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InterRidge - international cooperation in ridge-crest studies
<http://www.interridge.org/>
CNRS - Centre National de la Recherche Scientifique, France
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MOI - Mauritius Oceanography Institute, Mauritius
<http://moi.gov.mu/>

International Conference

Ridges and Hotspots around the Mascarene Islands

3-7 September 2012, Hotel Tamassa (LUX Island Resorts, Mauritius)

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Bramley Murton (National Oceanography Centre, Southampton, UK)
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Kensaku Tamaki† (University of Tokyo, Japan)
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† deceased

This meeting is dedicated to the memory of our colleague and friend Kensaku Tamaki.



Kensaku Tamaki in his office, Tokyo, February 2005.

Kensaku led several cruises in the Western Indian Ocean, and he participated (himself or through Japanese colleagues, engineers, students, and/or even instruments) in many others. His interest in this area started in 1993 with the exploration of the Rodrigues Triple Junction, where he took advantage of a new generation of instruments to build on previous American, French, British and German efforts on this peculiar plate tectonic feature. He later focused on the ultra-slow Southwest Indian Ridge, an effort that culminated with cruise FUJI (France-UK-Japan-InterRidge) in 1997. This cruise, which gathered R/V Marion Dufresne of France, TOBI side-scan sonar of UK, funding from Japan and scientists from all over the World, prepared under the auspices of InterRidge, opened the way for a remarkable international collaboration on this ridge, regarded as one of the greatest InterRidge achievements. After joining French, then British efforts on the Central Indian Ridge at 19°S, he conducted cruises in 2006 and 2010 on this area of ridge-hotspot interaction, the latest ultimately leading to the discovery of two new hydrothermal sites, the Great Dodo and the Solitary, both having been detected in the water column thirty-two years ago.

Aside from his scientific achievements and discoveries, Kensaku undertook a fair share of community work. He chaired InterRidge for four years (2000-2003) and then accepted a leading position in the scientific hierarchy of the Integrated Ocean Drilling Program. He was also a member of the United Nations Commission on the Limits of the Continental Shelf for almost ten years (2002-2011).

He was also a good friend of Mauritius, where he boarded so many research vessels. During his last expeditions he developed productive collaboration with the Mauritius Oceanography Institute.

He supported the project of holding this meeting in Mauritius from the beginning. Indeed we will miss his presence during these few days of scientific exchange, on a topic which interested him so much, in a country he really appreciated.

Foreword

Mauritius is better known as a vacation island than a scientific destination. The Mascarene Islands, however, are a first class location for Earth scientists. *La Réunion* and its active volcano, *Piton de la Fournaise*, are presently located above the hotspot that formed Mauritius about 8 millions years ago and the Deccan Trapps in India 65 millions years ago. Further east, the third Mascarene Island, Rodrigues, is likely the result of interactions between the hotspot and the nearby Central Indian Ridge during the last 10 million years.

These islands and the neighbouring oceanic floor have been the goal of many scientific expeditions aimed at exploring the nearby mid-ocean ridges, the formation and erosion of the islands, and the ridge-hotspot interaction. The Rodrigues triple junction, located 900 km southeast of Rodrigues Island, is the place where the three contrasted Indian ridges meet and has been the focus of American, French, British, German, and Japanese efforts. The geophysical, petrologic and hydrothermal peculiarities of the ultra slow-spreading Southwest Indian Ridge have attracted the attention of French, Japanese, and British scientists, and more recently American and Chinese scientists. The intermediate-spreading Southeast Indian Ridge has been the target of systematic geophysical and geochemical exploration led by American and French scientists, with specific attention given to the St Paul-Amsterdam plateau and its formation in relation to another hotspot. The slow-spreading Central Indian Ridge near Rodrigues Island has been the focus of ridge-hotspot interaction studies led by French, British, Japanese, and American teams, whereas Russian and Indian, and more recently Korean teams have investigated the northern part of this ridge. The Rodrigues Ridge has been surveyed and sampled by British scientists, its eastern end by French, Japanese, and American teams. *La Réunion* and its surrounding seafloor have been studied in some detail by five recent French scientific cruises.

With regards to the considerable amount of data and knowledge generated by expeditions during the last 15 years, it therefore seemed timely to hold an international scientific meeting aiming to present results, exchange information and ideas, build collaborations, and prepare new projects. Such goals fit well the objectives and the very essence of InterRidge.

Of major importance is the emergence of regional players both in Mauritius and *La Réunion*. Mauritius has the responsibility of a large Exclusive Economic Zone, including a significant section of the Central Indian Ridge east of Rodrigues Island. The creation, in 1999, of the Mauritius Oceanography Institute, and its growing interest in the deep ocean, means that international scientists willing to work in this part of the world could establish fruitful collaborations with a local partner. In the same direction, *Université de La Réunion*, and in some aspect *Observatoire Volcanologique de La Réunion*, have for quite some time now developed interest in the surrounding ocean. Colleagues from the University will soon lead a major marine experiment around the Mascarene Islands.

It was therefore important to hold the meeting in the Mascarene Islands. Through the relation established with the Mauritius Oceanography Institute, it was soon obvious that Mauritius was the right place... then started the quest for a reasonably-priced hotel on the shore!

A significant part of the recent expeditions conducted in the region has economic, and not only scientific purposes. The growing expectations countries are placing on the ocean resources, both living and non-living, mean that scientists will have to share their knowledge with industry, for the better and sometimes for the worse. It may also mean more difficult exchange of information, less international collaboration and more national competition. We hope this conference will help to maintain InterRidge's tradition of open scientific exchange and collaboration, without which our present knowledge on ridges would be much more partial!

Last but not least, we would like to thank InterRidge, CNRS and MOI for their support, as well as individuals who have helped us in various ways – some of them are listed in the “Scientific Committee”. Let's now share the excitement of recent discoveries - enjoy the meeting!

The organizing committee (Dass Bissessur, Jérôme Dymont, and Debbie Milton)

International Conference
Ridges and Hotspots around the Mascarene Islands
Program (1/3)

Monday, September 3rd, 2012

Opening ceremony		11:00-12:00
Session 1: The Mascarene Islands and Plateau		13:30-17:15
Rezah Badal	Extended continental shelf in the Mascarene Plateau region	13:30-14:00
Prem Saddul	The hotspot theory and the evolution of the Mascarene Islands	14:00-14:30
David Obura	The role of the Mascarene hotspot and ridge in the evolution and biodiversity of reef-building corals in the Western Indian Ocean	14:30-15:00
Coffee break		15:00-15:15
Christine Deplus	Emplacement of La Réunion hotspot volcano on pre-existing structures of the oceanic lithosphere: insight from the FOREVER cruise	15:15-15:45
Jérôme Dymont	A large, catastrophic flank collapse in Mauritius ~3.5 millions years ago?	15:45-16:15
Discussion		16:15-16:45
Posters (short presentations and questions)		16:45-17:15

Monday, September 3rd to Wednesday, September 5th, 2012

Session 8: Posters

Anne Briais	Structure of the Central Indian Ridge from Rodrigues Triple Junction to 19°S
Gabriele Morra	Stochastic Multiscale BEM models of melt percolation at mid-ocean ridges
Babu Mourya	Manganese immobilizing bacteria in Carlsberg Ridge rock: dominant genera and their activity
P.P Sujith	Mobilization of manganese from ridge rock by indigenous microbial communities
Simon Williams	The tectonic evolution of the Perth Abyssal Plain

International Conference
Ridges and Hotspots around the Mascarene Islands
Program (2/3)

Tuesday, September 4th, 2012

Session 2: Plate tectonics and hotspots		09:30-10:45
Joanne Whittaker	Combining plate tectonic reconstructions and data-mining to investigate the relationships between LIPs, plumes and plate boundaries	09:30-10:00
Yasushi Harada	Reunion-Mascarene hotspot track and rotation of the African plate	10:00-10:30
Coffee break		10:30-10:45
Session 3: Ridge-hotspot interactions in the Indian Ocean		10:30-12:45
Jérôme Dymont	Reunion hotspot: 65 millions years of ridge-hotspot interaction	10:45-11:15
Dass Bissessur	Ancient ridge-hotspot interactions in the Mascarene Basin	11:15-11:45
Marcia Maia	Building of the Amsterdam-Saint Paul plateau: a 10 Myr history of a ridge-hotspot interaction and plume pulses	11:45-12:15
Christophe Hémond	interactions of Ridges and Hotspots of the Indian Ocean	12:15-12:45
Session 4: Investigating the Indian Ocean mantle		14:00-17:15
Bramley Murton	Evolution of the Reunion hotspot from its traces across the Indian Ocean	14:00-14:30
Guilhem Barruol	Mantle flow beneath La Réunion hotspot track from SKS splitting	14:30-15:00
Barry Hanan	The Southeast Indian Ridge: Isotope Constraints on the Origin and Scale of Mantle Source Heterogeneity	15:00-15:30
Coffee break		15:30-15:45
Christine Meyzen	An assessment of the record in compositional variations from mantle source to magmatism at East island, Crozet archipelago	15:45-16:15
Guilhem Barruol	The RHUM-RUM project - imaging the deep Reunion plume	16:15-16:45
Discussion		16:45-17:15

International Conference
Ridges and Hotspots around the Mascarene Islands
Program (3/3)

Wednesday, September 5th, 2012

Session 5: The Central Indian and Carlsberg Ridges **10:00-12:30**

Kattoju Kamesh Raju	Marine geophysical investigations over the slow spreading Carlsberg and Central Indian ridge segments, Indian Ocean	10:00-10:30
Ulrich Schwarz- Schampera	Cruise INDEX2011 - Exploration along the Central Indian Ridge	10:30-11:00
Coffee break		11:00-11:15
Taichi Sato	Near-bottom geomagnetic survey over NTO (Non-transform offset) massif between Central Indian Ridge segment1 and 2	11:15-11:45
Abhay Mudholkar	Oceanic core complexes along Carlsberg Ridge	11:45-12:15
Informations on InterRidge	(Debbie Milton, InterRidge Coordinator)	12:15-12:30

