DEEP-SEA DRILLING IN THE NORTHERN INDIAN OCEAN: INDIA’S SCIENCE PLANS

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PREFACE

Secretary
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Message

Director,
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CHAPTER 1: AN OVERVIEW

Earth’s evolutionary history through the geologic time has been distinctly recorded in the rocks on its surface as well as at depths. The seafloor sediments and extrusive volcanic rocks represent the most recent snapshot of geological events. Beneath this cover, buried in sedimentary sections and the underlying crust, is a rich history of the waxing and waning of glaciers, the creation and aging of oceanic lithosphere, the evolution and extinction of microorganisms and the building and erosion of continents. The scientific ocean drilling has explored this history in increasing detail for several decades. As a consequence, we have learnt about the complexity of the processes that control crustal formation, earthquake generation, ocean circulation and chemistry, and global climate change. The Ocean Drilling has also elucidated on the deep marine sediments, mid-ocean ridges, hydrothermal circulations and many more significant regimes where microbes thrive and natural resources accumulate.

The Integrated Ocean Drilling Program (IODP) began in 2003, envisaged as an ambitious expansion of exploration beneath the oceans. The IODP is an international marine research endeavor that explores Earth's structure and history recorded in oceanic sediments and rocks and monitors sub-sea floor environments. IODP builds upon the earlier success of DSDP (1968-1983) and ODP (1985-2003) and augments the reach of these programs using multiple drilling platforms. The first phase of IODP campaigns is scheduled for completion by 2012 which would mark the beginning of new phase of IODP (2013-2023).

The centerpiece of IODP’s deep-water efforts during the first phase is a brand new riser-equipped, dynamically positioned drillship, operated by JAMSTEC (Japan Marine Science and Technology Center). This vessel “CHIYKU” is partnered with a modern, non-riser, dynamically positioned drillship, a successor to the Ocean Drilling Program’s JOIDES Resolution, supplied and operated by the US National Science Foundation. In addition, the European and circum-Pacific nations have taken the initiative to provide “mission-specific platforms (MSP)” for small-scale ocean drilling (See Annexure I).

IODP’s scientific objectives are organized into three major themes: The Deep Biosphere and the Sub-seafloor Ocean; Environmental Change, Processes and Effects; and Solid Earth Cycles and Geodynamics. Within these three themes, the following eight initiatives have been identified that are ready to be addressed within the first decade of IODP drilling:

- Deep Biosphere;
- Extreme Climates;
- Rapid Climate Change;
- Continental Breakup and Sedimentary Basin Formation;
- Large Igneous Provinces;
- Gas Hydrates;
- 21st Century Mohole;
- Seismogenic Zone
Against the above background of IODP operations and science plan and in the context of the front-ranking scientific endeavors being planned/being undertaken by India in the ocean domain, the Ministry of Earth Sciences (MoES), Government of India took an initiative during 2008-09 towards India joining the IODP fraternity as an Associate Member. A formal MoU in this regard was also signed between MoES and NSF/MEXT- the two lead Agencies for IODP Operations.

Under the MoU with IODP, a total of five scientists from some of the leading geoscientific institutions in the country have been nominated to participate in the following IODP activities during 2009-10:

- IODP Pacific Equatorial Age Transect Expedition 321
- JOIDES Bering Sea 323
- CHIKYU Nankai Trough Japan 322
- MSP (Europe) GBR 325
- JOIDES Wilkes Land 318

However, looking beyond the participation of Indian scientists in the IODP activities elsewhere in the world, there is an imperative need for the country to develop a concrete Science Plan of its own, addressing the scientific issues pertaining to the seas around India which calls for deep-drilling. Taking cognizance of this need, the Ministry constituted an Expert Group to co-ordinate India’s initiatives in this regard and to help develop a Science Plan for deep drilling in the Arabian Sea, Bay of Bengal and Indian Ocean sectors.

The first meeting of this Expert Group was held at the National Centre for Antarctic and Ocean Research (NCAOR) on the 28th November 2008 (Friday) under the chairmanship of Director, NCAOR. Based on detailed deliberations at this meeting, the Group identified the following major themes for incorporation in the Science Plan:

1. **Crustal Evolution**
   - **Western Continental margin**
     - Continent Ocean Boundary
     - Characterization of crust at selected locations (Laxmi Basin, Chagos-Laccadive Ridge, etc)
     - Mesozoics under the traps
     - SW coast of India and Gulf of Mannar
   - **Eastern Continental margins**
     - Continent Ocean Boundary – Transect drilling
     - Mesozoic crust
     - Sampling of 85E ridge
     - Afanasy Nikitin Sea mount
     - Distal Bengal for KT super-chron
Andaman Sea
- Spreading centre
- Barren Island – Heat flux from the crust,
- Earthquake swarms

Mid Ocean Ridges
- Carlsberg Ridge (RTI zone, core complexes, hydrothermal vent fields)
- Triple junctions

2. Gas Hydrates -
- Sediment character, BSR characteristics and GH occurrence
  (West coast – Off Mangalore and Cape Comorin)

3. Climate Change-
- Timing of the SW monsoon and NE monsoon and their later evolution
- Sediment fluxes in BOB through time and linkages with Himalayan Orogeny

4. Deep biosphere-

In the following pages, we seek to expand on the above themes within the overall science framework of IODP. To this end, we have adopted a three-pronged strategy. In Chapter 2, we summarize some of the significant achievements of the Ocean Drilling Program, and follow it up in Chapter 3 with an overview of the major geological and tectonic features of the Northern Indian Ocean, stressing some of the ongoing topics of academic debate. In Chapter 4, we provide details of the deep sea drilling campaigns in the seas around Indian subcontinent, before describing the country’s Science Plans in Chapter 5.
Earth system components, processes and phenomenon (Image courtesy: Asahiko Taira, University of Tokyo).
CHAPTER 2: MILESTONES OF THE OCEAN DRILLING PROGRAM

SOLID EARTH CYCLES & GEODYNAMICS

VALIDATION OF PLATE TECTONIC THEORY
Dating of igneous basement rocks and overlying sediments recovered by scientific ocean drilling has demonstrated that the age of the oceanic crust increases systematically away from ridge crests, validating a fundamental prediction of plate tectonic theory.

EVOLUTION OF PASSIVE CONTINENTAL MARGINS
Drilling results and seismic data from the passive rifted margins have facilitated the development of new rifting and extensional deformation models of the continental crust.

Drilling has established that seaward-dipping reflections identified on multichannel seismic reflection data from many passive continental margins consist of vast subaerial outpourings of lavas rapidly emplaced during the time of final continental separation and the initial formation of ocean basins. In some instances, enhanced melt production can be related to mantle plume heads thousands of kilometers wide, but other instances appear unrelated to known plumes.

THE OCEANIC CRUST
To date, knowledge of the oceanic crust and shallow mantle has been largely restricted to geophysical observations, seafloor dredge samples and ophiolite studies. Limited ODP drilling into the oceanic mantle and principal crustal layers partly confirms models derived from these earlier studies, but also reveals major discrepancies that will change the estimates of the flux of heat and mass between mantle, crust and oceans over the last 250 million years. ODP drilling results have also challenged the assumption, critical to estimating the composition and volume of the oceanic crust, that seismic structure and igneous stratigraphy can be directly correlated.
MASSIVE SULFIDE DEPOSITS
Drilling into actively forming volcanic- and sediment-hosted metal sulfide deposits has established that seafloor sulfide deposits are direct analogs with on-land massive sulfide deposits, in terms of ore-forming process, and with respect to size and grade of mineralizations.

CONVERGENT MARGIN TECTONICS AND SUBDUCTION RECYCLING
Strikingly different styles of convergent margin tectonics have been imaged by seismic data and constrained by scientific drilling, ranging from dominantly accretion to the overriding plate, to subduction of most trench sediment, to erosion at the base of the overriding plate. Drilling of down-going slabs and comparison with arc magmatism have provided the beginning of a quantitative understanding of subduction recycling.

HOT SPOT TRACKS ON THE OCEANIC CRUST
Dating of sediment and basaltic rock recovered by drilling has documented a systematic age progression along several seafloor volcanic chains or ridges, verifying the hypothesis that these features were formed by relatively stable hot spots beneath the moving lithosphere. These drilling samples also provide the main observational evidence that hot spots are generated by deep mantle plumes. In addition, this work has helped establish the absolute movement of lithospheric plates with respect to the lower mantle.

HYDRATED MANTLE IN MANY TECTONIC ENVIRONMENTS
Unexpected mantle-derived serpentinites at shallow crustal levels have been documented by drilling in a variety of tectonic settings from rifted continental margins to fore-arcs to spreading ridges. These results indicate that upper mantle alteration is much more pervasive than previously believed.

ENVIRONMENTAL CHANGE, PROCESSES AND EFFECTS

DEVELOPMENT OF THE FIELD OF PALEOCEANOGRAPHY
The near-global network of continuous stratigraphic sections obtained by ocean drilling is the foundation of the field of paleoceanography. Paleoceanographers study changes in the life, chemistry and surface, intermediate and deep
circulation of the oceans through time. Paleoceanography provides the reference frame for nearly all other investigations of global environmental change.

