F. Tebbens, Douglas T. Wilder
The Farallon to Nazca plate transition: The missing time period [33]

Jennifer E. Georgen, Jian Lin
Plume-transform interactions at ultra-slow spreading ridges: Implications for Marion/Southwest Indian Ridge interactions [21]

Anne Briais, Marcia Maia, Jérôme Dyment, and Pascal Gente
Influence of the Reunion hotspot on the Central Indian Ridge [13]

Steve Tyler, Lindsay Parson, Jon Bull
An investigation of evidence for Ridge-Hotspot Interaction along the Central Indian Ridge [42]

Nauret, F., Abouchami, W., Galer, S.J.G., Hofmann, A.W., Hemond, C.
Is there really a plume-ridge interaction along the Central Indian Ridge between 18º and 20ºS? [34]

Raymond Lataste, Anne Briais, Olga Gomez
Evidence for anomalously hot mantle East of the Autralia-Antarctica Discordance [29]

Barry B Hanan, Douglas Pyle, Janne Blichert-Toft, Francis Albarede, David M Christie
Origin of the Indian- and Pacific-type MORB mantle isotope signatures [23]

N. Seama
Seafloor magnetotelluric experiment using ocean bottom electro-magnetometers [36]

14:50 Poster viewing session

15:40 Coffee Break (Poster session continues)

Workshop

16:00 Workshop starts

18:30 Back to hotels

Wednesday 10th - morning

08:30 Hotel pick up

09:00 Javier Escartin
MOMAR: long term monitoring and Azores hotspot - MAR interaction

09:30 Workshop continues…

10:30 Coffee Break

11:00 Workshop continues…

12:30 Lunch

Wednesday 10th - afternoon

14:00 Workshop continues…

15:40 Coffee Break

16:00 Workshop continues…

17:30 Pot de départ

18:30 Back to hotel

List of Abstracts

Rifting above a mantle plume: structural analysis of Iceland and analogue modelling

Olivier Bourgeois[1] and Olivier Dauteuil[2]

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[2] Geosciences Rennes (UMR CNRS 6118), Campus de Beaulieu, Rennes, France.

The Mid-Atlantic Ridge is a slow-spreading oceanic ridge. In Iceland, it is located above a mantle plume and rises above sea-level. Iceland thus constitutes a unique opportunity to constrain tectonic models of rifting above mantle plumes. Ridge-plume interactions have been widely studied with regards to asthenospheric flow, mantle melting, composition of rocks, crustal thickness and surface morphology. In contrast, effects of mantle plumes on the mode of lithospheric deformation at oceanic ridges remain largely obscure.

Slow-spreading ridges are usually composed of an axial valley, 1 to 20 km wide, where magmatic material arising from the mantle is constantly added to the crust. At the same time, the newly formed crust is continuously stretched in response to plate separation. Stretching is accommodated by faulting in the upper part of the lithosphere; the faults generally dip towards the spreading axis (which remains pinned at the plate boundary) and bound outward-tilted blocks. Balance between supply of magmatic material to the crust and stretching of the crust usually yields a symmetrical, steady state process of rifting.

The structure of Iceland differs from that of other slow-spreading ridges. Lithospheric spreading is currently accommodated in a 200 km-wide zone, by west-dipping half grabens controlled by east-dipping faults. Several field cross-sections show that similar structures with various polarities have been preserved in the lava pile. We identify these structures with lithospheric rollover anticlines, which developed in hanging walls of listric faults. An interpretative cross-section throughout the island illustrates how the plateau has developed by birth, growth and decay of individual growth fault/rollover systems associated with magma chambers at depth. These systems partially overlap each other. They formed at different times and at different places. Volcano-tectonic activity thus wandered through time, within a 200 km-wide stripe corresponding to a diffuse plate boundary. Analogue modelling indicates that this non steady-state mode of rifting is caused by unbalance between supply of magmatic material from the mantle to the crust and stretching of the crust.

Plume-Ridge tectonics in Iceland

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The slow spreading plate boundary across Iceland is characterised by structurally more complex rift- and transform zones than their oceanic counterparts. The rift zones are made up of volcanic systems (rifting segments) rooted in a crust 3-5 times thicker than normal oceanic crust. Close to 30 volcanic systems make up the approximately 650 km long and 50-80 km wide plate boundary across Iceland. Large variations in topography, compressional velocities and geochemistry reflect different evolutionary stages of central volcanoes within each system, some of which have developed calderas. Some central volcanoes, arranged en echelon along the plate boundary, may have semi-radial fissure systems reflecting localised stress fields, whereas the elongated fissure swarms, specified by rifting structures such as crater rows, normal faults and open fissures, commonly lie at an azimuth perpendicular to the regional spreading direction. The volcanic systems are activated during rifting episodes, sometimes lasting for years. During non-magmatic events, seismicity along the plate boundary is highly variable both spatially and temporally, but seems to be mostly confined to the uppermost 10 km of the crust. Some central volcanoes have quite persistent seismicity whereas others are remarkably quiet. Doming of the lower crust is observed beneath both active and eroded central volcanoes. Within some of the more active volcanoes 1-2 km thick, localised magma chambers sit on top of these high-velocity domes (chimneys), at around 3 km depth, i.e. approximately at the level of buoyant equilibrium for basaltic melt within the crust. The domes likely consist of olivine-rich cumulates, formed at the base of magma chambers and subsequently advected downward and outward during the spreading process. Seismic and geodetic data from the recent rifting episode within the Krafla volcanic system, N-Iceland, offered an unique opportunity to study the episodic accumulation of magma into the central volcano, followed by the migration of this magma away from a shallow crustal magma chamber along the rift axis. Two transform zones, the South Iceland Seismic Zone (SISZ) and the Tjörnes Fracture Zone (TFZ), offshore N-Iceland separate the Eastern Volcanic Zone of Iceland from the onland extension of the Reykjanes Ridge and Kolbeinsey Ridge. Both lack the clear topographic expression typical of oceanic fracture zones. The 80 km wide (E-W) SISZ is made up of more than 20 N-S aligned right-lateral strike-slip faults whereas the TFZ consists of broad zone of deformation roughly 150 km wide by 75 km long (N-S) defined by 3 major extensional basins and two WNW-trending seismic zones - the Grímsey seismic lineament (GSL) on the north and the Húsavík-Flatey strik-slip fault (HFF) on the south. Newly collected high-resolution multibeam bathymetry data, multichannel seismic and chirp profiling data provide a new perspective on the structure and neotectonics of the TFZ. The sediment-filled basins are bounded by numerous NS-trending faults, some of which extend to the seafloor, suggesting they are actively extending. Reflection records indicate an increased dip-slip component of motion westwards along the HFF, on which severe earthquakes occurred in 1755, 1867 and 1872. In contrast, the GSL consists of numerous NS-trending, left-stepping, en-echelon rift valleys, akin to the fissure swarms observed on land. These are volcanically and hydrothermally active. The Kolbeinsey Ridge emerges from the westernmost TFZ basin as a narrow, well-defined rift zone north of ~66°50'N. As the northern section of the Eastern Volcanic Zone has propagated northward over the past 2 my, deformation within the TFZ may have shifted from predominately strike-slip motion along the HFF to extension along en-echelon rift zones. Tectonically, the GSL thus resembles the northernmost Reykjanes Ridge and Reykjanes Peninsula in southwestern Iceland rather than a conventional oceanic transform with narrow zones of predominately strike-slip motion.

Melt migration in plume-ridge systems

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We assess the potential for melt migration, separate from solid flow, to accommodate the transport of plume-signature material from off-axis mantle plumes to nearby mid-ocean ridges. We use a boundary-element method to estimate the solid pressures induced by buoyant plume flow, and find that the solid pressure gradients are small compared to melt buoyancy, suggesting that melt streamlines in mantle plumes are essentially vertical. We combine our plume pressure solutions with analytical pressure fields for ridge corner flow and find that the combined plume ^ridge pressure field is not sufficient to drive porous flow in the upper mantle over the distances (hundreds of km) observed in many natural systems. We also examine melt transport via porous flow in a melt-rich layer at the base of the lithosphere for plume-ridge systems, and find that melts can traverse plume ^ridge offsets of several hundred kilometres in a few hundred thousand years, or less. Our results suggest that plume signatures observed in ridge basalts can be explained by lateral migration of plume melts in a sub-lithospheric channel augmented by solid flow pressure gradients. We apply our models to the Galapagos plume ^ridge system and find that melt migration, as opposed to solid flow, provides a means to explain many aspects of the observed chemical anomalies on the Galapagos Spreading Centre, including the position of the maximum anomalies due north of the archipelago, the symmetric pattern, and the gradual along-axis gradient.

Influence of the Reunion hotspot on the Central Indian Ridge

Anne Briais[1], Marcia Maia[2], Jérôme Dyment[3], and Pascal Gente[2]

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[2] Institut Universitaire Europeen de la Mer, Brest, France
[3] Institut de Physique du Globe de Paris, France

We present an analysis of multibeam bathymetry, backscatter imagery, and gravity data collected during the Magofond2 and Gimnaut cruises, and of satellite-derived gravity anomalies, on the flanks of the Central Indian Ridge (CIR). The bathymetry data reveal that the CIR axis near 19°S is about 1000 m shallower than normal, slow-spreading ridge axes. In this area, the ridge flanks display low-relief abyssal hills, up to 100 km long, which are similar to those observed on intermediate-spreading centres, contrasting with the rougher abyssal hills observed farther south on the CIR, where the spreading rate is slightly higher. The traces of the axial discontinuities in the ridge section between 18°30'S and 20°S are marked by series of low-relief bathymetric saddles, contrasting with the deep basins marking the ridge offsets farther south. A series of jogs of the axial valley forms a larger, 15 km offset between 18.6S and 19S. The off-axis trace of this axial discontinuity is a W-shaped series of lows, implying that the offset has propagated north between 4 Ma and about 1.5 Ma, and has been migrating south since then. Bathymetric highs are observed on the eastern flank of the ridge near the centre of two segments at 19°10'S and 19°30'S. The Mantle Bouguer Anomaly (MBA) map shows two small-amplitude, negative anomalies associated with the two bathymetric highs, superimposed on a broader regional negative anomaly, centred on the ridge segment at 19°30'S. The pattern of MBA is asymmetric, displaying more negative values on the west flank, towards a group of small off-axis, elongated ridges. These off-axis ridges form the easternmost part of a major aseismic, E-W trending ridge, the Rodrigues ridge. The residual mantle Bouguer anomaly in our study area displays a similar pattern as the MBA. The negative anomalies are suggestive of thicker crust and/or hotter mantle beneath the ridge axis and the western ridge flank. The backscatter images reveal highly reflective seafloor on the west flank of the CIR, near the off-axis bathymetric ridges at 19°40’S, and near off-axis volcanoes at 19°25’S, suggestive of off-axis volcanic activity. The off-axis volcanism, the low-relief bathymetry between 18°30'S and 20°S, the asymmetry of the gravity anomalies, and the good correlation between both the regional and more localized MBA lows and the off-axis volcanic ridges suggest an influence of the Reunion hotspot on accretionary processes and volcanic construction near the CIR axis. The thermal influence appears to spread over a large area, certainly due to the large distance of about 1000 km between the ridge and the hotspot. The contrast between the low-relief bathymetry between 18° 30'S and 20° S and the high reliefs observed farther south coincides with a contrast in roughness in the free-air gravity anomaly maps derived from satellite altimetry data. In the corridor bounded by the Egeria and Marie Celeste transform faults, closest to the Rodrigues ridge, the signature of the non-transform discontinuities in the gravity is too subdued to be identified. The traces of the discontinuities disappear in this corridor around 20 Ma near Marie Celeste fracture zone, and later toward the south, forming an oblique boundary between lineated seafloor and smooth seafloor.