Session 6: Hydrothermalism along the Carlsberg and Central Indian ridges **14:00-16:15**

Durbar Ray	Nature of recently discovered hydrothermal plumes over the slow – spreading Carlsberg ridge, northern Indian Ocean	14:00-14:30
Shinsuke Kawagucci	Characteristics of known hydrothermal vents on the Central Indian Ridge	14:30-15:00
Girish Beedessee	Revised ecological settings along the Central Indian Ridge with the discovery of two hydrothermal vents	15:00-15:30
Discussion		15:30-16:00
Coffee Break		16:00-16:15

Session 7: Future plans **16:15-17:15**

Sang-Mook Lee	New marine scientific research in the Indian Ocean spearheaded by Korean academic community using new research vessel	16:15-16:45
General discussion:	future experiments and possible collaborations	16:45-17:15

Thursday, September 6th, 2012

Field trip in Mauritius **9:00-18:00**

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Abstracts

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A geospatial computation of the limits of the Continental Shelf in the region of the Mascarene Plateau

R. Badal, B. A. Motah, H. Runghen, A. Rawat, V. Ramchandur, M. Singh

Mauritius Oceanography Institute, France Centre, Victoria Avenue, Quatre-Bornes, Mauritius

In December 2008, the Republic of Mauritius and the Republic of Seychelles made a joint submission to the United Nations Commission on the Limits of the Continental Shelf for an Extended Continental Shelf beyond their 200 nautical miles Exclusive Economic Zones in the region of the Mascarene Plateau.

The area, under this submission, comprises of a vast extent of the seabed and the underlying marine subsoil of approximately 385,000 square kilometres. This Extended Continental Shelf area represents nearly twenty percent of the size of our Exclusive Economic Zone and is located North East of the St Brandon Group of Islands (Mauritius) and South East of Frégate Island (Seychelles). It commences at the neck of the Nazareth Bank which lies in the EEZ of Mauritius to join the Correira Bank Rise that lies within the EEZ of Seychelles. The area comprises of the whole extent of the Saya de Malha Bank.

The Commission on the Limits of the Continental Shelf (CLCS) has as function to facilitate the implementation of the United Nations Convention on the Law of the Sea (the Convention) in respect of the establishment of the outer limits of the continental shelf beyond 200 nautical miles. In respect of this convention, scientific and technical guidelines have been developed to enable Coastal States to formulate their submission. The Government of Mauritius has entrusted the Mauritius Oceanography Institute with the task of delineating the Extended Continental Shelf. In this paper, we demonstrate, according to the Convention, how the Republic of Mauritius and the Republic of Seychelles have computed their extended continental shelf which comprised of the seabed and subsoil of the submarine areas that extend beyond their territorial seas. The natural prolongation of their land territories to the outer edge of continental margin is also established. The Extended Continental shelf is determined through the application of the 'Hedberg formula' and is demarcated using geospatial techniques and the software 'GEOCAP and ArcGIS'.

The hotspot theory and the evolution of the Mascarene Islands

Prem Saddul

Central Water Authority, Mauritius

This paper attempts to highlight the basics of the hotspot model put forward by Tuzo Wilson (1963) and its application in relation with movements of the Mid Indian Ocean Ridge, the Somali tectonic Plate and resulting volcanic activities.

The presentation will focus on the probable origin of the Mascarene Islands by highlighting some grey areas on their hotspot origin. The aim is to ignite further reflection and discussion on the geological evolution of the three islands.

The role of the Mascarene hotspot and ridge in the evolution and biodiversity of reef-building corals in the Western Indian Ocean

David O. Obura

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Plate tectonics drive macro-evolutionary processes in shallow marine fauna, whereby global hotspots of diversity are created where crustal collisions create extensive shallow seas, only to be obliterated as the ongoing collisions raise up mountain ranges. This has been documented three times during the Cenozoic – in the West Tethyan Sea in the Eocene, the East African-Arabian Province (EAAP) in the Oligocene and the Indo-Australian arc from the Miocene to the present (Renema et al. 2008). Mid-ocean ridges drive these processes of continental collisions, and the western Indian Ocean provides a case study of how ridge and hotspot interactions may affect biodiversity away from the collision hotspots. Following the mass extinction event co-occurrent with the superplume event at the Cretaceous-Tertiary (K-T) boundary, the Mascarene-Reunion hotspot produced a string of islands on the Mascarene Ridge across the Indian Ocean, still active today building the island of la Reunion.

During the Eocene-Oligocene, hotspot products on the Mascarene Ridge may have formed a near-continuous island chain that more completely blocked east-west flow across the Indian Ocean, strengthening north-south connectivity with the Tethyan and EAAP high biodiversity provinces. From the Miocene till today, the Saya de Malha, Nazareth and Cargados Carajos banks influence east-west connectivity in the South Equatorial Current, by deflecting and concentrating its flow to the south, and producing complex but poorly known circulation patterns in the Mascarene Basin. Sea level fluctuations during the Plio-Pleistocene and Holocene may add further variation to this flow, resulting in fluctuating levels of connectivity with the Indo-Australian high biodiversity province.

Recent studies on coral biogeographic patterns (Obura 2012a,b) suggest an ancient (Eocene-Oligocene) affinity of endemic Western Indian Ocean (WIO) corals and older coral lineages with the Tethyan/EAAP provinces, as compared to younger (Miocene to Plio-Pleistocene) lineages with stronger affinities to the Indo-Australian province. These patterns appear to conform with the evolution of the Mascarene Ridge and its influence on the oceanography and connectivity of the Indian Ocean, whereby the WIO has been a ‘museum’ preserving older lineages of the Tethys/EAAP provinces. Now, however, invasion of younger lineages characteristic of the current high biodiversity Indo-Australian province is in progress. In the future, the WIO may also preserve these as the Indo-Australian hotspot becomes obliterated by ongoing tectonic collision.

This understanding of geological processes underlying present-day patterns of both oceanography and biodiversity can be important in informing present day initiatives to manage and conserve marine biodiversity. For the Mascarene Ridge this may include national and joint initiatives related to the Mauritius-Seychelles seabed extension, and multinational initiatives such as through the Convention on Biological Diversity and the World Heritage Convention.

This paper will present these emerging patterns with the objectives to:

- a) elicit deeper insights from the InterRidge community to improve understanding of the ridge/hotspot dynamics of the Mascarene Ridge and how these affected ocean circulation during the Eocene – Miocene periods;
- b) stimulate discussion, collaboration and new research in significant gaps, such as in how geological processes affect biological evolution and biogeography;

- c) strengthen efforts at national and international levels for good governance of the environments and resources of the Mascarene Ridge.

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- Obura, DO (2012a) The diversity and biogeography of Western Indian Ocean reef-building corals. PloS ONE. (in review)
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Emplacement of La Réunion hotspot volcano on pre-existing structures of the oceanic lithosphere: insight from the FOREVER cruise

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It is now clear that the structure and the mechanical properties of the lithosphere have to be taken into account to understand how mantle plumes are expressed by surface volcanism. La Réunion is a large volcanic system in the Indian Ocean, widely considered as the most recent expression of a mantle plume. It has emplaced on the oceanic lithosphere of the Mascarene Basin, an oceanic basin created by sea-floor spreading ~ 85 to 60 Ma ago. Previous studies have suggested that La Réunion could have developed on pre-existing structures such as a fossil spreading centre or a fracture zone.

Cruise FOREVER (FORmation and Evolution of the Volcanic Edifice of Reunion) of french R/V L'Atalante has surveyed the oceanic plate around La Réunion Island in 2006 in order to investigate possible relationships between the structures of the plate and the emplacement of surface volcanism. The cruise collected swath bathymetry and back-scatter data, as well as magnetic, gravity, 3.5 kHz echosounder and 24-channel seismic reflection profiles. The coverage extends up to 250 km around the island.

The new data confirm that the formation and evolution of the oceanic plate in La Réunion area display an unusual complexity. Oceanic magnetic lineations are not parallel to the extinct spreading axis and display various directions. They do not support another fossil axis located close to the volcano, as previously proposed, but can be explained by the trace of the Indian Ocean triple junction that could be located in the area before anomaly 29 (64 Ma).

In addition to La Réunion and Mauritius large volcanic edifices, the high resolution bathymetry coverage reveals numerous volcanic features on the surrounding oceanic plate: a series of elongated ridges regularly-spaced, several elongated volcanic structures and large isolated seamounts. The volcanic ridges may have been formed by a hotspot-ridge interaction at the time of the inception of La Réunion hotspot (see *Bissessur et al., this meeting*) while the seamounts display morphologies which look quite recent. Work is in progress to constrain the origin of these volcanic structures.

The seismic data, gathered during the cruise, document the flexure of the lithosphere related to Mauritius and La Réunion loading. Complemented by older multi-channel seismic data (cruise REUSIS, 1993), they allow investigations of the oceanic plate topography beneath the sedimentary cover and La Réunion volcanic edifice. Results indicate that a fossil spreading axis is unlikely to underlie La Réunion, in agreement with magnetic data interpretation, but reveal, beneath the volcano, an EW alignment of topographic highs and a N35° E topographic structure, possibly a short fracture zone.

A large, catastrophic flank collapse in Mauritius ~3.5 Millions Years ago?

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Mauritius is a volcanic island built by the Reunion hotpot ~10 to 7 Myr ago. Unlike Reunion Island, Mauritius does not present large volcanic edifices anymore. The highest mountains (max. 827 m) make a discontinuous chain on the western part of the Island. Lower mountains (max. 480 m) are found along a limited section of the East coast. These mountains are the remains of the large shield volcano which constitutes the foundation of the island and represents the Older Series, extruded between 7.8 and 6.8 Ma ago. The less voluminous Intermediate Series, formed between 3.5 and 1.9 Ma, and Younger Series, between 0.7 and 0.17 Ma, cover the rest of the island on monotonous slopes from the Central Plateau, ~400 m high, to the sea. The plateau is topped by recent volcanoes aligned along a NNE-SSW trend.

