Detailed Report on

International Workshop on Scientific Drilling in the Indian Ocean

Goa, INDIA

OCTOBER 17-18, 2011

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Detailed Report on

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and other workshop participants

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OVERVIEW

An Indian Ocean IODP Workshop was hosted in Goa in October 2011 by the National Centre for Antarctic and Ocean Research (NCAOR). With no scientific ocean drilling in the Indian Ocean for nearly a decade, this region remains a major gap in our understanding of global geoscientific processes, past and present, and their implications for the future.

The workshop was initiated and planned by Australian and Indian scientists, and it aimed to improve existing proposals (Table 1.1), build new proposals, and initiate the international scientific alliances that are essential for strong drilling proposals. Because of piracy in the northern Arabian Sea only one of the four highly ranked existing Indian Ocean IODP proposals is feasible - that to drill the Bengal Fan.

Proposal	**Short title**	Lead Proponent
549 Full6	Northern Arabian Sea Monsoon	Lückge, Germany
552 Full3	Bengal Fan	France-Lanord, France
595 Full4	Indus Fan and Murray Ridge	Clift, UK
667 Full	NW Australian Shelf Eustasy	Fulthorpe, USA
701 Pre2	Great Australian Bight Deep Biosphere	Wortmann, Canada
702 Full	Southern African Climates	Zahn, Spain
704 Full2	Sumatra Seismogenic Zone	Goldfinger, USA
724 Full	Gulf of Aden Faunal Evolution	de Menocal, USA
727 APL	Afar Mantle Plume Dispersion	Shinjo, Japan
760 Pre	SW Australia Margin Cretaceous Climate	Groke, UK
776 Full	Arabian Sea Paleoclimate	Pandey, India
778 Full2	Tanzania Margin Paleoclimate Transect	Wade, UK
780 Pre	Rodriguez Triple Junction Microbiology	Kumagai, Japan
783-APL	indian monsoon history	Hathorne, UK
788-Pre	Shiva Impact Structure	Chatterjee, Indian
790-Pre	Indian Ocean Neogene monsoon	Betzler, Germany

Table 1.1: A list of the current active proposals in the Indian Ocean.

About 70 Indian scientists and 40 international scientists attended. There were two intensive days of plenary and breakout sessions. Many papers were presented and work was started to improve existing proposals and build new proposals. Abstracts of papers presented are at http://www.ncaor.gov.in/IODP/index.html. Participants stressed the importance of the Indian Ocean in the planned new phase of scientific ocean drilling, the International Ocean Discovery Program, due to start in late 2013. Numerous global science problems remain to be addressed here, with a better understanding of the Asian monsoon high on the list. Our aim is to have several new drilling proposals submitted by April 2012, for the next meeting of the IODP Proposal Evaluation Panel, for drilling by *JOIDES Resolution* in 2014, or later by alternative platforms. It was agreed that these proposals would address the themes above, with themes 1-3 (below) giving rise largely to free-standing proposals. Theme 4, the deep biosphere, would be addressed initially as part of other proposals.

Key localities, drilling prospects and existing proposals are illustrated on Figure 1.0.

The workshop themes and subthemes identified were:

1) **Cenozoic oceanography, climate change, gateways and reef development**, which covered broad questions related to the Indian Ocean, and narrower ones such as the causes and effects of the Indonesian Throughflow current and of sea level rise and fall, and the origin of late Pleistocene reefs. Three subthemes were identified from the discussions:

(i) Evolution of the shallow carbonate environment: with emphasis on drilling the Maldives to elucidate deep water current history and the origin of atolls.

(ii) Deep ocean record of palaeoceanography/climate: several pre-existing proposals were reviewed - 724 Full, 760 Pre and 778 Full. Two types of drilling transect targets were identified representing “Walvis Ridge Transects” and “Pacific Equatorial Age Transects”.

(iii) Ocean margin boundary currents and gateways: these are key drivers for continental climate and sea surface temperature variations. Two pre-existing proposals were reviewed 667 Full (this will be resubmitted in future as a new proposal) and 702 Full. Potential drilling targets include the Conrad Rise investigating Antarctic Circum-Polar history.

2) **The history of the monsoons** involved tectonics, uplift, weathering and erosion, sediment deposition, and climate and oceanography. Two subthemes emerged:

(i) Monsoonal Paleoclimate and Paleoceanography (MPP): focused on the pelagic and hemipelagic archives as recorders of the local and regional responses to monsoon winds and precipitation. This included a review of 549 Full and 783 APL

(ii) Sedimentary Source-to-Sink studies, using submarine fan (SF) archives: as recorders of long-term changes in erosion, transport and deposition linked to tectonics and climate change principally in the Himalaya. This included a review of 609 Pre, 552 Full and 552 Add, 595 Full and 776 Full.

A two month drilling program entitled *iMonsoon* is suggested that would cover the topics above where most localities can readily be tied to 2D and 3D seismic.

3) **Tectonics and volcanism:** Tectonic problems identified that can be readily investigated by drilling the Indian Ocean include those associated with:

(i) Subduction—fault properties and slip, sediment effects, role of fluids, segmentation, rupture, tsunamigenesis—along the Sunda Arc, site of the great 2004 Indian Ocean earthquake and tsunami;

(ii) Tectonic plate breakup and reorganization associated with Kerguelen and Réunion hotspot activity; nature of crust under the Laxmi and Laccadive ridges and adjoining basins, intraplate deformation and possible incipient plate breakup along the Ninetyeast Ridge and origin of 85^0 E ridge.

Major geodynamic issues that can be investigated comprise:

(i) Hotspot – spreading ridge interactions and hotspot constraints on the mantle reference frame: eg. Afar, Kerguelen, Réunion

(ii) Backarc spreading magmatism, hydrothermal activity, mineralization, metallogenesis, and biosphere;

(iii) Large Igneous Provinces: the testing of existing models and development of new models for flood magmatism; and the origin and alteration of oceanic core complexes.

4) **The deep biosphere:** Scientific ocean drilling has revealed the existence of a deep biosphere in sediments and rocks far below the marine surface world. It is widespread, genetically and geochemically diverse, and comprises a significant fraction of Earth’s total living biomass. Several geomicrobiological questions were identified that may be answered by targeted drilling of Indian Ocean sediment:

(i) How has uplift of the Himalayans influenced monsoon and input of terrestrial matter into the Bay of Bengal and Arabian Sea, and impacted the development of the deep biosphere since the Oligocene?

(ii) How has the drainage from the Himalayan rivers influenced the development of subseafloor community structures and diversity?
(iii) How has the subseafloor biosphere been inoculated with terrestrial microorganisms (biogeography)? Are there regional differences between the Bay of Bengal and Arabian Sea?
(iv) How are deep biosphere ecosystems related to the formation of ferromanganese nodules?

Other questions may be answered by drilling Indian Ocean Crust:
(i) What is the diversity and biogeography of microbial communities in the very heterogeneous ridge systems?
(ii) Which microbial communities and functions exist in different crustal provinces and structures? How are they related to hydrogeology and to the alteration of the crust?

The thematic breakout group identified several pre-existing proposals that might facilitate enhanced geomicrobiological investigations (549 Full, 609 Pre, 552 Full, 609 Pre, 701 Pre and 760 Pre) and prospects for new proposals around the Ninetyeast Ridge, the Andaman back arc and the Krishna-Godavari Basin.

By increasing international cooperation and collaboration the workshop was an important step towards future scientific drilling in the Indian Ocean.

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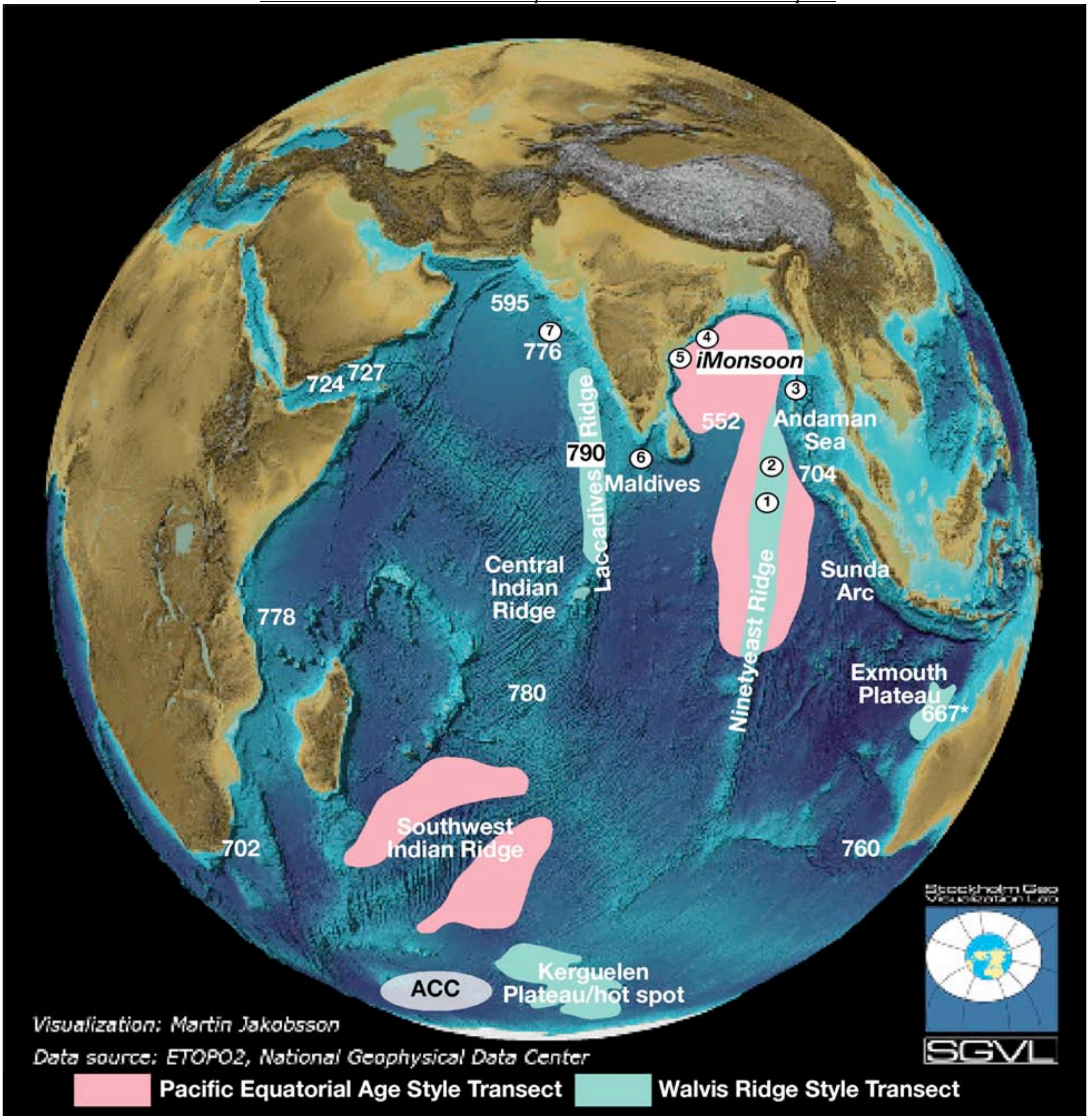


Figure 1.0 A map showing pre-existing proposals and future drilling prospects in the Indian Ocean. Potential Theme 1 targets include: two types of deep ocean transects; ACC = Antarctic Circumpolar Current drifts proposal; Maldives atoll & deep-water proposals. Theme 2 targets include *iMonsoon* with locations 1. DSDP 216: 2. ODP 758; 3. Andaman Sea; 4. Mahanadi Basin; 4. Krishna-Godavari Basin; 5. Cape Cormorin; 6. Kerala-Konkan Basin. Theme 3 target include most tectonic features illustrated. Theme 4 could be accommodated in most expeditions.

THEME 1: Cenozoic oceanography, climate change, gateways and reef development

This theme outlines existing proposals and potential drilling prospects that cover broad questions related to the Palaeoceanography of the Indian Ocean. It also focuses on the causes and effects of the boundary currents, the Indonesian Through-flow and the influence of sea level variability on the origin of late Pleistocene reefs.

Assoc. Prof. Stephen Gallagher, microfossils and palaeoceanography, Melbourne University, Australia (Chairman).
Prof. Andre Droxler, Sea level and reefs, Rice University, USA.
Dr. Divakar Naidu, Palaeoceanography, National Institute of Oceanography, India.
Dr. Andrew Heap, marine geology, Geoscience Australia.
Several other participants contributed to this review, these are listed below.

1.0 Focus topics of interest within breakout groups

Three subthemes emerged from the discussions that focused on the entire Indian Ocean (Fig. 1.1):

(i) Evolution of the shallow carbonate environment

Proposal (780 Pre) and a prospective proposal (to be submitted in April 2012) focus on drilling a series of deep and shallow sites in the Maldives Archipelago. Proposal 780 Pre aims at better understanding the influence of the monsoon-generated current system and sea level fluctuations on the Neogene development of the Maldives carbonate platform. Drilling a series of transects in the Maldives Inner Sea using a non-riser platform such as the D/V JOIDES Resolution will address the larger scale development of the Maldives carbonate platform and associated adjacent sediment drifts, resulting of an interaction between the long-term Neogene global cooling and sea level fluctuations, in addition to the Miocene onset and strengthening of the monsoonal system in the past 8-10 My. Moreover a proposal requesting alternate and non-riser drilling platforms will be submitted in April 2012 to determine the origin of modern atolls and drowned flat top banks in the context of sea level fluctuations since the Pliocene.

(ii) Deep ocean record of palaeoceanography/climate

This subtheme reviews the deep ocean records of Cretaceous to Neogene climate. It is proposed to drill a series of site transects to obtain the long-term history of palaeo-CO_2 levels, sea surface temperatures, ocean anoxic events and the Indian Ocean Dipole. Existing proposals and potential future proposals are reviewed and summarized here. This section avoids reference to the Indian Monsoon, as this topic is reviewed at length under Theme 2 of this workshop, although this topic is considered under the *potential linkages* heading below. Several proposals focusing on recovering deep oceanic and climatic Cretaceous to Neogene records (760 Pre, 724 Full and 778 Full) have been submitted to the IODP. These proposals will be reviewed followed by a list of potential proposal prospects.

(iii) Ocean margin boundary currents and gateways

Ocean boundary currents are key drivers for continental climate and sea surface temperature variations. They also are migration pathways for organisms. The Indonesian Throughflow is an important arm of the global thermohaline circulation; it is a feature that regulates sea surface temperatures and climate in the Indian Ocean. The Antarctic Circumpolar Current is a key driver of Antarctic glacial dynamics and global climate. Understanding, back in time, the responses of these ocean currents to glacio-eustatic and tectonic triggers will allow us to predict their behavior in the future in the context of global climate change. Two proposals (667-Full and 702 Full) have been submitted to IODP under this theme. These proposals will be reviewed here, and followed by a list of potential proposal prospects.

The main objectives of each proposal will be summarized, listing related proposals and drilling prospects that have been identified during discussions at the IODP Goa workshop.

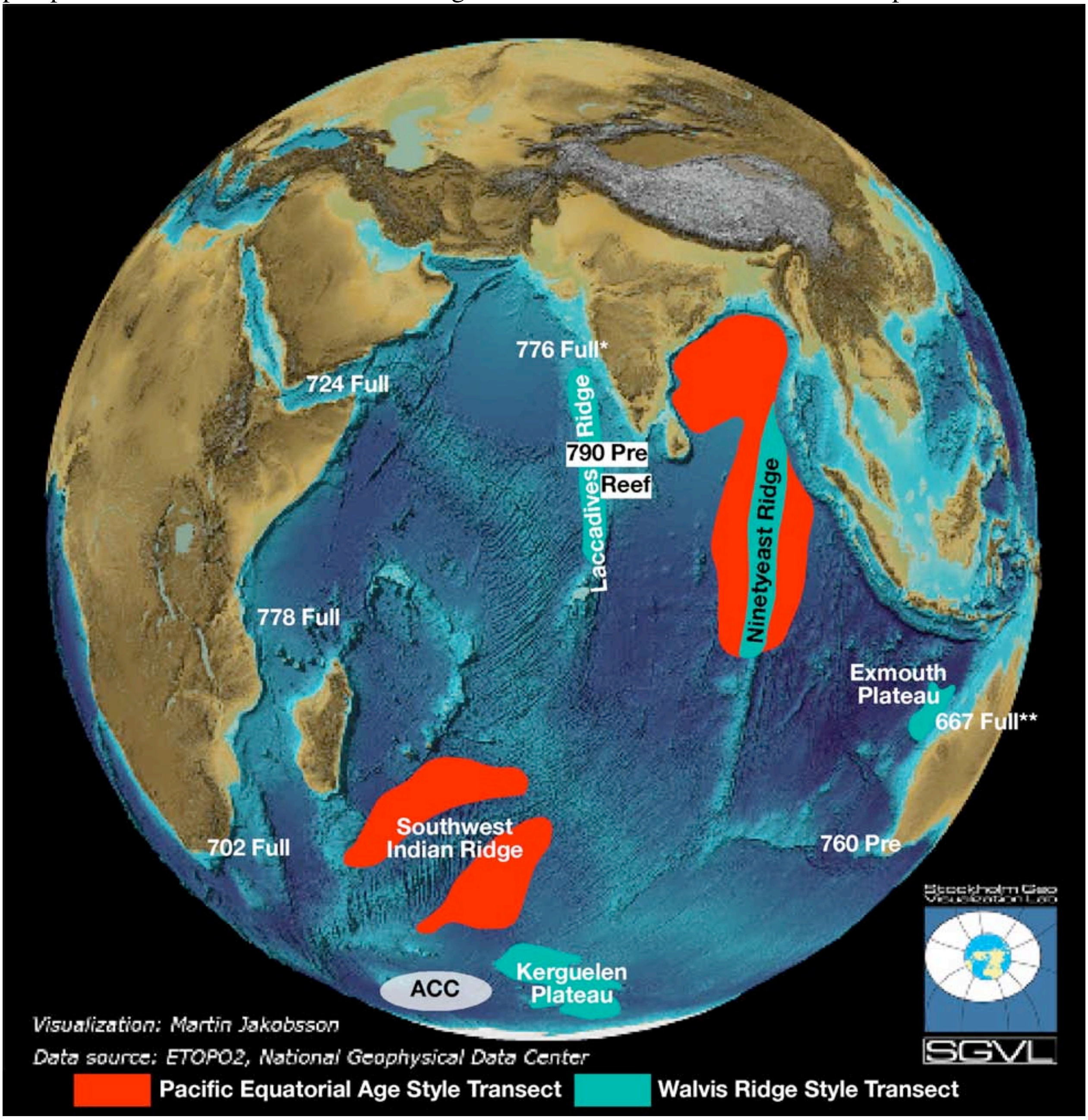


Figure 1.1 A map showing Theme 1 proposals and prospects. Potential targets include: two types of deep ocean transects; ACC = Antarctic Circumpolar Current drifts proposal; Reef = Maldives atoll proposal. Note: 776 Full* is included in the Theme 2 (monsoon) and 667 Full** will be resubmitted as a new proposal.