**Orbital Variability during the Cenozoic**
By linking the record of climatic variation preserved in deep-sea sediments to calculated variations in Earth’s orbital parameters, scientists have demonstrated the role of orbital variability in driving climate change.

**Development of High-Resolution Chronology**
Complete recovery of fossiliferous marine sedimentary sections has greatly facilitated linking Earth’s geomagnetic polarity reversal history to evolutionary biotic changes and to the isotopic composition of the global ocean. Also of great significance is the orbitally tuned determination of time within marine sections, which has resulted in a greatly refined calibration of the Geomagnetic Polarity Time Scale back to 30 Ma. This newly calibrated, globally applicable time scale is crucial for determining rates of processes operating in every aspect of the terrestrial and marine geosciences.

**Ocean Circulation Changes on Decadal to Millennial Time Scales**
The record preserved in marine sediments and recovered by ocean drilling has clearly demonstrated that deep- and surface ocean circulation is variable on decadal to millennial time scales, confirming results from ice cores. This body of marine-based data has provided the evidence linking ocean-atmosphere-cryosphere interactions in and around the high-latitude North Atlantic to instabilities in thermohaline circulation, which propagates abrupt climate change to the farthest reaches of the globe.

**Ocean Biogeochemical Cycles**
The concept of Earth System Science has evolved with detailed analyses of the relatively complete deep-sea sedimentary sections recovered by ocean drilling. These studies have revealed major changes in biogeochemical cycling through time, especially in the complex carbon cycle, resulting from evolutionary changes in the biota, tectonic changes, changes in climate, variations in seafloor hydrothermal activity and major alterations in ocean circulation.

**Global Oceanic Anoxic Events**
Deep-sea sediments exhibit specific times when the surface water productivity of large areas of the ocean was unusually high. At these times, the global ocean developed zones of depleted oxygen content, and vast amounts of organic carbon were incorporated and preserved in marine sediments as black shales. Scientific ocean drilling has provided insights into oceanic anoxic events, which
are a key to understanding short- and long-term perturbations in global climate and carbon cycling, as well as the timing of significant petroleum source-rock deposition.

**VAST SAND DEPOSITS IN DEEP WATER**
Drilling has confirmed that the construction of deep-water fan systems controlled largely by changes in sea level. The hydrocarbon industry is intensively exploring deep-water sand “plays” contained in these fan systems for their proven economic potential.

**TIMING OF ICE-SHEET DEVELOPMENT IN ANTARCTICA AND THE ARCTIC**
Drilling has revealed that Earth’s entry into its current Ice Age extended over 50 m.y. and involved a complex history of uni-polar, then bi-polar, ice-sheet buildup. Ice streams reached the Antarctic seas as early as 40 Ma, but major ice-sheet formation on Antarctica apparently did not occur until some 25 m.y. ago. Northern hemisphere ice sheets did not begin to develop until sometime after 15 Ma, and major northern hemisphere continental glaciations did not start until after 4 Ma. This extended period of climate change appears to have occurred in relatively rapid steps, each associated with major tectonic changes that affected both atmospheric and oceanic circulation.

**SEA-LEVEL CHANGE AND GLOBAL ICE VOLUME**
Marine sediments recovered from shallow water areas have shown that important global sea-level changes have occurred synchronously through at least the past 25 m.y., and that these changes can be matched to oxygen isotope records of climate produced from the deep sea. The new understanding of global eustasy has become a primary interpretative tool in unraveling the history of continental margin growth and in the search for hydrocarbons in margin settings.

**UPLIFT OF THE HIMALAYAS AND THE TIBETAN PLATEAU**
Drilling in both the Indian and Pacific Oceans has helped to establish the timing of the Tibetan Plateau uplift, and to determine change in coastal upwelling, carbon sequestration, and regional and global climate associated with this tectonic event. Drilling results have shown that the onset and development of both the Indian and Asian monsoons are the result of climate change associated with this uplift.
**THE DEEP BIOSPHERE & THE SUB-SEAFLOOR OCEAN**

**EXTENSIVE MICROBIAL POPULATIONS BENEATH THE DEEP SEAFLOOR**

Sampling deep within the marine sedimentary section and in basaltic crust has revealed what appears to be a diverse and often very active microbial ecosystem. Recent sampling efforts have demonstrated that uncontaminated samples of these microbes can be recovered for laboratory study.

**FROZEN METHANE RESERVOIR BENEATH THE SEAFLOOR**

Extensive reservoirs of gas hydrates beneath the seafloor have been sampled by ocean drilling, providing valuable information regarding their possible impacts on the global carbon budget, submarine slope stability and their resource potential. Currently, only ODP technology is capable of retrieving and maintaining gas hydrates samples from the subseafloor marine environment at in situ pressures.

**FLUID PRESSURE AND DISCHARGE ALONG MAIN THRUST FAULT ZONES**

Drilling through the thrust faults at convergent plate boundaries has confirmed three-dimensional seismic observations that fluids actively flow along the slip zone. These fluids have distinctive geochemical signatures and are likely involved in the mechanics of thrust faulting.

**HYDROTHERMAL FLUID FLUX IN THE UPPER OCEANIC CRUST**

Drilling of marine sedimentary and crustal sections is beginning to determine the sources, pathways, compositions and fluxes of fluids associated with mineralization within active submarine hydrothermal systems, and the influence of fluid circulation on ocean chemistry, crustal alteration and the crustal biosphere.
CHAPTER 3: MORPHOLOGICAL FEATURES OF THE NORTHERN INDIAN OCEAN

1. General Introduction

The subcontinent of India divides the Northern Indian Ocean into two zones, with the Arabian Sea and Laccadive Sea in the Northwest Indian Ocean (NWIO) and the Bay of Bengal and Andaman Sea in the Northeast Indian Ocean (NEIO; Figure 1). The eastern Arabian Sea, which forms a part of the Northwestern Indian Ocean, is marked by several surface/subsurface structural features. These include the Chagos–Laccadive ridge (CLR), Laxmi ridge, Pratap ridge and a belt of numerous horst-graben structures in the sediment filled basins bordering the west coast of India (Figure 1). Naini and Talwani (1982) observed that the CLR and Laxmi ridges divide the eastern Arabian Sea into two provinces, the Western and Eastern basins. While it is widely agreed that the Western basin is underlain by oceanic crust (McKenzie and Sclater, 1971; Whitmarsh, 1974; Naini and Talwani, 1982; Chaubey et al., 1995), the nature of crust below Eastern basin is debated.

2. Plate tectonic evolutionary history of the Indian Ocean

The evolution of the Western Indian Ocean is essentially related to the evolutionary history of the Indian Ocean (Figure 2), which formed as a result of fragmentation and dispersal of a super continent named Pangea. At about 200 Ma the Pangean super continent began to split into Laurasia (northern part) and Gondwanaland (southern part). The main Gondwanaland, which consisted of the present day South America, Africa, Arabia, Madagascar, Seychelles, India, Sri Lanka, Antarctica, Australia and New Zealand, fragmented and dispersed in different episodes, each marked by many major and minor events.

Integrated geophysical and geological studies carried out to unravel the evolutionary history of the Indian Ocean have considerably improved the understanding about the ocean as well as its tectonic configuration. Magnetic data interpretation constrained by ODP and DSDP drilling results has further provided a better understanding on the tectonic scenario. As deduced from these studies, the stage-wise development of the Indian Ocean has been summarized below (Figure 2).
Figure 1. Morphological features of the Northern Indian Ocean
The initial break-up of Gondwanaland seems to have resulted from the interaction of a series of hotspots or mantle plumes, of which the Karoo mega-plume was possibly the cause of the first split (Lawver et al., 1998). Rifting episode, which might have been initiated earlier than 152 Ma (late Jurassic), resulted in the commencement of seafloor spreading along short E-W trending spreading segments offset by long N-S trending transform faults by \textbf{152 Ma}. This divided the Gondwanaland into \textbf{West Gondwanaland} consisting of Africa, Arabia and South America and the \textbf{East Gondwanaland} consisting of Antarctica, Australia, New Zealand, Madagascar, Seychelles and India. This was the stage during which the Mozambique, the Western Somali and probably the Northern Somali basins began to form marking the opening of the Indian Ocean (Cochran, 1988; Gombos et al., 1995). After this break up, east Gondwanaland moved south in comparison to west Gondwanaland.

Further break up of eastern Gondwanaland began in Cretaceous and a three plate system in the Indian Ocean area developed. Around \textbf{135 Ma} (Early Cretaceous) initiation of seafloor spreading separated South America from Africa (Storey, 1995). At about \textbf{133 Ma} (Early Cretaceous) the conjoined Antarctica-Australia rifted from Madagascar-Seychelles-India fragment (Curray et al., 1982; Powell et al., 1988; Lawver et al., 1991; Holmes and Watkins, 1992; Ramana et al., 1994; Gombos et al., 1995; Gopala Rao et al., 1997; Gaina et al., 2003, 2007) and relative plate motion started between these two continental masses in a NW-SE direction.