Examining Mauritius topography reveals a clear asymmetry between East and West coasts. The East Coast is characterized by gentle slopes and a wide coastal plain (except where old mountains subsist, see above), whereas most of the West Coast presents steeper slopes and a narrow coastal corridor. Both the Central Plateau and the line of recent volcanoes are shifted westward with respect to the island centre. East and West coasts also differ in shape. If we include the lagoon areas, the East coast (from *Cap Malheureux* to *Le Morne Brabant*) presents a circular shape and is quite well adjusted by a circle of radius ~33 km. Conversely, the West Coast is better fit by a straight line, except between Port Louis and Tamarin.

These observations suggest, by analogy with other ocean islands (e.g. Hawaii, Canary), that Mauritius Island may have initially had a round shape and was later affected by a large, catastrophic flank collapse. Assuming the island to have initially a circular shape, geometrical considerations suggest that ~36% of the initial island area would have collapsed in this event. Such an event can account for the topographic asymmetry of the island and other morphological observations. For example, *Le Morne Brabant* is likely a collapsed block.

A large flank collapse may be the cause of the rejuvenated volcanism at the origin of the Intermediate Series, after 3.3 Myr of volcanic quiescence: removing a large amount of material from the island means unloading the underlying mantle, which as a result would start to melt and eventually produce volcanism. As an alternate hypothesis, the volcanic rejuvenation may be triggered by independent mantle processes, at the same time the oldest known samples of Reunion were formed, and melt percolating in the crust would be the cause of the flank collapse. The volcanic and collapse events are clearly linked, the line of recent volcanoes being sub-parallel to the West Coast - the scar of the inferred collapse event. This link implies that the collapse would have happened at ~3.5 Ma.

Such an event should have left traces on the nearby seafloor as well. The bathymetric coverage around Mauritius is far from complete but the available data do not reveal the peculiar signature of large debris avalanches. The bathymetry off the West Coast is flat instead, as a result of later sedimentation. A WNW -ESE seismic profile shot southwest of Mauritius during cruise Forever of R/V *L'Atalante* in 2006 shows the southern continuation of the West Coast scarp and possible debris avalanche deposits covered by sedimentary layers. A detailed seismic investigation is required off Port Louis and the West Coast to confirm or infirm our "large flank collapse" hypothesis.

An analysis of the Western Indian Ocean LIPs and the evolution of the associated oceanic crust

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We use plate tectonic reconstructions and data-mining functionality in GPLates to investigate the spatio-temporal relationships between the formation of oceanic LIPs, plumes, and plate boundaries. We investigate (i) the most likely plume responsible for the formation of each LIP, (ii) differences between ‘deep’ and ‘shallow’ plumes, and (iii) relationships between the age of the oceanic lithosphere and LIP formation. We assess >65 oceanic LIPs and >70 proposed hotspots in the framework of a global plate tectonic model which incorporates dynamically evolving plate boundaries. Globally, we find that oceanic LIPs (excluding seamount chains) predominantly form on young ocean crust (mean age ~17 Myr), and from plumes sourced from deep within the mantle. In the western Indian Ocean, our analysis shows that the Crozet, Conrad and Del Cano Rise likely formed from the same mantle plume source. However, current plate tectonic reconstructions do not reflect this shared evolution. We develop a new plate tectonic model for the evolution of the ocean crust between Madagascar and Antarctica that models the formation of the Crozet, Conrad and Del Cano Rises as a single LIP now separated by an extinct mid-ocean ridge. Our model incorporates a previously unmodelled extinct mid-ocean ridge, the existence of which is supported by observations from gravity and magnetic anomaly data, and resolves large asymmetries in the distribution of oceanic crust on the conjugate Antarctic and Madagascan flanks.

Reunion-Mascarene hotspot track and rotation of the African plate

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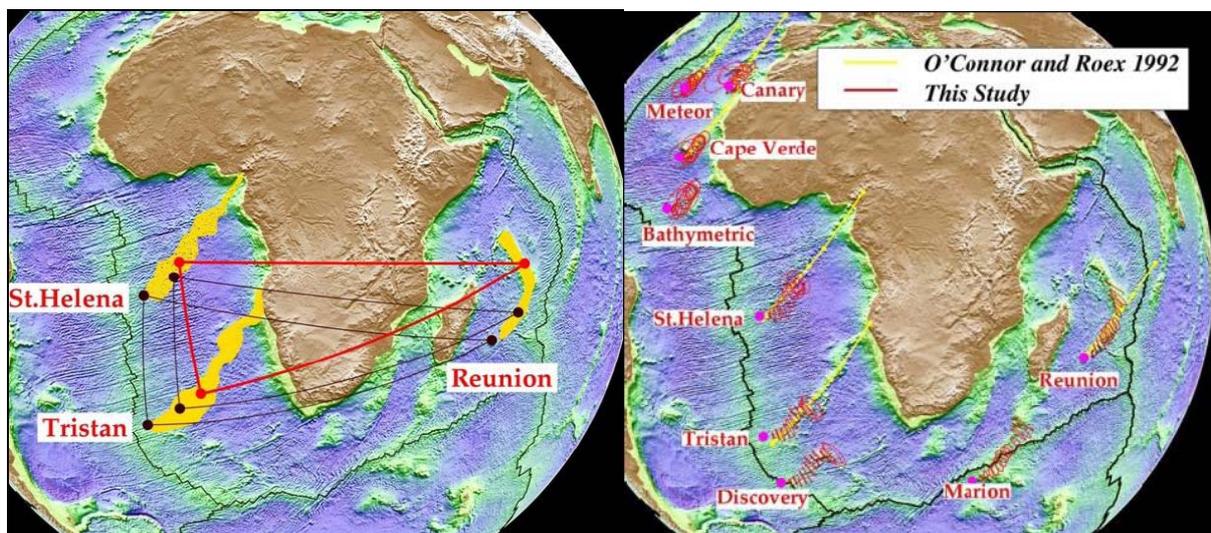
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Observed ages of the Mascarene Plateau and the Reunion hotspot tracks show age progression except for the continental block of the north end of the Plateau, the age progress with distance from the Reunion Island, therefore it looks like a typical hotspot track. However it was difficult to construct a model of the African plate motion to include all trends of the African hotspot tracks, such as the Reunion, the Tristan, and the St. Helena hotspot tracks using conventional stage pole fitting method.

The polygonal finite rotation method (PFRM) that Harada and Hamano (2000) developed is a useful solution for this problem and there exist congruent triangles inside the African plate with the age since about 65Ma (Figure left below). The new age data sets of the African hotspot tracks are more consistent with each other than previous models of the African absolute plate motion. The newly determined model of the African absolute plate motion fits with trends of the Marion, the Discovery, the Meteor, the Canary, the Cape Verde, and the Bathymetric hotspot tracks, and has an abrupt clockwise rotation at about 45 Ma just as in the model of the Pacific absolute plate motion (Figure right below). The timing and the direction of the change is also consistent with trends of fracture zones in the African –Antarctica plate boundary.



Reunion Hotspot: 65 Millions Years of Ridge–Hotspot Interaction

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The Reunion hotspot is generally presented as a typical intraplate hotspot, and its history is described as the continuous building of volcanic structures from the Deccan traps to Mauritius and Reunion Islands as the Indian then the African plates were moving northward. However, geochemical and geophysical evidences from the Central Indian Ridge (CIR) around 19°S support the occurrence of two recent episodes of ridge-hotspot interaction, the first one at 11-8 Ma with the emplacement of the Rodrigues Ridge, and the second one since about 2 Ma with the formation of Rodrigues Island and a set of smaller volcanic ridges, the Gasitao and Three Magi ridges, which extend the Rodrigues Ridge eastward up to the CIR axis. These episodes are reflected in the age distribution of the volcanic ridges, but also in the detailed tectonic evolution of the CIR during the last 10 Ma.

Ridge-hotspot interaction is presently observed while the CIR and Reunion Island are about 1000 km away from each others. Because the Reunion hotspot was generally closer to spreading centres, it probably interacted with the nearby Carlsberg Ridge (CR) and the CIR during most of its history, starting as early as the hotspot inception by the Indian plate which triggered the cessation of spreading on the Mascarene (now fossil) spreading ridge and the opening of the CR between 65 and 61 Ma (see *Bissessur et al.*, this meeting).

Between 58 and 43 Ma, systematic ridge propagation on the CR reflects its interaction with the Reunion hotspot, whereas any interaction with the CIR was blocked by the long Mauritius-Chagos Fracture Zone. We suggest a CR segment remained in the close vicinity of the hotspot, resulting in the Chagos, Nazareth, and Cargados Carajos Banks having formed on the African plate as conjugate of the Maldives and southern Laccadives Banks on the Indian plate. The saddle between the Maldives and Chagos Banks would represent the last location of this segment, i.e. a fossil spreading centre, before the Indian Ocean spreading system reorganized as a consequence of the collision of India with Eurasia ~43 Ma ago. Moreover, the good fit between Chagos Bank and the Mascarene Plateau suggests subsequent rifting and break up of pre-existing structures between 43 and 35 Ma, as part of the above-mentioned reorganization, rather than the passing of a mid-ocean ridge over a hotspot. Our alternative model advantageously explains (1) the linearity of the reconstructed Chagos and Southern Mascarene Plateau, which are parts of a unique structure created on the African plate, and (2) the bend of the hotspot trace between Maldives and Chagos Banks, which reflects the different velocities of the Indian and African plates with respect to the hotspot, two observations which otherwise remain unexplained by the conventional intraplate model.