1.1 Evolution of the shallow carbonate environment: Proposed Drilling programs in the Maldives Inner Sea and Archipelago

Contributors: Christian Betzler, Andre Droxler

1.1.1 Maldives deep-water drilling project: Maldives Inner Sea

The overall objective of the project is to place the Maldives current system, as recorded in the sediment drifts, into the larger scale development of the oceanic current system during long-term Neogene global cooling and the onset of the modern system. This will be achieved by accomplishing the following special goals: (i) to provide a detailed reconstruction of the pre-drowning, drowning and post-drowning evolution of the carbonate platform by linking the seismic stratigraphic record to the sedimentary record; (ii) to constrain the timing of this evolution thus allowing age assignments of unconformities, sedimentary interruptions, sedimentary turnovers, and onset of drift deposition; (iii) to integrate results from other ODP and IODP expeditions like the South Atlantic or the Mediterranean outflow expedition to place the Maldives system into a global context.

These objectives relate to two challenges expressed in the IODP Initial Science Plan. *Challenge 3* addresses the variations in regional monsoon systems over a multimillion-year time scales. *Challenge 2* addresses the question of how ice sheets and sea level respond to a warming climate, reducing the uncertainties in our understanding of the magnitude and rate of past sea-level change.

<u>Needs for drilling to accomplish the scientific objectives</u>

The herein expressed hypothesis is largely based on seismic stratigraphic data, multibeam and parasound data. As it stands, a very limited insight into the depositional dynamics of the drifts is provided only by shallow piston cores recovered during cruise M74/4 of the RV Meteor, and by ODP Site 716. This site, however, on one hand is positioned in a random location for analysis of the drifts; on the other hand, the site only penetrates the upper 280 m of the sedimentary column in the Inner Sea. The base of the core falls within the upper Miocene and thus by far does not reach the base of the drifts. The commercial well ARI 1 drilled by Shell was washed though for the upper 500 m, so does not provide samples.

The first objective of the proposal is to understand the turnover from the prograding bank depositional system to the drift sedimentation, which is separated by a regional drowning unconformity. To achieve this goal, the clear geometrical evolution has to be verified by a detailed facies reconstruction and dated by stratigraphic techniques. Two drill sites (MAL-01A, MAL-02A) thus are needed to (i) ground truth the hypothesis that the late platform stage sequences S7-S10 are carbonate platform and platform margin sequences, with facies deposited near sea level, and that these sequences have a LST-HST subdivision. These drill sites (ii) will also allow reconstructing the drowning and post-drowning history (i.e. succession S10 - D1). It is expected to recover a sedimentary succession reflecting increased nutrient input into shallow water areas (drowning sequence) overlain by a package of periplatform hemipelagic carbonate sediments (drifts). This is quite similar to the sequence successfully drilled during ODP Leg 194 on the Marion Plateau (Australia), comprising a succession with a neritic platform overlain by a drowning unconformity and by current-controlled deposits.

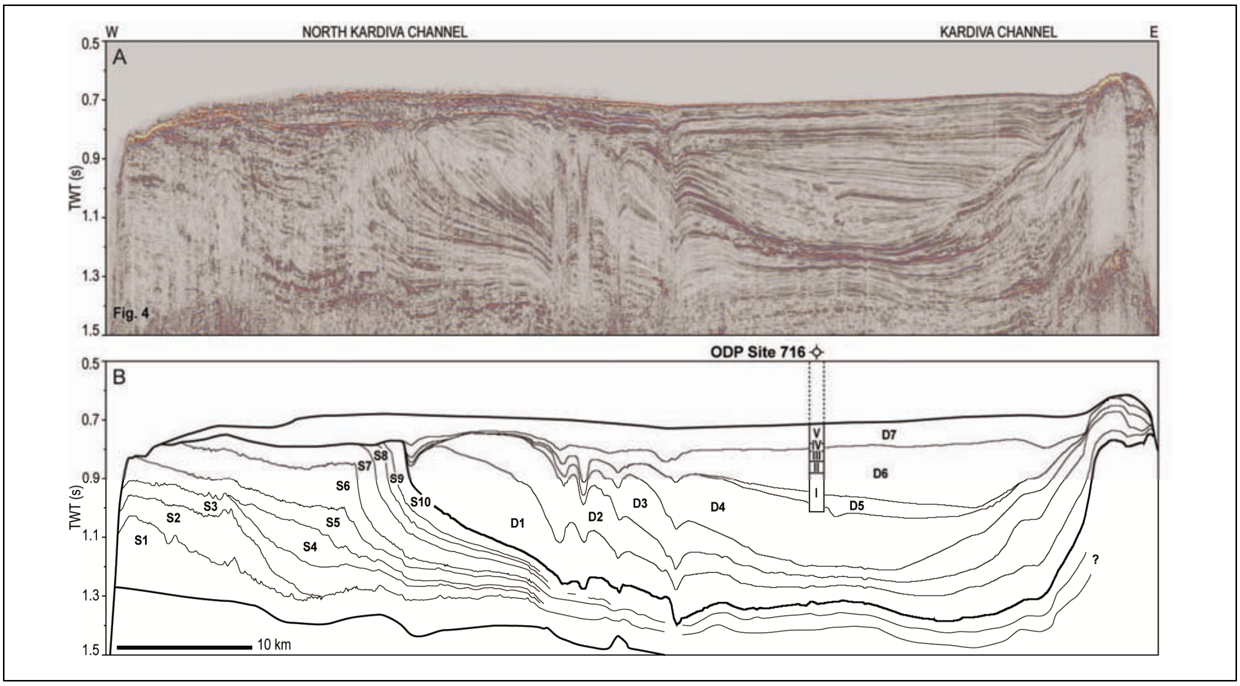
To establish a chronostratigraphy of the Neogene succession, the second objective of the proposal, cores are needed to recover a number of samples based upon which an age model can be determined. The dating of platform carbonate facies will rely on a combination of biostratigraphic zonations (large benthic foraminifers, planktonic foraminifers, calcareous nannoplankton) and Sr-isotope dating.

To accomplish the third objective of the proposal, i.e. to perform a cyclostratigraphic analysis of the sediment drift succession and to retrieve a monsoon signal, core data at the location of drill sites MAL-03A, MAL-04A, and MAL-05A, combined with downhole logging data, are needed. Drift sediments are generally the result of long-term stable bottom currents. The enhanced accumulation rates make them attractive as a target for paleoceanographic studies. Several past IODP legs have targeted giant contourite drifts that accumulated along continental margins of the Atlantic and Southern Oceans. The Indian monsoon upwelling along the Oman margin was studied during ODP leg 117 in the late eighties. 20 years later, the East Asian monsoon was the focus of ODP Leg 184 in the South China Sea. Here, site 1144 delivered a high-resolution monsoon record and was drilled on a giant elongated drift body. The Maldives open up a unique opportunity to retrieve a continuous high-resolution record of the Indian monsoon history starting with its onset in the Upper Miocene. A large suite of proxies will help to unravel the past ocean-climate conditions including e.g. the analysis of foraminifer assemblages (T, S, productivity, water mass tracer), $d^{18}O$ (T, S, global ice volume), $d^{13}C$ (ocean ventilation), $^{143}Nd/^{144}Nd$ (water mass tracer), sortable silt-fraction (current velocity), alkenone maturation index (T) $^{231}Th/^{230}Pa$ (ocean ventilation).

The NE-Monsoon winds also bring the low salinity waters around the tip of India. Mg/Ca ratios in foraminifer shells for temperature combined with the $d^{18}O$ will allow discriminating between temperature and salinity signals, similar to studies performed in the eastern Arabian Sea. Thus the drift sediments would also record the history of low salinity water in the area.

<ins>North Comorin Ridge</ins>

The proposal is aimed at testing the hypothesis that the SW and NE monsoonal regimes are associated with the productivity and Oxygen Minimum Zone (OMZ), by exploiting the possibility of resolving it at centennial time scale due to the known high sedimentation rate (40-50 cm-kyr) in this region. Further, it is proposed to investigate the ventilation history and the relationship between the proxies of externally sourced water masses, and compare them with those from higher latitudes. The proposal is strongly linked to IODP proposal 790_Pre and its objectives would be complimentary. It is proposed to accomplish these objectives through an optimized transect which will also illuminate the influence of deep-water masses. High resolution multichannel seismic data sets are available throughout the Maldives Inner Sea and the North Comorin Ridge to characterize the proposed sites for drilling.



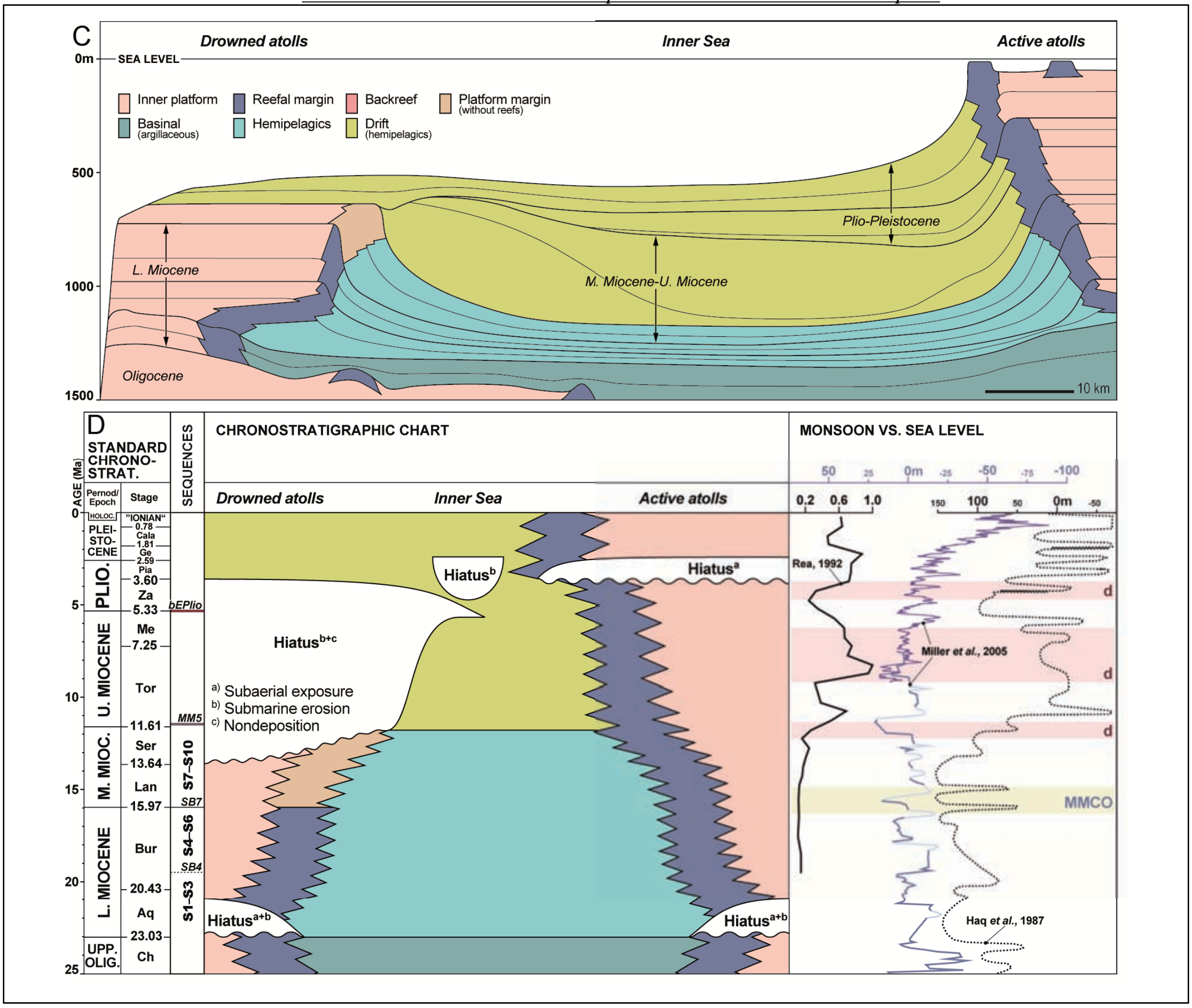


Figure 1.2: A: W-E seismic section of the Maldives showing the prograding shallow-water bank, a drowning of the shallow-water bank and drift sediments. I–Upper Miocene, II–Lower Pliocene, III–Middle Pliocene, IV–Upper Pliocene, and V–Pleistocene. B: Sequence stratigraphic interpretation of the Lower and Middle Miocene with position of ODP Site 716. C: Synthesized model of the Maldives carbonate platform architecture. D: Synthesized tentative chronostratigraphy of the Maldives with a normalized curve of the monsoon intensity and sea level curves. After Füerstenau et al., Bas. Res, in Review.

1.1.2. Origin of Modern Atolls: *Challenging by IODP drilling the deeply ingrained Darwin model for modern atoll formation*

In brief, proposed drilling program(s) to be submitted for April 2012 will test the “Antecedent Karst Theory” to explain the origin of modern atolls in the Maldives Archipelago and in the Eparses islands (Mozambique Channel) in the context of the relatively well-known, last 5.0 My, sea level variations and the Indian monsoon high-energy environment.

The proposal’s main objective is to test the model that atolls in the Maldives, classic coral-capped ring reefs enclosing relatively deep lagoons, like most atolls globally established in the low latitudes, are linked to the well-established pattern of sea level fluctuations and, therefore, ice volume variations in the last 5 My, although a strong monsoon high-energy regime should also influence their overall formation, (see Figure 2.1. on page 10 in the IODP 2013-2023 science plan). In trying to understand modern atoll formation, this proposal would help in constraining how ice volume, and therefore sea level, have varied since the early Pliocene, a time when Earth atmospheric CO2 concentrations were probably equivalent to the current CO2 concentration values and those forecasted for the next century. Atmospheric CO2 values are intimately connected to the global carbonate system and vice versa. This proposal addresses, therefore, some questions directly embedded in the first two challenges listed in the IODP science plan for 2013-2023: " *1. How does Earth's climate system respond to elevated levels of atmospheric CO2?"* and *"2. How do ice sheets and sea level respond to a warming climate?"*

The proposed drilling program will test whether the "Antecedent Karst Theory" can explain how the classic modern atolls in the Maldives grew on top of early Pliocene flat top carbonate banks into late Quaternary atoll reefs. The modern atolls in the Maldives would have formed from the interaction between karst morphology developed during repeated times of exposure (glacial stages) and stacked coral reef mostly vertical growth phases during times of re-flooding and sea level highstands (deglaciations and interglacial stages). Moreover, the monsoon unusually high-energy regime in the equatorial Indian Ocean has added some non-negligible environmental factors that challenged the growth of the atolls during times of sea level rise and highstands. In the Maldives, only some atolls (such as Goidhoo and Rasdhoo) are true atolls, while others (such as Ari and North Male) are partially drowned atolls most likely caused by the monsoon's high energy level.

Commonly, a central depression surrounded by raised margins forms during times of exposure, creating a template for future atoll formation through successive coralgal aggradation, preferentially along the margins of the system, in successive periods of re-flooding during sea level transgressions and high stands. The duration of each late Pleistocene sea level highstand, on the order of 10-15 kyr, is not long enough for atoll lagoons to be filled up with carbonates produced within the lagoon or imported from carbonate produced on the atoll rim. If high sea level during late Pleistocene interglacials had remained constant for a much longer period of time, as during the early Pliocene, atolls would have evolved into flat-topped banks. Such bank morphology is clearly observed in the Maldives during the Pliocene as drowned banks (i.e. Fuad Bank) or in seismic lines crossing the modern atolls (i.e. North Male Atoll). The "Purdy model" is often referred to "Antecedent Karst Theory", which has never been fully tested yet through drilling. The main objective of this proposal is to test the "Antecedent Karst Theory" in the context of the relatively well known evolution of the Maldives carbonate system over the last 5 My, by focusing on the Goidhoo/Rasdhoo Atoll rims and lagoon, in addition to their adjacent drowned extensions (northern part of Ari Atoll and southeastern part of Goidhoo Atoll) and intervening drowned Fuad Bank, in the Equatorial Indian Ocean.

Expected results from the proposed comprehensive drilling program, on Goidhoo and Rasdhoo/Ari Atolls, their adjacent drowned flat top extensions, and the intervening drowned flat top Fuad Bank, will test the model linking the relatively well-established pattern of sea level fluctuations and ice volume variations in the last 5 My with the systematic evolution of Pliocene flat top banks into late Quaternary atoll reefs in the Maldives. This model is uniquely anchored in a wide range of seismic and morphological data sets already available in the close vicinity of Goidhoo and Rasdhoo/Ari atolls (1975 Elf Aquitaine and 1989 Shell seismic data sets, 2007 R/V Meteor NEOMA data sets, shallow borehole drilling on the rim of Rasdhoo Atoll and of Baa Atoll, in addition to unpublished recent seismic survey data and vibrocoring within Goidhoo/Rasdhoo atoll lagoons themselves).

In the proposed model, the early Pliocene flat top banks would have remained exposed most of the time for about 2 My, prior to being successively flooded and exposed by a series of five, 120 m plus high amplitude, mid to late Brunhes sea level rises and falls. The exposed banks might have been also briefly re-flooded in the early Pleistocene and late Pliocene at ~ 1.0 Ma (MIS 31-37), 1.5 Ma (MIS 47-49), and ~ 2.0 Ma. Karst topography, enhanced during the series of exposures, became the substratum for reef development during the intervening intervals of sea level rise and, therefore, would explain, by the Purdy Antecedent Karst Theory, the modern atoll physiography observed in the Maldives Archipelago. The proposed drilling program on Goidhoo/Rasdhoo Atoll rims and lagoons, in addition to drilling their adjacent drowned extensions and intervening drowned Fuad Bank, would test this relatively simple model in the context of the fairly well-established sea level fluctuations and global ice volume variability in the past 5 My. If eustatic sea level fluctuations are involved, as we believe, this model can easily be applied globally and would not only be applicable for the atolls in the Maldives Archipelago. As a conjugate drilling project and to demonstrate, by drilling in a different tectonic context, the potential global Plio-Pleistocene atoll formation model, a sister proposal to the Maldives atoll proposal will be submitted by IFREMER and CEREGE to drill a series of sites on the atoll rims, in the lagoons, and the adjacent drowned flat banks in the Bassas da India and Europa atolls (Mozambique Channel).