Spreading rate and geodinamic conditions of the mid-ocean ridge mantle magmatism.

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[2] Geological institute RAS, Moscow, Russia

The coexisting of six stable groups of TOR (the alternative term to MORB) incoming two major mid-ocean ridge basalt assemblages have been founded on the statistic base (Dmitriev, 1998; Dmitriev *et al*, 1999; 2000):

1) Spreading assemblage (SA) including TOR-2 group as the analog N-MORB and dominated in this assemblage, small group TOR-Na - the most depleted MORB with the minimal volcanic productivity, and group TOR-Fe(Ti) – the product of the developed fractionation on TOR-2 in magma chambers. The main SA compositional feature is the relative enrichment in Na_2O and TiO_2.
2) Plume assemblage (PA) including TOR-1 group as the background PA (N-MORB with the trace of enrichment), small group TOR-K – the transinional type (T-MORB) and group TOR-Fe – the product of TOR-1 fractionation. PA is moderately enriched in K_2O.

PT conditions of the primary mantle melt origin determined by the melt inclusion study and thermodynamic calculation (Sobolev, Dmitriev, 1989) have been accepted as the petrological signature of SA and PA generation: 15-20 k bar and 1400° – 1450° C for PA and 6 – 8 k bar and 1200° – 1250° C for SA.

The generalisation of the existed actual material on PA and SA distribution along MOR system, on their connections with tectonics, with gravity field change and data on seismotomography leds to the following.

- SA is forming due to the pasive mantle upwelling from the depth no more 200 km as the result of spreading ("well effect").The volcanism of the minimal productivity (TOR-Na) is located in the limited areas with the cold solid lithosphere and accompanied by Hess crust formation.
- PA is forming by the local active mantle upwelling from the depth 400 – 1000 km out connection with spreading.
- The "local trend" of fractionation (Klein & Langmuir, 1987) is characteristic for slow spreading rate. The formation of the separated specific basalt provinces, the low degree of TOR-2 (SA) fractionation and the high degree of TOR-1 (PA) fractionation are also typical.
- The high spreading rate coordinated with the regional, intensive and long lived passive mantle upwelling led to PA and SA mixing and to the "global trend" of fractionation corresponding to the continuous change of melt composition depend on PT conditions and extent of melting along the significant interval of the depth. The separated basaltic provinces are not forming there.
- The extention of spreading rate leds to the intensive fractionation and to the limited formation of melt enriched in water.

The Mid-Atlantic Ridge between 40 and 45°N: High precision Pb, Sr, Nd isotopic data

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In 1998, the TRIATNORD cruise (*Goslin et al., 1999*) took place between 40 and 45°N along the mid-atlantic ridge, north of the geochemical anomaly related to the Azores plume at 38°N. It allowed completion of the sampling previously done by J.-G. Schilling (TRIDENT, 1971-1974) and thus gave the possibility to (1) look at the northern extent of the Azores plume influence as well as (2) discuss the relations between geochemical mantle heterogeneities and accretion processes along the axis and (3) investigate the mantle isochron question following a previous study south of the Azores. This last point was made easier by the technical advance made in Pb measurements with the availability of double spike techniques for mass fractionation correction. Some Sr-Nd data have been previously reported for this segment of the MAR, but only one sample has been previously reported for Pb isotopes in the segment. The studied ridge section defines a geochemical positive anomaly limited to the south by the Kurchatov Fracture Zone (F.Z.) at 40˚N. When examining the Sr isotopic variation along the axis, it is clearly located in the most radiogenic part of the Northern MAR (Mid-Atlantic Ridge). Although more radiogenic Sr values are found south of the Azores, the baseline of the Sr isotopic variation shows a steady increase towards the north from 0.7023 at Kane F.Z latitude to 0.7030 at 45°N. A closer look at the geochemical parameter variations along the ridge axis allows a more precise description of this anomaly. The 40-46°N anomaly is in fact a combination of 3 smaller anomalies located close to 42°N, 43°N and 44°N. The relative amplitudes of these secondary anomalies are variable according to the parameter used : if $^{206}Pb/^{204}Pb$ and $^{207}Pb/^{204}Pb$ are concerned, the largest anomaly amplitude is to the south at 42 °N, whereas for other parameters the largest amplitude is at 43°N. In all cases but Sr where the most radiogenic value of 0.70347 is reported at 43.94°N, the least pronounced anomaly is the northern one at 44°N. A detailed look at individual samples from 40-45°N allows one to group them according to their location along the ridge axis. Zones A to D are thus defined from north to south. Zone B includes the "transitional" section of the ridge where the ridge axis is difficult to locate precisely and where serpentinized rocks were recovered. It shows the most 'enriched' Sr-Nd isotope compositions. Zone C has generally lower Nd isotopic ratios than are observed in zones A and D. The detail of the 40-46°N sample fields in Pb-Pb diagrams confirm the distinctive character of zone C, especially in the $^{208}Pb/^{204}Pb$ vs $^{206}Pb/^{204}Pb$ diagram where the points are located below the Northern Hemisphere Line (NHRL). There are good correlations in the $^{207}Pb/^{204}Pb$ vs $^{206}Pb/^{204}Pb$ diagram for zones A and B samples (under the NHRL), with correlation coefficients of 0.998 and 0.986, and slopes of 0.088 and 0.089 respectively, corresponding to secondary isochron ages of 1.4 b.y. In the $^{143}Nd/^{144}Nd$ vs $^{147}Sm/^{144}Nd$ diagram, a correlation is found essentially for zone B samples. Its slope corresponds to an isochron age of 255Ma, similar to the age found on the ridge section south of the Azores. Before concluding whether the reported isotopic variation reflects multicomponent mixing or an heterogeneous mantlewith mantle isochrons, further discussion is needed.

Goslin, J. et al. (1999). Geology ***27****(11): 991-994.*

Interaction between the Deccan-Reunion hotspot and the Central Indian Ridge : present

Jérôme Dyment[1], Cruise Magofond[2] Scientific Party[2], & Cruise Gimnaut Scientific Party[3]

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[2] J. Dyment, Y. Gallet, A. Briais, P. Gente, M. Maia, P. Patriat, C. Tamura, R. Thibaud, M. Benoit, H. Guillou, C. Hémond, K. Tamaki.
[3] J. Dyment, C. Hémond, C. Bollinger, M. Benoit, A. Briais, A.K. Chaubey, H. Horen, M. Kitazawa, B. Le Gall, M. Maia, M. Ravilly, F. Nauret.

The interaction of a mid-ocean ridge with a nearby hotspot generates specific bathymetric features such as oceanic plateaus or elongated ridges, as well as contaminated basalt on the spreading center. The Reunion hotspot is quite a specific case: although it is located 1000 km away from the Central Indian Ridge (CIR), the linear Rodrigues Ridge, the geochemical enrichment, peculiar morphology, and geophysical signature of the CIR at 19°S support some kind of active or recent interaction, as Morgan (1978) noted first. The Rodrigues Ridge, a 600-km long volcanic structure, is neither parallel to seafloor spreading flow-lines nor to the "absolute" motion of Africa in the hotspot reference frame. Ar-Ar dating of dredged samples suggests a rapid emplacement of the whole ridge at 8-10 Ma between the former position of the Reunion hotspot and the nearest CIR segment. 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 are aligned along an E-W direction at 19°40'S. Samples from the Gasitao Ridge have provided samples dated 0.4 and 1.8 Ma. Isotopic compositions are intermediate between those measured on Rodrigues Ridge and the CIR axis.

Two distinct episodes of ridge-hotspot interaction should therefore be considered. The older one has formed most of the Rodrigues Ridge (excluding Rodrigues Island) between 8-10 Ma, a time of abundant magmatism on Mauritius Island. The younger one has formed Rodrigues Island and the Three Magi and Gasitao Ridges during the last 2 Ma, a time of strong volcanic activity on Reunion Island. Our data only allow a detailed investigation of the latter episode. The lack of conjugate bathymetric feature and the age measured on the Gasitao Ridge demonstrate that it was built off axis, in the close vicinity of the CIR. The sigmoid morphology and en-echelon alignment of Three Magi and Gasitao Ridges suggest tension cracks filled by magmas resulting from decompression melting of underlying mantle. Repetition of such magmatic events results in increasing volume as ridges get older, in agreement with the morphology. The isotopic contamination could be explained either by asthenospheric flow of hotspot material toward the ridge or by remnants of the wide initial Deccan-Reunion plume head

A wide seismic and electromagnetic experiment could be a possible way to discriminate among the various models proposed for this area, as it would decipher thermal anomalies and melt distribution within the lithosphere. Such an experiment would be essential to investigate if indeed a physical connection exists today between the Reunion hotspot and the CIR, or if the CIR is only sampling remnants of the Reunion hotspot history.