Acknowledgements: This work includes results of cruises Magofond 2, Gimnaut and Knox 11-RR, and of the Indo-French project IFCPAR 1907-1. Participation and contributions from M. Benoit, G.C. Bhattacharya, A. Briais, C. Bollinger, A.K. Chaubey, J. Day, C. Deplus, E. Füre, Y. Gallet, P. Gente, H. Guillou, C. Hémond, D. Hilton, H. Horen, M. Kitazawa, B. Le Gall, M. Maia, B. Murton, F. Nauret, P. Patriat, M. Ravilly, J.Y. Royer, K. Srinivas, K. Tamaki, C. Tamura, R. Thibaud, and V. Yatheesh are gratefully acknowledged.

Ancient ridge-hotspot interactions in the Mascarene Basin

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La Réunion hotspot is one of the best examples of a classical mantle plume which reached the lithosphere about 65 Ma ago and formed continental flood basalt, the Deccan trapps, then made an almost continuous trail as the Indian and African plates moved northward, building the Laccadives, Maldives, and Chagos Ridges between 60 Ma and 35 Ma, then the Mascarene Plateau around 35 Ma, Mauritius Island between 10 Ma and 8 Ma, and now La Réunion Island. Seafloor spreading in the Mascarene Basin was active between about 85 Ma, when Africa (including Madagascar) and India (including Seychelles) separated, up to 59 Ma, when the Carlsberg Ridge was fully open between Africa (including Madagascar and Seychelles) and India. The coincidence between the inception of La Réunion hotspot on the Indian lithosphere and the opening of the Carlsberg Ridge, both at about 65 Ma, strongly suggests a causal relationship and therefore some kind of interaction between La Réunion hotspot and the former Mascarene spreading centre. Indeed, cessation of seafloor spreading in the Mascarene Basin occurred in two distinct stages: first in the northern part of the basin at anomaly C29r (65 Ma), then in the southern part at anomaly C26r (60 Ma). It can be explained by a progressive transfer of the spreading centre from the Mascarene Basin to the Carlsberg Ridge, that included opening of the Gop and Laxmi basins (possibly at Chrons C29) and of the Carlsberg Ridge *sensu stricto* north of the Seychelles Plateau (at Chron C28y), before its propagation to the south-east (Chron C26r).

Volcanic ridges are often observed in areas of interaction between a hotspot and a spreading centre, specifically in areas where the spreading centre is not located on top of the hotspot (Rodrigues, Three Magi and Gasitao ridges near the Central Indian Ridge). The location of a set of volcanic ridges south of La Réunion Island with respect to the location of the two fossil spreading centres, dated by anomalies C26r and C28n, enable their dating to between 65 and 62.5 Ma. These volcanic ridges would therefore represent the expression of a past interaction between the nascent La Réunion hotspot and the (now fossil) Mascarene Basin spreading centre. This interaction may however not have been limited to the southern part of the ridge, but probably affected the whole Mascarene Basin spreading centre for about 3 Ma. Indeed, a closer look to the satellite gravity anomaly map reveals that the flanks of the whole Mascarene fossil spreading centre exhibit various features. Their distribution is however systematically asymmetric, with most of the larger and elongated features located on the eastern, Indian flank. Some of these elongated features are roughly parallel to the volcanic ridges surveyed south of La Réunion Island, lie on oceanic lithosphere of the same age, and seem to abut the fossil axis. We propose that these structures are similar volcanic ridges and therefore that La Réunion hotspot interacted with most of the Mascarene spreading centre at the paroxysm of its activity, when it formed the Deccan trap. When the hotspot reduced its activity, the new Carlsberg Ridge opened in its closer vicinity.

Building of the Amsterdam-Saint Paul plateau: a 10 Myr history of a ridge-hotspot interaction and plume pulses

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The Amsterdam-Saint Paul (ASP) plateau results from the interaction between the South East Indian Ridge (SEIR) and the ASP hotspot. The plateau formed over a large time span of ~ 10 Myr. During this time, a complex interplay of plume flux variation, of intraplate deformation and of ridge-hotspot relative migration resulted in a highly variable ridge structure and lithosphere rheology. Two periods of increased melt supply at the SEIR axis (~10-6 Ma and ~3-1 Ma) are associated with thick crust and smooth, axial high type morphologies. The two periods are separated by a low magmatic phase, where crust is closer to world average values and the morphology is of a rift valley type. The changes in the lithosphere rheology are linked both to temporal variations in the mantle temperature and in the melt availability and to the consequent variations in crustal thickness. Periods of weak lithosphere and thick crust are marked by the smooth morphology. The temporal variations observed at the ridge axis can be linked to the ridge-hotspot relative motion but also to variations in the plume flux. We interpret the two phases of high melting rates and mantle temperature as being the consequence of an increase in plume flux. Periods of high flux feed the ridge axis, provided the plume is close enough to the ridge for the connection to be established. The first phase (~10-6 Ma) was built probably while the ASP hotspot was slightly off axis. The second and more recent magmatic phase was associated with higher crustal production, probably because a high plume flux coincided with an on-axis position for the plume. A low plume flux causes the ridge to behave in a more “normal” way, even if the plume is located relatively close to the axis. This is observed in the past, but also at present times, when the plume is located west of, but very near the SEIR axis, and the ridge shows a “colder” morphology, associated with the breakup of the plateau and the recent development of transform discontinuities [Maia et al., 2011].

Increased plume flux may also feed a layer of material ponded beneath the plate, thus allowing volcanism to occur off-axis. In the interaction between a weak plume and the lithosphere, the surface magmatism can be controlled by the existence of weakness zones in the plate. In the off-axis Dead Poets volcanic chain, two groups of volcanoes were dated 8 Ma and less than 2 Ma [Janin et al., 2011]. The first group can be directly linked to the intraplate phase of the ASP hotspot, but it is possible that their emplacement was highly favored by intraplate deformation, active in this part of the Indian Ocean [Royer and Gordon, 1997]. The second group cannot be explained by the position of the ASP hotspot alone. However, the large size of the edifices requires enough melt availability to form. The existence of a thin layer of ponded plume material beneath the plate, fed during periods of increased flux can explain the melting source. However, a weak plume will not generate enough stresses to crack the plate. Intraplate deformation can thus provide the lithospheric mechanism to release stress and allow the volcanoes to form. No large volcano of the intraplate chain was dated between 8 and 2 Ma and, although sampling is not complete, it is likely that this period corresponds to a low volcanic activity [Janin et al., 2011]. Some authors argue that the lithospheric deformation in the Indian Ocean is a continuous process that started 8 Myr ago [Royer and Gordon, 1997]. If so, the best explanation for this gap is the decrease in the plume flux.

As a general conclusion, the ASP-SEIR system can be seen as resulting from the interaction between a shallow, weak compositional plume, mildly hot, and the lithosphere, where the plume surface expression would be strongly conditioned by variations in the plume flux, by the presence of a migrating intermediate spreading ridge and by a narrow area of intraplate deformation.

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Indian Ridges, Hotspots and interactions: Réunion - Central Indian Ridge and Amsterdam - St Paul-South East Indian Ridge cases

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A comprehensive sampling of the area where an interaction between the Reunion plume and the Central Indian Ridge occurs today, allows a thorough investigation of that process. Recent He data (Füri et al. 2011) support the model proposed by Nauret et al. (2005) i.e. there seems to be a flux of ^3He enriched material through the off axis ridges Three Magi and Gasitao toward the southern end of the CIR involved segment. Radiogenic isotopes establish that this material derives from the Reunion plume and traveled from the present position of the plume until the spreading axis. Witnesses of this transfer are the off axis ridges produced by melting of the underlying mantle through tension cracks in the lithosphere and may be also the island of Rodrigues.

The Pluriel cruise (2006) on the St Paul-Amsterdam plateau has completed the cruise Boomerang 6 (1996) in investigating the off axis volcanism of the plateau. Isotope data on Boomerang samples along the spreading axis were published by Nicolaysen et al. (2007) and pointed out the complexity of the interaction between the ASP plume and the SEIR. Our new radiogenic isotope data establish a link between the seamount chain, the plateau and the islands. Subtle changes in composition are due to the two stages construction process of the plateau and seamounts. Some of them, highly alkaline, derive from lithospheric melting along tension cracks during a last phase of off axis magmatism on the Australian plate (Janin et al. 2011).

In conclusion, in both locations, it appears that the construction of plateau and/or off axis ridges/seamounts is related to the level of activity of the plume that seems to pulse with time.

Evolution of the Reunion hotspot from its traces across the Indian Ocean

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The Central Indian Ridge (CIR) preserves a record of the passing influence of the mantle hotspot that currently underlies La Réunion. Bathymetry along the CIR (between the Marie Celeste and the Egeria fracture; 16.7° and 20.6°S) shows an anomalously shallow region of seafloor between 18.8-19.8° S. Here a series of off-axis ridges that link the CIR to Rodrigues Island (the Rodrigues, Gasitao and 3 Magi ridges) intersect the CIR at 19.65°S.

From its trace element geochemistry, the CIR appears to form a mixing line between depleted MORB mantle and an enriched component that resembles modern La Réunion mantle. However, both the He and radiogenic Pb isotopic data suggest a more complex story.

The Pb isotope compositions show a distinct difference in the lavas from the shallow region of the CIR relative to the samples from the deeper parts of the CIR to the south and north; the latter have higher $Pb^{\Delta 8/4}$ at a given $Pb^{206/204}$ indicating that the shallow CIR region lavas are effectively of a more radiogenic (isotopically enriched) composition. As such, the Pb isotope composition of the shallow CIR lavas lie between the surrounding CIR and the off-axis Rodrigues/Gasitao, 3 Magi ridges compositions, and part way to the general compositions of the modern La Reunion Lavas.