Following the separation of Madagascar-Seychelles-India block from Antarctica-Australia, the spreading of seafloor continued in a uniform fashion for a period of about 15 million years. This was followed by a change in spreading pattern between the Africa-Arabia and the Madagascar-Seychelles-India blocks (Besse and Courtillot, 1988). While the spreading in Mozambique basin continued, at \textbf{118 Ma} spreading stopped in the Western and Northern Somali basins. As a result of this \textbf{reorganization}, Madagascar – Seychelles -India block again got attached to the African plate.

The next major event in the evolutionary history took place 30 Ma later when the Madagascar – Seychelles -India block possibly came over the location of the Marion Hotspot. Due to the influence of this hotspot, rifting was initiated and around \textbf{84 Ma} (chron 34ny) the seafloor spreading separated Madagascar from Seychelles-India block (Besse and Courtillot, 1988, Storey, 1995, Subrahmanya, 1998), leaving Madagascar attached to the African plate. The event resulted in the
opening of the Mascarene Basin and establishment of a three-plate system with a triple junction (Indian Ocean triple junction) at 55°S in the western Indian Ocean. Shortly after that, the Marion Plume possibly came in the proximity of the nearby Indian Ocean triple junction and their interaction caused an anomalous volcanism which created a large oceanic plateau edifice of the Madagascar ridge (Storey, 1995). Most importantly this event probably marked the beginning of the tectonic events, which resulted in shaping the present-day deep offshore regions off the west coast of India. After separation, Seychelles-India block continued northward drift and at the same time experienced a gradual anti-clockwise rotation (Pariat and Achache, 1984).

[5] During the same time when Madagascar and India-Seychelles separated (late Cretaceous – 83 Ma), a major plate reorganization also happened in which Australian plate separated from Antarctica plate (Mutter et al., 1985; Sayers et al., 2001) with the development of Australia-Antarctica Ridge (southeastern limb of the Southeast Indian Ridge). Relative plate motion between India and Antarctica changed from the NW-SE direction to N-S direction during this Cretaceous long normal magnetic period (Larson, 1978). After this plate reorganization, India drifted rapidly away from Antarctica forming anomalies 34 to 22 (82 to 54 Ma). This second spreading phase is constrained by the east-west-trending magnetic anomaly lineation patterns identified as anomalies 34 through 21 in the Central Indian and western Wharton Basins (Sclater and Fischer, 1974). It was during this period of spreading that India made its spectacular rapid northward flight.

[6] While drifting northward, around 69-65 Ma (late Cretaceous), wide spread volcanism took place over the Indian landmass and created the Deccan Trap continental flood basalt province which is related to the onset of the Reunion hotspot activity (Duncan, 1990). Around ~63 Ma (late Paleocene), spreading in the Mascarene Basin gradually ceased (Schlich, 1982) and jumped north of Seychelles, carving the Laxmi Ridge out of the Seychelles to form a new spreading centre – the paleo-Carlsberg Ridge (Figure 2). The spreading along this paleo-Carlsberg Ridge caused the opening of the conjugate Arabian and Eastern Somali basins and welding of the Seychelles to the African Plate. Coinciding with this time was the commencement of rapid northward drift of India. As Indian plate continued to move northward, the adjacent offshore areas came under influence of the Reunion hotspot. This resulted in commencement of formation of the Chagos-Laccadive Ridge and reorganization of the nearby spreading centers.
Figure 2. Cartoon depicting the plate tectonic evolutionary history of the Indian Ocean.
As the rapid northward movement of India continued, the Arabian and Eastern Somali basins continued to grow and simultaneously the Neo-Tethys continued to be subducted. Finally around 50 Ma (Middle Eocene), the continental India came into contact with the Kohistan-Ladakh Island arc system and gradually closed the Neo-Thethys along the Indus-Tzangpo suture zone (Windley, 1996). This event is termed as “soft collision” or the first contact between India and Asia (Kennett, 1982; Curay, 1982), which set the initial stage for the formation of mighty Himalayas. The collision also resulted in slowing down of the spreading rates at the Carlsberg, Central Indian and Southeast Indian ridges (Curay and Moore, 1974; Sclater and Fischer, 1974; Curay et al., 1982; Patriat and Achache, 1984; Chaubey, 1993). The event also initiated major plate reorganizations. The east-west-trending spreading centre reoriented to a northwest-southeast direction, and connected with the Australia-Antarctica spreading center to form the Southeast Indian Ridge.

In response to the continued collision of India and Asia, the plate boundaries in the Indian Ocean area started re-organization and by about 40 Ma the plate boundaries in the Indian Ocean began to assume the present day configuration (Vine and Matthews, 1963).

During late Miocene, shortly before the time of anomaly 5 (~11 Ma), the Carlsberg Ridge spreading centre propagated westward as the Sheba Ridge and opened the Gulf of Aden. The accelerated spreading caused subduction of entire oceanic crust north of Indian Plate and brought continental crust of Indian and Eurasian plates into contact. This contact or the “hard collision” as it is known (Kennett, 1982) might probably have occurred during Middle Miocene (~16-11 Ma) and as a result of which the Himalayas emerged as a highland. The rapid rise of the Himalayas continued and by late Miocene (~11-7.5 Ma), the Himalayas became a lofty mountain range. Consequent accelerated erosion of the Himalayas brought large volume of sediments in the Indus and Bengal fan area (Valdiya, 1999). The eastern part of the Indian plate has been continuously subducted into the Sunda subduction zone.

Last of the plate reorganizations happened during Miocene age, when high-magnitude earthquakes and large-scale lithospheric deformation in the central Indian Ocean have contributed to the splitting of traditionally believed single Indo-Australian plate into three component plates (India, Capricorn and Australia) and multiple diffuse plate boundaries (Wiens et al., 1985; Gordon et al., 1990; Van Orman et al., 1995; Royer and Gordon, 1997; Gordon et al., 1998; Krishna et al., 2001a; DeMets et al., 2005; Krishna et al., 2009).
The Indo-Burmese range and the Andaman arc system in the northeast Indian Ocean define a zone of underthrusting of the Indian plate below the Southeast Asian (“Burma”) plate, and provide an important transitional link between the Himalayan collision zone and the Indonesian arc (Rudolf, 1969; Curray et al. 1979; 1982; Figure 3). This zone of active convergence has led to the formation of a major island arc-trench system (the Burmese - Sunda arc system) extending for over 1100 km from Myanmar in the north to the Indonesian island of Sumatra in the south. The Andaman island arc including the Andaman and Nicobar islands together with the Andaman backarc basin is a part of this major arc-trench system (Figure 3). The sedimentary cover on the subducting Indian plate is very thick because of the Bengal Fan (Curay et al., 2003), and sediments and ocean crust have been accreted and uplifted into the Indo-Burman Ranges, the Andaman–Nicobar Ridge and the outer arc ridge off Sumatra and Java. The trench extends continuously from east of Java westward and northward to where it is overwhelmed by sediment of the Bengal Fan, and the surface trace of the subduction zone rises out of the depths onto land as the thrust faults of eastern Bangladesh, eastern India, western Myanmar and the southeastern edge of the Assam Valley. The accretionary prism forms an entire mountain range, the Indo-Burman Ranges.

Figure 3. Subduction of the India plate under the Burma plate
3. **Tectonic elements in the Western continental margin of India and the adjoining Ocean basins**

For a detailed understanding of the evolutionary history of the Western Indian Ocean, it is necessary to understand the genesis of each of the major tectonic elements that formed as a consequence of rifting and drifting among Madagascar, Seychelles and India. The Arabian Sea is divided into several deep ocean basins by submarine plateaus, aseismic ridges, the active mid ocean ridges and several fracture zones. The main surface/subsurface features in the eastern Arabian Sea includes Chagos-Laccadive ridge, Laccadive basin, Prathap ridge, Terrace of Trivandrum, Laxmi ridge, Laxmi basin, Panicker Ridge, Indus fan etc (Figure 4). A brief description of each of these features is provided in the following sections.