Interaction between the Deccan-Reunion hotspot and the Central Indian Ridge : past

Jérôme Dyment[1] & CEFIPRA Project 1911-1 Team[2]

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The Deccan-Reunion hotspot evolution is often described as the smooth and continuous building of the Deccan traps, the Laccadives, Maldives, Chagos, Nazareth, Cargados Carajos, and Soudan Banks, and finally Mauritius and Reunion Islands, as the Indian and -more recently and in a lesser extent- the African plates were rapidly moving northward. Such a model does not consider the nearby plate boundaries, except when the hotspot "crossed" the Central Indian Ridge (CIR) at about 35 Ma - without so much consequences on either the hotspot trace or the ridge. Unlike this simplistic model, we consider that the Deccan-Reunion hotspot had a long history of interaction with the Carlsberg Ridge (CR) and the CIR.

This interaction started as early as the hotspot inception by the Indian plate, triggering rifting between India, the Laxmi and Seychelles Blocks between A29r and A27 (65-61 Ma). The CR progressively opened from NW (A28, 63 Ma) to SE (A26r?, 59 Ma) between India and Laxmi on the North, Africa and Seychelles to the South, whereas seafloor spreading has ceased in the Mascarene Basin by A26r. The Laccadives and Salha de Malha Banks formed at ~A28-A27 (63-61 Ma) and were soon separated by the Carlsberg Ridge.

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 some 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 new interpretation of Anomaly 24 (53 Ma) on a profile located east of the Maldives Bank suggests that the CR was above the hotspot at that time. Such a short distance suggests that a strong interaction existed between the Deccan-Reunion hotspot and the CR. A significant part of the Chagos, Nazareth, and Cargados Carajos Banks may have been formed on the African plate, as a conjugate of the Maldives and southern Laccadives Banks. Their physiography agrees with such a model, as well as the ages provided by drilling sites. Once reconstructed, the conjugate tracks are symmetrical; they narrow and deepen with younger age, showing a likely decrease in the hotspot strength. The saddle between the 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 the Chagos Bank and the Mascarene Plateau suggests rifting and break up of preexisting structures between 43 and 35 Ma, instead of a mid-ocean ridge passing over a hotspot.

The hotspot would have been quiescent between 45 and 10 Ma, its surface expression being possibly inhibited by the thick northeastern Mascarene plateau created in its earlier stages of evolution. The causes for its rejuvenation at 10-8 Ma (Soudan Bank, Mauritius Island and Rodrigues Ridge) and for the last 2 Ma (Reunion Island, Rodrigues Island, Three Magi and Gasitao Ridge) is unclear and may be related to internal deformations of the African plate and its separation in Nubian and Somali plates.

Testing such alternative, more complex model requires additional ages as well as geochemical analyses, i.e. new drill holes on the hotspot track and magnetic data in the nearby basins!

The resurrection of DeRidge: New German ridge activities in the Atlantic

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The German Science Foundation ("Deutsche Forschungsgemeinschaft", DFG) is funding interdisciplinary research on the Mid-Atlantic Ridge for a period of 6 years as of October 2003. Of the two study areas to be looked at, one is near the island of Ascension between 4-11°S. The closeness to the intraplate volcano Ascension Island, the vast variations in relief along axis (from ca. 1200m to > 4000m) and geophysical evidence for thickened oceanic crust all point towards hotspot-ridge interaction being an important theme in this area.

The 6-year program will be cover the following themes:

- Energy and material transport from the mantle to the ocean
- Time scales of tectonic, magmatic, hydrothermal and biological processes on the spreading axis
- Characterization of the submarine volcanism (eruption rates, eruption volumes, eruption centres)
- Structural and spatial distribution of hydrothermal systems below the ocean floor
- Interaction of biological and hydrothermal processes
- Distribution of fauna along the spreading axes

The program has two particularly highly innovative features:

- The integrated study of pre-defined areas by groups covering the highly disparate fields of petrology, volcanology, geodynamics, geophysics, hydrothermalism, microbiology, macrobiology, oceanography, water chemistry and convection modelling
- The use of a state-of-the-art remotely-operated vehicle (ROV) for precise, well-located sampling and observation of the seafloor.

Details of the work to be carried out, cruises planned to the area and the scientists involved can be found on the web-site:
http://www.palmod.uni-bremen.de/FB5/Ozeankruste/SPP1144/SPP_1144_gb.htm

Interactions of the Easter and Foundation Plumes with the East Pacific Rise: A comparison

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Both the Easter and the Foundation Hotspots are located closely to the East Pacific Rise and in both cases the spreading rates are relatively fast. The plumes appear to form asymmetric bathymetric and geochemical anomalies of several 100 km width on the neighbouring spreading axes indicating a biassed material flow along the axis. However, while volcanic ridges of the Foundation Hotspot occur very close to the spreading axis, there is an about 150 km wide gap without volcanism between the Easter Hotspot and the East Rift of the Easter Microplate. This may indicate differences in the material flow and shape of the melting zone between the Easter and the Foundation systems.

The source compositions of the Easter and Foundation plumes resemble each other in terms of Sr, Nd, and Pb isotope ratios. Thus, the plumes probably sample the same source region in the lower mantle. Isotopic gradients along the spreading segments close to the plumes suggest mixing between plume material with high Pb isotope ratios and and material with low Pb isotope ratios residing either in the upper mantle or within the plume. No correlations exist between Pb isotopes and water depth possibly implying that the plume material can also have relatively low Pb isotope ratios. In this case, the radiogenic component may be easily fusible and is molten from the plume material as it ascends and melts beneath the spreading axis. Lateral flow along the axis may then lead to increasing depletion and exhaustion of the plume material. However, melting above the plume and at the spreading axes occurs over a range of pressures but we find no geochemical evidence for the presence of enriched garnet pyroxenite in the plumes.

The isotopic gradients occur in both cases along propagating ridge segments indicating that the tectonic evolution of the axis is coupled to the inflow of plume material. The bathymetric anomalies are only about 300 m shallower than the surrounding spreading axes and e.g. Na_2O contents in the basalts do not indicate a significantly increased degree of melting at the point of maximum inflow of enriched plume material. Consequently, both plumes appear to have relatively low excess temperatures (<50°C).

Interaction between the Mid-Atlantic Ridge and the Azores Hotspot during the last 85 Ma : emplacement and rifting of the hotspot-derived plateaux.

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New 1km x 1km bathymetric and Mantle Bouguer anomalies grids provide new insights on the temporal and spatial variations of melt supply to the ridge axis. The elevated seafloor of the Azores plateau is interpreted as resulting from the interaction of a mantle plume with the Mid-Atlantic Ridge. The presence of a large region of elevated seafloor associated with a thick crust between the Great Meteor Seamounts and the Azores platform on the Africa plate, and less-developed conjugate structures on the North America plate, favour genetic relations between these hot spot-derived structures. This suggests that a ridge-hotspot interaction has occurred in this region since 85 Ma. This interaction migrated northward along the ridge axis as a result of the SSE absolute motion of the Africa plate, following a direction grossly parallel to the orientation of the MAR. Kinematic reconstructions from chron 13 (~35 Ma) to the present allow a proposal that the formation of the Azores plateau begun around 20 Ma and ended around 7 Ma. A sharp bathymetric step is associated with the beginning of important melt supply around 20 Ma. The excess of melt production is controlled by the interaction of the ridge and hot spot melting zones. The geometry and distribution of the smaller-scale features on the Plateau record episodic variations of the hot spot melt production. The periodicity of these variations is about 3-5 Ma. Following the rapid decrease of widespread volcanism, the Plateau was subsequently rifted from north to south by the Mid-Atlantic Ridge since 7 Ma. This rifting begins when the MAR melting zone is progressively shifted away from the 200-km plume thermal anomaly. These results bear important consequences on the motion of the Africa plate relative to the Azores hotspot. They also provide an explanation to the asymmetric geochemical signature of the Azores hotspot along the Mid-Atlantic Ridge.

Plume-transform interactions at ultra-slow spreading ridges: Implications for Marion/Southwest Indian Ridge interactions

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We explore a potentially important variable in controlling ridge-hotspot interaction, the effect of transform offsets in limiting along-axis flow of plume material. We focus on the Southwest Indian Ridge (SWIR), where the "transform damming" effect is likely to be pronounced because of both long offset lengths and large contrasts in lithospheric thickness across the transform faults due to the ultra-slow spreading rate. We investigate the degree to which transform faults affect axial asthenospheric flow by performing a series of three-dimensional (3D) numerical experiments with simplified channel-flow geometry. 3D mantle viscosity structure for a ridge-transform-ridge system is determined based on temperature- and pressure-dependent viscosity laws. We consider six transform lengths, spanning 0 to 250 km in increments of 50 km. We then calculate the 3D viscous flow in response to an along-axis pressure gradient corresponding to a ridge-centred hotspot. Modelling results predict that transform faults affect along-axis asthenospheric flow in two important ways. First, transforms reduce along-axis flux. The longer the transform offset, the greater the reduction in across-transform flux relative to the zero-offset case. Second, transforms deflect shallow asthenospheric along-axis flow. The predicted transform damming effect is most pronounced for a viscosity structure that is strictly pressure- and temperature-dependent. Flux reduction effects could be less significant for viscosity laws that additionally consider dehydration, melting, and change in deformation mechanism. This model predicts that the waist width of an on-axis plume is dependent not only on such previously-explored factors as buoyancy and spreading rate, but also on the geometry of ridge segmentation. Along the SWIR, axial flow driven by the Marion plume is likely curtailed by the long-offset Andrew Bain and Discovery II fracture zones, severely limiting its lateral extent.

Helium Isotopes and Mantle Plume-Spreading Ridge Interactions

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Helium isotopes in oceanic basalts provide some of the most basic geochemical information on mantle reservoirs and their interaction. The ubiquitous presence of ^{3}He in mantle-derived rocks indicates that primordial volatiles are still being degassed from the Earth's interior. Helium escapes from the Earth's atmosphere and is not recycled by plate tectonics to the mantle, making the $^{3}He/^{4}He$ ratio unique among mantle tracers. The highest $^{3}He/^{4}He$ ratios, along with Ne isotope ratios that approach solar values, are found at Iceland and Hawaii. This is currently the strongest geochemical evidence that relatively undegassed deep mantle sources are involved in ocean island (hotspot) volcanism.