Pb isotope trends for the combined northern and southern CIR (i.e. outside of the shallow region) do not lie within the mixing triangle formed by the modern La Réunion compositions and the average depleted Indian Ocean mantle composition. The northern and southern CIR lavas form a trend in $Pb^{\Delta 8/4}$ vs. $Pb^{206/204}$ which lies sub-parallel to the shallow CIR region lavas. Hence, these northern and southern CIR lavas cannot mix between any reasonable Indian MORB composition and modern La Réunion. Furthermore, the Gasitao/Rodrigues/3 Magi ridge section appears to form a second sub-parallel trend but displaced to higher $Pb^{206/204}$.

Helium abundance and isotope results for basaltic glasses from the (CIR) and Mascarene Islands (Réunion, Mauritius, and Rodrigues) show a similar story. Along the CIR, MORB-like $He^{3/4}$ ratios are found in the south (in the vicinity of the Egeria fracture zone) but there is a marked increase in values up to ~11 R_A in the shallow region of the CIR. The lowest $He^{3/4}$ ratios (< 8 R_A) are found in the very far north, just south of the Marie Celeste Fracture Zone. Paradoxically, this is where the incompatible trace element ratios (e.g., La/Sm) show the highest La Réunion like enrichment.

We propose that the high $^3He/^4He$ ratios on the CIR axis adjacent to the Gasitao/3 Magi ridges, as well as along these off-axis ridges, are consistent with lateral flow of hotspot mantle material from La Réunion (~ 1100 km to the west) into the sub-ridge mantle of the CIR. However, the distinct Pb isotopic composition of this mantle reflects changes in the La Réunion plume over the time it has taken to reach the CIR. Furthermore, the distinct, low $He^{3/4}$ ratios in the northernmost region of the CIR (just south of the Marie Celeste FZ) are explained by an “ancient” La Réunion hotspot mantle component, embedded into the sub-ridge mantle when the migrating CIR passed over the hotspot at ~34 Ma.

Upper Mantle flow beneath La Réunion hotspot track from *SKS* splitting

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Recent temporary and permanent seismological deployments on the Piton de la Fournaise volcano, the active locus of La Réunion hotspot, provide the opportunity to analyze azimuthal anisotropy detected by *SKS* wave splitting and to scrutinize the various possible origins of anisotropy beneath the Western Indian Ocean.

We particularly try to decipher the sublithospheric plume spreading signature from the large-scale mantle flow patterns induced by the buoyancy-driven upwelling of the African superplume. If upper mantle anisotropy beneath fast-moving oceanic plates is generally aligned parallel to the plate motion directions, it is indeed not the case beneath slow-moving oceanic plates like the African plate, where the upper mantle may accommodate the relative motion between the moving plate and the underlying large-scale convecting mantle.

By comparing our *SKS* splitting observations to various geodynamic mantle flow models, we show that the large-scale anisotropy pattern obtained in the SW-Indian Ocean may be rather well explained by asthenospheric flow resulting from the plate motion and the deep mantle circulation. The seismic stations installed on La Réunion Island show however a complex signature characterized by numerous "nulls" and by fast split directions trending normal to the plate motion that can be explained by neither a single nor two anisotropic layers. Despite the rather sparse spatial coverage, we show that the observed anisotropy pattern is compatible with a simple model of sublithospheric spreading of the Réunion upwelling plume. A grid search taking into account the plate motion, the plume parabolic width, and the upwelling conduit location suggests that the plume conduit could be located 100 to 200 km north of La Réunion Island. Anisotropy beneath the GEOSCOPE station recently installed in Rodrigues Island does not appear to be influenced by the Réunion plume spreading signature but is fully compatible with either a model of large-scale deep mantle convection pattern and/or with a channeled asthenospheric flow beneath the Rodrigues ridge.

The Southeast Indian Ridge: scale of source heterogeneity and origin of the DUPAL anomaly

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Results - Pb, and Hf, isotope ratios from 124 basalt glasses, and preliminary Sr and Nd data from the same glasses, sampled at < 10 km intervals along 2000 km of the Southeast Indian Ridge (SEIR) between 86°E and 110°E, combined with previously published data between 80°E and 118°E, show bimodal distributions. The bimodality in both Pb and Hf isotope ratios confirms the presence of ancient compositional streaks in the Indian Ocean upper mantle [1]. The density of streaks is well described by a Poisson distribution having a characteristic thickness of ~25 km.

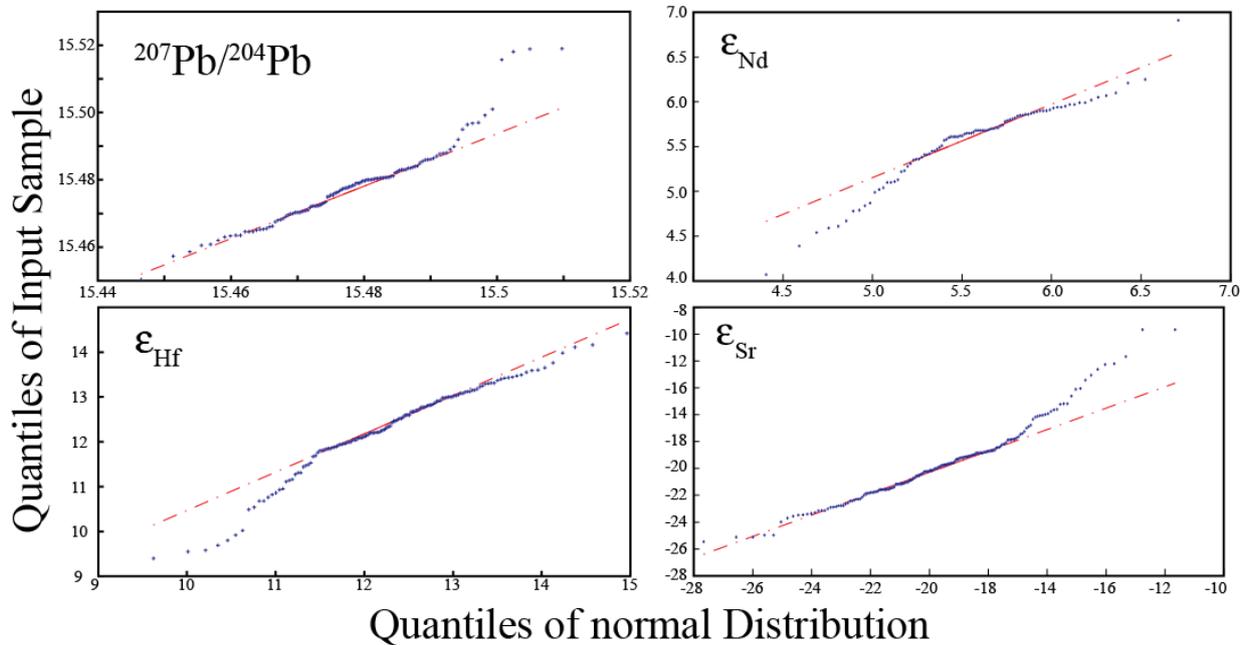


Figure 1: QQ plots for Pb, Hf, Sr and Nd isotopes for 197 SEIR glasses [this work; 1, 2] show that these MORB melts reflect a mantle source in which the isotope compositions are bimodal rather than a single gaussian population.

Implications - Pb isotopes in SEIR basalts all carry a DUPAL [3] isotope signature. Two possible origins for the bimodality and DUPAL signature are: (1) ancient melting that involved garnet fractionation, with subsequent pollution of the upper mantle by continental material during Gondwana breakup; (2) inherited heterogeneity from the early Earth.

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An assessment of the record in compositional variations from mantle source to magmatism at East island, Crozet archipelago

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Geological exploration at high austral latitudes has long been hampered by the area's harsh climate and remoteness. As a consequence, the Antarctic region and surrounding sub-Antarctic islands remain among the least-studied parts of the earth's crust, although because of the region's fossil fuel potential and its role in controlling Tertiary to recent climate, interest in studying its geological evolution is growing. At present, comprehensive studies of austral islands drawing upon evidence from major and trace elements, isotopes and tectonic setting are still very few. We have undertaken a comprehensive investigation of the petrological and geochemical evolution of East Island. This island, the second largest and most easterly of the Crozet archipelago, rises over 1000 m above sea level and was built up ca 10 Ma. Large cliffs form most of its coastline, making landing extremely difficult, accounting for the near absence of geological interest in this island for more than the last 30 years.

As observed in most other oceanic islands, Crozet lavas have abundances of incompatible elements, which require very low degrees of melting using conventional melting models involving a primitive mantle source. However, they display non-primitive isotopic compositions; their Sr, Nd and Pb isotopic compositions indicate lower than primitive Rb/Sr and Th/U ratios on a time integrated basis, and higher than primitive U/Pb and Sm/Nd ratios. The high concentrations of magmaphile trace elements observed in Crozet lavas thus appear to result from the involvement of differentiated precursor material in their mantle source, in the broad sense of the term. Only material that has experienced element transfer via melts enriched in incompatible elements might contribute to the observed degree of enrichment in the mantle source. In addition, the similarity of trace element ratios and the parallel nature of Rare Earth Element patterns in Crozet lavas indicate: (1) mantle source homogeneity over at least 1 Myr; (2) during most of the sub-aerial eruptive history, a uniformity of melting conditions (i.e. degree of melting and residual mineralogy) involving small degrees of melting of a garnet-bearing source, as expected beneath an old portion of a plate where the bottom of the lithosphere is at about 90 km, near the garnet spinel transition. Finally, compositions of clinopyroxene phenocryst rims and microphenocrysts in equilibrium with residual melts indicate final equilibration occurred at 5.8 ± 0.4 kbar and $1174 \pm 6^\circ\text{C}$, providing evidence for at least some crystallization and mixing at relatively high pressures.