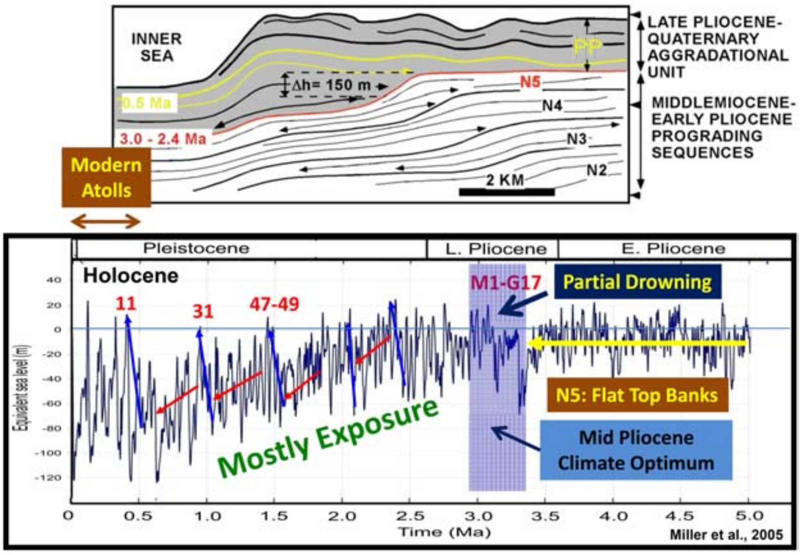


Figure 1.3: The relationship between platform aggradation and progradational geometries of the south Male atoll lagoon with sea level.

In the Maldives, we are proposing to develop a comprehensive Drilling Program in three phases.
Phase I: Goidhoo/Rasdhoo Atoll Rim Drilling Program with a land drilling rig (local company?): The main goal of this first phase is to drill four boreholes using four of the five existing islands widely distributed on the Goidhoo Atoll rim, and two boreholes using the existing islands on Rasdhoo Atoll rim, and one island on the northwest margin of Ari Atoll.
Phase II: Goidhoo/Rasdhoo Atoll Lagoon Drilling Program with a Jack UP Platform or Anchored Barge: The main objectives of this second phase are to drill a series of two deep boreholes (275 – 300 m) in each one of Goidhoo and Rasdhoo atoll lagoons, water depths ~ 40-50 mbsl.
Phase III: Drowned Flat Bank Top Drilling Program with D/V JOIDES Resolution. The main objectives of this third phase are to drill a series of seven 50-75 m deep boreholes through the drowned (most likely early Pliocene) flat platform attached on the east side of Goidhoo Atoll (2 sites), the drowned flat platform attached on the north side of Ari Atoll (2 sites), and the drowned Fuad Bank top (3 sites), at ~230-250 m in water depths.

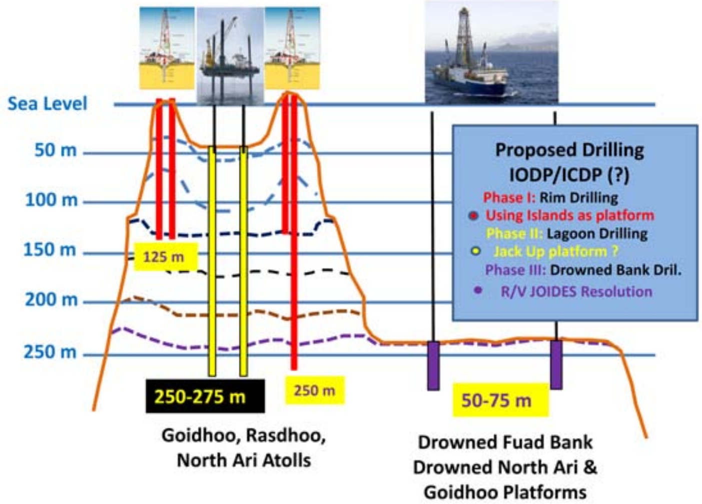


Figure 1.4: Proposed drilling program on the rim itself of Goidhoo Atoll in addition to a series of holes in its lagoon and across the eastern margin towards the flat topped, several km wide, terrace at about 230-250 m flanking the atoll itself.

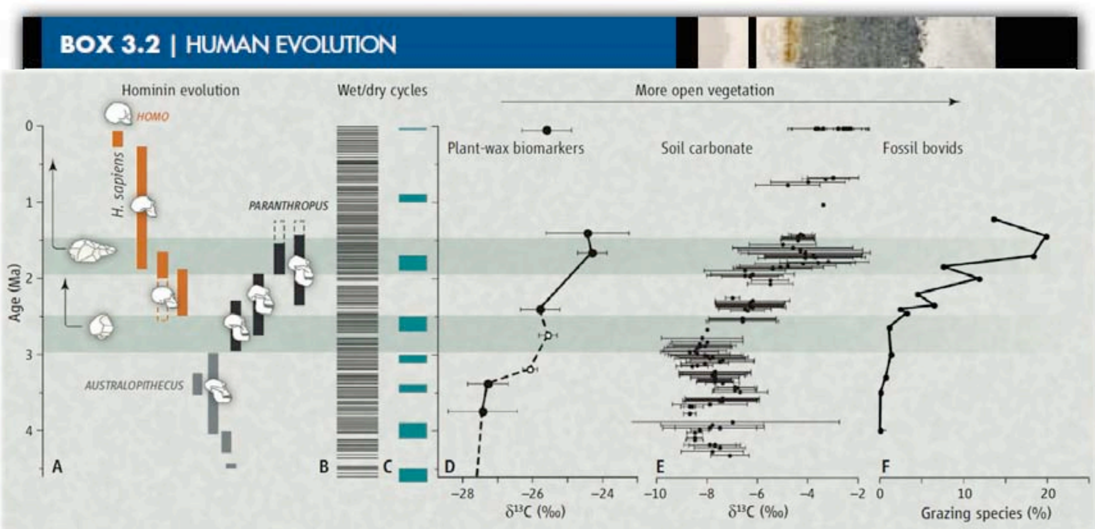
1.2 Deep ocean record of palaeoceanography/climate

This subtheme directly addresses grand challenges in Theme 2 of the Science Plan 2013-2023. "Climate and ocean Change Reading the past, informing the future".

Contributors: Sarah Feakins, Bridget Wade, Ben Slotnick, Brad Clemens, N.C. Pant, Cortez, Stephen Gallagher

1.2.1 Existing "deep ocean" IODP proposals

724-Full: This proposal intends to: (i) Reconstruct NE African paleoenvironmental change spanning the late Neogene (10Ma); (ii) Understand the causes of northeast African climate change during the late Neogene; (iii) Constrain tephrostratigraphic records documenting the late Neogene history of northeast African explosive volcanism; (iv) Late Neogene evolution of SW Indian monsoon intensity; (v) Late Neogene initiation and variability of Red Sea Overflow Water ventilation of the Gulf of Aden; (vi) Integration of drilling science results to understand the late Neogene evolution of northeast African paleoenvironmental change and its influence on African faunal evolution. This is a highly ranked proposal, and indeed it was ranked as the top for its science in 2007 by the IODP. However it is presently not viable because of the piracy and political situations.



This proposal was highlighted within Grand Challenge 7 (Box 3.2) above "How sensitive are ecosystems and biodiversity to environmental change" within theme 3 Biosphere Frontiers.

760 Pre: This pre-proposal intends to drill the Naturaliste and Mentelle basin off southwest Australia to obtain a high-resolution southern hemisphere Cretaceous climate record. Such southern hemisphere records are very rare The objectives are to: chart the climate and glacial history of a high palaeolatitude (60-65°) section; to document key Ocean Anoxic Events and understand the pre-conditions for their formation; provide insights into the breakup of Gondwana and evolution of key gateways between Antarctica and Australia. The drilling will also yield a high latitude record of Cenozoic climate and palaeoceanography. The drilling of two previous DSDP core holes in the region (Leg 26, Site 258 and Leg 28, Site 264) shows the potential to obtain Albian and Turonian intervals with high TOC's. An extensive set of geophysical survey data exists due to extensive exploration over past 5 years. Potential new sites could be targeted to obtain a record going back to the Lower Jurassic, and potentially the Paleozoic. Industry wells Challenger 1 and Sugarloaf 1 have ~3.5km of recovery dating back to the Bajocian.

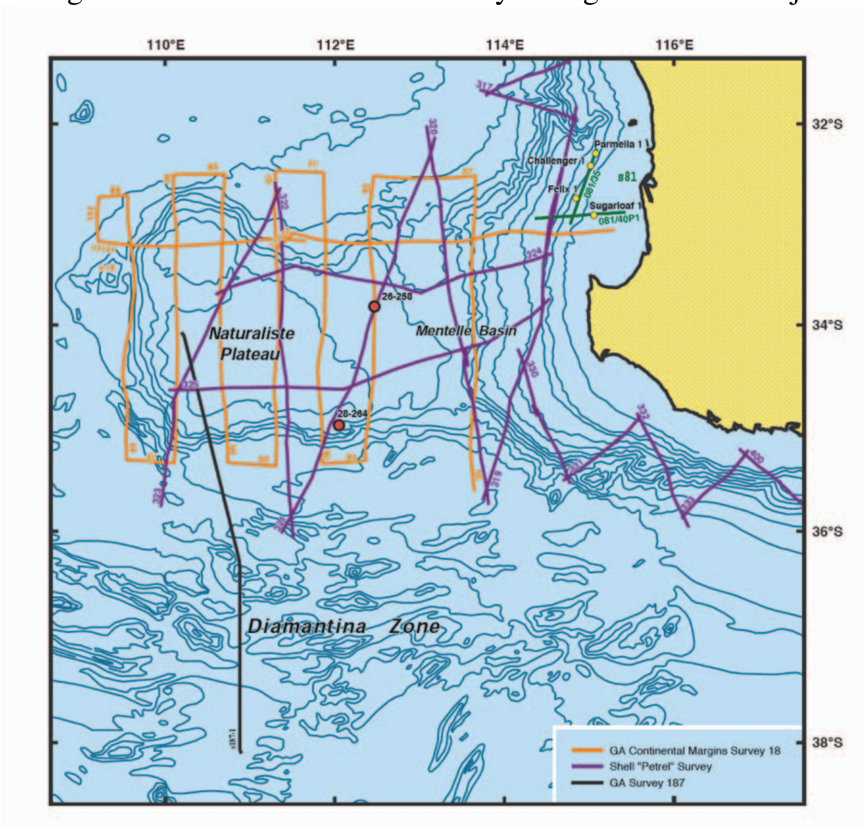


Figure 1.5: Extensive seismic data exist for this Pre-proposal.

The future intentions of the proponents of this proposal are not known. The proposal has scientific support from Australia's national geoscience agency Geoscience Australia.

This proposal clearly falls into Theme 2 of the Science Plan. It also falls into challenge 7 "How sensitive are ecosystems and biodiversity to environmental change" within Theme 3 Biosphere Frontiers.

778-Full: resubmitted as Full2: This proposal to drill on the Tanzanian margin has been revised and resubmitted. It intends to analyse an assemblage of exceptionally preserved glassy foraminifera and ages ranging from recent to Paleocene. The exceptional preservation of foraminifera provides many possibilities for geochemical analyses and paleoclimate reconstructions as well as age control. Complementary work has been done on shore with drill cores capturing uplifted marine sediments that inform the proposal. While numerous publications have resulted from these terrestrial cores, including high profile publications, a wider variety of organic proxies will be possible in marine cores, thus providing exceptional potential for sea surface temperature reconstructions, answering critical questions of palaeoceanography and also reconstructing terrestrial proxies fluvially transported off the continent. No existing cores are available for this time range: further south, DSDP Site 242 stopped short of the Paleocene due to time constraints. DSDP 245 has the PETM, although misplaced in original analyses, with K/T boundary basement, but the Neogene is below the CCD and cherts are present.

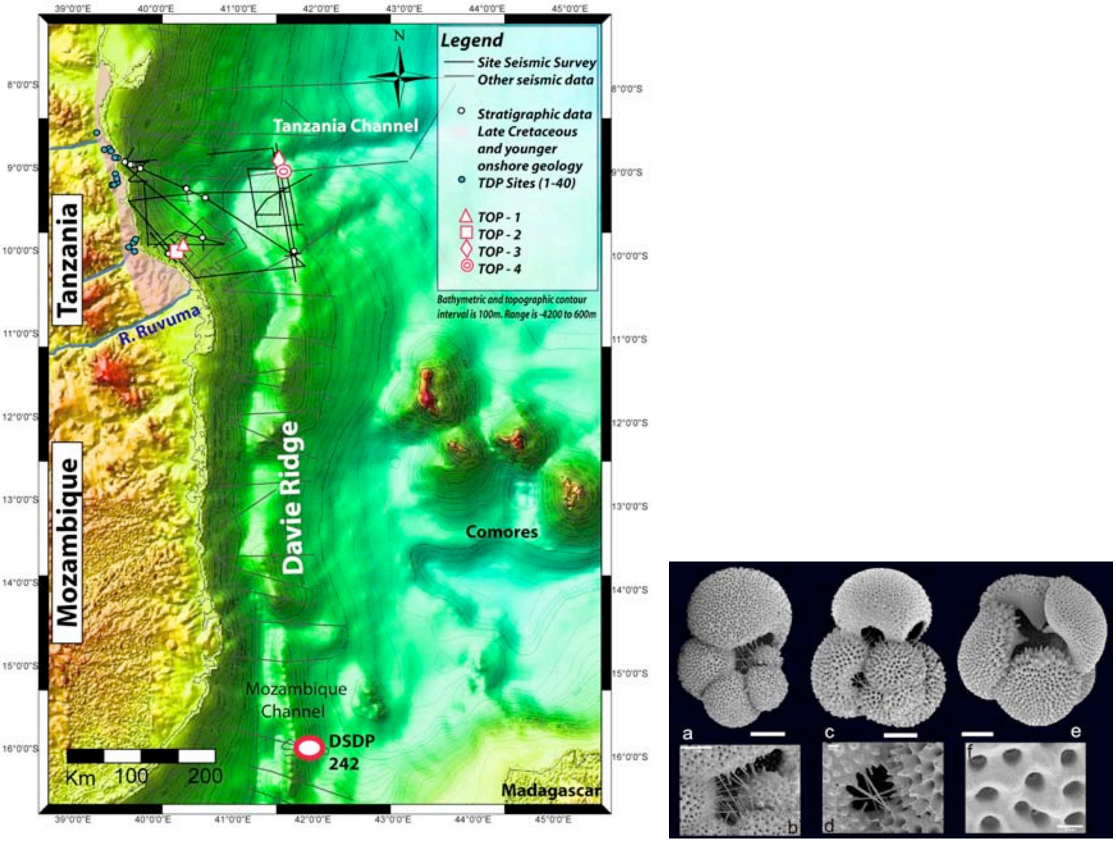


Figure 1.6: The location of the proposed drilling targets of 778 Full and the extremely well preserved foraminifera in previously studied on shore sites.

This proposal falls into Theme 2 of the Science Plan. It also falls into challenge 7 "How sensitive are ecosystems and biodiversity to environmental change" within theme 3 Biosphere Frontiers.

1.2.2 Potential IODP "deep ocean" proposals

Paleogene transects – Ben Slotnick
The PETM is of profound scientific interest because of the abrupt hyperthermals during a warm interval. Preliminary ideas on coring Paleogene sequences on ridges in the Indian oceans were proposed. The Indian Ocean offers uniquely a large number of ridge axes including two ridge axes that are oriented N-S. A latitudinal transect was proposed on Ninetyeast Ridge or the Laccadives. The Laccadives Ridge is a better location to capture the SST anomalies of the Indian Ocean that are critical for determining the strength of the African and Indian monsoon, and therefore would be a high priority for paleoclimate interests. The Laccadives Ridge coring would, in tandem with cores taken further east, allow a record of the Indian Ocean dipole over the last 2Ma. Site survey data do not exist for the Laccadives, requiring a longer lead-time for development.

The Ninetyeast Ridge has a practical advantage for building a proposal in that site survey data already exist from prior DSDP drilling. New cores are required because of rotary drilling disturbance and gaps; most of those cores miss the PETM. A Ninetyeast Ridge proposal could potentially be developed by 2014 and the group was strongly supportive of fast progress towards this goal. A drilling strategy might be a transect, just off the ridge axis with basement of the same age capturing the latitudinal climate gradient from 10°S to 2°N (between DSDP Sites 216 and 214) which would be a very powerful addition to PETM climate reconstructions, providing the latitudinal gradient across the tropics for testing climate model simulations. Drilling strategy could potentially also include a Walvis Ridge style depth transect from 5-2.5km water column depth to monitor for changes in the CCD over the PETM – while we have data on the CCD in the Atlantic and Pacific over the PETM, the addition of this data for the Indian Ocean would complete the global picture of changing ocean chemistry in relation to high CO_2 ocean acidification events (challenge 4).

This proposal falls within challenges 1 & 4 of theme 2 "climate and ocean change: reading the past informing the future".

1.3 Ocean margin boundary currents and gateways

This subtheme directly addresses grand challenge "Theme 2. Climate and ocean Change Reading the past, informing the future" Challenge 1: "How does the Earth's climate system respond to elevated levels of atmospheric CO_2" of the Science Plan. It also addresses Challenge 7. "How sensitive are ecosystems and biodiversity to environmental change?" in Theme 3, biosphere frontiers.

Contributors: Craig Fulthorpe, Annette George, Andrew Heap, Jody Webster, Stephen Gallagher, Neville Exon, and Minoru Ikehara

1.3.1 Existing "boundary current" IODP proposals
667-Full, Australian Northwest Shelf: not forwarded to OTF in 2011: possible new submission by Fulthorpe, Gallagher et al. 667 Full was first submitted in 2005 went for external review and stayed at SPC while proponents interpreted the upper part of the stratigraphy using newly donated expanded seismic data from the petroleum industry. The objectives of 667 Full were to understand the timing and amplitudes of global sea-level change (eustasy) and the stratigraphic response to eustatic change. Specifically to: (i) Calibrate sequence stratigraphy of late early Oligocene – Recent sequences by providing age control for global correlation and paleobathymetric estimates for determination of eustatic amplitudes; (ii) Reconstruct original

depositional geometries (uncompacted) and estimate eustatic amplitudes using 2D flexural backstripping; (iii) Investigate the stratigraphic response to sea-level change: extent of lowstand paleoshelf exposure; sediment transport mechanisms on shelf and slope; and history of reef development, interaction of carbonate and siliciclastic sedimentary processes through multiple sea-level cycles, and palaeocirculation (history of the Leeuwin current). However, it became clear to the proponents based on detailed interpretation of a large 3D dataset that deep penetration is probably not widely viable, given the widespread existence of the partially unconsolidated Bare Formation across the region. They also recognize that the margin is tectonically complex and that the proposed eustatic reconstructions would be challenging. However, in a new possible proposal it is intended to include geodynamic modelers as proponents.