3.1. **Laccadive Ridge**

The Chagos- Laccadive Ridge (CLR) is one of the most prominent physiographic and aseismic features in the Indian Ocean. This slightly arcuate major elongated tectonic feature is considered to extend for about 2500 km between 12°S and 15°N. A considerable length of the crest of this ridge is composed of shoals, banks, and coral reefs at depths less than 1500 m. This ridge can be divided into three main segments by breaches in its topographic continuity due to several relatively deep saddles like features (Bhattacharya and Chaubey, 2001). In literature, these three segments are referred by various names. The northern segment is referred as the Laccadive Islands (Lakshadweep) or Laccadive Plateau which generally call as Laccadive ridge, the middle segment as Maldive Islands or the Maldive Ridge, and the southern segment as Chagos Archipelago or Chagos Bank. The height of the Chagos- Laccadive Ridge relative to the adjacent deep basins, near the Maldives Island, is up to 2 km and its width in the upper part is 75–150 km. Along the northern part of the eastern coast there is a steep trench with a depth of 2.5–3 km. The ridge is bounded by broad accumulative plains that suggest efficient sedimentary supply from coral shallows and ridge slopes. In the south, the ridge has an asymmetrical structure. Its east slope is steeper, up to 10, as compared with the western slope (0.5). In the Chagos archipelago area, near the eastern ridge foot, there is the Chagos trench. The southern part of the ridge is rotated in the southwest direction. Its relief takes the orientation of the structures of the Central Indian spreading ridge (Kanaev, 1979). According to seismic data, the thickness of carbonate sediments (Vp=3 km/s) at the Chagos- Laccadive Ridge crest does not exceed 600 m and at the ridge foot 1000 m. The crustal thickness between the Maldives and Laccadive Islands is about 15 km and includes a layer with Vp=5 km/s and a thickness of 3 km, and a layer with Vp=6.8 km/s and a thickness of 12 km. A refractor with Vp=8 km/s lies below. The ridge is characterized by a weak variable magnetic field up to 300 nT. The ridge also is weakly expressed in the gravity field. The free-air anomalies over its foot are ~20 to ~60 mGal and those in the mountains and islands area amount to 50 mGal (Kanaev, 1979).
It is generally accepted that there was a spreading ridge jump at about anomaly 28-29 (65 Myr) from the Mascarene basin to the north of Mascarene Plateau. The Seychelles separated from India and spreading on Carlsberg ridge commenced, which ultimately led to the creation of the east Somali basin and Arabian Sea basin, south and north of the spreading ridge, respectively. This tectonic episode was contemporaneous with the passing of the Indian plate over the Reunion hotspot which resulted in the eruption of the Deccan continental flood basalts on western peninsular India and Seychelles at about 65 Myr (Fisk et al., 1989). As the Indian plate rapidly drifted northward, the Reunion mantle plume left a trail of volcanic ridges in the Laccadive, Maldive and Chagos islands.
At about 35 Myr the Reunion crosses the central Indian spreading ridge and the volcanic activity continued resulting in the emplacement of Saya de Malha and Nazareth Banks of the Southern Mascarene Plateau (SMP) (Ashalatha et al., 1991). The hotspot now sits under Reunion Island. Results from Leg 115 of the Ocean Drilling Program (Sinha et al., 1981) have provided convincing evidence from sites 707, 715, 713 and 706 that the hotspot trace along the CLR and SMP becomes progressively younger from north to south. Site 707 located southeast of Seychelles is considered contemporaneous to the Deccan flood basalts. Site 715 on the northern part of Maldives group of islands yields an age of 57 Myr, while Site 713 on northern Chagos bank gives an age of 49 Myr for basalts. The two sites have an age difference of just over 8 Myr whereas spatially they are separated by a distance of well over 1000 km. This would mean their rapid emplacement over a lithosphere which may not have significant variations in flexural rigidity characteristics. It is not clear whether the northernmost part of the CLR which is close to the west coast of India, was emplaced on an oceanic lithosphere or on a stretched continental lithosphere of the western margin of India.

A number of hypotheses regarding the genesis of the Laccadive-Chagos Ridge have been suggested. Krishnan (1968) considered this tectonic element as a micro continent while Narain et al. (1968) suggested this feature as a zone of transition between oceanic crust in the west and continental crust in the east. The subsequent studies put forward other views of leaky transform fault (Fisher et al., 1971; Sclater and Fisher, 1974) and hotspot trace (Francis and Shor, 1966; Dietz and Holden, 1970; Whitmarsh, 1974; Duncan, 1981; Morgan, 1981). According to Avraham and Bunce (1977), the Laccadive-Chagos Ridge is composed of structural elements of various origins, where the Laccadive ridge is composed of volcanic features associated with leaky transform faults. Ashalatha et al. (1991) also suggested that the Laccadive-Chagos Ridge have a different crustal structure commensurate with a volcanic emplacement on a thin, young oceanic lithosphere. Other views regarding the origin are: a continental fragment (Naini, 1980; Naini and Talwani, 1982), a continental fragment intermingled with volcanic intrusives (Chaubey, 1998; Chaubey et al., 2002b) and at some places, it may constitute volcanics emplaced over an oceanic crust (Chaubey et al., 1995).

Up to 10°N latitude, seafloor-spreading anomalies have been identified on the western flank of CLR. Detrick et al. (1977) have demonstrated from analysis of DSDP data that the CLR has subsided at rates similar to that of a normally subsided oceanic lithosphere. These arguments lend support to the view that the CLR loads an oceanic lithosphere, at least south of 10°N. Ashalatha et al (1991) suggest that at the time of emplacement of CLR, the oceanic lithosphere was thin, young and weak. Bonneville et al (1988) arrive at a similar conclusion for the SMP where, from analysis of geoid-bathymetry data, it was found that the SMP was emplaced on lithosphere of low flexural rigidity. It has been demonstrated that low Te values indicate emplacement of volcanic loads on an oceanic
lithosphere which was young, weak and thin. The tectonic setting for these emplacements must have been very close to a spreading ridge. From estimates of Te by Ashalatha et al. (1991), CLR was emplaced quite near the spreading ridge. The occurrence of the Chagos fracture zone, east of the Chagos Bank, also supports there idea that emplacement of the CLR was at a spreading centre - transform intersection.

3.2. Laccadive Basin

Laccadive Basin is a narrow triangular shaped basin, which is located between the Laccadive Plateau in the west and the southwestern continental slope of India in the east (Bhattacharya and Chaubey, 2001). The bathymetry varies from 20 m in the nearshore to 2000 m in the offshore. The seabed is characterized by an even topography between water depths of 20 and 100 m with a gentle gradient of 1:870. The shelf break with a steep gradient of 1:20 coincides with the 200 m depth contour. Beyond the shelf break, the area is characterized by a number of localized shoals. NNW-SSE, NW-SE, ENE-WSW and E-W magnetic trends dominate the southwestern continental margin. The depth to the magnetic basement varies between 0.5 and 6.0 km (Subrahmanyam, 1992). The previously identified features like a graben in the inner shelf, the mid-shelf basement ridge, the shelf-margin basin and the Prathap Ridge Complex (Subrahmanyam et al., 1993a, 1994) are seen continuing as regional features all along the shelf in this area. A maximum of thickness about 4.0 km of sediments is estimated in the region between 150 and 1000 m water depth. The crust-mantle boundary was computed to be at a depth of around 30 km in the nearshore region and gradually shallows further offshore (Subrahmanyam, 1992). A pile of sediments, about 4 km thick, fills a basin-like depression between the Prathap Ridge Complex and the paleo shell. This basin seems to be the continuation of the shelf-margin basin earlier identified in the north (Ramaswamy and Rao, 1980). Further west, another basin with a 2.3-km-thick pile of sediments is also noticed between the Prathap Ridge Complex and the Chagos-Laccadive Ridge system.

As this Laccadive Basin occupies a large intermittent region between India and Madagascar, it is essential to understand the nature of the underlying crust in this region. Based on limited magnetic and seismic reflection data, Rao and Bhattacharya (1975) inferred that the underlying basement in this region is block faulted. The seismic reflection studies (Naini and Talwani, 1982; Rao et al., 1987; Chaubey, 1998; Ramaswamy and Rao, 1980; Singh and Lal, 1993) suggest that the maximum sediment thickness in this basin is ~2.5 sec (TWT) in the south which gradually increases to ~3.5 sec (TWT) towards the northern part of the basin. The underlying basement widens and deepens towards south and is characterized by several basements high feature which form an approximately NNW-SSE trending lineament - the Pratap Ridge (Naini, 1980; Naini and Talwani, 1982). They suggested that the Laccadive Basin area is evolved by a taphrogenic process during early stage of rifting and therefore, the crust is
transitional in nature. Some other researchers (Biswa, 1988, 1989; Biswas and Singh, 1988; Chaubey, 1998) are of the opinion that part of the basin lying west of Prathap Ridge evolved during the post-rift phase by sea-floor spreading and therefore, the crust is oceanic in nature, whereas the basin east of the ridge evolved during early rift phase. They suggested that the boundary between the oceanic and continental crust lie close and parallel to the continental slope. These authors have postulated the possibility of oceanic crust west of Pratap Ridge. From the above studies, it is seen that different opinions exist about the nature of the crust underlying Laccadive Basin.