The RHUM-RUM project: passive seismic imaging of a mantle plume beneath La Réunion

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The island of La Réunion has been created by one of the most active volcanoes in the world. The hotspot track leads unambiguously to the Deccan traps of India, one of the largest flood basalt provinces on Earth, which erupted 65 Ma ago. But the genesis and the origin at depth of the mantle upwelling and of the hotspot are still very controversial.

RHUM-RUM (Réunion Hotspot and Upper Mantle - Réunions Unterer Mantel) is a French-German passive seismic experiment designed to image an oceanic mantle plume – or lack of plume – from the crust to the core and to understand these results in terms of material, heat flow and plume dynamics. This comprises the vertically ascending flow in the plume conduit, as well as any lateral flow spreading into the asthenosphere of the western Indian Ocean. RHUM-RUM aims at establishing the origin of the heat source that has been fueling this powerful hotspot: Is there a direct, isolated conduit into the deepest mantle, which sources its heat and material from the core-mantle boundary? Is there an isolated plume conduit connecting to the African superswell at mid-mantle depths? Or might the volcanism reflect merely an upper mantle feature? RHUM-RUM also aims at studying the hotspot's interaction with the neighboring ridges of the Indian Ocean. In particular, there is a long-standing hypothesis, not yet examined seismically, that channelized plume flow could feed the Central Indian Ridge at 1000 km distance. The aseismic Rodrigues Ridge is indeed presumed to be the surface manifestation of this asthenospheric flow channel.

In the frame of the RHUM-RUM program, we will deploy 57 German and French ocean-bottom seismometers (OBS) over an area of 2000 km x 2000 km² centered on La Réunion Island, using the “Marion Dufresne” and “Meteor” vessels. The one-year OBS deployment (2012-2013) will be augmented by land seismographs in the Iles Eparses in the Mozambique Channel, in Madagascar, Seychelles, Mauritius, Rodrigues and La Réunion islands. A significant number of OBS will be also placed along the Central and South West Indian Ridges to image the lower-mantle beneath the hotspot, but also to provide independent opportunity for the study of these ridges and of the plume-ridge interactions.

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Marine Geophysical Investigations Over the Slow Spreading Carlsberg and Central Indian Ridge Segments, Indian Ocean

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Mid-Ocean ridge system in the northern Indian Ocean remains poorly explored for seafloor hydrothermal activity, with only four active sites confirmed near to the Rodriguez Triple Junction. A systematic multidisciplinary exploration of the Carlsberg and Central Indian Ocean ridges has been taken up to fill this gap with an objective of understanding the ridge segmentation and locating new vent fields. The segmentation pattern of 600 km long section of the Carlsberg Ridge between 62°20'E and 66°20'E, in the northwest Indian Ocean, has been studied using multibeam bathymetry and magnetic data. Four segments have been identified based on the topographic fabric, along-axis depth variations and the presence of off-axis traces of transform and non-transform discontinuities. These segments constitute four distinct domains representing magmatic and sparsely magmatic crustal accretion. Magnetic model studies show this section of the ridge is a slow spreading ridge with full spreading rates varying from 22 to 32 mm/yr. Along-axis variations in the magnetic anomalies and crustal magnetization, the presence of axial volcanic ridges on the inner valley floor, variations in the depth and geometry of the rift valley, and recovery of mantle derived peridotites from the inner valley floor suggest distinct variations in the accretionary processes along the ridge.

Extensive seabed sampling, deep-tow and water column investigations carried out along the axial valley region of the Carlsberg Ridge suggest the presence of two vent fields near 3°42'N, 63°40'E and near 3°41.5'N, 63°50'E, on a segment that is apparently sparsely magmatic. Ultramafic rocks have been recovered near to these sites, however, the plume characters indicating dissolved Mn anomalies suggest that the vent fluids are the result of fluid-basaltic/gabbroic interactions, and the vent fields may be similar to Rainbow and Logatchev fields of the Mid-Atlantic Ridge.

At a slightly faster spreading rate of 26 to 38 mm/yr the Central Indian Ridge (CIR) represents a section of the Indian Ridge system that displays distinct segmentation pattern. The segmentation pattern of 750 km long CIR between 3°S and 11°S latitudes in the Indian Ocean has been studied using multibeam bathymetry and magnetic data. The seafloor topography different from the normal ridge parallel fabric observed at few places over the NE flank of the CIR is suggested to be the consequence of gradual and progressive influence of the distributed diffuse plate boundary (between the Indian-Capricorn plates), on the newly generated oceanic lithosphere. Twelve ridge segments were identified that are separated by well defined transform faults and non-transform discontinuities. Further, we documented distinct ridge-transform intersection (RTI) highs, three of these RTI highs are identified as oceanic core complexes / megamullion structures. Megamullion structures are found to be associated with less magmatic sections.

Cruise INDEX2011 - Exploration along the Central Indian Ridge

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The INDEX 2011 expedition to the Central Indian Ridge aimed at the reconnaissance of seafloor massive sulphides and their geological framework including the ridge geometry, geophysical properties, volcanology and volcanic petrology, fluid flow, as well as their biodiversity. Known seafloor massive sulphides occur off-axis at the flanks of the active spreading graben. The associated spreading segments show indications for temporally and spatially elevated volcanic activity forming flat but characteristic regional dome structures along the spreading graben and leading to prominent volcanic ridges. The sulphide occurrences are closely associated with volcanic centers formed from pillow basalt lava. Inactive fields are characterized by an extensive lateral distribution of hydrothermal precipitates. Active vent fields show sustained highly focused venting with only a few discharge edifices at the top. The seafloor massive sulphides are characterized by a chalcopyrite-dominated mineralogy. Rock sampling revealed lithologies from the upper mantle (dunite, pyroxenite), intrusives from the lower crust (olivine-rich gabbros), and pillow and sheet flow basalts and volcanoclastic sediments at the seafloor. Locations of recent spreading are represented by young glass-rich pillow mounds in the center of the graben. Mineralization is likely affiliated with intensely tectonized and structurally controlled graben flanks with distinct proportions of exhumed lithosphere. The associated fault zones with large vertical displacements and multiple reactivations represent important conduits for hydrothermal fluids. Metal contributions from the crystalline rocks are suggested.

Near-bottom geomagnetic survey over NTO (Non-transform offset) massif between Central Indian Ridge segment1 and 2

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Near-bottom magnetic signals may reflect differences of rock types and/or degrees of weathering, rather than magnetic polarity reversal pattern. Near-bottom magnetic surveys over hydrothermal fields are carried out for many times and revealed some relationships. For example, if the host rock is extrusive rock, low magnetization by thermal demagnetization is expected, and if the host rock is upper mantle rock, positively enhanced magnetization by magnetite caused through serpentinization is expected. Near-bottom magnetic characteristics inform us the size of the hydrothermal field but also may help the discoveries of new hydrothermal fields.

On November 2010, we conducted near-bottom magnetic survey using an AUV called R2D4, during KH10-6 cruise of R/V *Hakuho-maru*. Three-component magnetometer was attached in the front area of the vehicle. One dive was done at NTO (Non-transform offset) massif between Central Indian Ridge segment1 and segment2. The survey was consisted of four North-South trend lines with the length of approximately 6km and the interval of approximately 500m. Vehicle height varied between 40 and 200m, and the mean height was 80 m. A figure 8 turn was done before entering the survey line to calculate the vehicle magnetization coefficient. Three component magnetic data were calculated by removing ship magnetization, and the total magnetic data was calculated from the three components of magnetic data. Total magnetic anomaly was calculated by subtracting the IGRF value. Several crustal magnetization were calculated through a new magnetic inversion method (Honsho et al., JGR, 2012), by changing the shapes of the magnetic layer.

Despite different shapes of the magnetic layer, relatively high positive magnetization is seen at the southeastern portion of the survey area. This area corresponds to the North-South trending small hill. Basalt, peridotite and serpentinized peridotite were dredged at the western slope of this hill during the same cruise. In addition, peridotites and dead-chimneys were collected at the top of the hill by *Shinkai 6500* on 2009. These samples suggest that the hill is comprised of peridotite. Therefore, the high positive magnetization may be attributed to the induced magnetization through serpentinization of peridotite. As the other possibilities, because of the discovery of the dead-chimneys, magnetic minerals in hydrothermal deposit formed through hydrothermal activity may be attributed to magnetic signals.

Oceanic core complexes along Carlsberg Ridge

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Oceanic core complexes (OCCs) provide windows to the earth's mantle, which is a source to the basalts erupting along the mid-ocean ridges. These OCCs usually form at the ridge-transform intersections, e.g. Atalntis Bank (SWIR) Atlantis Massif (MAR). For the first time a shallow flat topped Varun Bank, that rises from 4500-m to ~950 m depth composed of serpentinites, peridotites, and amphibolitized gabbros has been mapped under the Indian Ridge program. Varun Bank flanks the Owen Fracture Zone on the Carlsberg Ridge on ~52 Ma seafloor. During this period the Carlsberg Ridge spread at 120mm/yr, making it the only documented oceanic core complex emplaced at a fast spreading ridge. Three more exposures of mantle rocks along the axial valley of Carlsberg Ridge wall are mapped and sampled. Serpentinites, peridotites and norite, olivine free gabbro, have been recovered from a non-transform discontinuity at 8° 39.4N; 58° 22.8E. A suite of mantle rocks was recovered from the sparsely magmatic ridge segment with wide rift valley at 3° 40.8'N; 63° 50.5'E. From another site (8° 39.4N; 58° 22.8E) only serpentinites were dredged.

Mineralogical and EPMA studies on the MORBs glasses recovered from various locations along CR indicates the presence of the olivine crystallites with forsterite content varying from 85 to 88. Melt inclusions in the olivine crystals have composition that shows scatter with few melt inclusions showing primitive melt characteristics (MgO~13.07-17.35; CaO/Al₂O₃~0.69-0.71). Melt inclusions exhibit the post entrapment depletion of major element oxides related to the host olivine crystal. This melt variation in the melt inclusions compositions suggests inhomogeneities in the source mantle peridotites.