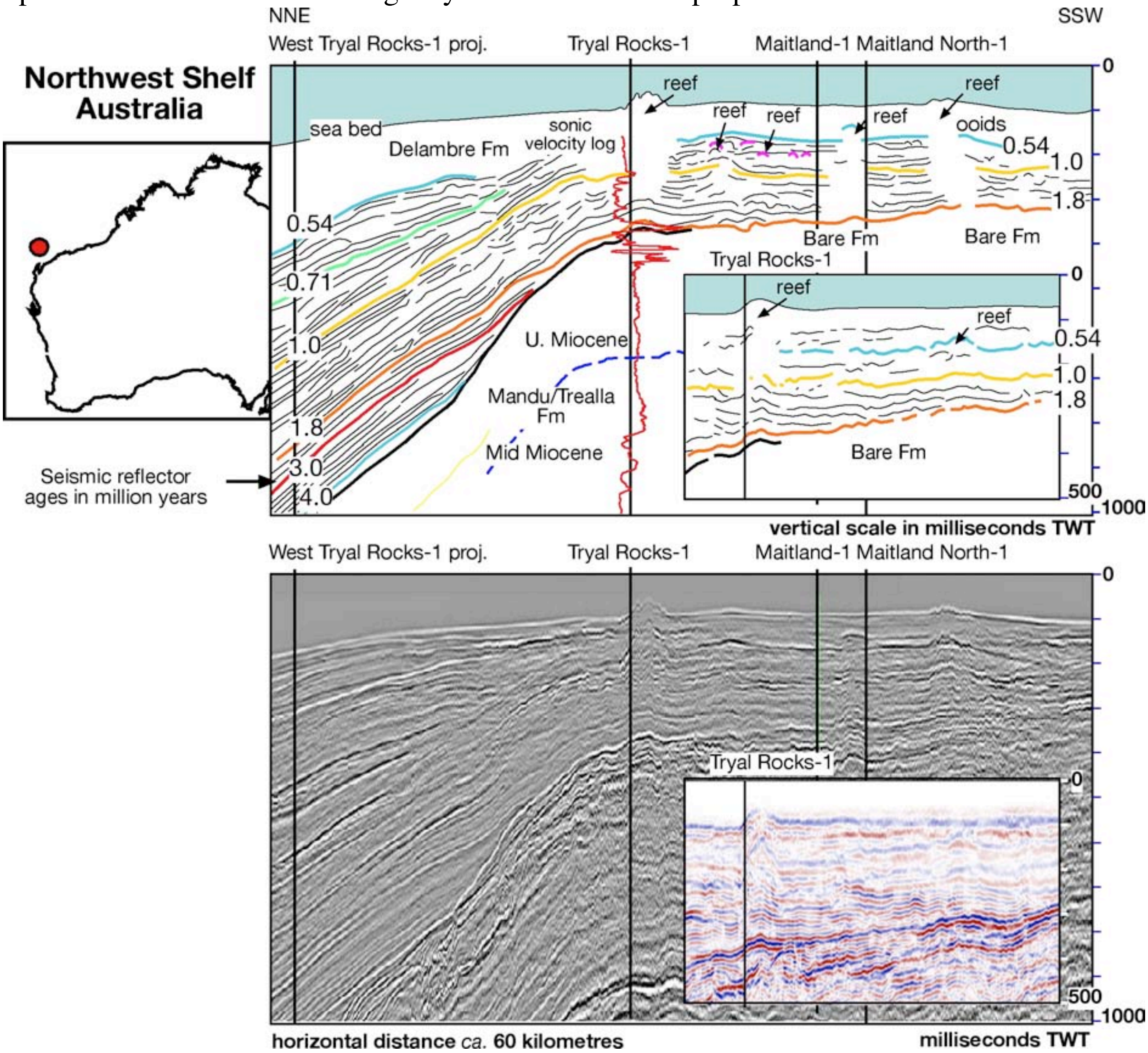


Figure 1.7: Potential additional "shallow" targets for the new proposal to replace 667-Full.

A **new proposal** is proposed is "Reefs, oceans and climate: a 5 million year history of the Indonesian throughflow on the northwest shelf of Australia". Its objectives are to:

(i) Document the 5 million year history of the ITF and the Leeuwin Current;

(ii) Constrain the ocean climate conditions that preceded the onset of aridity in Australia;

(iii) Understand relative sea level history of the NW Australian margin in the context of differential subsidence caused by the northward subduction of the Australian plate as revealed by carbonate platform histories;

(iv) To understand the ocean, sea level and climate thresholds leading to tropical platform and coral reef initiation;

(vi) Understanding the ocean and climate triggers for the switch from siliciclastic (Bare Formation) to tropical carbonate sedimentation (Delambre Fm).

To address several hypotheses:

(i) That tectonic throughflow restriction was highly variable on a 100 kyr or greater scale;
(ii) The switch from siliciclastic to carbonate deposition was related to the initiation of the Leeuwin current at 1.6 Ma or related to the onset of the Northern Hemisphere glaciation (3.2 Ma);
(iii) Platform spatial asymmetry is related to changes in ocean current dynamics;
(iv) Reef development was intermittent and asynchronous;
(v) reef expansion is directly related to key climate and ocean thresholds; with a direct relationship between warm surface current variability, tropical platform and reef development through time.

This new proposal requires reassessment of the significant seismic database that exists in order to refine new or revised drilling targets. A new Full or Pre proposal will be submitted in 2012.

702-Full: The scientific objectives of the SAFARI (Southern African Climates, Agulhas Warm Water Transports and Retroflection, and Interocean Exchanges) drilling proposal, on Plio/Pleistocene time scales, cluster around a series of palaeoceanographic and palaeoclimatic themes: (i) Agulhas Current warm-water transport during periods of accelerated climate changes; (ii) linking between Antarctic climate variations, circumpolar ocean front mobility, and impacts on Agulhas leakage into the Atlantic; (iii) influence of upstream forcing: monsoon, ITF and Red Sea outflow; (iv) impact on southern African climates and east-west asymmetry; (v) vigour and hydrography of NADW transported to the CDW and Indian Ocean; (vi) contribution of Southern Ocean deep and bottom water masses to global ocean THC; (vii) advective salinity feedback between Agulhas Leakage and Atlantic MOC.

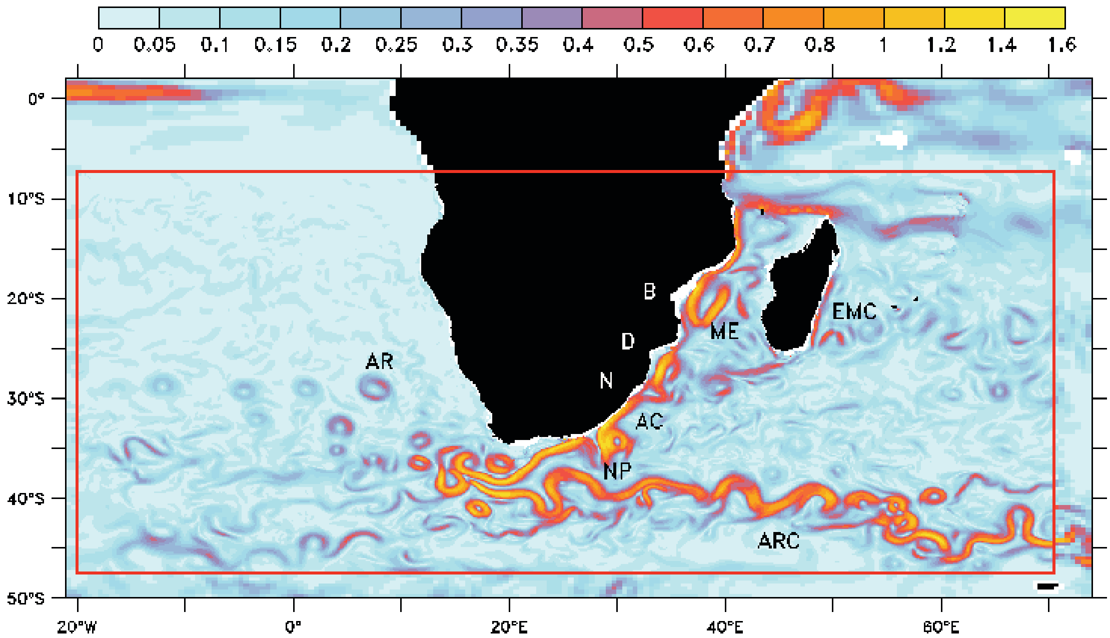


Figure 1.8: Alguhas Current and retroflection, a high resolution eddy-resolving ocean model nested in a global, low resolution general circulation model. Agulhas Current (AC), Agulhas Ring (AR), Agulhas Return Current (ARC), East Madagascar Current (EMC), Mozambique Eddy (ME) and Natal Pulse (NP). Agulhas Rings
100 - 400 km diameter and 800 - 2000 m deep, volume transport = 70 x 10^6 m^3 s^{-1}, Temperature > 21°C, Salinity > 35.5.

The site surveys are at an advanced stage and it is intended that Full2 be submitted in October 2012.

This proposal falls within challenges 1 & 2 of theme 2 “climate and ocean change: reading the past informing the future”.

1.3.2 Potential "boundary current" IODP proposal

Proponent: Minoru Ikehara

High-resolution climate variability and Antarctic Circumpolar Current (ACC) evolution history from the Conrad Rise sediment drift the Southern Indian Ocean

The position and strength of the ACC is very important, because it is closely linked with the intensity of the Southern Hemisphere westerlies. These are responsible for the thermal transport from mid-latitudes to the Antarctica. This proposal plans to drill a series of sediment waves/drift deposits to chart ACC variability over the past 5 Ma. The drift sediments lies at water depths >2400 m, and have wave lengths of 1 to 2.5 km, heights of 80 m and widths from 5 to 40 km. These features continue at least 400 m below the seabed and have the potential to yield a fine scale record of ACC history. Drift deposits like these are rare at this scale and are invaluable for reconstructing palaeocurrents in other contexts eg. Mediterranean inflow. Preliminary piston core data suggest high accumulation rates (40cm/kyr).

Scientific objectives:

(i) To chart the history of the Antarctic Circumpolar Current (ACC) and Weddell Gyre system: test the hypothesis that the significant expansion of the ACC and Weddell Gyre caused a global cooling and of East Antarctic Ice Sheet (EAIS) expansion associated with the Mid-Pleistocene Transition (MPT).

(ii) To document the variability of the Antarctic climate and sea ice distribution during the Quaternary: reconstruct high-resolution records of ACC migration, sea-ice coverage, surface stratification, biological pump, acidification, and eolian dust inputs in the Southern Ocean.

(iii) To determine the origin of the Conrad Rise: test the hypothesis that the Conrad Rise is a continental fragment, which was left behind in the middle Indian Ocean during Gondwana breakup process between India and Antarctica.

Key drilling objective: to date the wave field. Preliminary interpretation of seismic data suggests that the sediment drift may have formed ~1Ma when the ACC may have migrated north, associated with the MPT (Mid Pleistocene Transition). To determine how the strength of the ACC and position of the polar front and sea ice extent vary through time. Several drift proxies would be used to reconstruct variability of the ACC speed including: wave morphology, grain size, Nd, ice rafting debris, SST proxies, diatom evidence for sea ice extent. Given the interest in sea ice extent associated with anthropogenic climate change this aspect of the proposal should be developed in addition to ACC strength. Drilling should also capture data on eddies – the largest eddy field in the world is in the ACC northern margin downstream of South Africa. Additional hypotheses that could be addressed include questions of heat transport – dynamical questions in modeling are currently a hot topic and this paleoclimate constraint would be highly valuable. The pre drift laminar sediments are a deeper target, to obtain a high resolution record of Plio-Pleistocene paleoclimate and paleoceanographic change using multiple proxies, with a particular focus on obtaining a southern hemisphere record of the NHG (Northern hemisphere glaciation).

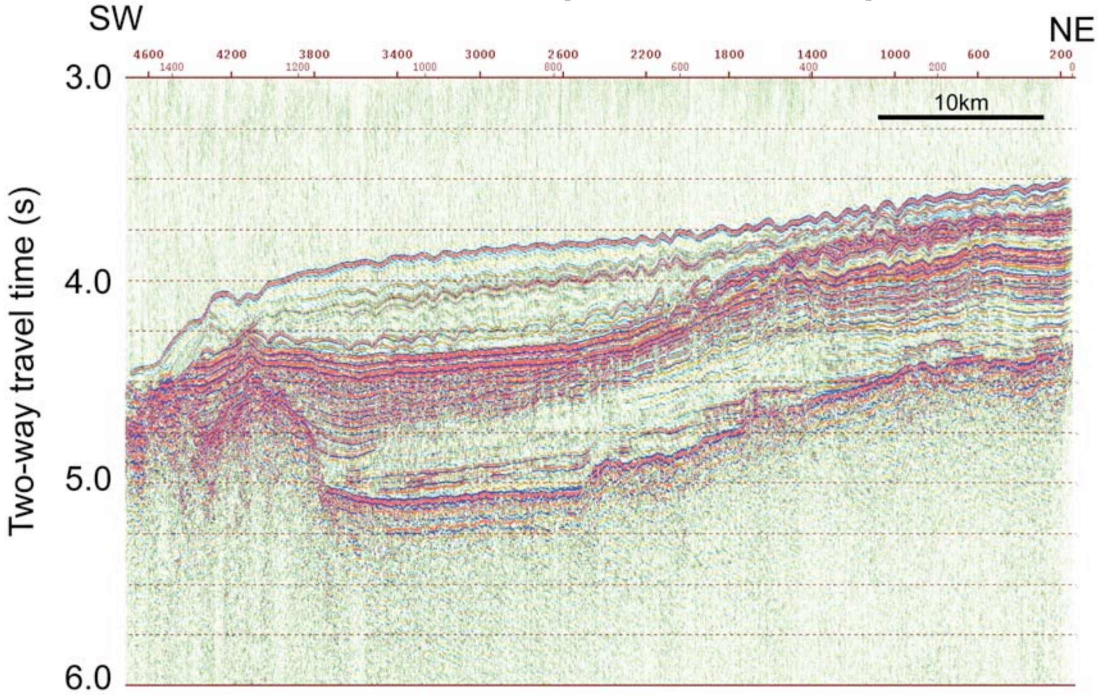


Figure 1.9: The sediment waves on the Conrad Rise are formed by ACC. Thus, sub-surface sediment waves observed in the seismic sections also would be formed by paleo-ACC.

There is a large amount of site survey data and the proposal could be submitted in 2012. Prior history: a mudwave field was sampled in 172 on the northern Bahamas Bank. There is a strong JAMSTEC contingent to this project, as well as scientists from New Zealand, France, Korea, and Italy. Co-proponents include ANDRILL project scientists, enabling correlation to the Antarctic margin record. Additional collaborators associated with Nd would strengthen the proposal.

This proposal falls within challenges 1 & 2 of theme 2 "climate and ocean change: reading the past informing the future".

1.4 Linkages with other proposals and workshop themes

724 Full has strong links with Theme 2: the history of the Monsoons. The Paleocene transects prospect can be combined with targets identified within the tectonics/igneous processes Theme 3: for example volcanic ash from terrestrial volcanism is documented further north in the Arabian Sea. Depth transects off the Ninetyeast Ridge could take additional basement rock samples to answer tectonic questions.

667 Full is strongly linked with Subtheme 1: evolution of the shallow carbonate environment.

The Indian Ocean dipole has been traced in modern oceanography and IODP cores 721 and 762 and is known to date from 2 Ma. Additional insights into the Indian Ocean Dipole in the last 2 Ma could be captured by better placement of cores within the dipole in modern SST data and where sediments and bathymetry co-operate. To this end the latitudinal transect of Paleogene cores with also Plio-Pleistocene recovery would be complementary, if taking the Laccadives Ridge and the shallow cores being proposed off the Northwest Shelf of Australia (667 Full). Prior to the onset of the dipole, investigating SST anomalies in the Indian Ocean would be important, as this is strongly related to gateway and boundary current evolution.

702 Full addresses downstream aspects of the Indian Monsoon (Theme 2). There is also a strong relationship between this and 778-Full and ACC-preliminary - when did the ACC become established, and the influence on the Agulhas current could also be captured in the Tanzanian

margin cores. Seasonally the Agulhas varies, millennial scale is the best possible hope in the Tanzanian cores and this would limit the strength of the connections that could be developed. Drilling the Conrad Rise (ACC history) to basement would yield key clues on LIP and seamount formation. Furthermore dredging and gravity data suggest continental crust exist beneath the rise (Theme 3) drilling would test the hypothesis that the Conrad Rise is a continental fragment, which may have been left behind in the middle Indian Ocean during Gondwana breakup process between India and Antarctica. The charting of gateways using oceanographic records also overlaps with Theme 3, especially with respect to the tectonics of the Indonesian archipelago.

All prospects/proposals can be linked with Theme 4, the deep biosphere, via APL's.

THEME 2: Monsoon history

This theme reviewed the tectonic, climatic and oceanographic controls on the Indian Monsoon. It included all Indian Ocean areas affected by monsoons. This allowed discussions about and nurturing of proposals that have emerged since the Detailed Planning Group (DPG) workshop on monsoon in 2008.

Dr. S. Rajan, Sedimentology, NCAOR, Goa, India (Chairman).
Dr. Peter Clift, Monsoon, University of Aberdeen, United Kingdom.
Dr. Steven Clemens, Paleoceanography, Brown University, USA.
Prof. Anil K Gupta, Himalayan uplift & Paleoclimatology, Wadia Institute of Himalayan Geology, India.
Dr. Liviu Giosan, proxies for monsoon, Woods Hole Oceanographic Institute, USA.

2.0 Focus topics of interest within breakout groups

Within Theme 2, two subthemes emerged, one dealing with the Monsoonal Paleoclimate and Paleoceanography (MPP) and another addressing sedimentary Source-to-Sink studies, particularly utilizing submarine fan (SF) archives. The MPP subtheme focused on the pelagic and hemipelagic archives as recorders of the local and regional responses to monsoon winds and precipitation while the SF subtheme focused on fan deposits as recorders of long-term changes in erosion, transport and deposition linked to tectonics and climate change principally in the Himalaya.

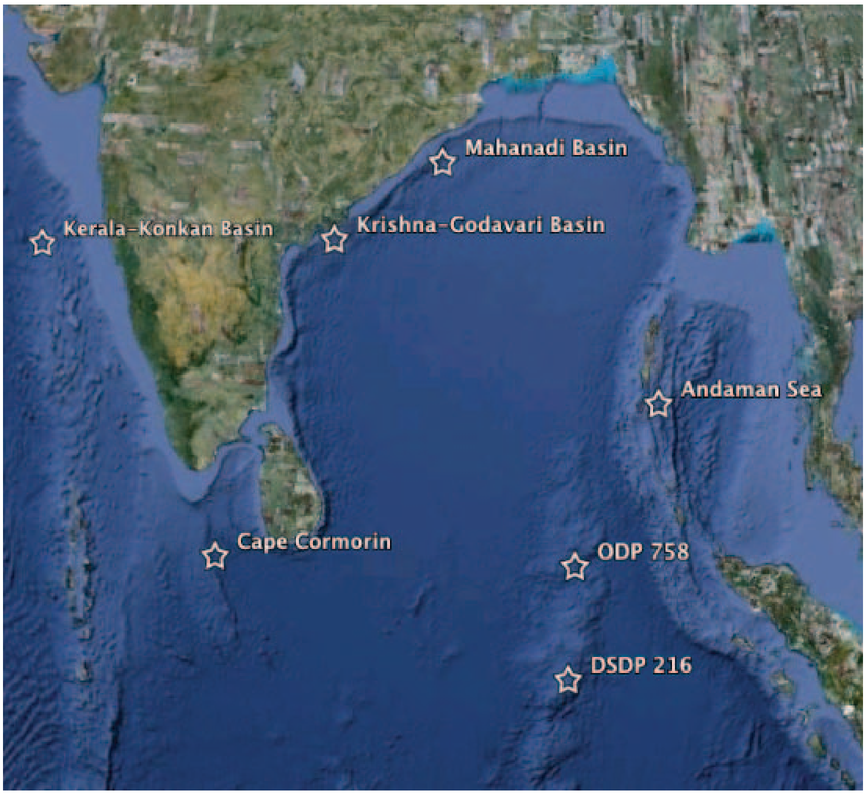


Figure 2.1. Potential iMonsoon sites comprising a full two-month leg. All sites have 2/3D seismic control with the exception of Cape Comorin (in progress).