3.3. Prathap Ridge

Pratap ridge is a shallow basement high over continental crust formed during rifting and formation of CLR due to Reunion hotspot at the edge of continental crust (Radhakrishna et.al., 2002). With reference to Subramanium et al. (1995), as the area of uplift expands, the crust breaks to form a sub-parallel fault pattern. The magnetic magma most probably intruded along these faults. A schematic model representing the various stages of development of the southwestern continental margin of India from the Late Cretaceous to Present is shown in Figure VI-6. The formation of the Prathap Ridge Complex and the mid-shelf basement ridge seems to be manifestations of these rifting processes. Magnetic model studies reveal that these ridges are comprised of mafic rocks (Subrahmanyam et al., 1989, 1993a, 1994). Therefore, the NNW-SSE trending mid-shelf basement ridge and the Prathap Ridge Complex may have evolved parallel to the southwest coast of India during the initial break-up of India from Madagascar. The trend of these features strangely coincides with reported Precambrian trends suggesting that the alignment of these structures was influenced by the pre-existing structural fabric of the continent as mentioned by Kennett (1982). On the basis of above inferences, the spreading axis between India and Madagascar should lie west of the Prathap Ridge Complex, i.e., in the oceanic crust. The interpretation of the gravity data across the southwestern continental margin of India (Subrahmanyam, 1992) shows the presence of thick (around 30 km) continental crust in the nearshore areas which gradually thins out west of Prathap Ridge Complex and farther offshore, perhaps indicating a transition from continental to oceanic crust. The oldest oceanic crust that lies west of the Prathap Ridge thus may be younger than 84 Ma and closer to Anomaly 28 (or 68 Ma) crust as the separation of India and Madagascar seems to have taken place in more than one episode as evidenced by ridge jumps around Anomaly 28 time on the eastern side of Madagascar (Schlich, 1982). The Mascarene-Chagos-Laccadive volcanic lineament is a major aseismic ridge system that connects the young volcanic activity of the Reunion hotspot (Beckman et al., 1988). This lineament parallels the remarkable Ninety-east Ridge which is also a trace of a hotspot. Both these N-S-trending ridges record the northward motion of the Indian sub-continent away from stationary hotspots near Reunion and Kerguelen Islands, respectively. All hotspot traces (Emerick, 1985) in the Indian and South Atlantic oceans lie along definite paths that depict
the directions of plate motion. The approximate N-S direction of the Chagos-Laccadive Ridge system and the Ninety-east Ridge differ considerably from that of the NNW-SSE-trending Prathap Ridge and mid-shelf basement ridge, which both extend right to the southern tip of the Indian landmass. Furthermore, the ridges of hotspot origin do not show a consistent pattern of magnetic anomalies all along their length, whereas the Prathap and mid-shelf ridge are characterised by magnetic and gravity highs (Subrahmanyam et al., 1995). The subdued magnetic anomaly signatures at some places are due to the ridges being buried to various depths. The shallowest depth observed over the Prathap Ridge in their study is around 300-400 m from the chart datum and here the ridge is a flat-topped feature. The northern portion of the Prathap Ridge Complex and the trace of the Reunion hotspot seem to join around 17°N. We believe that thermal melting/metamorphism may have distorted the magnetic field considerably and given rise to ill-defined magnetic anomalies. Prathap Ridge Complex and the mid-shelf basement ridge have well-developed associated magnetic and gravity highs of ~ 300 and 200 nT, and ~ 70 and 60 mGal, respectively, all along their length, therefore, Prathap Ridge Complex and the mid-shelf basement ridge are different from the Chagos-Laccadive Ridge system. Their NNW-SSE orientation also differs considerably from that of the N-S-trending Chagos-Laccadive Ridge system. Further detailed geophysical studies are suggested west of the Prathap Ridge Complex for deciphering the continent ocean boundary (COB) since the Chagos-Laccadive Ridge system considerably affected the adjacent crust during its evolution.

3.4. Terrace off Trivandrum

The bathymetry map of the southwestern continental margin of India (Figure 3) reveals the presence of an anomalous terrace like feature located in the mid-continent slope region off Trivandrum. Yatheesh et al. (2006) made an attempt to provide an answer for the genesis of this anomalous feature through exercises with paleogeographic reconstruction models which constrain India-Madagascar juxtaposition and the available limited bathymetric and magnetic anomaly information. They suggest that the bathymetric protrusion of the terrace fits well in shape and size with the bathymetric notch located in the northern Madagascar Ridge. Hence, the Terrace off Trivandrum and the bathymetric notch of the northern Madagascar Ridge represent scars related to India–Madagascar break-up, the outlines of which were shaped by the rifted and transforms segments of the initial spreading geometry and the drifting of India from Madagascar was initiated around 86.5 Ma. Based on this India-Madagascar juxtaposition model and the published information about the nature of crust in the Northern Madagascar Ridge, they suggested that perhaps the terrace off Trivandrum also have a similar nature of crust as its conjugate areas of the northern Madagascar Ridge and this region probably represents areas of thinned continental crust on which at places Marion hotspot related volcanics might have been emplaced. A detailed analysis of gravity and magnetic data over the
Terrace off Trivandrum as well as the Northern Madagascar Ridge can make this observations and suggestions more reliable.

Figure 5: Schematic model showing the various stages of development of the southwestern continental margin of India from the late Cretaceous to Present (Subrahmanyam et al., 1995).

3.5. Laxmi Ridge

The Laxmi Ridge, an enigmatic continental sliver in the Arabian Sea, about 700 km long and 200 km across, occurs west of the Shiva crater (Figures VI-7, 8). This submarine ridge trends NW-SE and is located between latitude 14° and 19°N and longitude 64° and 69°E. It has a rugged topography buried under 0.5 km of sediments and an average water depth of about 2.8 km. It has a basement relief of up to 2 km and is underlain by a thick crust of ~ 21 km (Naini 1980). The origin of Laxmi Ridge is controversial. Based on gravity and seismic
data, Dyment (1998) and Talwani and Reif (1998) suggest that it is quite different from a typical oceanic ridge and is probably continental in origin. It formed two basins, the East Arabian Basin (EAB) or Laxmi and the West Arabian Basin (WAB).

The geophysically enigmatic Laxmi Ridge is associated with a prominent elongated negative gravity anomaly. A seismically and geodynamically constrained detailed 2D gravity modeling suggests an 11-km-thick normal oceanic crust and an asthenospheric up-warp to a depth of 35 km. The apparent thickening of the crust may be due to a possible emplacement of an anomalous subcrustal low-density layer between 11 and 19 km depth. O. P. Pandey (1995) hypothesize that a K-T boundary bolide impact near the Bombay offshore led to several geological events, including eruption of Deccan flood basalts (Figure VI-7). The spreading Carlsberg Ridge in the Indian Ocean and rifting associated with Deccan volcanism generated the compressive regime, which perhaps originated the Laxmi Ridge.

Figure 6: Paleogeographic positon of India-Seychelled-Greater Somalia block during the KT boundary (~65 Ma) when a larger bolide, about 40km diameter, crashed on the western shelf of India to create the Shiva crater (Chatterjee et.al., 2006).

The crustal structure beneath this ridge is reported to be somewhat similar to that obtained below some aseismic ridges, ocean rises, and plateaus, apart from the mantle plume generated areas such as Iceland and Hawaii, which are normally
found associated with positive gravity anomalies. In contrast, the gravity anomalies over the Laxmi Ridge are negative (~ 30-40 mgal) (Naini and Talwani 1982) (Figure 5). It is also characterized by a negative Airy (T = 30 km) isostatic anomaly of about 30 mgal (Naini and Talwani 1982). The ridge is reported to be underlain by a thick crustal layer above the Moho with an anomalous velocity of 7.2 km/sec (Naini 1980), which is rather unusual for a normal ocean basin crust.

The Laxmi Ridge is neither seismically nor volcanically active (McKenzie and Sclater 1971). It did not act as a spreading center and has no definite magnetic lineation (Naini 1980). In the absence of active rifting, the negative gravity anomaly may have been possible with the emplacement of some low-density material below the crust, which could be either in the form of serpentinized olivine basalt/peridotite or low-density fractionated magma related in some way to the Deccan volcanic episode. This massive flood basaltic episode occurred at the K-T mass extinction boundary (~65 Ma) and covered a large part of western and central India. Some flows close to Bombay indeed exhibit partial or complete olivine alteration (Deshmukh 1984; Subba Raju et al. 1992). Deccan magmas are indeed highly differentiated and have low Mg ratios (Pandey and Negi 1987a; Sen 1988). Estimated depth to the thermal lithosphere beneath the Laxmi Ridge (~35 km) suggests a considerable degeneration of its base (about 40 km), as proposed under the entire Indian continental region after its breakup from the Gondwanaland (Negi et al. 1986b; Pandey and Negi 1987b). The thinning of the lithosphere beneath the ridge may have been caused as a result of super mobility of the Indian plate between 80 and 53 Ma when its velocity is known to have jumped from 35 cm yr^-1 to more than 20 cm yr^-1 (Negi et al. 1986b; Powell, 1979). Rapid movement of the plate would cause frictional heat at the base of the lithosphere. This heat coupled with the already hot upper mantle conditions below the Indian plate would generate substantial melt at that depth, causing a rise of the isotherm, which would result into sub crustal melting within the lithosphere. This process might have been accelerated prior to Deccan Trap eruption and allowed partial melting of lithospheric mantle at the lower depth range of tholeiitic magma generation. The build up of heat at the lower lithospheric level would give rise to a hot-cell like condition, which, due to insulating effect of the upper continental lithosphere, would induce the formation of a large scale convection cell (Anderson 1982; Gurnis 1988; Smith 1993), a condition which is conducive for the initiation of rifting. The rapid eruption and lateral migration through the hot cell magma reservoir may have been facilitated by a large bolide impact (> 10 km) at the K-T boundary near Bombay (Negi et al. 1992, 1993). The impact may have brought Deccan flood basaltic magma to the surface and initiated the formation of the Carlsberg ridge in the Indian Ocean, which led to the break up of the Seychelles block from India's west coast. On the continental side, the impact may have rejuvenated the existing zone of weaknesses such as Koyna and Kurduvadi rifts postulated by Krishna Brahmam and Negi (1973) (Figure VI-8). It also reactivated a preexisting zone of weakness within a supposedly rigid block, which, due to the horizontal compressive regime from either side (riifting associated with Deccan volcanism on the east and rapid
spreading across the Carlsberg ridge in the west), facilitated buckling up of the lithosphere, leading to the formation of the Laxmi Ridge. Sea floor magnetic lineations (Naini 1980) suggest it to be slightly younger than the Deccan volcanic event. Therefore it is believed that the reported thickening of Moho (Naini 1980) in this region is due to low-density underplating of magma below a normal oceanic Moho that subsequently got serpentinized/ fractionated. A shallow asthenosphere and high heat flow around this ridge is expected similar to that observed over the western margin of India (Negi et al. 1992, Pandey et al. 1995). The conclusion reached by (Naini and Talwani, 1982) was that Laxmi Ridge consists of continental crust.