Mid-ocean ridge basalts away from hotspots display a narrow range of $^{3}He/^{4}He$, with a median value of 8.1 R_A. Ocean island basalts are more variable and often extend to higher $^{3}He/^{4}He$; the highest reported values of ~50 R_A are associated with the proto-Iceland plume. The large $^{3}He/^{4}He$ difference between the upper mantle MORB source and mantle plume sources makes He a powerful tracer of plume-ridge interaction. The classical example is the ~1000 km long $^{3}He/^{4}He$ gradient south of the ridge-centred Iceland hotspot. Such observations are consistent with mixing of plume-derived material and the asthenosphere, as proposed by J.-G. Schilling more than 30 years ago.

Spatial $^{3}He/^{4}He$ variations associated with off-axis plume sources are best documented at Easter, Bouvet, Amsterdam-St. Paul (ASP) and Galápagos. The spreading ridges in the vicinity of the Easter and ASP plumes both show along-axis variations related to melting and/or degassing of plume-derived material prior to when it mixes with the sub-ridge mantle.

In the Galápagos archipelago, volcanism is spatially dispersed across more than 500 km, due to shearing of the mantle plume away from the ridge by rapid, oblique motion of the Nazca plate. Geochemical mapping of the region therefore provides a rich picture of plume structure, flow patterns from plume to ridge, and the extent to which the plume influences melting processes and segmentation along the Galápagos Spreading Centre (GSC). Despite the presence of $^{3}He/^{4}He$ up to 30 R_A at the western and southern islands, no high values are observed along the GSC at a sampling density of <20 km. A large gradient between 89-93°E is observed, with $^{3}He/^{4}He$ decreasing westward from 8.5 to 6.8 R_A. Superposed on this gradient are small excursions in $^{3}He/^{4}He$ that are generally bounded by intersections of the ridge axis with volcanic lineaments radiating northward from the archipelago.

The $^{3}He/^{4}He$ results for the Galápagos plume-ridge system highlight some outstanding questions about what controls the geometry and wavelength of along-axis chemical variations. These include: the extent of chemical depletion/degassing by partial melting in the plume, how plume heterogeneity is transferred to the sub-ridge mantle, the extent of melt migration in sub-lithospheric channels between plume and ridge, and the relative importance of basal lithosphere topography sloping toward the ridge vs. lithosphere erosion by the hot plume centre.

Origin of the Indian- and Pacific-type MORB Mantle Isotope Signatures

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The origins of the geochemical heterogeneity of the upper mantle are fundamental constraints for mantle dynamics. An important first requirement to understanding plume-ridge interaction is a knowledge of the origin of MORB source heterogeneity. The Australian-Antarctic Discordance (AAD) is a geochemical boundary between Indian-type and Pacific-type upper mantle provinces that is unaffected by plume-ridge interaction. The juxtaposition of the two distinct mantle domains makes this an excellent location to explore and contrast the nature and extent of upper mantle geochemical heterogeneity.

Indian and Pacific Ocean MORB define two distinct bisecting arrays in a diagram of $^{206}Pb/^{204}Pb$ versus εHf. Basalts with ultra-depleted trace element signatures (e.g., low La/Sm) from the Indian side of the boundary represent one end-member of the Indian MORB array. These Indian ultra-depleted MORB have a unique isotope signature, with very high εHf and εNd and low $^{206}Pb/^{204}Pb$. Ultra-depleted Pacific MORB, represented by basalts from the Garrett transform fault, define one end-member of the Pacific MORB array. These Pacific ultra-depleted MORB have very similar εNd and $^{206}Pb/^{204}Pb$ to the ultra-depleted Indian-type, but have significantly lower $^{87}Sr/^{86}Sr$, εHf and $^{207}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ (for a given $^{206}Pb/^{204}Pb$ ratio). All of these ultra-depleted MORB may represent re-melting of a heterogeneous source that previously supplied MORB melt to the adjacent mid-ocean ridges.

The divergence of the isotope signatures of Indian- and Pacific-type MORB, including the ultra-depleted basalts, requires long-term differences in Rb/Sr, U/Pb, Th/Pb, Sm/Nd, and Lu/Hf parent-daughter ratios. The isotopic contrasts could be explained by different source compositions and/or ages of origin. The crossing quasi-linear isotopic trajectories are consistent with different pollution mechanisms of the upper mantle by recycled components. The Indian-type isotope signature may result from delamination and stirring of garnet facies continental material during rifting, while the Pacific-type may originate from processes associated with slab subduction, or by pollution with plumes containing recycled slab material.

Does the Icelandic plume really interact with the Mid-Atlantic Ridge?

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Iceland is certainly the best known example of a hotspot interacting with a spreading axis. Pioneer works have suggested that a mixing process occurs beneath Iceland in which N-MORB like melts derived from the depleted upper mantle mix with enriched melts derived from a deeper mantle. This enriched mantle is brought to the surface of the Earth by a plume of hot material rising by convection from the deeper mantle. Further works, essentially on O isotopes, proposed that recycling of a hydrothermally altered basaltic crust may play an important role as this seemed the only plausible solution to explain the rather low $\delta^{18}O$ measured in many fresh lavas. The large volume of acidic rocks also supported models implying an important recycling and melting of the present crust. Then, further radiogenic isotope studies demonstrated that mixing indeed occurs between the Icelandic melts and both spreading axes (Kolbeinsey and Reykjanes), but along these ridges and not beneath Iceland. They also showed that Iceland magmas contain a depleted component, which is isotopically and chemically distinct from the one seen along the Northern Mid-Atlantic ridge. Recent works have suggested that the influence of the surrounding upper mantle is almost not seen on radiogenic isotopes of incompatible trace elements and, thus, that Icelandic magmatism is mostly plume related. It has been proposed that the geochemical heterogeneity of the magmas come from the plume which is assumed to contain fragments of an ancient (1.5Ga) recycled oceanic crust. This layered crust contained both basalts and gabbros, which now melt within the plume in different conditions and proportions leading to the geochemical signatures of the alkali basalts and olivine tholeiites. The most recent works suggest the existence of more discrete components within the plume related to a more complex composition (presence of sediments) of the recycled crust. In conclusion, it does not seem necessary to involve a contribution of N-MORB-like melts to Icelandic magmatism to explain the heterogeneity of the basalts.

Plume-ridge interaction north of Iceland: Kolbeinsey Ridge seismic experiment

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Hotspot-ridge interactions affect the melt production at nearby mid-ocean ridges; the spatial and temporal pattern of this interaction can be measured by determining crustal thickness variations. We present results from a seismic refraction experiment to measure crustal thickness along and across the Kolbeinsey ridge north of Iceland (KRISE). Crustal thickness variations along the ridge axis will help constrain geodynamic models of the influence of the Iceland hotspot on the spreading centre, while variations perpendicular to the ridge axis should reveal temporal variability in hotspot influence.

We surveyed a 230-km-long along-axis line, situated about 10 km east of the Kolbeinsey Ridge, and two cross-axis lines which were 710 and 140 km long, and located 70 and 180 km north of the Icelandic coast, respectively. The three profiles were surveyed during June, 2000, using the University of Bergen research ship *Håkon Mosby* and the Icelandic Coast Guard Cutter *Ægir*. We used 33 three-component ocean bottom seismometers (OBS) from the University of Hokkaido. The OBSs were placed at 15 km intervals along the ridge axis, 10 km intervals across the ridge axis, and 30 km intervals east of the Iceland margin. The seismic source was a 4800 cu. in. four-element airgun array and the shots were spaced 200 m. We also collected magnetic, gravity and ministreamer reflection data along the refraction lines.

For each refraction line, we invert Pg and PmP arrivals using the tomography method of Korenaga *et al*. (JGR, 1999). We include the sediments *a priori* based on the ministreamer reflection data. We find that crustal thickness decreases to the north along the Kolbeinsey Ridge; the crust is about 13 km thick at 200 km from the centre of the Iceland hotspot and about 10 km thick at 400 km from the centre of the hotspot.

The melt flux at the Kolbeinsey Ridge appears to be smaller than at similar distances along the Reykjanes Ridge to the south of Iceland (where crustal thickness is 18 km and 11 km, at 200 and 400 km from the hotspot centre, respectively). This observation is consistent with the north-south asymmetry in ridge axis elevation; to the north along the Kolbeinsey Ridge the ridge axis deepens more rapidly than to the south along the Reykjanes Ridge. We find that the Iceland hotspot enhances melting more substantially at the Reykjanes Ridge than along the Kolbeinsey Ridge. This asymmetry in interaction between a hotspot and the adjacent spreading centres has not yet been explained by geodynamic models.

Seismic Imaging of the Galápagos Plume and Implications for Plume-Ridge Interactions

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The near-ridge setting of the Galápagos provides ideal conditions for investigating plume-ridge interactions. In anticipation of future experiments designed to investigate the Galápagos hotspot and the adjacent Galápagos Spreading Center (GSC) system, we conducted a land-based seismic experiment designed to image the structure of the crust and upper mantle beneath the archipelago. The data comprise broadband, three-component seismograms recorded at twelve sites over 3.5 years and an active-source seismic refraction profile. We discuss our findings and their implications for future experiments.

Receiver function analysis indicates that the Galápagos plume extends to depths of at least 410 km. We observe a thinning of the mantle transition zone by 18 ± 8 km relative to the surrounding region within an area approximately 100 km in radius centered about 40 km SW of the center of the island of Fernandina. This anomaly is consistent with an excess temperature of 130 ± 60 K within this volume of the transition zone, comparable with that inferred beneath the Iceland and Society hotspots. While the anomalously thin region of the mantle transition zone is spatially restricted, active volcanism in the Galápagos occurs to the east and north. This implies that ascending mantle is deflected eastward by the motion of the Nazca plate over the plume and that it is also transported northward to the Galápagos spreading center by plume-ridge interactions.