2.1 First-order thematic scientific problems addressable by drilling

Globally, Indian monsoonal circulation represents the largest atmospheric transport system on Earth, including latent heat (moisture) sources in the southern Indian Ocean, cross-equatorial transport with large-scale convergence and precipitation over the Indian and Southeast Asian region, influencing some three billion people on a seasonal basis.

This interhemispheric circulation system is complex, driven by cross-equatorial pressure gradients dictated by changes in both the Siberian High (winter monsoon) Indo-Asian low (summer monsoon) and both summer- and winter-season changes in the Mascarene High of the southern subtropical Indian Ocean. These atmospheric pressure systems can be independently influenced by hemispheric ocean and atmospheric processes and yet, at the same time, are coupled by meridional atmospheric circulation. The magnitude and regularity of the cross-equatorial flow makes the Indian monsoon unique among global monsoon systems.

Previous meteorological and paleoclimatic work has clearly documented that Indian monsoonal circulation is highly dynamic on various timescales, ranging from that associated with weekly to monthly variability linked to short time scale ocean-atmosphere interactions (the break monsoon) to that associated with reconfiguration of the continents over time scales of tens of millions of years (tectonics). At the latter time scale, monsoon-driven runoff has built the two largest fan systems on Earth, the Indus and Bengal (Ganga) Fans. These sedimentary archives host a treasure trove of information on the long-term history of uplift, erosion, deposition, and carbon burial.

A comprehensive understanding of the mechanisms driving monsoon climate changes at different time scales is of high societal importance; each yields an understanding of how monsoon circulation is either driven by or responds to changes in important external (solar radiation) and internal boundary conditions (e.g., terrestrial ice volume, greenhouse gases, modal ocean circulation).

As detailed in the following text, Theme 2 drilling (Monsoon History) will produce records resolved at time-scales from decadal to tectonic, addressing aspects of all research themes identified in the IODP Scientific Plan, but especially including Challenges 1, 3, 4, 5-7, 11 and 13.

2.2 Existing "monsoon" IODP proposals

Seven proposals currently exist within the system (549-Full6, 552, 552-Add, 595-Full4, 609-PRE, and 783-APL, and 776-Full). Of these proposals, three are currently at the operations (OTF) stage (549 595, and 552).

2.3.1 Monsoonal Paleoclimate and Paleoceanography (MPP)
549: (Monsoonal Variability and Oxygen Minimum Intensity in the Northern Arabian Sea) objectives include (i) Late Neogene evolution of millennial-scale variations in OMZ intensity, (ii) Biogeochemical cycling, (iii) Deep biosphere, (iv) Astronomical pacing of the Indian monsoon during long-term global cooling, and (v) Tectonic-scale palaeoceanographic and climate changes.

783-APL: (A complete and continuous record of the Indian monsoon since the Oligocene; re-drilling ODP Site 758). Objectives include (i) Precise determination of the timing of intensification of the Indian monsoon, as evident from increased freshwater input to the Bay of Bengal, (ii) Study of the relationship between Indian monsoon variability and past climate changes, including the Oligocene/Miocene cooling, late Early Miocene warming, the Mid Miocene Climatic Optimum, Mid Miocene cooling, and the Plio-Pleistocene enhancement of Northern Hemisphere glaciation, (iii) Recover a continuous stratigraphic reference section in the Bay of Bengal to establish a detailed and astronomically tuned timescale incorporating data from calcareous and siliceous microfossils, paleomagnetic data, and tephra chronology, for the

Oligocene to the Present and (iv) Obtain well preserved microfossils from the Oligocene through the Recent of the under-sampled Indian Ocean to be analyzed and incorporated into global compilation studies of paleoclimatic and biotic evolution.

2.3.2 Submarine Fans (SF)

609-Pre: (Studying links between Land and Ocean, Climate and Tectonics, 'Source and Sink' by a multiplatform approach for drilling in the Bay of Bengal) represents part of an initial larger proposal that comprised a wide range of drill sites from the shallow shelf to the deep-sea fan, which required operations by several drilling platforms. The ODP/IODP panels requested a more focused approach without using different platforms. Consequently a revised proposal 552 was submitted in June 2003 with the title "Neogene and late Paleogene record of Himalayan orogeny and climate: a transect across the Middle Bengal Fan". Proposal 609-Pre represents the remaining part of the original drilling plan.

552 and 552-Add: (Neogene and Late Paleogene record of Himalayan erosion and weathering and evolving environmental conditions: a transect across the Middle Bengal Fan) seeks to investigate interactions between the growth of the Himalaya and Tibet and the development of the Asian monsoon, as well as processes affecting the carbon cycle and links between this region and the global climate. Primary objectives include (i) defining the earliest, yet unknown, stage of rapid Himalayan erosion during the Oligocene, (ii) quantifying Neogene erosion and accumulation rates and the environments in the Himalayan foreland basin, with implications for the development of the Asian monsoon, and (iii) documenting sediment transport and depositional processes in such a giant fan in order to constrain depocenter migration time scales during the Quaternary.

A set of six holes at the middle fan and at the same latitude, 8°N, including DSDP Site 218, are proposed to recover a complete Neogene sequence from the laterally shifting depocenters of the turbidite fan. One deep hole to 1500 m is planned at the eastern flank of the Ninety East Ridge with the purpose of recovering sediment back to the Eocene.

The first holes MBF-1A and MBF-2A will sample 900 m of mainly muddy turbidite to recover a complete Neogene sequence from the shifting depocenters of the middle fan. The first hole will reoccupy DSDP Site 218, thus exploiting the considerably improved drilling techniques to derive a better, more continuous core. The third deep hole, down to 1500 m sub-seafloor, will be used to define the Neogene lateral shifts and, in addition, addresses Paleogene paleoceanographic changes recorded in sediments directly overlying the western flanks of the Ninetyeast Ridge. Here the oldest sequences spanning the initiation of fan deposition near the Paleocene-Eocene boundary are expected, which will document the initial rise of the Himalaya. Three drill sites MBF-4, MBF-5, and MBF-6 along the east west transect, each penetrating about 300 m deep, are needed to complete the recovery of the lateral shifting depocenters.

Presently Proposal 552 is with the OTF and has to be finally evaluated by the safety advisory structure of IODP. The seismic lines for the six drill sites are submitted to the data bank. The Site Survey Panel SSP requested crossing lines for each site, which have been recovered during the latest SONNE cruise, but have not yet been submitted. All necessary data, especially the seismic data are processed and ready to be transferred to the site survey data bank.

595: (Deep Drilling on the Indus Fan and Murray Ridge: Reconstructing Erosion of Tibet, the western Himalaya and the Karakoram from the detrital record). The primary objectives are to investigate the erosional record of the Indus Fan since the India-Asian collision, and to assess its relationship to regional and global climate change. This fan differs from the Bay of Bengal in mostly draining sources to the north of the Himalaya, within pre-collisional Asia (i.e. western Tibet and the Karakoram). Pilot work suggests that erosion from the Greater Himalaya may have been very modest before 5 Ma with most material coming from the Karakoram. The climate of the Indus basin is moreover significantly drier than that in the Bay of Bengal. The primary objective is to determine how weathering and erosion have changed in a region where the monsoon climate has already been partly reconstructed from earlier drilling of the Oman margin in order to see how changing climate impacts orogenic erosion and tectonic evolution. The proposal especially targets the Oligocene-Lower Miocene, which is known to be the time when the Greater Himalaya began to exhume but which is a time of unconformity in the foreland basin. This section will be recovered by a single non-riser hole (MU-3A) of around 1900 m penetration. Dating the acceleration in erosion and exhumation and relating that to monsoon intensity (or not) is a key objective of this proposal. The proposal will test the hypothesis that the Early Miocene was the time of initial monsoon intensification and of faster orogenic erosion. Proposal 595 has been sent to OTF for scheduling and has yet to be approved by EPSP, although this panel has examined earlier versions. SSP has requested submission of further justification for an additional site aimed at recovering the 16–20 Ma (Lower Miocene) section, which is not believed to be sampled by the single hole (MU-3A) that is located on the flank of Murray Ridge. Drilling strategy is designed to recover the older Paleogene while penetrating a reduced Neogene section.

776-Full: (Deep sea drilling in the Arabian Sea: Discovering the tectono-climatic unknowns) is a new proposal for the eastern Arabian Sea that augments the objectives of Proposal 595. Specifically this proposal aims to drill in the Laxmi Basin to recover a clastic fan record from the Indus fan in order to test the link between Himalayan uplift and Indian Monsoon (ISP Theme - Environmental Processes and Effects). A major objective is to obtain high-resolution (decadal-scale) climate records from regions of high terrigenous sedimentation in the Arabian Sea to compare with records of Himalayan erosion in the Indus Fan). The proposal aims to determine the timing of onset of the Indian Monsoon and to reconstruct the erosion response of the western Himalaya to proposed monsoon strengthening at 8 Ma. The proposal also aims to investigate the crustal characteristics of the Laxmi Basin area and offshore extension of the Deccan Flood Basalts (ISP Theme -Solid Earth Geodynamics) through sampling the basement rocks. The proponents aim to recover the pre-Tertiary basement rocks from the Arabian Sea to define the offshore extent of the Deccan Traps and the character of underlying Mesozoic sedimentary rocks. The proposal is currently at revision stage.

2.4 Discussions of current MPP and SF proposals

Discussion of the MPP proposals addressed the extent to which these proposals targeted core geographic regions of the monsoon system where underlying sediments were most likely to record changes in monsoon wind and/or precipitation forcing. Proposal 549, targeting the OMZ in the northern Arabian Sea, was considered ideal in this regard, focusing on changes in the intensity of the OMZ as a function of wind-driven upwelling and biological productivity. This proposal is a logical follow-on to previous drilling offshore Oman (ODP Leg 117), which was located in the core of the low-level summer monsoon jet. At the current time, the probability of drilling in this region is complicated by piracy. Nonetheless, Northern Arabian Sea drilling targets were viewed as optimal for recording changes in monsoonal wind fields and a close watch needs to be maintained to see if the operational conditions improve.

Further discussion in the subgroup identified a scientific and geographic gap in the current list of MPP proposals, namely the lack of targets capable of recording changes in monsoonal precipitation (i.e., run-off). The core of the monsoon precipitation signal resides in the Bay of Bengal and is targeted by only one APL. Discussion of Proposal 783 APL (re-drilling ODP Site 758) highlighted the point that it is at the distal (southern) end of a very large Bay of Bengal salinity gradient and would constitute an excellent component of a drilling plan that also includes more northerly sites located in the core of low salinity plumes from the Irrawaddy, Ganga and

Brahmaputra Rivers. Site 758 is the only site to the east of the Indian landmass that contains a record of monsoon history since the late Paleogene.

Justification for targeting the salinity gradient in the Bay of Bengal is threefold. First, the Bay of Bengal and surrounding catchment is within one of Earth's strongest hydrocycle regimes, impacting billions of people. Second, recent studies have brought into question the extent to which monsoon winds and other oceanographic sub-systems are coupled over a range of time scales. For example, nearly all proxies indicate strong coupling at the millennial scale, while some orbital-scale proxies indicate different responses between Arabian Sea summer monsoon wind indicators and Indian and East Asian summer monsoon precipitation indicators. Third, recent work suggests that the OMZ signal in the Arabian Sea may be complicated by changing oxygen content of southern-source intermediate waters (of non-monsoon origin).

All proposals for fan drilling are well developed and already forwarded to the OTF for drilling when possible. Consequently the SF sub-committee did not think that these existing proposals should be strongly changed. However, these existing plans could be modified to integrate with new opportunities and proposals arising from this workshop. The possible synergies between Proposals 595-Full4 and 776-Full were noted.

2.5 MPP and SF Subgroup Results

2.5.1 Monsoonal Paleoclimate and Paleoceanography (MPP)

From June to September, India receives over 80% of its annual precipitation. Southwesterly winds of the Arabian Sea branch of the monsoon deliver their moisture primarily to the western coast of the Indian peninsula, where the Sahyadri mountain range (Western Ghats) limits the penetration of rains toward the interior. The monsoon branch in the Bay of Bengal brings rain to most of the Indian peninsula. Aspects of this regional precipitation regime, such as magnitude and seasonality, are essential to understanding the theoretical, as well as socio-economic aspects of the monsoon. Historical records show that variability in monsoon precipitation led to droughts that were significantly more severe and longer lasting than anything encountered in the observed recent record, often linked to societal unrest and famine. The symbiotic relationship between climate and society in South Asia provides impetus towards a more predictive understanding of the monsoon. Whereas the fundamentals of the monsoon are well established, our understanding of the spatial and temporal complexity of the monsoon precipitation is conspicuously poor beyond the last 150 years. Targeted paleoclimate research can alleviate this gap. On the eastern side of India, the Bay of Bengal and Andaman Sea are characterized by the lowest salinities found in the open ocean as a result of the monsoon's direct precipitation and river discharge. The large contrast in salinity and other water properties between the Arabian Sea and the Bay of Bengal provides the perfect opportunity to reconstruct the Indian monsoon.

Sites recently drilled by the National Gas Hydrate Program (NGHP) of India along the continental margin of the Indian Peninsula in the Arabian Sea and the Bay of Bengal, as well as in the Andaman Sea, are uniquely positioned for reconstructing the Indian monsoon history on tectonic to decadal time scales. The drilled sites revealed properties highly desirable for paleoceanographic work and dense 2/3D seismic grids are available at and near these sites in the Andaman Sea and along the Indian continental margin, negating the need for additional site survey work. Although the NGHP cores document the viability for paleoclimate work, only single holes were drilled at each site and large portions of each core utilized for hydrate analyses, making the remaining material unusable for time-series reconstructions.

The NGHP sites located in the Arabian Sea and the Andaman Sea comprised hemipelagic foraminifera-rich sediments that are perfectly suited to look at the contrast between basins at tectonic to orbital time scales. The hemipelagic sites from the Krishna-Godavari and Mahanadi continental slopes combined with the Andaman Sea site are well positioned for reconstructions of zonal and meridional gradients in surface water paleo-properties within the Bay of Bengal-Andaman Sea region at decadal to orbital time scales. In addition, recent work on seismic structure and short cores south of Cape Comorin (southern tip of India) showed that this region is suitable to look at the water exchange between eastern and western region of the northern Indian Ocean, offering the possibility to assess changes in the seasonality of the winter and summer monsoon systems.

"What controls the variability of Indian monsoon precipitation?" emerged as an overarching question for future Indian Ocean future drilling; project "iMonsoon" was envisioned as a means of answering this question. Substantial and rapid progress in understanding Indian monsoon paleoclimate and paleoceanography can be achieved using triple APC coring and logging at sites in Indian waters that have not yet been drilled for the purpose of paleoclimate reconstruction. These sites have documented temporal resolutions spanning tectonic to decadal time scales. Key components of the scientific plan can be addressed by project iMonsoon, designed to take advantage of the contrast between precipitation and outflow/run-off patterns that cause the salinity gradients within and between northern Indian Ocean basins. Four sites (Figure 2.1) are envisioned including the Andaman Sea, East Indian margin (Bay of Bengal), Cape Comorin (southern tip of India) and West Indian margin (Arabian Sea). By analyzing sediments from these regions and comparing the results with existing data sets, we will be able to:

(i) Derive the sensitivity of monsoonal climate change to greenhouse gas forcing, high latitude ice, meridional ocean circulation and orbital/secular changes in insolation forcing,
(ii) Document the extent to which winds and precipitation are coupled at different timescales,
(iii) Assess the extent to which the Indian and East Asian monsoon systems are coupled or uncoupled by comparison with existing records from the South China Sea and terrestrial records from southeast China (loess and cave records),
(iv) Establish the extent to which northern hemisphere paleomonsoon precipitation is linked to southern hemisphere moisture export as in the modern and suggested by paleoclimate modeling and
(v) Differentiate changes in summer and winter monsoon circulation strength by assessing changes in the strength of water exchange between the Arabian Sea and Bay of Bengal.

Regional differences in precipitation will be revealed in site-to-site comparisons among the Andaman Sea site (Irrawaddy), East Indian margin (Ganges and Godavri) and West Indian margin (Ghats runoff). Cross-basin exchange will be monitored via the Cape Comorin site. All will be referenced to ODP Site 758, representing the distal end of the summer monsoon salinity gradient. A large range of proxies is available to monitor the system response to changes in monsoon circulation (salinity, temperature, chemistry of waters and suspended particulates, ecosystem changes and biodiversity) as well as terrigenous fluxes from catchment basins (organic and inorganic).

Ancillary contributions of the project iMonsoon include the volcanism in the Andaman-Burma region using tephras and tephrochronology, evaluation of the (relatively weak) oxygen minimum zones at Cape Comorin and in the eastern Arabian Sea for understanding its deep biosphere and contributions to the nitrogen cycle and understanding the tectonics of the Indian peninsula including the formation of the Chagos-Laccadive Ridge.

2.5.2 Submarine Fans (SF)

The development of large deep-sea fans on both sides of the Indian Peninsula in the Arabian Sea and the Bay of Bengal has been controlled by monsoonal precipitation and tectonic history of the Indian plate. The fans, as the end member of a fluvial-deltaic-turbiditic transportation process, potentially contain a high-resolution record of the climate and tectonics of their catchment areas.

In particular, weathering and transportation are dominated by the monsoonal climate and associated precipitation. On the other hand, weathering and erosion are linked with the exhumation and uplift history of the Himalaya, which may themselves be climatically modulated. These climatic–tectonic processes are linked because the rising Himalayan mountain chain will increase and focus the monsoonal precipitation, resulting in accelerated erosion, exhumation, and further isostatic-driven uplift. Hypothetically, faster erosion may even have increased the rate of the subduction by reducing friction along the plate boundary. The changes within this tectonic-climatic linked system of the Asian monsoon also interact with the global climate on many time scales.

Specific principal questions, which can be addressed by drilling the fans, are still a matter of debate: timing of India-Asia collision, the unroofing of the Greater Himalaya, estimating exhumation rates and their evolution, initiation and intensification of the monsoon during the Tertiary and the Pleistocene glacial-interglacial perturbations, as well as regional shifts of monsoonal precipitation patterns. Increased rates of erosion also result in further chemical weathering, which is a globally effective feedback mechanism on climate change via CO_2 uptake. Increased sediment transport also affects marine productivity, burial rates of organic carbon and the changing global inventory of strontium-isotopes.