3.6. Laxmi Basin

In the East Arabian Basin, which is also known as Laxmi basin (Bhattacharya et al., 1994) was at the stage of rifting when the ridge suddenly jumped more than 500 km westerly to the West Arabian Basin on the other side of the Laxmi Ridge, as a possible response to the Shiva impact (Talwani and Reif 1998). This ridge jump is synchronous with the Mascarene Basin jump of the Carlsberg Ridge. In the West Arabian Basin, regular sea-floor spreading anomalies have been identified; the oldest anomaly was chron 28R. Pandey et al. (2006) speculate that the sudden westerly jump of the Laxmi Ridge at KT boundary time may be linked to the Shiva impact, which readjusted the plate tectonic framework of the Arabian seafloor coinciding with the northerly jump of the Central Indian Ridge.

Bhattacharya et al. (1994) speculated that sea-floor spreading anomalies exist in the Laxmi Basin. Seismic velocities under Laxmi Ridge and the Laxmi basin are similar (Naini and Talwani, 1982). Miles et al. (1998) believe the 7km/s layer to underplated thinned continental crust beneath the Laxmi basin. Malod et al. (1997) observed the continuation of the Laxmi basin magnetic anomalies to the north, but bending westwards so that the central anomaly lies over Gop rift ties in with two other observations. Miles and Richards (1998) have shown that the Laxmi Ridge also continues northwards and bends to the west. The satellite altimeter-derived gravity data (Sandwell and Smith, 1997) as well as shipboard data, also suggest a similar bend in the Laxmi basin.

Basement of the Laxmi Basin includes numerous highs, which make the basement uneven and shallower compared to the Western Basin. The Laxmi Basin is characterized by a broad gravity high and a narrower prominent gravity low within it, while within the basin the broad anomaly gradually increases towards north. The Panikkar Ridge is associated with the gravity low, which is comparable, at least in sign, to known negative gravity anomaly of the Laxmi Ridge. Intrusive structures mapped in the Laxmi Basin coincide with significant magnetic anomalies, which were earlier interpreted as seafloor-spreading
anomalies. Model studies of Krishna et al. (2006) reveal that the Laxmi Basin consists of ~14 km thick stretched continental crust, in which magmatic bodies have been emplaced, whereas the Panikkar Ridge remains less altered stretched continental crust. The crust of the Laxmi Basin is mostly thinner than crust under the Laxmi Ridge and continental margin. In addition to the rift drift-related stretching of the continental margin, the Laxmi Basin possibly has undergone extra stretching in E-W direction during the pre-Tertiary period. At ~68 Ma Deccan volcanism on Western India may have disrupted the initial conditions that were leading to onset of spreading in the basin. Subsequently the Reunion hot spot had emplaced the volcanic material within the stretched thinned continental crust. They interpret the Laxmi Basin as a failed rift, undergone stretching following intra plate kinematics prior to Deccan volcanism. The Laxmi Basin is one such runs parallel to the western margin of India and occupies an area of about 2.4x10^5 km^2 between the Laxmi Ridge and margin between latitudes 15°N and 20°30N. Although several investigations were carried out in the Laxmi Basin, the nature of the crust under the basin is still uncertain. This is a key issue for paleogeographic reconstructions of the western Indian Ocean. If the crust in the Laxmi Basin is continental, it has to find a place in the reassembled Gondwana; alternately if it is oceanic, it has to be included in the complex spreading history, which separated Africa, Madagascar, Seychelles microcontinent, Laxmi Ridge and India.

On the basis of the magnetic anomaly pattern, Naini and Talwani (1983), Miles and Roest (1993), Miles et al. (1998), Chaubey et al. (1998) and Dyment (1998) have identified seafloor spreading magnetic anomalies and propagating ridges in the Western Basin and inferred that the basin is underlain by oceanic crust. From sonobuoy refraction results, Naini and Talwani (1983) have suggested that the Eastern Basin is underlain by about 14 km thick crust that is thicker than normal oceanic crust but thinner than normal continental crust. They favored continental origin for the Eastern Basin as it was hard to identify seafloor spreading type anomalies in the Eastern Basin. Subsequent investigations of the Laxmi Basin, a sub basin within the Eastern Basin, gave rise to two divergent views about the nature of the crust. One considers presence of stretched/extended continental crust beneath the basin (Kolla and Coumes, 1990; Miles et al., 1998; Todal and Eldholm, 1998; Mishra et al., 2004). The other, on the basis of magnetic anomaly picks, considers presence of pre-Tertiary oceanic crust along with extinct spreading center in Laxmi Basin (Bhattacharya et al., 1994a; Talwani and Reif, 1998) and in Gop Rift (Malod et al., 1997). The extinct spreading center of the Laxmi Basin was earlier identified as a subsurface basement structure between 16°N and 18°30N and named as the “Panikkar Ridge” (Gopala Rao et al.,1992). From crustal models and tectonic implications, Pandey et al. (1995, 1996), Miles et al. (1998), Todal and Eldholm (1998), Singh ([1999, 2002), and Radha Krishna et al. (2002) have suggested the possible magmatic impact of the Reunion hot spot along the western margin of India, but no concrete evidences were offered with observational data for demonstrating the presence of hot-spot-related magmatic intrusions within the preexisting continental crust.
3.7. Panikkar Ridge

The extinct spreading centre of the Laxmi Basin was earlier identified as a subsurface basement structure between 16°N and 18°30'N and named as the "Panikkar Ridge" (Gopala Rao et al., 1992). It is a prominent feature, having width and length of about 30 km and 600 km respectively, lies in the middle of the Laxmi Basin and trends in NW-SE direction. The gravity anomalies of the Panikkar Ridge are similar with those of the Laxmi Ridge in character (negative anomaly), although the former is narrow in width. The Laxmi Ridge trends approximately in NW-E direction and veers nearly E-W direction at about 19°N latitude. The Panikkar Ridge also parallels the Laxmi ridge in NW-SE direction, but terminates at 19°N latitude.
Isolated seamounts (Wadia, Panikkar and Raman) and intervening basement highs in the Laxmi Basin form a continuous structure, named the Panikkar Ridge. The Panikkar Ridge is associated with 10 mGal low gravity anomaly and highs within it at seamount locations. Towards north the gravity anomalies of the ridge become subdued as its structure deepens to sub-crustal depths where it meets the E-W trending significant positive gravity anomalies of the Palitana Ridge. It may be noted that both the gravity and magnetic signatures of the Panikkar and Palitana ridges are markedly different. Considering the positive relief of the Panikkar Ridge the low gravity anomaly is enigmatic and need explanation. Igneous intrusives, dykes, sills and seaward dipping reflectors imaged in seismic reflection data have been considered as sources in magnetic model studies. The model studies show that the Panikkar Ridge consists of about 14 km thick and 60 km wide, low density (0.05 g/cc density contrast) and non-magnetic rocks relative to the crustal rocks of the adjacent basin. The Laxmi Ridge associated with low gravity anomaly is also explained by ~14 km thick and 0.05-0.1 g/cc low-density rocks in contrast to adjoining crust. Sonobuoy refraction investigations (Naini and Talwani, 1983) have revealed more than 16 km thick crust beneath the Laxmi Basin and the Panikkar Ridge. Thus the NW-SE orientation, low gravity anomaly and crustal structure of both the Laxmi and Panikkar ridges are all similar and therefore, may presumably consist of similar rocks.

3.8. Deccan Traps

The Deccan traps are one of the largest continental volcanic provinces of the world. It consists of more than 2 km of flat lying basalt lava flows and covers an area of 500,000 km². Estimates of the original area covered by the Deccan lava flows including the Seychelles-Saya De Malha Bank are as high as 1,500,000 km² (White and McKenzie 1989). The Deccan traps are flood basalts.

Currently three models for the origin of the Deccan basalt volcanism have been proposed: mantle plume theory, plate rift theory, and impact-induced theory. In mantle plume theory, Deccan flood basalts were the first manifestation of the Reunion hotspot that rose from the core-mantle boundary and subsequently produced the hotspot trails underlying the Laccadive, Maldive and Chagos islands; the Mascarene Plateau; and the youngest volcanic islands of Mauritius and Reunion (Morgan 1981). The age of the hotspot tracks decreases gradually from the Deccan traps to the Reunion hotspot, thus appearing to be consistent with the northward motion of the Indian plate over a fixed plume (Duncan and Pyle, 1988).