Nature of recently discovered hydrothermal plumes over the slow – spreading Carlsberg ridge, northern Indian Ocean

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Recently two hydrothermal plumes from unknown active vents have been discovered over the slow-spreading Carlsberg Ridge in the northern Indian Ocean (Ray et al 2012). Non-buoyant plumes were found at the depth of about 3000 m near 03°42'N, 63°40'E and 03°41.5'N, 63°50'E. Both the plumes were identified based on several physiochemical signatures in water column like temperature, optical backscatter (OBS), redox (Eh), dissolved manganese (DMn) and helium-3. The deeper (>3000 m) plume had prominent backscatter and redox anomaly and slightly elevated levels of DMn and $\delta^3\text{He}$ while the shallow (~2900 m) plume shows significant change in redox potential. Ultramafic rocks have been recovered at all the dredging stations in this area with maximum locations consisting of peridotite, serpentinite, gabbro and basalts. The dissolved Mn anomalies and significant reducing condition in deep water column imply that the plumes arise from the source fluids originating from both ultramafic and basaltic/gabbroic fluid-rock interaction. It is inferred that the nature of plumes are very similar to that found in Rainbow and Logatchev fields of the Mid-Atlantic Ridge. Strong backscatter anomalies in water column indicates heavy load of suspended particulate matter (SPM) within the laterally dispersed plume layer. Here we present the external morphology (including size, shape, surface features) of large particles and chemical characteristics of the particulates filtered from plume water and compared with elements composition of normal oceanic SPM from different depths at same location. SEM-EDS analysis of large (20 - >50 μ) vesicular particles shows enrichment of Fe however; some particles with smooth surface were quite rich in Mg. The bulk composition of suspended particulate in deeper plume was characteristic with high Fe, Mn and Cu. Predominance of Fe-oxyhydroide particles and relatively low abundance of particulate Al (low Al/Fe ratios) in SPM of this plume layer is similar to the particles in ultramafic hosted Rainbow plumes.

Characteristics of known hydrothermal vents on the Central Indian Ridge

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The late professor Kensaku Tamaki conducted cruises with his colleagues to reveal hydrothermal activities on the Central Indian Ridge (CIR) from 1993. They found the first high-temperature hydrothermal vent field, Kairei, located near the Rodriguez R-R-R triple junction in 2000 (Gamo et al., 1996; 2001). In 2006 and 2009, the team Tamaki, under the collaboration with Mauritius scientists, discovered two high-temperature hydrothermal vent fields, named Solitaire and Dodo (Kawagucci et al., 2008; Nakamura et al., 2012). While these are all located on the CIR, each of these three fields shows distinguishable characteristics in their geological background, fluid geochemistry, microbial ecosystems, and macro fauna communities. The Kairei field is the most investigated field on the CIR because there is abundant H₂ and a H₂-based hyperthermophilic subsurface lithoautotrophic microbial ecosystem (HyperSLiME), a likely modern analogue for the early Earth ecosystems prior to photosynthesis (Takai et al., 2004; 2006; Kumagai et al., 2008; Nakamura et al., 2009). In addition, an iron sulfide-coated ‘scaly-foot’ gastropod has been identified in the Kairei field. At the Solitaire field, where a ridge-hotspot interaction is suggested from geological setting and fluid geochemistry, a new morphotype of scaly-foot gastropod has been found (Nakamura et al., 2012). The both types of scaly-foot gastropods in the Kairei and Solitaire fields has similar morphological and anatomical features and genetically belong to the same species according to analyses of their COI gene and nuclear SSU rRNA gene sequences. However, the new morphotype completely lacks an iron-sulfide coating on the sclerites. The Dodo field is characterized by ¹³C-depleted methane and high H₂ concentration in spite of basaltic lave-covered seafloor (Kawagucci et al., 2008; Nakamura et al., 2012) suggesting involvement of subseafloor microbial methanogenesis as well as the Kairei field. These significant intra-CIR variations among the known (only) several vent fields will be further understood by finding and comparing more hydrothermal vent fields especially in central to northern Indian Ocean.

Revised ecological settings along the Central Indian Ridge with the discovery of two hydrothermal vents

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More than thirty years have passed since the discovery of the first hydrothermal vents on the Galapagos Rift in the eastern Pacific Ocean and numerous vents continue to be observed and catalogued around the world. These vents are usually associated with a dense ecosystem of organisms that are patchily distributed and often characterised by an amazing array of physiological, morphological and behavioural adaptation. Till 2009 only two hydrothermal fields were known to exist along the Central Indian Ridge (CIR), Kairei and Edmond, until an expedition revealed the existence of two new fields named as Dodo field and Solitaire field. Submersible observations and invertebrate sampling using the *Shinkai6500* showed that these fields host organisms that share affinities with Pacific and Mid-Atlantic counterparts. Dispersal ability is one of the main factors to maintain the species in spatially and temporally discrete environment of deep-sea hydrothermal vent fields. Data concerning the dispersal abilities of four representative vent animals, Alviniconcha and scaly-foot gastropods, bythograeid crab *Austinograea rodriguezensis*, and alvinocaridid shrimp *Rimicaris kairei* will be discussed. These findings allow the pieces of the “biogeographic puzzle” to fall in their place and thus contribute important insights into the biodiversity of vent-endemic ecosystem in the Indian Ocean.

**New marine scientific research in the Indian Ocean beginning in 2014
spearheaded by Korean academic community to address
important global and regional issues using new research vessel**

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Korea is a country with relatively small territorial waters and as a result most of the marine scientific research effort has been focused on coastal regions. Since the late 80s the country has started to venture out into the open ocean, however, the main target was the deep-sea manganese nodules in the eastern Pacific with the intent to assert them as potential mineral resources in the future under the auspices of the United Nations International Seabed Authority. This deep-sea minerals government program is still continuing and has branched out to include the search for massive hydrothermal deposits in back arc basins (around the equatorial Western Pacific) starting in the late 90s and recently in the northern Central Indian Ridge. While these events were happening, the academic community in Korea (composed of universities as opposed to government-supported institutes) was virtually shut out from accessing the modern research vessels and securing financial support to conduct open ocean research was impossible unless the project was done as under the short-term piggyback projects of the government's mineral-resources-search effort. The search for deep-sea mineral resources is important and not surprising for countries like Korea which has little natural resources within its own territory, and thus has to seek them from abroad including deep oceans to sustain its economic growth. However, the shortsightedness and the single-mindedness of the past practices have in many ways deprived new generation of scientists the opportunity to tap into a more fundamental and global marine scientific issues and, by creating a stifled system of monopoly, it also refuted the healthy competition which is essential for any good scientific advancement. After more than 30 years, finally a new wind of change is blowing in the horizon. With the construction of new 5000-ton research vessel in 2014 which is more than three times larger than the previous vessel *Onnuri*, an opportunity will be given to the academic community to use the research vessel for up to four months a year to independently conduct open-ocean research. For the first time, the world-ocean class research vessel will be shared by for all including those in academia, government and industry, a tradition that is already set in place in most of the leading countries in the world. The primary objective of the marine scientific research program proposed by the academic community will be the advancement of science, and its content will be interdisciplinary and multidisciplinary to include not just marine geology and geophysics but also physical oceanography, atmospheric science, marine chemistry, marine biology and applied ocean engineering. We anticipate that it will host and support many international collaborations especially with scientists from countries in the region. In addition, though at very premature stage, the Korean program will provide opportunities to talented students with disability both in Korea and in developing countries to become earth scientists in conjunction with current efforts to promote high-performance scientific computing and simulation-based science and engineering.

Structure of the Central Indian Ridge from Rodrigues Triple Junction to 19°S

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We review the structure of the Central Indian Ridge (CIR) from the Rodrigues Triple Junction to about 19°S, based on multibeam bathymetry, backscatter imagery, and gravity data collected during the French Magfond2 (N/O Marion Dufresne), Larjaka and Gimnaut (N/O L'Atalante) cruises, the Gemino (R/V Sonne) cruises, and on satellite-derived gravity anomalies. The axis of the CIR is offset by one transform fault (Gemino TF) at 22°45'S, by a series of large transform faults (Egeria TF system) at 20.5°S, and by non-transform discontinuities elsewhere. The second-order segmentation is clearly marked by mantle Bouguer anomaly (MBA) lows near the segment centers and MBA maxima at the ridge offsets, with peak to trough amplitudes of 10 to 30 mGal. These variations are similar to those observed along the Mid-Atlantic Ridge. A regional variation is also observed along the CIR, in the topography, the free-air gravity anomalies and the MBA. The ridge axis deepens and the relief across the axial valley increases from north to south, except for the segments within the Egeria transform fault system, which show deep axial valleys. The MBA shows a long-wavelength gradient of about 7 mGal/100 km that is of the same order as MBA gradients near the Azores hotspot. This long-wavelength variation is associated to the influence on the CIR of the Reunion hotspot. Although the hotspot is presently located about 1000 km from the ridge axis, its influence on the ridge in the section close to Rodrigues Island is also shown by geochemical anomalies. The segments within the Egeria TF system show higher MBA, probably due to the presence of large offsets implying cooler mantle environment.

Between the Marie Celeste and Egeria transform faults near 19°S, the CIR axis is about 1000 m shallower than normal, slow-spreading ridge axes. In this section, the ridge flanks display low-relief abyssal hills, up to 100 km long, which are similar to those observed on intermediate-spreading centers. 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. Bathymetric highs are observed on the eastern flank of the ridge near the center of two segments at 19°10'S and 19°30'S. The MBA pattern is asymmetric, displaying more negative values on the west flank, towards a group of small off-axis, elongated ridges. The residual mantle Bouguer anomaly displays a similar pattern. The negative anomalies are suggestive of thicker crust and/or hotter mantle beneath the ridge axis and the western ridge flank. 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/Rodrigues hotspot on accretion processes and volcanic construction near the CIR axis. The thermal influence appears to spread all the way south to the Rodrigues triple junction, certainly due to the large distance of about 1000 km between the ridge and the Reunion 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.