Because of rapid sediment deposition on the fan, these bodies also conserve organic carbon from both terrestrial and marine sources, which reflect paleoclimatic and paleoceanographic changes. In addition, the role of the fan sedimentary system as a sink for the global carbon budget has still to be evaluated, although initial estimates indicate that these may be significant.

In summary, the Indian Ocean fans contain an extremely valuable archive of the source-to-sink processes of monsoonal Asia. Drilling of these fan deposits addresses the initiation and subsequent Neogene changes in the South Asian monsoonal system.

The fan sub-group recognized that long-term erosion records from the Indus and Bengal Fan are crucial if we are to understand how changing monsoon strength has affected the erosion and tectonic evolution of the Himalaya, and to what extent the growth of the Himalaya may have triggered monsoon intensification and distribution. Specifically, a well dated erosion record can be used to reconstruct the changing rates of exhumation in the mountains that can then be correlated (or not) with changes in the monsoon intensity, which must be derived from paleoceanographic records elsewhere. The fan records will tell us nothing about the height of the Tibetan Plateau, but when coupled with independent climate records and data concerning the structural evolution will allow the proposed links between surface processes and orogenesis to be tested. In particular, the fan drilling is crucial to the Middle Miocene to Oligocene because rocks of that age have been eroded away in the ranges themselves, so that the earlier exhumation history has been lost. This critical period spans the onset of Greater Himalayan exhumation. Earlier drilling in the Bay of Bengal penetrated only to ~19 Ma; which is ~4 Ma after the onset of Greater Himalaya exhumation and motion on the Main Central Thrust. Comparison of cooling and depositional ages of detrital minerals will allow periods of accelerating exhumation to be pinpointed. These constraints are important in understanding the age and origin of the orogenic syntaxes at Nanga Parbat and Namche Barwe. Debate continues as to what processes are responsible for triggering these tectonic aneurysms and their duration.

The subgroup also emphasized the importance of dating the base of the fan sequences, which will provide a test for the still controversial age and geometry of India-Eurasia collision. The lowest Eocene sediment will illuminate the development of the Himalaya prior to the start of rapid thrusting and exhumation that mark the growth of the Greater Himalaya. An array of chemical weathering proxies can be applied to the sediments, which will allow the total weathering flux from the Himalaya to be quantified. This is central to attempts to test the model that it is intensified erosion (i.e., organic carbon burial and/or chemical weathering) in South Asia that is responsible for the long-term drawdown of CO_2 in the atmosphere, triggering the deterioration of global climate during the Tertiary. Fan drilling will further allow the processes affecting the carbon cycle to be quantified. Not only is this of interest to further hydrocarbon exploration, but also will allow an improved global carbon budget to be constructed over long periods of geologic time. Carbon capture in the giant fans may have been a key sink in controlling atmospheric CO_2 during the Neogene.

2.6. Suggestions for future efforts

2.6.1 Monsoonal Paleoclimate and Paleoceanography (MPP)

Development of a full proposal (iMonsoon) in time for drilling in 2014 is only possible in the context of the existing and available 2/3D seismics for the Andaman Sea, eastern Indian Margin, and western Indian Margins. Similarly, 758 has already been drilled and has existing seismics. The status of available seismics for the Cape Cormorin site is under investigation. Even with these advantages, submission of a full proposal will require a great deal of effort from a core group of PIs. We have identified a core group of PIs from a range of IODP member countries including India, the US, Germany and Japan. The MPP subgroup recommends a **workshop** geared specifically at producing a full (2 month) iMonsoon proposal in time for consideration by the program panels.

2.6.2 Submarine Fans (SF)

The greatest scientific needs in submarine fan drilling that are not addressed by existing proposals lie in understanding the processes that form the fans, because until we understand how sediment is fluxed from source to the deep sea sink it is impossible to read the record of erosion and weathering preserved in the fans. Existing proposals target the long-term erosion of both eastern and western river systems but more detailed drilling, higher on each fan would allow the transport history to be better constrained. Fundamental questions include quantifying the transport times for sediment grains between source and sink that would result in a lag between trigger and sediment record. We also highlight the need to quantify the amount of sediment recycling and storage on land, as well as in the shallow marine shelf deltas. If the turbidites of the deep basin are largely formed by reworking of sediment stored on the shelf during sea level high-stand periods then the erosional record on the fans would not be able to be used to look at millennial or sub-millennial processes. Initial studies suggest that buffering on the shelf should be more important on the Indus compared to the Bengal Fan, but this hypothesis needs to be tested by drilling across the upper parts of the delta and fan systems. Even after the sediment is delivered to the slope it is presently unclear how many stages of reworking and transport are required to bring the material to its final depocenter. New drilling is now being proposed to address the source-to-sink issues through drilling of the delta and upper Bengal Fan, as well as channel-levee complexes. These latter units represent the building blocks of the fans but imply that in any one place the erosional record will be discontinuous. Determining the duration over which individual channel-levee complexes were constructed, and what causes each to be abandoned in turn is central to understanding how the world's largest sediment bodies were constructed.

The SF sub-committee recommended a **workshop** on geohazards in the northern Bay of Bengal, focusing on the frequency of tropical cyclones, earthquakes during the late Holocene, late Pleistocene subsidence, and changing sediment supply into the sea caused by deforestation and agriculture of the onshore catchment area.

A workshop concerning source-to-sink processes in relation to the submarine fans would allow the science of drilling on the upper slope and even the shelf to be explored. This workshop could be used to discuss new coring and seismic data and to nurture proposal 609-Pre.

THEME 3: Tectonics and volcanism

There are many questions related to the tectonism of the Indian Ocean, such as plate tectonics, the evolution of the oceanic crust including mid-ocean ridge formation, and theformation of large igneous provinces; continental rifting and related deposition; subduction, arc volcanism and earthquakes.

Dr. Mike Coffin, Marine geophysics and LIPS, University of Tasmania, Australia (Chairman).
Dr. K. S. Krishna, Marine Geophysics and Tectonics, National Institute of Oceanography, India.
Dr. Richard Arculus, Igneous petrologist, Australian National University,
Dr Jim Mori, Kyoto University, Seismogenic zones, Kyoto University, Japan.

3.1 Introduction to Tectonics, Geodynamics, and Magmatism Theme

The Indian Ocean hosts exceptional examples of Earth system processes and products that scientific ocean drilling will play a key role in illuminating. Salient tectonic problems include those associated with subduction—fault properties and slip, sediment effects, role of fluids, segmentation, rupture, tsunamigenesis—along the Sunda arc, site of the great 2004 Indian Ocean earthquake and tsunami; tectonic plate breakup and reorganization associated with Kerguelen and Réunion hotspot activity; India-Madagascar and India Seychelles break-up, origin and evolution of Laxmi and Laccadive ridges and intraplate deformation and possible incipient plate breakup along the Ninetyeast Ridge. Major geodynamic issues comprise hotspot – spreading ridge interactions and hotspot constraints on the mantle reference frame. Outstanding magmatic matters include those associated with hotspots—Afar, Kerguelen, Réunion—that have sampled nearly the entire “mantle zoo” of source compositions; backarc spreading magmatism, hydrothermal activity, mineralization, metallogenesis, and biosphere; the testing of existing and development of new models for flood magmatism; and the origin and alteration of oceanic core complexes.

3.2 Accretionary Prisms: Sunda Arc

Accumulating volumes of sediment at the trenchward edge of subduction zones (accretionary prisms) are important structures that control processes on the shallow portion of the megathrust. The Sunda Arc provides a unique opportunity to study accretionary prisms in a variety of settings from collisional tectonics, through typical subduction, to oblique subduction. The main goal of this initiative is to drill several accretionary prisms along the arc to compare the different mechanical properties of the tip of the megathrust, especially in relation to the occurrence of great tsunamigenic earthquakes.

Studying the accumulating and eroding sediments at the toe of the megathrust in the Sunda Arc builds on previous scientific drilling investigations of accretionary prisms in Nankai, Costa Rica, and Tohoku. Comparisons of faulting structures and earthquake occurrence in these regions of different sediment conditions will lead to a comprehensive understanding of the role of sediment structures in large earthquakes. Past modeling of faulting in accretionary prisms has usually indicated that large displacements do not occur during large subduction earthquakes; however recent events in Sumatra and Japan seem to indicate this is not the case.

Specific scientific issues that can be addressed with borehole sampling and geophysical monitoring include:

- Understanding of slip on steeply dipping splay fault versus sub-horizontal megathrust
- Frictional properties of faults in the accretionary prism
- Effect of sediments on the shallow faulting
- Role of fluids in the shallow faulting
- Understanding segmentation and source areas of large earthquakes along the subduction zone
- Influences on subduction process and large earthquake rupture at the intersection of Ninetyeast Ridge
- Generation of large tsunami from faulting in the accretionary prism

We propose a drilling program of four to six sites that represent the transition from collisional tectonics in the east to oblique subduction in the northwest. Currently, IODP proposal 704 Full2 Sumatra Seismogenic Zone targets shallow structures near the fault of the 2004 Sumatra earthquake and provides the first building block for this initiative.

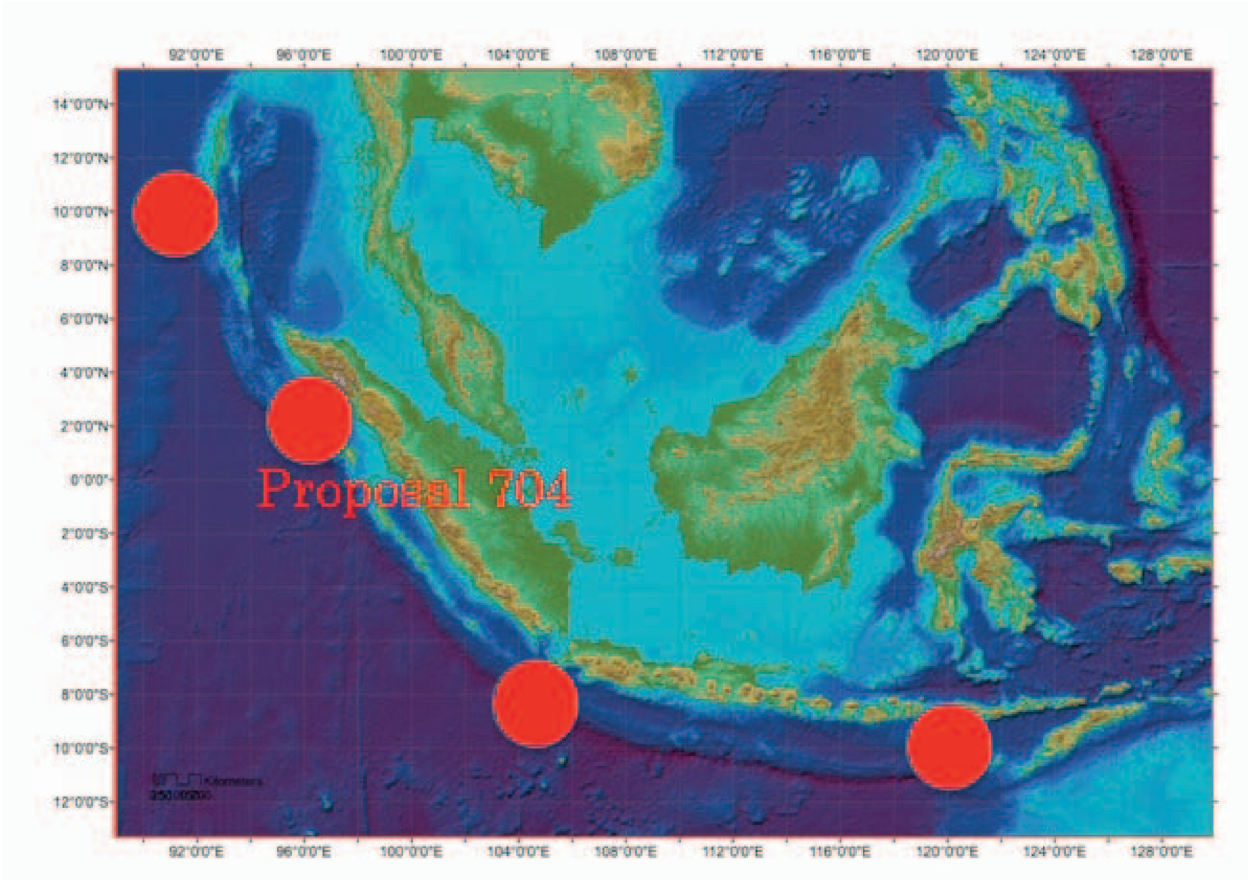


Figure 3.1. Possible drill sites along the Sunda Arc that represent the transition from collisional tectonics in the east to oblique subduction in the northwest.

Numerous fault segments along the Sunda Arc have the potential to produce future large earthquakes. Faulting in the accretionary prisms during large earthquakes can be the primary source of destructive tsunami, so there are important contributions of this project to understanding regional geohazards.

This is a newly proposed large-scale drilling program and needs a **workshop** to clarify and establish consistent research goals for widely spaced drilling sites along the Sunda Arc.

3.3 Backarc Spreading: Andaman Sea

The Andaman Sea region in the backarc region of the Sunda Arc provides an optimal site for study of sedimentation, regional geology, volcanism, and hydrothermal processes in a spreading tectonic setting. The region has some of the highest rates of sedimentation of any backarc region, while within the same region there are low sedimentation rates. Sampling at both sediment-rich and sediment-poor sites can provide important information on the effects of the sedimentation rate on tectonic and mineralization processes. In addition, there are likely significant hydrothermal systems that have strong effects on the chemical processes. A multi-disciplinary study of tectonics, volcanism, sedimentology, geochemistry, and hydrology can lead to an understanding of the physical and chemical interactions in this complex area. At present there are very few IODP investigations in backarc regions.

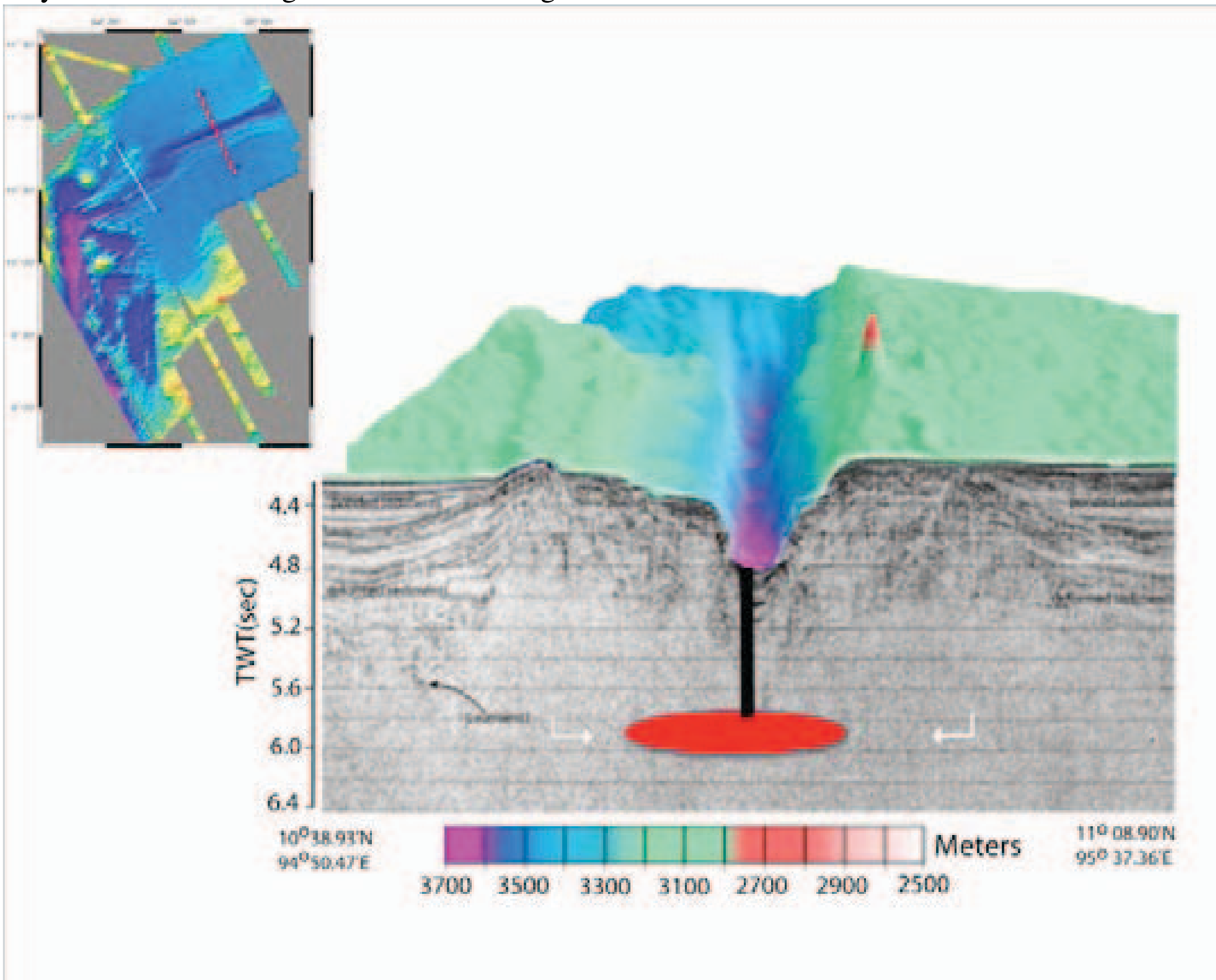


Figure 3.2. Bathymetry (upper left) and example of a seismic section in the backarc region of the Andaman Sea. Schematic borehole plan penetrates sediments near the crest of a spreading ridge and into basement and possible (old) intrusive dikes.

This geological setting of the Andaman Sea is a present day analog to giant sediment-hosted mineral deposits, such as those seen at Broken Hill and Mt Isa in Australia, and presents a unique opportunity to study active mineralization processes. In addition, microbiological and chemical sampling will provide valuable data for study of the deep biosphere in a hydrothermal system.

Drilling strategies will consist of boreholes through the sediment into basement rock and intrusive dikes. Coring and fluid sampling will provide data for understanding:

- Comparisons of tectonic processes in sediment-rich and sediment-poor areas of same system

- Comparisons of mineralization in sediment-rich and sediment-poor areas of same system
- Roles of organic materials in mineralizing processes
- Interactions between volcanic, intrusive, sedimentary and hydrothermal processes
- Chemical and hydrological effects on the deep biosphere

A **workshop** is necessary to clarify scientific goals and identify drilling strategies for this new project.

3.4 Hotspots and Global Mantle Geodynamics: Afar and Kerguelen Hotspots

Hotspot basalts are the most direct probes of mantle geodynamics below that sampled at mid-ocean ridges. Indian Ocean hotspots provide a unique laboratory for these probes: they span the entire range of hotspot – spreading ridge interactions, comprise two of the five major hotspot systems needed to constrain the mantle reference frame, and sample nearly the whole "mantle zoo" of source compositions.