Geochemical analysis indicates that the likely source for the Deccan volcanism is rift volcanism rather than Reunion hotspot (Mahoney, 1988). Later, Mahoney et al. (2002) recognized several phases of non-MORB phases of Deccan volcanism. Further geochemical and geothermal evidence suggests that Deccan
magmas were generated at relatively shallow (34-45 km) depth and rules out the possibility of its origin by a deep mantle plume (Sen, 1988). To circumvent these criticisms, White and McKenzie (1989) proposed a model that combines both plume and rifting origins. They argued that the Deccan volcanism was associated with the break up of the Seychelles micro continent from India. The enormous Deccan flood basalts of India and the Seychelles-Saya de Malha volcanic province were created when the Seychelles split above the Reunion hotspot. However, there is some conflict of timing between these two events: the onset of Deccan volcanism and rifting of India and Seychelles. What triggered the rifting of the Seychelles from India? Was it the Reunion hotspot or the Shiva impact? The Carlsberg rifting that separated Seychelles from India did not start before chron 28R (63 Ma), whereas Deccan volcanism started somewhat earlier around 30N (66 Ma) (Fig. VI-8). Thus the Deccan volcanism predates the India-Seychelles rifting event, making the causal link unlikely (Chatterjee and Rudra 1996). A third view for the origin of the Deccan Traps is the impact-triggered model. The spatial and temporal coincidence of Deccan volcanism with the Shiva crater led to the suggestion that the Deccan Traps might mark the site of the asteroid impact (Alt et al. 1988; Alvarez and Asaro 1990; Basu et al. 1988; Hartnady 1986). The slow outpouring of Deccan volcanism preceded the KT impact by 400 Kyr or more. Thus, impact cannot be the proximate cause for the initiation of the Deccan volcanism (Bhandari et al. 1995; Chatterjee and Rudra, 1996). However, impact could enhance the volcanic activity by decompression melting beneath the impact site (Jones et al., 2002; Elkins-Tanton and Hager, 2005). At the KT boundary (65 Ma), the trickle of Deccan lava eruption became a torrent as is evident from the thick pile of lavas; seismic shock waves from the Shiva impact might have galvanized the proximate Deccan-Reunion hotspot and induced spectacular burgeoning of the Tertiary Deccan volcanism by rifting India and Seychelles. An impact of this magnitude could raise the crust-mantle boundary close to the surface by decompression, as seen in the western coast of India, and create a large volume magma chamber. The Shiva impact might be indirectly responsible for rapid and spectacular areal distribution of the Deccan lava piles during its waxing stage. Sen (1988) noticed that continental lithosphere was involved in the melting and contamination process during the generation of the Deccan lava. Perhaps impact rather than the plume was the cause of the lithosphere melting during the KT boundary eruption. Although the close temporal coincidence between the Shiva crater and the Reunion hotspot that created the Deccan volcanism is statistically an unusual event, it is not entirely impossible; the modern analogy would be a large bolide striking close to the Yellowstone hotspot, Kilauea, Reunion, Kerguelen Islands, or near any of the numerous active hotspots. The pre-KT Chicxulub impact nearly coincides with first phase of the Deccan volcanism (Keller et al., 2003). Is there any causal link between these two events, which are located almost in antipodal positions? Impact-induced antipodal volcanisms are suggested from Mars.

Naini (1980) also reported the crustal thickness below this ridge to be about twice that of normal oceanic crust (10-11 km). Under plating of magma usually occurs
by partial melting and metamorphism associated with a rising isotherm, wherein dense magmas float off the crust and underplate at the Moho depth (Fyfe, 1990). It may be mentioned here that such a low-density underplated material is not only confined to this region but occurs over a rich larger area. It seems to be present: (1) just below the Moho (between 11 and 20 km) in the entire eastern basin (Negi et al., 1994), (2) beneath extremely thinned crust of the Cambay graben (Singh et al., 1991; Kaila et al., 1990), and (3) within the subcrustal lithosphere (45 and 60 km) in the continental parts of western India (Negi et al., 1994). The possible presence of such a layer in the continental region is well substantiated by travel-time modeling of the subcrustal lithosphere beneath the Koyna region of the Deccan Traps (western India), which reveals an almost 10% drop in P wave velocity, from 8.3 to 7.4 km s\(^{-1}\) between 45 and 60 km. This corresponds to a zone of low strength, low viscosity (Krishna et al., 1991), and reduced density of about 0.3 \(\text{g cm}^{-3}\). Assuming a 40-km constant crustal thickness for India, results from the inversion of the gravity data of India have also indicated the presence of low-density contrast anomalies below more than two thirds of the Indian subcontinent (Negi et al., 1989).

In these crust-mantle transition zones, lower crust is altered by injection of high-density basic magmatic material from the upper mantle as a consequence of lithospheric stretching. This would give rise to positive gravity anomalies (Verma et al., 1968). In contrast, the negative character of the gravity anomaly over the Laxmi Ridge and the occurrence of a 7.2 km s\(^{-1}\) velocity layer below are unusual for a typical ocean basin crust (Naini, 1980). Although some active volcanic regions such as Iceland, Hawaii, and the mid-Atlantic Ridge, in the oceanic environment are reported to be underlain by such anomalous velocities (Ftovenz and Gunnarsson, 1991), they are associated with hotter than normal upper mantle. These regions are characterized by high heat flow beneath which the thermal boundary layer reaches almost to the surface (Sclater et al., 1981). The Laxmi Ridge, on the other hand, is neither seismically nor volcanically active (McKenzie and Sclater 1971; Sclater et al. 1981). It did not act as a spreading center and has no definite magnetic lineation (Naini, 1980). In the absence of active rifting, the negative gravity anomaly may have been possible with the emplacement of some low-density material below the crust, which could be either in the form of serpentinized olivine basalt/peridotite or low-density fractionated magma related in some way to the Deccan volcanic episode. This massive flood basaltic episode occurred at the K-T mass extinction boundary (~65 Ma) and covered a large part of western and central India. Some flows close to Bombay indeed exhibit partial or complete olivine alteration (Deshmukh, 1984; Subba Raju et al., 1992). Deccan magmas are indeed highly differentiated and have low Mg ratios (Pandey and Negi, 1987a; Sen, 1988). Estimated depth to the thermal lithosphere beneath the Laxmi Ridge (~35 km) suggests a considerable degeneration of its base (about 40 km), as proposed under the entire Indian continental region after its breakup from the Gondwanaland (Negi et al., 1986b; Pandey and Negi, 1987b). The thinning of the lithosphere beneath the ridge may have been caused as a result of super mobility of the Indian plate between 80
and 53 Ma when its velocity is known to have jumped from 3.5 cm yr\(^{-1}\) to more than 20 cm yr\(^{-1}\) (Negi et al., 1986b; McA Powell, 1979). Rapid movement of the plate would cause frictional heat at the base of the lithosphere. This heat coupled with the already hot upper mantle conditions below the Indian plate would generate substantial melt at that depth, causing a rise of the isotherm, which would result into sub-crustal melting within the lithosphere. This process might have been accelerated prior to Deccan Trap eruption and allowed partial melting of lithospheric mantle at the lower depth range of tholeiitic magma generation. The buildup of heat at the lower lithospheric level would give rise to a hot-cell like condition, which, due to insulating effect of the upper continental lithosphere, would induce the formation of a large scale convection cell (Anderson, 1982; Gurnis, 1988; Smith, 1993), a condition which is conducive for the initiation of rifting. The rapid eruption and lateral migration through the hot cell magma reservoir may have been facilitated by a large bolide impact (> 10 km) at the K-T boundary near Bombay (Negi et al., 1992, 1993). The impact may have brought Deccan flood basaltic magma to the surface and initiated the formation of the Carlsberg ridge in the Indian Ocean, which led to the break up of the Seychelles block from India's west coast. On the continental side, the impact may have rejuvenated the existing zone of weaknesses such as Koyna and Kurduvadi rifts postulated by Brahmam and Negi (1973). It also reactivated a preexisting zone of weakness within a supposedly rigid block, which, due to the horizontal compressive regime from either side (riifting associated with Deccan volcanism on the east and rapid spreading across the Carlsberg ridge in the west), facilitated buckling up of the lithosphere, leading to the formation of the Laxmi Ridge. Sea floor magnetic lineations (Naini, 1980) suggest it to be slightly younger than the Deccan volcanic event. A shallow asthenosphere and high heat flow around this ridge is expected similar to that observed over the western margin of India (Negi et al., 1992).

### 3.9. Indus Fan

With a length of 1600 km and a maximum width of 1000 km, covering an area of approximately 1.1–1.25 million km\(^2\) (McHargue and Webb, 1986; Kolla and Coumes, 1987), the Indus Fan is the second largest deep-sea fan in the world. The Indus Fan developed off the passive continental margin of Pakistan–India and is bounded by the Chagos–Laccadive Ridge in the east, by the Owen–Murray Ridges in the west, and by the Carlsberg Ridge in the south (Prince et al., 2000). Another topographic feature is the Lakshmi Ridge that divides the Arabian Basin into two sub-basins, referred to as the Western and Eastern Basin by Naini and Kolla (1982). The initiation of Indus Fan sedimentation in the middle Oligocene to late Miocene was related to the uplift of the Himalayan mountain range possibly combined with sea-level lowering (Kolla and Coumes, 1987). In the shelf and slope area near the Indus Delta, three canyon complexes merge landward into one extensive erosional zone referred to as the Indus Trough (McHargue and Webb, 1986; Kolla and Coumes, 1987). Several large channel–levee systems radiated from each canyon complex. The youngest complex is
connected to the recently active Indus Canyon (Kenyon et al., 1995; vonRad and Tahir, 1997).