Tomographic inversion of body-wave delay times reveals a pronounced low-velocity anomaly centered above the area of thinned transition zone. At 200 to 300 km depth this anomaly, which we interpret to be the axis of the plume, is narrower and more pronounced than the anomaly imaged beneath Iceland. At depths less than 150 km the region of lowest seismic velocities, inferred to be plume-derived material, is deflected first to the northeast beneath the central archipelago and then to the north-northwest toward the Wolf-Darwin lineament. There is little evidence of hot plume material "pancaking" beneath the lithosphere, particularly beneath the northern islands of Pinta, Marchena, or Genovesa, which appear to be underlain by mantle that is seismically fast in comparison with mantle beneath the Wolf-Darwin lineament. The delivery of plume material to the ridge axis along the Wolf-Darwin lineament, as our initial results suggest, cannot be the result of simple thermal erosion at the base of the lithosphere by a fixed plume because the geometry is not that expected from plate kinematics.

On the basis of our results, we suggest that future experiments be designed to image structure in at least three crucial areas: (i) to the southwest of Fernandina where the plume penetrates the mantle transition zone; (ii) near the Wolfe-Darwin lineament that connects the Galápagos archipelago to the nearby GSC; and (iii) to the east of the archipelago where upper mantle velocities appear seismically fast, possibly indicating the presence of depleted, buoyant upper mantle that supports the hotspot swell.

Geochemical Systematics of Hotspots and Mid-Ocean Ridges Arising from Melting and Buoyant Upwelling of a Non-Layered Heterogeneous Mantle

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Large gradients in trace-element and isotope compositions of mid-ocean ridge magmas are dominant manifestations of hotspots-ridge interactions, but the chemical mixing processes that cause these observations are still poorly understood. A common explanation is that mantle plumes deliver lower mantle material to mid-ocean ridges and this material is compositionally distinct from the ambient upper mantle. The lower-mantle, "plume material" is most concentrated in magmas erupted near hotspot centres, but is proposed to becomes progressively weaker away from hotspot centres as the plume mixes with the ambient asthenosphere until eventually, only upper mantle feeds mid-ocean ridge magmatism. A dilemma arises because models of the mantle dynamics predict that as plume material expands along the mid-ocean ridge, it pushes all of the ambient mantle out of its way so that no mixing is possible between the two materials over the whole length of ridge influenced by the plume. Another problem arises from global-scale geodynamic models that predict convection to efficiently stir the whole mantle such that a compositional distinction between the lower and upper mantle cannot develop in the first place.

We present models of decompression melting in which mantle heterogeneities are present as veins or small blobs equally numerous in plume mantle as it is in the ambient mantle. We consider three different components, each with different trace element and isotopic characteristics. Enriched mantle (EM) is highly concentrated in the most incompatible trace elements, has isotopic characteristics reflecting long-term enrichment, and begins melting deepest. Pyroxenite has a depleted trace-element composition, Pb isotope compositions reflecting a high U/Pb ratio, and begins melting at intermediate depths. Depleted mantle (DM), the most abundant (90%) component, is depleted in the most incompatible elements, has corresponding isotope signatures, and begins melting shallowest. Models predict the deeper melting EM and pyroxenite components to be preferentially extracted at intraplate settings where thick lithosphere limits melting to large depths and low extents. In contrast, the shallower melting, DM is more heavily sampled at mid-ocean ridges where thinner lithosphere allows for shallower and more extensive melting. Another factor that is predicted to contribute to differences between hotspot and normal mid-ocean ridge basalt chemistry is the pattern of mantle flow. EM and pyroxenite can be heavily extracted by plume-driving upwelling, which is most rapid at depth and decreases to zero at the base of the lithosphere. In contrast, all mantle components, including DM, can be more evenly sampled at normal mid-ocean ridges where plate spreading allows for more uniform upwelling with depth. The overall consequence is incompatible trace-element and Sr, Nd, and Pb isotope ratios with large variability, extending to more enriched compositions at hotspots, and a smaller range of variability, with more depleted compositions at mid-ocean ridges. We thus show how many major systematics of MORB and OIB geochemistry can arise from a ubiquitously heterogeneous mantle without large-scale chemical layering between the upper and lower mantle. The implication for mantle plume-ridge interactions is that plume-driven deep upwelling is likely to be strongest where the ridge is closest to the plume centre, and can decrease with along-axis distance away from the plume. These along-axis changes in upwelling could be responsible for the changes in EM and pyroxenite contributions to mid-ocean ridge basalts and the associated mixing trends along hotspot-influenced ridges.

Hotspot influence at the Galapagos spreading centre: inferences from Galapagos island seafloor morphology and geochemistry

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The Leading Edge of the Galapagos Hotspot: Geochemistry and Geochronology of Submarine Glasses coupled to new sidescan sonar imagery

Recent mapping of the western Galapagos archipelago (on *R/V Revelle*, using the HMRG towed sidescan sonar MR1, and Simrad EM120 multibeam) provides a dramatic new view of the volcanic constructional processes that have created the Galapapagos islands. The western flank of Fernandina volcano, which is at the leading edge of the hotspot (with respect to plate motion) is characterized by prominent Northwest, West, and Southwest rift zones, which are constructed of hummocky pillow lavas. Older lava flow terrain is distinguished by weaker acoustic return, whereas extensive younger flows are characterized by strong backscatter patterns with distinctive flow-like margins. MR1 sidescan sonar mapping provides an important new geologic and stratigraphic context for understanding the submarine Galapagos platform, particularly from a geochemical perspective. Fernandina lavas have high $^{3}He/^{4}He$ ratios, up to 29 times atmospheric, and solar-like neon isotopic compositions, characteristics which suggest they are derived from deep mantle sources. The high $^{3}He/^{4}He$ ratios, and rapid eruption rates at Fernandina also indicate that it lies directly above the center of the Galapagos hotspot. New data shows that the western Galapagos submarine lavas have similar geochemical characteristics to the most closely associated subaerial lava flows. The hotspot influence, as inferred from $^{3}He/^{4}He$, falls off in all directions from Fernandina, suggesting that it can be viewed as a "point source". The helium data from Fernandina, in conjunction with new data from the Galapagos Spreading Center (Detrick *et al.*, 2002), are supportive of the recent model of Braun and Sohn (2003) which suggests that hotspot geochemical contributions to the Galapagos spreading center are controlled by melt transport rather than solid mantle flow.

Evidence for anomalously hot mantle east of the Australia-Antarctic Discordance

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We present the results of an investigation of the crustal structure of the axis and flanks of the South East Indian ridge (SEIR) from 130°E to 160°E. This area corresponds to the eastern side of the Australia-Antarctic Discordance, a section of the SEIR which displays axial morphology and discontinuity characteristics of a slow-spreading ridge, despite its intermediate spreading rate. The AAD morphological anomalies are inferred to result from a mantle temperature colder than normal. Previous studies have shown that to the west of the discordance area, the transition between intermediate-spreading and slow-spreading ridge characteristics appears relatively smooth. The eastern side of the AAD, however, is poorly known. We investigate the morphology and crustal structure in the Australia-Antarctic basin east of the AAD, by estimating bathymetry anomalies with respect to a model of lithospheric cooling, residual mantle Bouguer anomalies (RMBA), and crustal thickness variations. We use free-air gravity anomaly deduced from satellite altimetry measurements, and bathymetry measured along ship tracks.

Free air gravity anomalies (FAA) display numerous gravity highs on the flanks of the SEIR between 130°E and 160°E, and between 40°S and 63°S, which we interpret to be off-axis volcanoes and volcanic ridges. The bathymetry anomaly in the basin defines an arcuate-shaped series of bathymetric lows marking the AAD, pointing west. East of the AAD, the depths are generally shallower than predicted by the lithosphere cooling model. The bathymetry anomaly displays a pronounced asymmetry, with anomalously shallow areas on the southern flank of the SEIR. The maps of RMBA and crustal thickness variations show a similar pattern. The gradient along an isochron for these anomalies is larger east of the AAD than west. All anomalies display a strong asymmetry, with shallow depths, RMBA lows and crustal thickness maxima south of the SEIR, between 135°E and 160°E. The amplitude and the distribution of the anomalies suggest that the crust is anomalously thick and/or that the mantle anomalously hot in this area, not only compared to the AAD, but also to the rest of the Australia-Antarctic basin. These observations tend to confirm the interpretation of the gravity highs in terms of off-axis volcanoes and volcanic ridges. These inferences are also supported by a positive geoid anomaly and tomographic data showing that the Rayleigh wave velocity is particularly fast under this area at depths deeper than 200 km. All these results seems to indicate that the mantle temperature under the flank of the SEIR east of the AAD is anomalously hot. There seems to be a transition between an anomalously hot mantle east of the AAD and an anomalously cold mantle under the AAD. The origin of these mantle temperature anomalies and the existence of an asthenospheric flow from east to west in the area are still debated.

Ridge-hotspot interactions at ultra-slow spreading conditions: Bouvet/Marion hotspots and the SW Indian Ridge

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The central and western SW Indian Ridge (SWIR), which spread at ultra-slow full rates of only 14-18 mm/yr, provide a unique setting to investigate a number of fundamental problems in plume-ridge interactions. Two factors are important for plume-ridge interaction at such ultra-slow spreading rates: (1) very thick lithosphere as a result of rapid lithospheric cooling; and (2) complex ridge segmentation pattern. The Bouvet and Marion hotspots interact with the SWIR near 5°E and 37°E, respectively, yielding the following geophysical anomalies: (1) The Bouvet hotspot, approximately 300 km east of the Bouvet Triple Junction and 55 km south of the SWIR, imparts a high-amplitude (~100 mGal) mantle Bouguer gravity anomaly low to the SWIR, implying considerable crustal thickening, anomalously warm mantle, or a combination of both. The Bouvet anomaly is quite localized between the Bouvet and Islas Orcadas FZs. (2) There is little off-axis indication of a Bouvet hotspot track in crust formed ~30-90 Ma, possibly suggesting that the flux of the hotspot may change with time, or that the hotspot may not be a deep-seated mantle plume but rather a recent local melting anomaly enhanced by proximity to the SWIR and complex upwelling patterns around the Bouvet Triple Junction. Our geophysical mapping in 2001/2003 revealed that the northern flank of the Shaka fracture zone is overlain by a number of relict volcanic cones. The largest of these volcanic cones is associated with a –50 mGal mantle Bouguer gravity low. The rocks dredged from the cone contain layered ashflows and lapilli tuff, supporting the hypothesis that Bouvet hotspot interacted with the Shaka fracture zone about 20 Ma. (3) The Marion hotspot is a long-lived feature that is associated with widespread, 88-85 Myr-old flood basalts in Madagascar and the adjacent northern Madagascar Ridge. At present the Marion hotspot lies about 260 km south of the SWIR and is associated with a clear mantle Bouguer gravity low both off and on the SWIR axis. We postulate that the Andrew Bain and Discovery II FZs, with offsets of 720 and 350 km, respectively, act as “transform terminators” that limit the along-SWIR flow of the Marion plume.