The Afar hotspot offers a unique opportunity to study uppermost mantle flow, early stages of continental rifting, and a possible complete plume head – plume tail pair. Off-axis drilling in the Gulf of Aden is needed to constrain the transition between the 30 Ma Ethiopian/Yemen flood basalts and zero-age down axis flow along the Gulf of Aden spreading center. The paleoclimate objectives of #724 (Demenocal) would provide acceptable sites to investigate these basement objectives.

Radial, finger-like volcanic ridges striking between the Kerguelen Archipelago and the Southeast Indian Ridge (SEIR) are perhaps the best example of the least understood type of hotspot – spreading center interaction, and might provide the most robust constraints on upper to middle mantle flow (Figure 3.3). The ridges formed between about 40 and 20 Ma, with no apparent ridges formed after 20 Ma, providing a complete test at greater hotspot – spreading center separation. Dense dredging of zero-age basalt along the SEIR is also available to fully test along axis flow models.

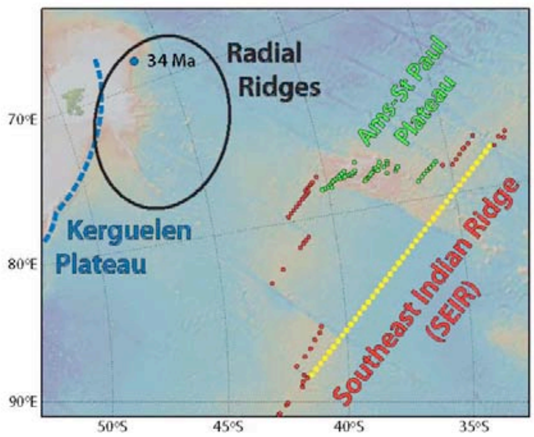


Figure 3.3. Radial volcanic ridges (within black ellipse) striking NE of the Kerguelen Archipelago. They formed 40 to 20 Ma, between the Kerguelen hotspot and the young Southeast Indian Ridge (SEIR), directly after the SEIR separated the Cretaceous Kerguelen Plateau basement (to the left, south of dotted blue line) and Broken Ridge (not shown). Although there are no apparent ridges younger than about 20 Ma, the current SEIR is offset up to 550 km towards the Kerguelen hotspot (extrapolated SEIR without the Kerguelen offset shown in yellow). Red circles show SEIR dredge samples with typical MORB compositions; green circles show segments influenced by the much more recent (< 3 Ma) Amsterdam-St Paul hotspot.

Tests of both intra- and inter-ocean basin hotspot models require robust paleolatitude and age constraints. Current constraints of 12° relative motion between the Kerguelen/Ninetyeast Ridge (NER) and Deccan/Reunion hotspot systems are consistent with mid-mantle return flow models. The NER system is relatively well studied, but basement recovery in the northern NER buried underneath Bay of Bengal sediments would make a significant contribution to testing these models. Similarly, new drilling along the Chagos-Maldives-Laccadive ridge also would be critical for more robust global tests, but the existing sample data set probably should be re-investigated in more detail first.

One or more **workshops** are needed to advance these ideas into one or more mature IODP proposals.

3.5 Hotspots and Plate Breakup/Reorganization: Kerguelen and Réunion Hotspots

Understanding the mantle sources and causative geodynamic processes for the formation and evolution of large igneous provinces (LIPs) as well as the magmatic and tectonic relationships between LIPs and plate breakup/reorganization are first-order problems in Earth science. These objectives address the Earth Connections: Deep Processes and Their Impact on Earth's Surface theme of the IODP New Science Plan (NSP), *Illuminating Earth's Past, Present, and Future*. Moreover, they focus on three challenges of the NSP: What are the composition, structure, and dynamics of Earth's upper mantle (8); How are seafloor spreading and mantle melting linked to ocean crustal architecture (9); and What are the mechanisms, magnitude, and history of chemical exchanges between the oceanic crust and seawater (10). The Kerguelen Plateau/Broken Ridge LIP and the Deccan Traps are the foci of much discussion involving the first problem. With respect to the issue of LIPs and plate breakup/reorganization, the Kerguelen hotspot may have been active at the time of breakup among Antarctica, India, and Australia, although the massive magmatism that formed the Kerguelen Plateau/Broken Ridge did not commence until well after breakup; the Réunion hotspot was active at the time of breakup between India and Seychelles; and both hotspots were certainly active during several post-breakup oceanic plate reorganizations.

We will accomplish our scientific goals through drilling, coring, and logging holes through the sediment section and from 250 to 500 m into igneous basement. Specifically, this work will:

(i) Elucidate the temporal, volumetric, petrologic, and geochemical development of massive Early Cretaceous Kerguelen magmatism as well as associated uplift and subsidence, valuable for testing long-lived plume and other geodynamic models for flood volcanism, and for developing new geodynamic models; and

(ii) Define temporal, spatial, petrologic, and geochemical relationships among volcanic rocks on the Kerguelen Plateau, in the Princess Elizabeth Trough, on the Antarctic margin (Bruce Rise), on the Naturaliste Plateau (Australian margin), and on the 85°E Ridge, and determine the uplift and subsidence histories of these features. We will then relate this magmatism and tectonism to continental breakup among Antarctica, India, and Australia, providing critical parameters for testing existing and developing new geodynamic models for plate breakup/ reorganization.

(iii) Define temporal, spatial, petrologic, and geochemical relationships among volcanic rocks of the Deccan Traps, Seychelles, Laxmi Ridge, and Laccadive Ridge, and determine the uplift and subsidence histories of these features. We will then relate this magmatism and tectonism to breakup between India and Seychelles, providing critical parameters for testing existing and developing new geodynamic models for plate breakup/reorganization.

Multiple **workshops** will be needed to develop full IODP proposals from these ideas.

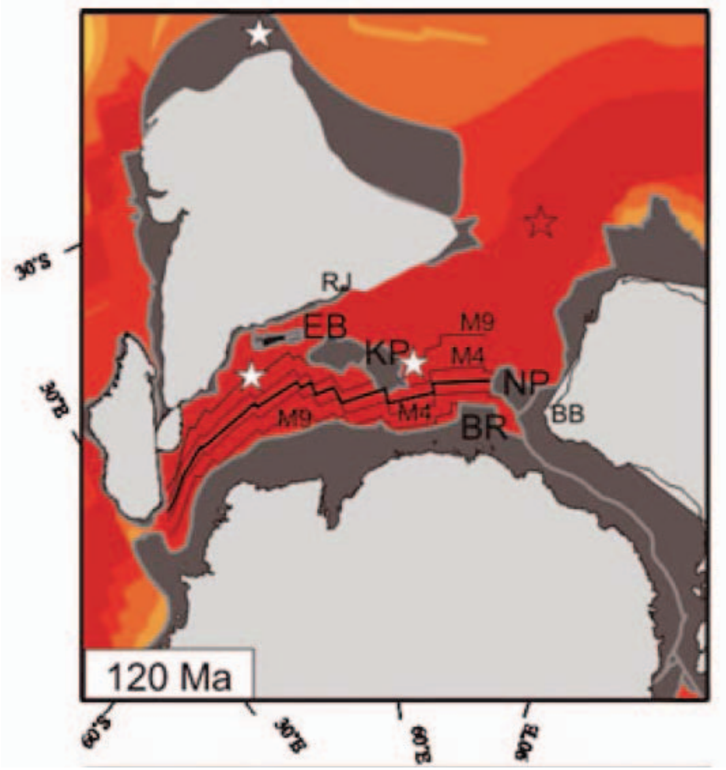


Figure 3.4. Early Cretaceous plate reconstruction model of Antarctica, Australia, and Greater India (after Gaina et al., 2007). Stars indicate Marion (left) and Kerguelen (right) hotspots. Proposed IODP drill sites to investigate plate breakup/reorganization associated with Kerguelen hotspot activity are located between the Kerguelen Plateau (KP) and Antarctica, on the southern Kerguelen Plateau, on Bruce Rise (BR), on the Naturaliste Plateau (NP), and between Elan Bank (EB) and India on the 85°E Ridge (unmarked). BB, Bunbury Basalts; RJ, Rajmahal Traps.

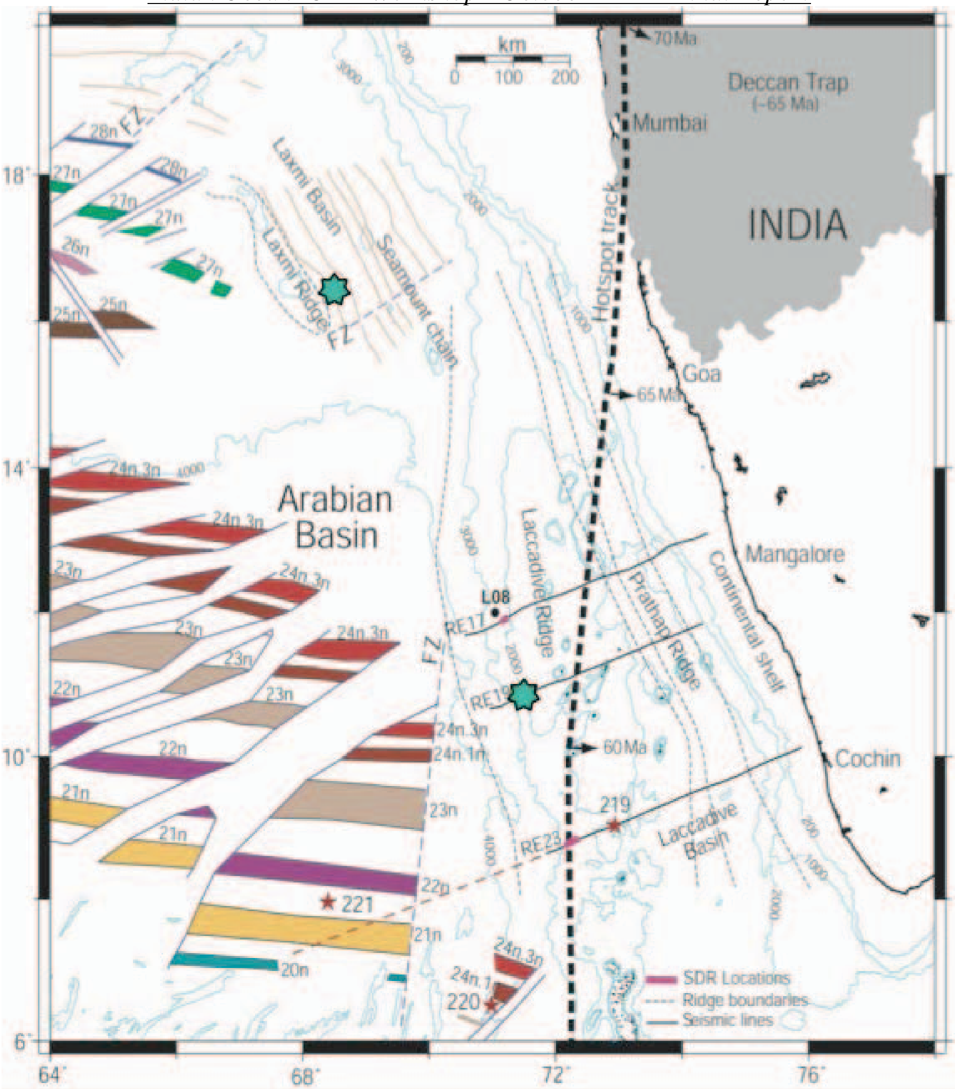


Figure 3.5. Map of India (including Deccan Traps), Arabian Basin, Laxmi Ridge and Basin, and the Laccadive Ridge. Proposed IODP drill sites to investigate plate breakup/reorganization associated with Réunion hotspot activity are indicated by green symbols.

3.6 Intraplate Deformation and Plate Breakup: Ninetyeast Ridge

Ninetyeast Ridge (NER) is a complex volcanic ridge in the Indian Ocean and is thought to have formed by hotspot volcanism on both the Indian and Antarctic plates from ~90 to 43 Ma. The central Indian Ocean is the best example on the Earth of large-scale oceanic intraplate deformation and formation of diffuse plate boundaries, which have led to the division of the single, large Indo-Australian plate into three component sub-plates (Indian, Australian, and Capricorn). NER is also unusual in that it is located at a "diffuse triple junction", the nexus of diffuse boundaries of the sub-plates (Figure 3.6, left). As a result, lithospheric deformation occurs throughout NER, but changes in style and magnitude along the length of the ridge. Furthermore the ridge is thought to be a significant tectonic boundary in the Indian Ocean deformation zone, so its study is also important for understanding the phenomenon of plate breakup.

Seismic reflection profiles over NER show two main tectonic events. The first extensional phase related to initial ridge formation is indicated by normal faulting of basaltic basement. Disruption of sedimentary layering above the ridge (Figure 3.6, right), suggests a secondary tectonic phase causing large-scale faulting and block rotation. These faults often have features associated with compression or strike slip motion and are associated with ongoing large-scale lithospheric deformation. The key to understanding the tectonic history is to core and date sediment layers that are perturbed by the tectonic activity. New cores are required because of stratigraphic complexity and paucity of stratigraphic information from previous drilling.

The strategy for NER drilling is to core a transect of approximately five sites along the length of the ridge to look at the deformation pattern in space and time. The tectonic history for the NER will be integrated with the known timing of onset of deformations in Central Indian and Wharton basins for the purpose of understanding the phenomenon of Indo-Australian plate breakup, formation of diffuse plate boundary and possibly subduction initiation processes. Furthermore, the drilling results are expected to provide information on whether the Indo-Australian plate initially broke into two or three sub-plates.

In addition, the NER is an important element of the global hotspot array and is one of the longest continuous hotspot tracks. Moreover, the hotspot that formed NER interacted with a spreading ridge throughout much of the history of the NER. Hence, this is one of the best volcanic features for studying hotspot-ridge interactions and behavior of oceanic hotspots. Drilling on NER also offers possibilities for allied interdisciplinary studies: geochemistry, geochronology, paleo-latitude, paleoceanography, and deep biosphere studies.

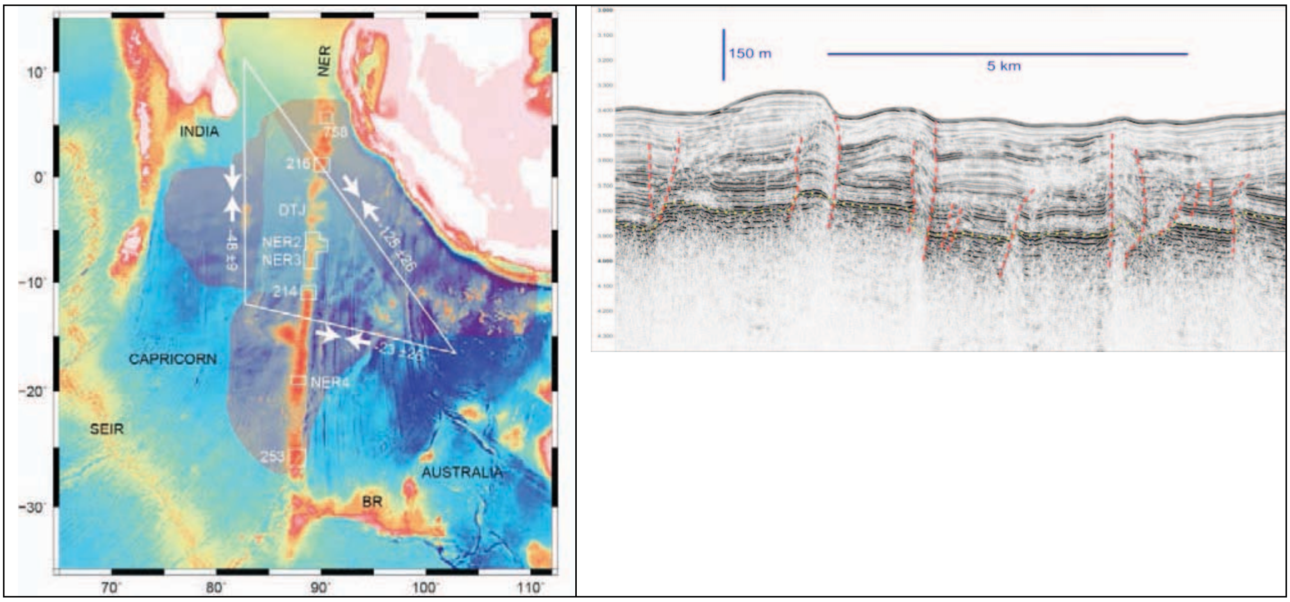


Figure 3.6. Left - Diffuse plate boundary divides the Indo-Australian plate into three sub-plates. Most of the NER resides within the zone of complex deformation. Boxes on NER indicate the locations, where seismic profiles were acquired. Right – Seismic section close to site NER3 shows intense deformation with numerous faults. Some faults are active and extend to surface, whereas others were active in the past

3.7 Oceanic Core Complexes: Central and Southwest Indian Ridges

Oceanic Core Complexes (OCC's) provide windows into the shallow mantle: the source of mid-ocean ridge basalt – the most abundant magma on Earth. Typically formed at the inside corner of ridge-transform intersections, OCC's exposing lower crust have been studied and drilled with great success on the slow-spreading Mid-Atlantic Ridge (1400-m Hole U1309D at Atlantis Massif and 209-m Hole 1275D at 15°44'N), and the ultraslow spreading SW Indian Ridge (1508-m Hole 735B at Atlantis Bank). The deepest hole into the oceanic mantle (Hole 1274A), however, reached only 156 meters, and did not penetrate deep enough to recover fresh peridotite, thus failing to accomplish several major objectives of such drilling. New OCCs have been located flanking transform faults on the northern Indian Ocean Ridges. Among them, two prominent OCCs, one at the Owen Fracture Zone, and another at the Vityaz FZ along Central Indian Ridge are identified for further detailed survey to characterize the geochemical and isotopic nature of the northern Indian Ocean mantle.

Varun Bank, is a shallow flat topped bank similar to Atlantis Bank that rises from 4500 m to ~950 m depth. Our surveys show that it is composed of serpentinites, peridotites, and amphibolitized gabbros. Varun Bank flanks the Owen FZ on the Carlsberg Ridge on ~52 Ma seafloor. During this period the Carlsberg Ridge spread at ~120 mm/yr, making it the only documented oceanic core complex emplaced at a fast spreading ridge. Its shallow depth makes it an ideal target for deep mantle drilling.

Vityaz Megamullion is located on the Central Indian Ridge at 5°25'S, 68°30'E close to the ridge axis. It was emplaced at a 32 to 50 mm/yr spreading rate, and thus constitutes the second fastest spreading rate for emplacement of a documented core complex. Sampling shows that it is also composed of peridotites and serpentinites.