Stochastic Multiscale BEM models of melt percolation at mid-ocean ridges

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New oceanic crust at mid-ocean ridges forms from the rising and solidification of melted rock, percolating through the solid phase up to the surface. Although its dynamics is simply described by a two-phase melt-rock dynamics, the intrinsic complexities of the two-phase flow and the lack of data necessary for a detailed tomographic description of the size, shape and orientation of the faults in the ridge interiors hampers the knowledge of the flow structures during the upwelling.

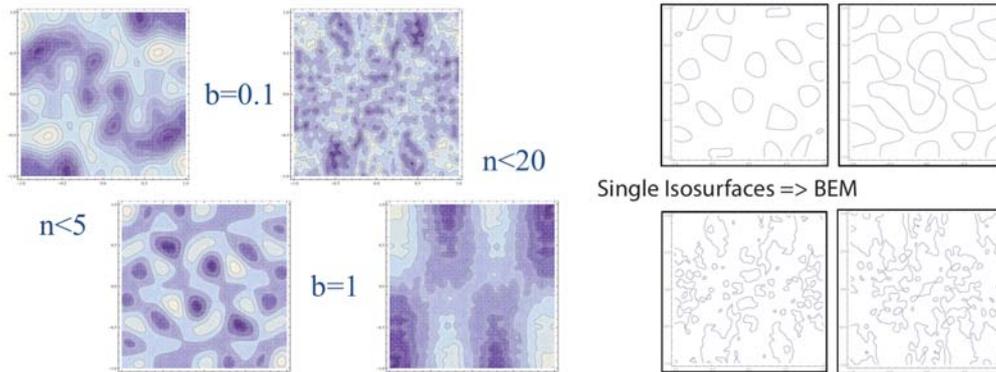


Figure 1 Synthetic porous systems generated with a Karhunen-Loeve Transform. After the extraction of single isosurfaces a BEM solution is calculated.

We propose here a numerical approach for studying a generic two-phase flow based on the use of the Fast Multipole Boundary Element Method. The multiscale description of the melt percolation is expressed through a background matrix generated by a non-gaussian stochastic transmissivity, mathematically obtained with a Karhunen-Love (KL) transform. The flow through each matrix configuration is obtained solving the boundary element equations (BEM) through the network. The implementation of a mixed gas-fluid phase in the porosity conduits and fracture is also considered and tested for unbounded flow.

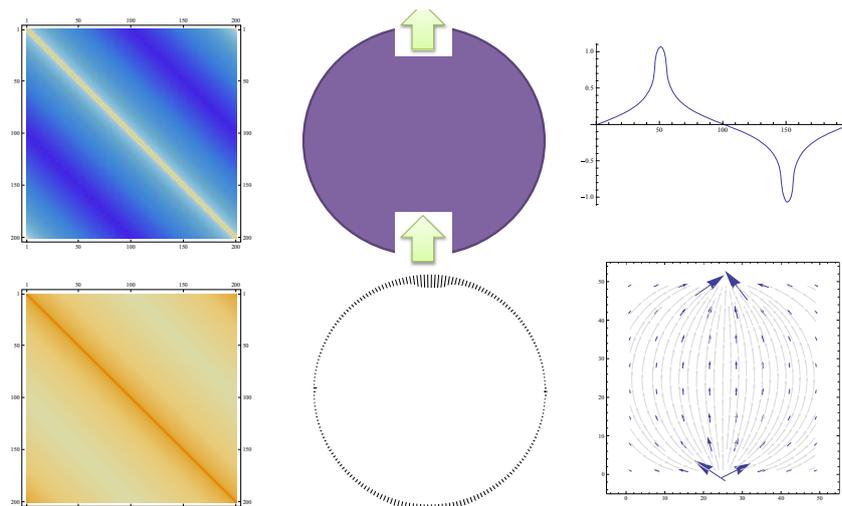


Figure 2 Calculation of the flow through a porous. On the left the graphical representation of the single and double layer matrices. On the right the emerging flow.

Manganese immobilizing bacteria in Carlsberg Ridge rock: dominant genera and their activity

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Ridges are elevated underwater chain of mountains formed by geological processes associated with seafloor spreading and plate tectonics. The microbial processes associated with ridge rock can lead to metal enrichment or dissolution. Carlsberg Ridge (CR) in the Arabian Sea a relatively suboxic environment could serve as unique niches for metal oxidizing groups of microorganisms. Therefore, in the present study, an attempt has been made to elucidate the abundance, identity and function of culturable manganese oxidizing bacteria from the CR ridge ecosystem. Bacteria associated with the ridge rock were enumerated and isolated on 0.01% nutrient agar amended with 100 μ M Mn²⁺. The identification of the bacterial isolates was carried out by morphological, phenotypic and 16S rRNA analysis. The yield of culturable Mn oxidizing bacteria was in the order of 5.47 \times 10³ CFU g⁻¹. Of the 10 representative bacterial isolates identified 5 belonged to Firmicutes, 3 to γ -Proteobacteria, 1 to α -Proteobacteria and 1 to Bacteroidetes. Firmicutes were represented by *Bacillus* (40%) and *Exiguobacterium*. Proteobacteria by *Idiomarina* (20%), *Serratia* and *Thalassospira* and Bacteroidetes by *Imtechella*. The paper would discuss the activity and ecological significance of the bacterial groups that participate in the accretion of manganese in the ridge environment.

Key words: manganese immobilizing bacteria, culturable bacteria, 16S rRNA, Mn oxidizing activity, Carlsberg Ridge.

Mobilization of manganese from ridge rock by indigenous microbial communities

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Carlsberg Ridge in the Arabian Sea a relatively suboxic environment could serve as unique niches for facultative chemolithoautotrophic or chemosynthetic mixotrophic microorganisms responsible for metal oxidation by accretion. However, the same microbial communities in the system may also be capable of dissolution by reduction especially in the organically replete conditions. The carbon concentration of the sample region is reported to vary seasonally between 68 to 71 μM at water depths of $>2000\text{m}$. With the possibility of reaching still higher concentrations raining from the surface layers after local blooms, in the present study, an attempt was made to elucidate the role of indigenous microbial communities from the ridge rock in mobilizing Mn both in the presence of glucose amended (G^+) and glucose unamended conditions. The experiment was conducted at near *in-situ* temperature of $4\pm 2^\circ\text{C}$ in the dark. The Mn mobilization in ' G^+ ' medium (5550 μM) was $1.76 \mu\text{g g}^{-1} \text{d}^{-1}$ and was 10 times more than in ' G^- ' medium. The pH in the ' G^+ ' medium decreased from 8.11 to 7.21 and Eh varied from +117.11 to -116.33 mV. Concomitantly, the total bacterial counts in the ' G^+ ' medium increased from initial 1.63×10^6 to 6.71×10^7 cells g^{-1} and cell size from 0.70 to 2.86 μm as opposed to very little change in the control. The mobilization of Mn by live microbial cells in the experiment with G^+ was 6.05 times higher than in azide poisoned and 5.66 times higher than in heat killed controls. The paper discusses the details of manganese mobilization by the communities and compares it with the immobilization rates. The paper suggests that the environment surrounding the CR ridge could stimulate the oxidative processes more on a long term basis.

Key words: Manganese, mobilization, microbial communities, Carlsberg Ridge

New constraints on the tectonic evolution of the Perth Abyssal Plain

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Oceanic crust within the Perth Abyssal Plain (PAP) west of Australia formed during the Mesozoic breakup of Gondwana. The patterns of magnetic anomalies within this crust are important constraints for reconstructing the relative motions between Australia, India and Antarctica during this breakup. We present new magnetic profiles for the Perth Abyssal Plain collected during voyage ss2011/v06 of the Southern Surveyor in 2011. These profiles provide evidence for previously unidentified M-series anomalies on the western flank of the Perth Abyssal Plain. The new data also provide evidence for differences in the spreading history between the northern and southern regions of the PAP.

Further evidence for the plate tectonic history of the comes from dredge samples recovered from the Batavia and Gulden Draak Knolls, which indicate that these bathymetric features are continental fragments rather than igneous plateaus related to Broken Ridge. These fragments rifted away from Australia with India during initial breakup at ~130 Ma, then rifted from India at ~108 Ma. Satellite-derived gravity anomalies and swath bathymetry profiles provide evidence for ridge propagation events within the PAP ocean crust, occurring during the Cretaceous Normal Superchron. This series of westwards jumps of the India-Australia plate boundary suggests a strong influence of the Kerguelen hotspot, located beneath eastern greater India at this time.

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La Réunion Island, Piton de la Fournaise volcano, as seen from the ocean (cruise Forever on R/V L'Atalante, Chief scientist C. Deplus, 2006; photos and assemblage J. Dyment).

Mauritius Island, West Coast, as seen from the ocean (cruise Forever on R/V L'Atalante, Chief scientist C. Deplus, 2006; photos and assemblage J. Dyment).

Bathymetry around the Mascarene Islands: bright colours depict multibeam bathymetric data acquired by ships, pale colours "predicted" bathymetry from satellite altimetry (Smith & Sandwell, 1997). This bathymetric compilation has been prepared for an optimal location of the OBSs (Ocean Bottom Seismometers) during the incoming Rhum/Rum experiment (P.I. Guilhem Barruol and Karin Sigloch).

Pillow-lavas at the axis of the Central Indian Ridge, 19°S, taken through the porthole of Deep Sea Submersible Nautille (cruise Gimnaut of R/V L'Atalante, chief scientist J. Dyment, 2000; photos J. Dyment).