While the above and other investigations point to the importance of thick lithosphere and large transform offsets in controlling the style of ridge-hotspot interaction in ultra-slow spreading environments, both the Bouvet and Marion hotspots have yet to be investigated in detail using extensive on- and off-axis multibeam bathymetric mapping, closely spaced and targeted rock sampling, seafloor geological observations using high-resolution acoustic and near-bottom geophysical instruments, and seismic refraction and reflection experiments to measure crustal thickness. We argue that it is of great merit to conduct such detailed investigations in the next decade in order to significantly advance our understanding of the end-member processes of ridge-hotspot interaction in ultra-slow spreading crust.

The Foundation Hotspot-Pacific-Antarctic Ridge System: the case of a spreading ridge moving towards a hotspot

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The Foundation chain formed during the last 21 Ma by the action of a hotspot, presently located roughly 35 km west of the axis of the Pacific-Antarctic Ridge (PAR). The Foundation-PAR system is the best documented case of a fast spreading ridge approaching a hotspot and interacting with it. The eastern part of the chain, near the Pacific-Antarctic ridge, is formed by volcanoes younger than 5 m.y., built on a plate less than 5 Ma old. They are distributed along two sub-parallel lines. The north line, corresponding to the larger volcanoes, is the main locus of the volcanism. The south line was probably formed along fissures on top of the flexural arch resulting from the emplacement of the north line. The approach of the PAR to the hotspot resulted in the reduction of the effective elastic thickness (Te) of the plate towards the spreading ridge from ~ 5 to 0 km. This spatial variation of Te correlates with a change in the morphology and in the volume of the volcanoes and with a reduction in the average distance between the north and south lines from ~100 to ~70 km. These observations suggest an important control of the lithosphere on the volcanic processes.

Off axis, the chemical and isotopic composition of the basalts reveal a growing influence of the ridge on the plume volcanism. The pattern is coherent with a mixing between two sources, occurring when the two melting zones merge and overlap. The morphology, crustal structure and the chemical composition of the lavas of the axial area of the PAR show evidence of the influence of the hotspot. The crust is 1.5 km thicker where the hotspot is nearer to the PAR. The anomalous ridge elevation is 650 m and the along-axis width of the chemical anomaly is at least 200 km. A comparison of these axial parameters with those derived for other ridge-hotspot systems suggests that the amount of plume material reaching the ridge axis is smaller for the Foundation-PAR system. Excess crust is being created at the PAR since ~1 Ma, at least. Accordingly, a progressive reduction in the volume of the off-axis volcanoes younger than 2 m.y. is observed. A possibility is that the reduction in the off-axis volcanism relates with the capture of an increasing amount of plume material by the ridge, thus acting as a drain. In this case, the connection between the ridge and the hotspot would have been active for the last 2 m.y.. These observations imply a weak connection between plume and ridge. Cumulative effects of a fast spreading rate and of a fast ridge-hotspot relative motion can be responsible for this weak plume-ridge flow as well as for a delayed connection. The flow from the hotspot may be less efficiently channeled towards the ridge axis when a fast ridge is rapidly moving towards a hotspot.

Plume-Ridge Interaction: a Geochemical Perspective from the Reykjanes Ridge

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A fundamental question for those of us studying Plume-Ridge interaction is by what processes do ‘plumes’ affect ridges. While the scientific community is currently contending the origin and nature of ‘plumes’, there is no doubt that close proximity to ‘plume’ centres causes spreading ridges to have certain structural, volcanic and geochemical effects. In essence, two end-member processes may account for the ‘plume’ phenomenon: the classic and current paradigm of a column of rising mantle, made buoyant by an excess of temperature and originating deep within the mantle, or a non-dynamic mechanism involving a geochemical anomaly, residing passively in the shallow mantle, that melts spontaneously as a result of intraplate stresses or asthenospheric motion. While *a priori*, both mechanisms may hold true, they can be distinguished for individual ‘plumes’ where they interact with a spreading ridge that leaves a lithospheric and crustal trail recording the history of that interaction.

The Reykjanes Ridge, southwest of Iceland, has all the attributes associated with a ridge-centred ‘plume’. These include: thickening of the crust, shallowing of the ridge axis, an increase in segment length, and enrichment in geochemical tracers of the ‘plume’ mantle. Evidence for dynamic interaction between ridge and plume comes from southward closing V-shaped ridges, centred on the plate boundary, that indicate southward advection of plume mantle away from Iceland. Geochemical tracers include incompatible trace element enrichment and isotope ratios (*e.g.* Sr, Nd, Pb and He) that show multi-component mixing between several depleted and enriched sources. These sources are resident in the mantle beneath the Reykjanes Ridge and show modification by melting processes, consistent with a history of advection away from Iceland. Further evidence for interaction between a dynamic ‘plume’ and spreading ridge comes from the Réunion-Central Indian Ridge couplet, which comprises an off-axis plume and medium-rate spreading centre. Here, the ridge also exhibits attributes associated with ‘plume’ influence such as shallowing depth, increase in segment length, and multi-component geochemical mixing that varies with distance along the plate boundary. The enriched components mimic the geochemical evolution of the Reeunion ‘plume’, which has changed particularly strongly over the past 8Ma.

Both the Icelandic and Réunion ‘plume’-ridge couplets provide compelling evidence for advection and lateral flow of ‘plume’ mantle away from a central source and subsequent mingling with depleted, sub-ridge mantle characteristic of MORB genesis. As such, these studies support the current paradigm for mantle ‘plumes’ as phenomena associated with actively upwelling material that has resided deep within the mantle and whose influence upon spreading ridges is profound. I suggest further experiments should be conducted to both reveal the effects of lateral ‘plume’-mantle flow and to determine better the evolution of ‘plumes’ by tracing their affects recorded by seafloor spreading.

The Farallon to Nazca Plate Transition: The Missing Time Period

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We present the final results of Doug Wilder's Master's thesis: A plate tectonic analysis of the Pacific-Nazca plate motions since 30 Ma. The magnetic anomalies have been well identified from Present to magnetic anomaly 3 and from magnetic anomaly 7 to anomaly 13 in the published literature. We chose to focus on the magnetic anomalies between these two time periods where a major plate motion change occurred (the break-up of the Farallon plate into the Nazca plate and the formation of at least one microplate and several propagating rifts). The primary transfer of lithosphere during this period was from the Pacific plate to the Nazca plate, thereby leaving a gap of magnetic anomalies on the Pacific plate and doubling them on the Nazca plate. We have extended our interpretation as far back as anomaly 5d, but were unable to proceed further. The new nine finite poles of rotation and stage poles were presented at the EGS-EUG-AGU meeting in Nice France earlier this year. We present our proposed plate tectonic evolution of this area, which can be readily tested with two separate magnetic and multibeam mapping expeditions between anomalies 5d and 7, one on each plates. Recent cruises in the south Pacific by the Germans, French, and Americans have focused on hotspot chains in the region. However, one of the biggest obstacles in resolving the hotspot-plate motion is the poorly defined Pacific-Nazca relative plate motion between anomalies 5d and 7. International collaboration to map these two remaining north-south corridors that involves a major change in plate motion direction and speed, propagating rifts, ephemeral microplates, and the associated lithospheric transfer, would lead to a definitive plate motion history and enable a more accurate test of hotspot fixity between the Pacific and Nazca plates.

Is there really a plume-ridge interaction along the Central Indian Ridge between 18º and 20ºS?

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The Central Indian Ridge (CIR) between 18º and 20ºS shows morphological evidence for hotspot-ridge interaction, such as longer segment than neighbourhood segments and the presence of off-axis ridges (Rodrigues, Three Magis and Gasitao ridges). It has been shown that the basalt chemistry of off-axis CIR ridges is influenced by the Réunion plume [1-2]. Do the basalt sampled along the CIR axis also show a Réunion plume influence?

We have measured major and trace elements and Sr, Nd and Pb isotopes on 35 glassy samples from the CIR segment between 18º and 20ºS. Major elements do not show large variations, but trace element ratios (TER) increase regularly from South to North (Ba/Th=68 to 99). Pb isotope data ($^{206}Pb/^{204}Pb$=18.304-18.703, $^{207}Pb/^{204}Pb$=15.502-15.571, $^{208}Pb/^{204}Pb$=38.182-38.737) define a linear array in both Pb isotope space. Sr and Nd isotopic compositions show little variations ($^{87}Sr/^{86}Sr$=0.7035-0.7039; ε_{Nd}= +7.0 to +8.2) and fall within the range of Indian MORB.

There are two lines of evidence indicating the absence of a Reunion plume influence on the CIR. First, the Pb isotope array does not trend towards the Réunion field. Second, Pb isotope ratios display an increase from South to North, similar to that observed with TER, resulting in correlation between TER (e.g. Ba/La, Ba/Th, Nd/Sm…) and Pb isotope ratios. None of these correlations points towards the Reunion field, ruling out a chemical interaction between the Reunion plume and the CIR.

The TER-Pb isotope correlations can be interpreted as reflecting melting of a heterogeneous source composed by two locally distinct end-member compositions [3]. Linear regressions of TER-Pb isotope data can be used to characterize the enriched and depleted end-member mantle sources. The enriched component is defined by $^{206}Pb/^{204}Pb$: 18.62; $^{207}Pb/^{204}Pb$: 15.55; $^{208}Pb/^{204}Pb$: 38.70 and the depleted component by $^{206}Pb/^{204}Pb$: 18.24; $^{207}Pb/^{204}Pb$: 15.50; $^{208}Pb/^{204}Pb$: 38.04. Extreme mantle components (as EM or DMM…) are not required.

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Fluid mechanics of plume-plate and plume-ridge interactions

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Most of what we know about mantle plumes is inferred from the strong geophysical and geochemical signatures generated by their interaction with the lithosphere. The purpose of my talk will be to review the fluid mechanics of this interaction, with an emphasis on physical scaling arguments and simple models.