These OCCs provide an exceptional opportunity to drill the first deep hole into the oceanic mantle. This will permit, or make major progress towards, the accomplishment of several long-recognized scientific and technical objectives of scientific ocean drilling:

(i) Constrain the depth of hydrothermal alteration and serpentinization of mantle exposed on the seafloor (and how this may vary with spreading rate).
(ii) Evaluate how carbon sequestration during alteration of mantle rock varies with depth.
(iii) Obtain fresh samples of abyssal peridotites for key mantle geochemical studies.
(iv) Test drilling conditions deep into mantle peridotite – a necessary prelude to a full penetration of the ocean crust into the mantle in the Pacific or elsewhere.

In addition, the proposed drilling will address several critical questions of scientific concern specific to the Indian Ocean and mantle evolution at fast spreading rates:

(i) Constrain the nature of mantle flow and emplacement to the seafloor at fast-spreading ridges.
(ii) Allow more precise determination of the trace element and isotopic composition of the mantle source for mid-ocean ridge basalt by eliminating alteration contamination.
(iii) Determine the extent and scale of local isotopic, trace and major element heterogeneity of the shallow mantle at the kilometer scale.
(iv) Explore the extent to which the isotopic composition of the mantle source in the Indian Ocean mirrors that of the associated basalts in the region of the famous DUPAL isotopic anomaly that is uniquely characteristic of the Indian Ocean and Gakkel Ridges.

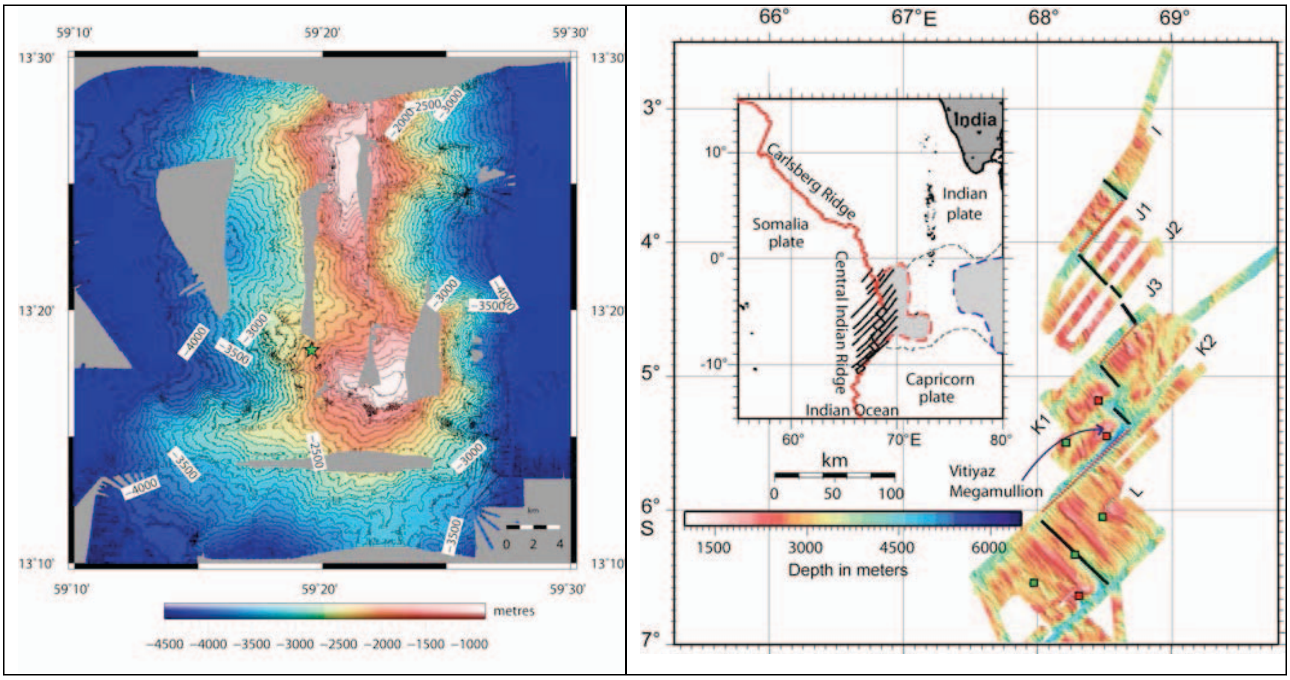


Figure 3.7: Left: The Varun Bank located on a 52 Ma crust at the Owen Fracture Zone. Right: the Vityaz Megamullion located at the RTI of the Central Indian Ridge. Black line - Fracture zone; red line -spreading axis.

THEME 4: Deep Biosphere

Pioneering studies of the 'extremophiles' of the deep biosphere in sediment and basalt have largely been concentrated in the Atlantic and Pacific Oceans. Given the different nature of the oceanography and inputs of organic matter into the Indian Ocean, the deep biota could be rather different in the Indian Ocean.

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4.1 Summary of prospective new proposals and revisions of previous proposals

General introduction to theme
Scientific ocean and continental drilling have revealed the existence of a deep biosphere in sediments and rocks far below the marine and terrestrial surface world. This deep subsurface biosphere is widespread with somewhat geological and geographical autochthonism, genetically and geochemically diverse, and comprises a significant fraction of Earth's total living biomass. High temperatures and pressures, variable pH and salinity conditions, and insufficient access to nutrients, carbon, or energy are potential limiting factors for life in the deep subsurface. The pervasiveness of buried microbial communities and the nature of their activities suggest that they may play important roles in global biogeochemical cycles, mineral alteration, and the production and destruction of hydrocarbons in oil reservoirs and sediments. For these reasons, the deep biosphere was identified as one of the major scientific themes in the Integrated Ocean Drilling Program (2003-2013) (IPSC, 2001) and the questions "What are the origin, composition, and global significance of subseafloor communities?" and "What are the limits of life in the subseafloor?" remain major challenges in the International Ocean Discovery Program (2013-2023) (IODP, 2011).

In the context of IODP, deep biosphere research builds on complex drilling and research strategies (IODP, 2011):

(i) Coring of entire sediment columns in a variety of marine environments provides insights into marine microbial communities and their survival strategies in general. It is a prerequisite to study the dispersal of microbial communities in the ocean and to address the question whether subseafloor sedimentary communities are typically assembled from microbes that were deposited on the seafloor and survived burial and passage through successive geochemical zones, or if the communities migrated through the sediment in response to ongoing chemical changes.

(ii) Drilling multiple sites along subsurface fluid-flow paths helps to determine whether seawater flowing into rock fractures introduces subseafloor microbes, or whether they migrate along flow paths from pre-existing communities in older rock, or from the overlying sediment.

(iii) Installation of long-term observatories facilitates integration of hydrological studies with microbiological and biogeochemical experiments and will help to identify the kinds of organisms that colonize rock below the seafloor and how they use chemical gradients and mineralogy to sustain life.

Moreover, deep biosphere research merges a broad range of experts and approaches:

(i) The investigation of microbial diversity including prokaryotes and eukaryotes employs nucleic acids-based approaches such as metagenomics and metatranscriptomics (mass-sequencing of 16S rRNA and existing DNA, single-cell genomics, functional gene and transcript analyses) as well as lipid-based phylogeny.

(ii) Conventional approaches of microbiology (cultivation, rate measurements) are not only complementary to the study of microbial diversity by nucleic acids-based approaches but also particularly helpful for bioprospecting of novel enzymes, antimicrobials and biomolecules of biotechnological application.

(iii) Investigation of biogeochemical processes and survival strategies specific for the deep biosphere requires both cultivation and cultivation-independent approaches (e.g. stable carbon isotope studies, experimental measurements of *in situ* metabolisms and functions, modeling of thermodynamic and kinetic energy limits).

(iv) The identification of key environments for studying the deep biosphere diversity is crucial and builds on seismic and heat flow studies (modeling), variability in organic matter inputs and preservation, pore-water biogeochemistry, the flux of electron donors and acceptors and their geologic record as documented in diagenetic signals.

(v) The low abundance, low metabolic activity, and novel character of microbial communities in the deep biosphere poses major challenges for sampling, analytical and cultivation techniques to find out a certain boundary between biosphere and abiosphere in this planet. Therefore, improvement of approaches is an important goal and on-going process; substantial progress is expected to be achieved within the next decade, in particular if rapid application and iteration are possible, and the development of novel and more sensitive techniques will also be highly interesting for other applications in environmental sciences.

Scientific ocean drilling with a specific focus on the deep biosphere started with ODP Leg 201 Microbial communities, Eastern equatorial Pacific and Peru Margin in 2002, and has since been continued and advanced during several deep biosphere dedicated IODP expeditions in the Pacific and Atlantic Ocean, including IODP Exp. 331 Deep Hot Biosphere, IODP Exp. 329 South Pacific Gyre Subseafloor Life, IODP Exps. 301 and 327 Juan de Fuca Hydrogeology, and IODP Exp. 336 Mid-Atlantic Ridge Microbiology. Moreover, IODP Exp. 311 Cascadia Margin Gas Hydrates aimed to constrain models for the formation of gas hydrate in subduction zone accretionary prisms and had a deep biosphere component. Similarly, in 2006 India National Gas Hydrate Program Expedition-01 was conducted with IODP technology, but outside the program, to study the formation of natural gas hydrates in marine sediments off India and had a microbiological and geochemical component. This expedition delineated and sampled one of the richest marine gas hydrate accumulations yet discovered (Site NGHP-01-10 in the Krishna-Godavari Basin), discovered one of the thickest and deepest gas hydrate occurrences yet known (offshore of the Andaman Islands, Site NGHP-01-17) and established the existence of a fully developed gas hydrate system in the Mahanadi Basin. All gas hydrate occurrences discovered during this expedition appeared to contain mostly methane generated by microbial processes (Collett et al., 2006). However, to date the deep subseafloor biosphere of the Indian Ocean has not yet been specifically addressed by a dedicated scientific ocean drilling project and only two active proposals for future expeditions exist in this field. Proposal **701-Pre** (Wortmann et al.) builds on findings of ODP Leg 182 and aims to study microbial carbon and sulfur cycling in the deep biosphere of the Great Australian Bight, where available evidence suggests that, unlike anywhere else, methanogenic archea co-exist with sulfate-reducing bacteria and high metabolic rates can be sustained to considerable depths. Proposal **780-Pre** (Kumagai et al.) aims to investigate serpentinization-associated hydrothermal circulation near the Rodriguez Triple Junction and addresses the question of how a heterogeneous shallow lithosphere feeds hydrogen-based chemolithotrophic microbial communities. While more specific deep biosphere oriented drilling proposals for the Indian Ocean need to be developed, active proposals in other fields provide ample opportunities to study deep biosphere related questions. We propose the incorporation of deep biosphere research in active proposals in order to sample sediments and crust wherever possible to address the following topics of interest in a wide variety of deep subseafloor environments.

4.2 First-order thematic scientific problems:

More general questions related to deep biosphere

(i) What are the limits of *in situ* growth, function and survival?
(ii) What are the food and energy sources of the deep biosphere?
(iii) How does the deep biosphere utilize organic and inorganic nutrients?
(iv) How is the deep biosphere linked to C-cycling, hydrocarbon gas formation and reservoirs?
(v) What is the origin of hydrocarbon gases?
(vi) How are microbial communities and biogeochemistry linked throughout strata and hydrogeologic constraints?

Questions specific for Indian Ocean Drilling - Sediments

(i) How has tectonic uplift of the Himalayas influenced the monsoon and input of terrestrial matter into the Bay of Bengal and Arabian Sea, and impacted the development of the deep biosphere since the Oligocene?
(ii) How has the drainage from the Himalayan rivers influenced the development of subseafloor community structures and diversity?
(iii) How has the subseafloor biosphere been inoculated with terrestrial microorganisms (biogeography)?
(iv) Are there regional differences between the Bay of Bengal and Arabian Sea?
(v) How are deep biosphere ecosystems related to the formation of ferromanganese nodules?

Questions specific for Indian Ocean Drilling - Crust

(i) What is the diversity and biogeography of microbial communities in the very heterogeneous ridge systems?
(ii) Which microbial communities and functions exist in different crustal provinces and structures?
(iii) How are they related to hydrogeology and to the alteration of the crust?

4.3 Conceptual IODP proposals

In the near future, the first-order thematic scientific problems can be addressed if deep biosphere related research is systematically incorporated in existing IODP proposals. We are looking for opportunities to join drilling expeditions primarily conducted by themes 1-3, and possibly to expand scientific objectives and samples by requesting additional coring through Ancillary Project Letters (APL). Coordination of sampling strategies and sample distribution, and sharing of data across multiple expeditions would help to address our first-order thematic scientific problems. In due course, the two existing deep biosphere specific pre-proposals need to be fully developed and further proposals should be initiated to explore the deep biosphere of the Indian Ocean.

During the workshop, we identified IODP proposals 552-Full and 595-Full as particularly interesting to address the overarching question of how variations in sediment input around India have influenced the deep biosphere. Proposals 552-Full3 and 552-Add (France-Lanord et al.) seeks to drill a transect across the Middle Bengal Fan in order to investigate interactions between the growth of the Himalaya and Tibet, the development of the Asian monsoon, associated erosion, weathering, and processes affecting the carbon cycle. The proposal provides excellent conditions to elucidate how the deep biosphere relates to carbon and energy sources, as it aims to investigate the history of organic carbon burial, changes in vegetation and thus organic matter quality over time, transport and deposition processes in the channel-levee system of the Bengal fan, and migration of depocenters at short time scales. Moreover, the proposal builds on a source-to-sink approach, which could be further extended to investigate the inoculation of the subseafloor biosphere with terrestrial microorganisms. A set of six holes at the middle fan and at the same latitude, 8° north, are proposed to recover a complete Neogene sequence from the laterally shifting depocenters of the turbidite fan. One deep hole to 1500 m is planned at the eastern flank of the Ninety East Ridge with the purpose of recovering sediment back to the Eocene. Proposal **595-Full4** (Clift et al.) and 776Full (Pandey et al.) aim to drill the Indus Fan in the Arabian Sea in order to reconstruct the erosion of Tibet, the western Himalaya and the Karakoram since the India-Asian collision, and to assess its relationship to regional and global climate change. The Indus Fan differs from the Bay of Bengal in mostly draining sources to the north of the Himalaya, within pre-collisional Asia (i.e. western Tibet and the Karakoram). The climate of the Indus basin is moreover significantly drier than that in the Bay of Bengal. The integration of deep biosphere research would be highly interesting to study the relation between the subseafloor microbial communities and organic matter sources and quality over time.

The combination of deep biosphere research in the Bay of Bengal and Indus Fan with the already proposed deep biosphere component of Proposal **549-Full6** (Lückge et al.) would be ideal. This proposal targets the Northern Arabian Sea where upwelling-induced marine productivity results in a stable, expanded open-marine oxygen minimum zone (OMZ), whose intensity is largely controlled by the strength of the summer and winter monsoon. The proposal seeks to drill two transects, i.e. a three site transect at the flank of the Indus Canyon and a four site transect at the Murray Ridge, in order to study changes in the intensity of the OMZ and the history of the monsoon on annual to tectonic time scales.

In the Bay of Bengal, pre-proposal Proposal **609-Pre** (Spiess et al.) would be an interesting target for a stronger consideration of the major deep biosphere challenges during the development of a full proposal. The proposal seeks to study the Himalayan-Bengal System complementary to **552** (Bengal Fan) drilling at 8°N, targets links between land and ocean, climate and tectonics, and uses a source to sink approach. Using a multiplatform approach, shelf, slope, canyon and channel-levee systems will be drilled in the Bay of Bengal and links to land studies are created with the PIRE project and a German-Chinese initiative to drill the Tibetan Lake NamCo through ICDP. Like Proposal **552-Full3**, incorporation of deep biosphere research into 609-Pre would help to elucidate how the deep biosphere corresponds to climate change induced vegetation history, organic matter sources, quality, transport, deposition, and degradation or preservation in the Bengal fan, and microbial communities in terrestrial and marine environments along the source-to-sink passage.

701-Pre (Wortmann et al.) specifically addresses questions related to biogeochemical processes in deep subseafloor microbial communities and aims to study microbial carbon and sulfur cycling in the Great Australian Bight, which constitutes a unique geochemical environment where methanogenic archaea co-exist with sulfate-reducing bacteria and high metabolic rates can be sustained to considerable depths.

In addition, consideration of deep biosphere aspects would be interesting for the development of a full proposal from pre-proposal Proposal 760-Pre (Gröcke et al.) which aims to drill five up 500 to 2500 m deep holes in the Naturaliste Plateau and Mentelle Basin, SW Australia, in order to recover Cretaceous high-latitude southern hemisphere sediments that experienced restricted and open-ocean circulation during the Cretaceous and Cenozoic, respectively. While the proposal primarily seeks to obtain climate and palaeoceanographic records, it will also allow the study of how the opening of ocean gateways affected circulation, productivity, and deep-water oxygenation. The development of oxygen-minimum zones and its impact on the deposition and preservation/demineralization of organic matter in the context of oceanic anoxic events provides an interesting context to investigate how the deep biosphere is linked to C-cycling, hydrocarbon gas formation and reservoirs.

780-Pre (Kumagai et al.) is currently the only active proposal that targets the deep biosphere in the crust of the Indian Ocean. It aims to investigate serpentinization-associated hydrothermal circulation near the Rodriguez Triple Junction, and addresses the question how a heterogeneous shallow lithosphere feeds hydrogen-based chemolithotrophic microbial communities. More generally, it will serve to study the diversity and biogeography of microbial communities in the very heterogeneous ridge systems of the Indian Ocean and their relation to hydrogeology and alteration of the crust.

During the workshop, ideas for new proposals were discussed and ranged from addressing questions specific for microbial life in the Indian Ocean Crust in the context of drilling the Ninetyeast Ridge (proposal in prep, Krishna et al.), over tying-in with the Andaman Backarc hydrothermal system drilling proposal as a multidisciplinary expedition (e.g., IODP Exp. 331 Deep Hot Biosphere in the Okinawa Trough), to deep drilling of the Krishna-Godavari Basin specifically for investigating biogenic vs. abiogenic sources of methane and limits of life and biosphere.

4.4 Ideas for future workshops

There is a capability to develop long-term (microbial, geochemistry, hydrogeology) observatories, especially in the crust and in various hydrothermal systems; and to improve the interaction between the deep biosphere theme and other themes, especially in the context of nurturing existing proposals.

References

Collett T., M. Riedel, J. Cochran, R. Boswell, J. Presley, P. Kumar, A. Sathe, A. Sethi, M. Lal, V. Sibal and the NGHP Expedition 01 Scientists (2006), Indian national Gas Hydrate Program Expedition 01 Initial Reports. Published by Directorate General of Hydrocarbons, Ministry of Petroleum & Natural Gas (India). www.dghindia.org

IPSC (2001) Integrated Ocean Drilling Program Initial Science Plan, 2003-2031. Available online: http://www.iodp.org/pdf/IODP_Init_Sci_Plan.final.pdf.

IODP (2011) Illuminating Earth's Past, Present and Future. The International Ocean Discovery Program. Science Plan for 2013-2023. Available online: http://www.iodp.org/Science-Plan-for-2013-2023/

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