The essential physical idea is that plume material impinging on the lithosphere spreads out in the form of a "pancake" whose characteristic width is much greater than its thickness. This fact allows one to predict the thickness of the pancake and the flow within it using the theory of viscous flow in thin layers (lubrication theory.) The shape and thickness of the plume pancake are controlled by a balance of three effects: isotropic gravity-driven spreading of the buoyant material; advection of that material by the ambient mantle flow associated with the plate motion; and the (possibly time-variable) flux of plume material from the deeper mantle. Lubrication theory enables one to include all these effects in a single partial differential equation which is easy to solve numerically.

The simplest version of the model is for the case of an "intraplate" plume spreading beneath a moving but non-rifting lithosphere. Using the example of Hawaii, I will show that the lubrication theory model successfully predicts the geometry of key surface observables such as the Hawaiian swell and its associated geoid anomaly. This success motivates the application of similar ideas to the more complicated case of a plume interacting with the rifting oceanic lithosphere at a mid-ocean ridge. Several new effects now come into play: a more complicated ambient mantle flow ("corner flow"); the sloping base of the lithosphere; and the possibility of migration of the ridge relative to the plume. I will show how these factors influence the along-strike width of the plume material beneath the ridge ("waist width"), a key quantity which should correspond to the typical width of the plume-induced geophysical and geochemical anomalies. I will also discuss how these model predictions are modified by accounting for a more realistic dependence of viscosity on temperature and water content. Finally, I will suggest that a critical unresolved question concerns the apparent conflict between the fluid dynamical models, which typically predict a broad distribution of plume material, and various lines of geochemical and morphological evidence that have been interpreted as requiring more localized or "channelized" flow of plume material beneath the lithosphere.

Seafloor Magnetotelluric experiments using Ocean Bottom Electro-Magnetometers

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The magnetotelluric (MT) method, applying to the ocean bottom electromagnetic (EM) data, allows us to estimate an electrical conductivity structure of the upper mantle beneath the ocean floor. Since the electrical conductivity depends on temperature, the presence of melt, the influence of volatiles such as hydrogen, and the a-axis of olivine in an anisotropic fabric, the ocean bottom EM study is a sensitive tool to probe these parameters in the upper mantle.

We have developed a new type of ocean bottom electro-magnetometer (OBEM) and a new technique for OBEM data analysis in order to obtain more accurate and reliable conductivity structure. Our OBEM is compact, easy to handle, and measures three components of magnetic field variation by fluxgate type magnetometers, three components of electric field variation by voltmeters with five Filloux-type silver-silver chloride electrodes (Filloux, 1987), instrument tilts, and temperature. Our new technique for incorporating seafloor topography as *a priori* information in electromagnetic modelling (Baba and Seama, 2002), overcomes a long-standing problem for seafloor EM studies; that is to model the effect of seafloor topography accurately but inexpensively. The technique is based on a transformation of the topographic relief into a change in electrical conductivity and magnetic permeability within a flat seafloor. The technique allows us to model arbitrary topographic changes without extra grid cells and any restriction by vertical discretization. Thus, we can model very precise topographic changes easily without an extra burden in terms of computer memory or calculation time.

We proposed seafloor MT experiments using the OBEMs for investigations on Ridge-Hotspot Interaction in the following two cases. The first case is a seafloor MT experiment on ridge axes near an on-axis hot spot to investigate the depth of the melt beginning beneath the spreading axes. Once the melting initiates, the conductivity value is expected to decrease from the conductivity value of influence of dissolved hydrogen on an olivine mantle to that of the dry olivine, as suggested by 1D conductivity structure nearly beneath the spreading axis of the Mariana Trough (Seama *et al*, in prep.). The change in the melt beginning depth as a function of the distance from the on-axis hot spot would be an important parameter on the Ridge-Hotspot Interaction. One of the possible targets for the experiment is the Mid-Atlantic Ridge with the Iceland hot spot. The second case is a seafloor MT experiment on ridge axes near an off-axis hot spot to investigate a passage of the hot spot material from the off-axis hot spot to the ridge axes. We do not know the existence of the passage from the structural point of view and what it looks like. A high conductive structure for the passage would be expected, if the passage would involve a partial melt. One of the possible targets for the experiment is the Central Indian Ridge with the Reunion hot spot.

Morphology of the Mid-Atlantic Ridge near the Iceland Hotspot

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The profound influence of Iceland hotspot on the slow-spreading (10 km Ma^{-1}) Mid-Atlantic Ridge (MAR) is most clearly seen on the Reykjanes Ridge (RR), which extends SW to Bight Fracture Zone (BFZ) at 57ºN, about 1200 km from the hotspot centre. South of BFZ the MAR has the characteristics of a "typical" slow-spreading ridge: a well-formed median valley offset and divided into segments orthogonal to the spreading direction by transform faults and non-transform discontinuities (NTDs), with a "rough" topography produced by large normal fault scarps. These characteristics change progressively as the hotspot is approached. The amplitude of the median valley diminishes, and around 58º45'N it is replaced by an axial high which grows in amplitude northwards to resemble the cross-section of a fast-spreading ridge. The segmentation breaks down, with the last clear NTD at 57º55'N, having a mere 3 km offset. Off-axis, satellite gravity and magnetic anomalies show that the ridge geometry has changed over time between orthogonal-with-offsets and oblique-without-offsets. In Early to Middle Eocene (~50 - 40 Ma), immediately following continental break up, the ridge was oblique. It became orthogonal with offsets around late Middle Eocene, but returned to an oblique state in a time-transgressive way, starting in Late Eocene (35 Ma) near the Greenland-Iceland-Faeroes Ridge in the north, and moving progressively south to reach BFZ today. The current Ridge trends 28º oblique to the spreading normal and exhibits little short-wavelength variation in the Mantle Bouguer Anomaly. Oblique spreading apparently occurs when the ratio of ridge spreading resistance to transform slip resistance falls below some critical value, presumably because the hotspot produces thinner and weaker lithosphere near the ridge axis. The RR axis is marked by a succession of partially overlapping, en echelon Axial Volcanic Ridges (AVRs) that trend sub-normal to the spreading direction in a 10-15 km wide axial zone. Their elevations tend to diminish toward Iceland. Minor faulting in this axial zone is also sub-normal to the spreading direction. Beyond this zone are major normal faults more nearly parallel to the oblique trend of the Ridge itself. The amplitude of normal faulting generally decreases towards the hotspot. The patterns of AVRs and faulting can be explained by the distribution of stresses that occur in an extending plate with an oblique, weak zone at its axis. Within the region of post-Eocene oblique spreading is a series of nested "V-shaped ridges" (VSRs) straddling the RR axis, characterised by high Free-Air gravity and thicker than normal crust. They have propagated south from Iceland at speeds of some 200 km Ma^{-1} and formed episodically about every 6 Ma. They are believed to reflect increases in mantle melting due to variability either of temperature or composition of the hotspot source. Superimposed on the monotonic changes is a second-order effect associated with the VSRs. Where they intersect the axis, hotspot-related features (axial high, diminished normal faulting and possibly higher degree of volcanism) are enhanced, reflecting the effects of more abundant melt and possibly hotter mantle. The effect of the hotspot on the MAR is asymmetric. The same hotspot influences, particularly the change from median valley to axial high, and to a less clear extent the VSRs, are seen on the Kolbeinsey Ridge (KR) north of Iceland, but to a diminished extent. The first major ridge offset north of Iceland, of some 50 km, occurs near 69ºN, about 450 km from the centre of the hotspot, and the median valley reappears just north of this. The RR and KR make an angle of 150º to each other, while in Iceland itself the active ridge (the eastern neovolcanic zone) is offset some 100 – 200 km eastwards via the South Iceland Seismic Zone and the Tjornes Fracture Zone. Thus, within some 250 km of the hotspot centre, the ridge is (and has been) jumping eastwards to remain over the hotspot, possibly at peaks of hotspot activity as represented by the VSRs.

Seismological Constraints on Mantle Flow and Melt Generation Beneath Iceland

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Characterized by bathymetric swell, an anomalously thick crust, and atypical geochemical signatures, Iceland and the adjacent Mid-Atlantic Ridge is a classical example of ridge-hotspot interactions. Several seismic studies, especially the recent broadband seismic experiments in Iceland, have provided a wealth of new information about the crustal and mantle structure beneath the hotspot. Initial analyses have revealed a cylindrical zone of anomalously low P and S wave velocities extending from the shallow upper mantle to at least 400 km depth and a thinner-than-normal mantle transition zone beneath Iceland that suggests this anomaly extends into the lower mantle. Several aspects of the mantle upwelling beneath the hotspot, however, remain unresolved due to a fundamental limitation in the previous studies, in which seismic waves were treated as one-dimensional rays. The ray approximation is valid strictly only for infinite-frequency waves. The observed seismic waves have a finite frequency range and are sensitive to three-dimensional (3D) structure off the geometric ray path. The travel time shift measured by broadband waveforms can differ significantly from the prediction of ray theory. Furthermore, because of the differences in their wavelengths, P and S travel times are sensitive to different 3D volumes even for pairs of P and S waves with the same ray paths. These limitations have rendered estimates of the magnitude of wavespeed perturbations and $\delta \ln V_s/\delta \ln V_p$, an important parameter often used as an indicator of the presence of melt or compositional heterogeneity, problematic.

We have developed a new tomographic method based on Born single-scattering approximation in conjunction with body wave propagation and applied the new method to the available seismic data from Iceland. The new formulation corrects the deficiencies of ray approximation by expressing explicitly the influence of velocity heterogeneity off the ray path upon a travel-time shift as a 3D "banana-doughnut" shaped sensitivity kernel. Given approximately equal fits to the travel time data, the magnitudes of both P and S velocity anomalies derived from finite-frequency travel time kernels are significantly greater than those from rays and in previous studies. The magnitude of kernel-derived P velocity anomaly is on average 2-3 times as large as that of the ray-derived in the depth range of interest (100-400 km). The magnitude of the S wavespeed perturbations increases by a factor of 1.6 to 2.3 in the finite-frequency models relative to the corresponding ray-based models. The greater magnitudes of wavespeed perturbations from finite-frequency travel times is in a better agreement with P-to-S conversions from the 410- and 660-km discontinuities beneath Iceland, which require that the average S velocity above the 410-km discontinuity is ~7% lower than in the IASP91 earth model. It is difficult to fully account for the large velocity anomalies by the excess temperature of the presumed mantle plume constrained by the thinning of the mantle transition zone and other observations (ΔT=150-250 K). A joint inversion of finite-frequency P and S travel times also reveals that $\delta \ln V_s/\delta \ln V_p$ is greater than 2 from shallow mantle to at least 400 km beneath central Iceland, further indicating the presence of melt over a much greater depth range than previously suggested.

Variations in the Geochemical and Isotope Characteristics of Mantle Peridotites along the Mid-Atlantic Ridge Strike and their relationships with Distribution of Plume and Spreading Magmatic Provinces

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All data on the variations of the petrological and geochemical parameters of the mantle peridotites along Mid-Atlantic Ridge (MAR) strike to North of the Equator suggest that compositional segmentation of the MAR is manifested not only in the basaltic layer but also in the associated mantle residues. The indicator petrogenetic parameters (melting degree, enrichment in LREE, and concentration of strongly incompatible elements) recorded in the residual peridotites are well correlated with the analogous parameters of the associated basalts and with the distribution of plume and spreading MAR segments along its axis.

The axis MAR zone north of the Equator contains two main groups of mantle peridotites with basically different $^{143}Nd/^{144}Nd$ ratios. The rocks of one of these groups show variations in the $^{143}Nd/^{144}Nd$ ratio along the ridge axis similar with the variations in the related basalts. This isotope correspondence can be traced throughout the whole MAR axial zone between 12° – 40°N. Variation in the Nd isotope composition of the MAR peridotites and spatially related basalts are clearly correlated with the alternation of plume and spreading MAR segments along its axis. The mantle peridotites of the other group are characterized by anomalously low $^{143}Nd/^{144}Nd$ ratios as compared with those of basalts in the Northern MAR. These peridotites have not isotope genetic relations with the products of basaltic magmatism in the MAR Rift Valley between 12° – 40°N. Mantle residues belonging to this group are exposed in the MAR axial zone immediately South and North of the 15°20’ FZ, at 25°N, and South of the intersection between the Rift Valley and the Hayes FZ.

In a Sm/Nd – $^{143}Nd/^{144}Nd$ space all plume segments of the Northern MAR correspond to discrete sections of the mixing line for the DM and HIMU components. The Iceland and Azores superplumes characterized by narrower compositional variations than those of the 14°48’N Anomaly, whose peridotites and basalts display variations over the whole DM – HIMU mixing line.

Metasomatic interaction between within-plate melts of OIB type and depleted mantle material is in good agreement with the observed mineralogical and geochemical features of the strongly depleted peridotites in plume MAR segments.

Hotspot-ridge interaction in the Gulf of Aden

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We have conducted a mapping and sampling cruise at the Gulf of Aden along its spreading axis by R/V Hakuho-maru for Dec. 2000-Jan. 2001. The mapping was done by SeaBeam 2120 with gravity and magnetics from 45.5 degree E to 50.5 degree E that occupies the main part of the Gulf of Aden. The obtained data shows the first and clear detailed bathymetry of the spreading system of the Gulf of Aden. The data were jointly analyzed with the bathymetric data at the Tadjoura Rift at the western end of the Gulf of Aden that was obtained by a French Tadjouraden cruise in 1995. The spreading system in the Gulf of Aden is characterized with an oblique and ultraslow spreading system (2.0 cm/y for full rate with N30E direction between Arabia and Africa plates). To the east from 46 deg 20 min E, the spreading system exhibits ridge-transform system with the lengths of each segment with 30 to 60 km. To the west from 46 deg 20 min East, E-W trending Tadjoura Rift is well developed with distinct en-echelon structures in the rift. In the easternmost part of Tadjoura Rift at 45 deg 35 min E we observed shallow peaked twin mountains (Aden New Century Mountains) along the central axis of the rift with the summit depth of 500m. We recovered fresh basaltic lavas from the mountain and the mountains are surrounded by many small volcanic knolls. Based on along-axis bottom rock sampling during the cruise with the compilation of Shilling et al. (1992) data, the Aden New Century Mountains zone shows highly positive anomaly of La/Sm REE anomaly suggesting deep mantle source and we temporarily calls the volcanic zone, the Aden New Century Hotspot. Along-axis profile of bathymetry and La/Sm REE anomaly displays typical pattern of hotspot-ridge interaction with the shallowing of each segment toward the hotspot as well as the increasing geochemical anomalies. Horizontal view of the ridge-transform pattern shows increasing distortion toward the hotspot. The case of hotspot-ridge interaction in the Gulf of Aden will provide valuable information to improve our understanding of the dynamics of hotspot-ridge interaction.

The effect of the Iceland plume on adjacent ridges: high precision Pb isotopic constraints

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Although the mid-Atlantic ridge adjacent to Iceland has been regarded as the type example of plume-ridge interaction there is substantial controversy over the magnitude of these effects. Are normal Atlantic MORB compositions present as mixing end-members in Iceland and adjacent ridges or does Icelandic mantle dominate magma source regions over much of the north Atlantic? We have carried out an extensive study of Pb isotope compositions of the Reykjanes and Kolbeinsey Ridges and of Iceland itself, using double spike methodology for mass fractionation correction, supplemented by high precision Nd-Sr isotopic work. The Pb isotopic data are expressed as Δ^{207}Pb and Δ^{208}Pb, deviations from the Northern Hemisphere Reference Line.

Compared with all Pacific and Atlantic MORB, the region from 57 to 70˚N is distinctive in having consistently negative Δ^{207}Pb of 0.7 to 3 units below the NHRL, and in samples with ^{206}Pn/^{204}Pb<18.5, this is accompanied by strongly positive Δ^{208}Pb. Elsewhere in the ocean ridge system, the sporadic negative Δ^{207}Pb seen in the conventional Pb data is found with nearby samples having positive Δ^{207}Pb, and shows positive correlations with Δ^{208}Pb that suggest mass fractionation errors. In the North Atlantic, the region with negative Δ^{207}Pb corresponds to that with ^{3}He/^{4}He elevated above 8x R_a, suggesting that there is substantial contribution from Icelandic mantle over the whole Reykjanes and Kolbeinsey ridge system, to both lithophile and atmophile elements. Generation of the negative Δ^{207}Pb in this region requires a dominant source in Palaeozoic recycled ocean crust.

If Icelandic mantle contributes over such a wide region, what then is the significance of the isotopic and chemical gradients on the Reykjanes Ridge long used as primary evidence for plume-athenosphere interaction, and their absence or weakness on the Kolbeinsey Ridge? Even with the high precision isotopic data, we observe binary mixing lines within error between 60 and 63˚N on the Reykjanes Ridge. These mixing lines intersect mixing lines observed in subaerial lavas of the Reykjanes Peninsula at ^{206}Pn/^{204}Pb =18.75±0.05, defining the enriched end-member of the 60-63˚N Ridge mixing array as a homogeneous mixture of Reykjanes Peninsula mantle sources. The depleted end-member, best observed around 60˚N, is not observed as a component in Icelandic magmatism, nor on the Kolbeinsey Ridge, nor does it resemble MORB from elsewhere. Its strongly negative Δ^{207}Pb (-2.4) indicates that it too was in part derived from recycled Palaeozoic crust and thus we have to infer that the strong mixing gradient is between different components in the recycled crust, not between plume and asthenosphere. South of 60˚N Δ^{207}Pb becomes less negative, and Δ^{208}Pb more positive with little change in ^{206}Pn/^{204}Pb, and compositions at 58˚N are identical in Sr-Nd-Pb-O isotopes to those from the Kolbeinsey Ridge at 70˚N. These are thought to represent mixtures of a depleted Icelandic mantle component and normal MORB mantle. ^{206}Pn/^{204}Pb is much lower in subaerial lavas from northern Iceland than in the Reykjanes Peninsula, but they have much higher Δ^{208}Pb than Kolbeinsey Ridge lavas at 70˚N. Accordingly, Δ^{208}Pb shows a strong increase southward toward Iceland, implying that Icelandic mantle also contributes Pb to all of the Kolbeinsey Ridge.

An investigation of evidence for Ridge-Hotspot Interaction along the Central Indian Ridge

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This study of structural and magmatic diversity along the Central Indian Ridge between 18° 30'S and 21°S is aimed to investigate progressive changes along the ridge as a result of greater ridge-hotspot interaction in the northern region of the study area. This region of the CIR is spreading at an intermediate rate of approximately 4.5cm a^{-1}. The ridge axis trends between 144° and 158° N while the major fault scarps strike slightly obliquely at 143-150° N. Volcanic features identified include axial volcanic ridges, hummocky mounds, sheet flows and seamounts, the latter between 0.5 to 1.5km in diameter. Deep-towed TOBI sidescan sonar data coupled with bathymetric data have been used to map magmatic features and have provided a basis for a structural analysis using GIS software. Modelling using FLAC (Fast Lagrangian Analysis of Continua) and UDEC (Universal Distinct Element Code) has provided a means of analysing the structural changes along the ridge and a way of modelling the changes in the stress fields for selected 2nd and 3rd order segments.

In total, six segments are identified within the study area, bounded by first and second order transform and non-transform ridge discontinuities. Within some segments the larger scale ridge morphology does not reflect an intermediate spreading rate and is more reminiscent of a slow-spreading morphology. By contrast segments closest to the Rodrigues hot spot are of greater length (130-160 km) more typical of faster spreading rates than those further away (c. 50km). A major change in volcanic signature occurs where the ridge axis is closest to the hotspot at 19°S, where predominantly hummocky terrain to the south is replaced northwards by an extensive sheet flows/volcanic facies. Coupled with this volcanic transition and the contrast in segment dimensions, is a change in tectonic style from long, large throw faults to the south, to short, small-scale faults with a higher fault density northwards. We interpret these changes as indicating a significantly warmer region of ridge closer to the position of the inferred hotspot.

Further structural modelling has provided an understanding of the behaviour of the neovolcanic zone in terms of its structural properties, with some segments appearing to behave as open cracks and others behaving as locked sections of ridge. These ridge properties consequently change the surrounding stress fields especially at segment tips. Further geophysical interpretation and its constraints on the structural modelling will be aimed at gaining a better understanding of the influence of this hotspot on tectonic and magmatic processes in this area.

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