4. **Tectonic elements in the Eastern continental margin of India and the adjoining Ocean basins**

The Eastern Continental Margin of India which lies in the Bay of Bengal is a passive margin which has evolved as a consequence of the breakup between the east coast of India and East Antarctica, and subsequent subsidence and sediment deposition in the marginal basins (Curray et al., 1982; Powell et al., 1988). The inland rivers form three major sedimentary basins in the continental margin, which, from South to North are the Cauvery Basin (CB), Krishna-Godavari Basin (KGB) and Mahanadi Basin (MB).

The Cauvery Basin (Figure 8) is located in the southeastern part of Peninsular India. The basin extends towards the east in the offshore area. The areal extension of this basin is approximately 25000 km² on land and 17500 km² offshore. It is a block-faulted pericratonic basin comprising horst-graben basin architecture. It includes several depressions separated from one another by subsurface (basement) ridges having a NE-SW alignment (Sastri et al. 1981). The Krishna-Godavari Basin occupies an area of 20000 km² on land and 13500 km² on the continental shelf. The Mahanadi Basin covers an area of approximately 18000 km² on land. The basin extends offshore over an area of 12500 km².

The Bay of Bengal overlies the entire eastern continental margin. Triangular in shape, it is bordered by Sri Lanka and India to the west, Bangladesh and the Indian state of West Bengal to the north, Myanmar and Thailand in the east. Its southern boundary has been defined by the IHO as the “imaginary line from Dondra Head (80° 35’ E, 5°55’) at the southern end of Sri Lanka to the northern tip of Sumatra”. An oceanic trench (Sunda trench) borders the eastern limit of the Bay of Bengal where the Indian Ocean plate subducts below the Burmese/Southeast Asian plate forming the island arc-trench system (Figure 9).

The Bay of Bengal occupies an area of about 2.2 million km² and the average depth is 2,200 m with a maximum depth of around 4500 m in the Andaman-Sumatra trench area. A large number of major rivers of the Indian sub-continent (the Ganges, Brahmaputra, Mahanadi, Godavari, Krishna, Cauvery, Meghna and Irrawady) flow into the Bay. The sediment supply from these rivers mainly controls the general morphology of the Bay of Bengal.
Figure 9: Physiographic map of the northern Indian Ocean showing the continuous eastern and western offshore margins of India.

The bathymetry of the Bay of Bengal shows an overall southward slope. Towards the northern margin of the Bay of Bengal, the bathymetry is shallow, and depth to the seabed is less than 2000 m. The bathymetry over central Bay of Bengal is relatively flat. Here average depth is around 3000 m. The seafloor gradient decreases gradually from north to south. Another important feature in the northern Bay of Bengal is the ‘Swatch of No Ground’ which is a shelf canyon that deeply incises the Bengal shelf near the Ganges–Brahmaputra river mouth (Michels et al., 1998; Sarma et al., 2000; Curray, 2003; Kamesh Raju et al., 2004). The head of the canyon lies at about 38 m water depth on the continental shelf of Bangladesh and continues seaward as a nearly linear trough for 160 km, with an average slope-gradient of 8.2 m/km (Curray et al., 2003). The width of the canyon valley is about 14 km (Sarma et al., 2000).

The complex evolutionary history and seismo-tectonic processes of the eastern margin have produced several sedimentary basins interspersed with terraces, aseismic ridges, an active arc-trench subduction system and the world’s largest submarine fan with the thickest accumulation of sediment (Sastri et al., 1981; Curray et al. 1982; Michels et al., 1998; Sarma et al., 2000; Curray et al., 2003).
Some of the prominent surface/subsurface features of relevance for the present submission are the sedimentary basins of the eastern continental margin, the 85°E Ridge, the Ninetyeast Ridge, the Bengal Fan and the Andaman arc-trench system with its accretionary prism (Figure 9).

![Figure 9: Major morphological features in the Bay of Bengal](image)

**Figure 9**: Major morphological features in the Bay of Bengal

### 4.1 Bengal Fan
The Bengal Fan which is the largest submarine fan in the world covers an area of approximately 2.8-3.0x10^6 km^2. It is currently supplied mainly by the confluent Ganges and Brahmaputra Rivers, with smaller contributions of sediment from several other large rivers in Bangladesh and India. (Curry and Moore, 1971; Curry, 2003). Figure 2.9 shows the aerial extension and the main subdivisions of the Bengal Fan.

The western margin of the Bengal Fan is the continental slope of the mainland India. The northern proximal or upper fan lies off the Bangladesh continental slope and the eastern margin is the Andaman trench and the accretionary prism of the subduction zone, extending from Myanmar, through the Andaman – Nicobar Ridge, into the Mentawai Islands off Sumatra. Much Bengal Fan sediment has been subducted and/or uplifted into this accretionary prism. The length of the Bengal Fan is between 2800 and 3000 km, extending from 20° 10’ N to 7° S latitude. Its greatest width is 1430 km at 15° N, and its narrowest part is at 6° N, 830 km between Sri Lanka and the Ninetyeast Ridge (Curry, 2003; Emmel and Curry, 1984).

Although relatively smooth when viewed as a whole, the Bengal Fan is marked by a series of channels or fan valleys that are open for various distances along the length of the fan. The most important one is the main central channel (AV) because it appears to be the only valley directly connected to the Swatch of no Ground submarine canyon at the present time (Figure 2.9). Based on the gradients of the central ‘active’ valley and of the fan surface, Fan system is divided into an **Upper fan**, with average valley gradients of about 2.39 m/km, and a fan gradient of about 5.7 m/km, **Middle fan**, where both the fan and fan valley gradients average about 1.68 m/km, and the valleys are smaller in cross-sectional area and a **Lower fan**, where the gradients drop to less than about 1 m/km, except locally where the gradient may increase because of valley fill (Curry, 2003).

### 9.2 Ninetyeast Ridge (NER)

This is a major aseismic ridge, separates the Central Indian Ocean Basin from the Wharton Basin to the east. It extends almost N-S as a topographic high and can be traced for more than 4500 km from 30°S to 10°N (Sclater and Fisher, 1974). Further north, continuity of the Ninetyeast Ridge upto 17°N latitude can be inferred mainly from single and multichannel seismic data as the ridge is buried under the thick pile of Bengal Fan sediments (Curry et al., 1982; Gopala Rao et al., 1997). Up to 7°S it is flat topped where as north of 7°S it appears segmented as a series of en-echelon northeast-southwest trending highs, which is evident from Figure 2.12. Two distinct blocks can be visualized,
Figure 10. Aerial extension and subdivisions of the Bengal Fan (modified after Curray et al., 2003; Emmel and Curray, 1984).

Geophysical data indicate that the Ninetyeast Ridge partially subducts below the Andaman trench (Curray et al. 1982; Mukhopadhyay, 1988; Mukhopadhyay and Krishna, 1995; Gopala Rao et al., 1997). Further, Dasgupta and Mukhopadhyay (1993) observed a contorted Benioff zone east of the Nicobar Islands and inferred as due to the effect of ridge subduction. Such characteristic changes in the seismicity pattern have been interpreted as due to subduction of aseismic
ridges (Vogt, 1973; Kelleher and McCann, 1976; Chung and Kanamori, 1978). Using marine magnetic data, Ghatak and Banerjee (2001) have also concluded that the northern part of the ridge is in the subduction zone. Tiwari et al (2003) investigated the mode of compensation, emplacement history and deep density structure of the Ninetyeast Ridge using spectral analyses and forward modeling of satellite gravity and bathymetry data and concluded that the northern (0 – 10°N) and the southern (20–30°S) parts of the ridge are flexurally compensated with an effective elastic thickness >15 km, whereas the central part (0–20°S) is locally compensated. These results suggest that the northern and southern parts of Ninetyeast Ridge were emplaced off to a ridge axis compared to the central one, which might have been emplaced on or near a spreading center. Locally compensated large topography, thick underplated crust in the central part might result from an interaction of a hot spot with the extinct Wharton spreading ridge.

Palaeontological, palaeomagnetic and radiometric studies of rock samples from DSDP legs 22 and 26 and ODP leg 121 indicate that the basement ages become older in a northward direction from approximately 38 My at DSDP site 254 near the northern terminus to 80-82 My at the most northerly ODP site 758 near 5°N (Peirce 1978, Royer et al. 1991, Duncan 1990). The general northerly increase in age relates Ninetyeast ridge and the 117My old Rajmahal traps to a long lived hotspot that progressively built both features on the Indian plate as the plate drifted northwards (Morgan 1981, Duncan 1991, Royer et al. 1991). Basement paleo-latitudes from most DSDP and ODP sites indicate that the hotspot plume remained at a constant latitude near 50°S, the present location of the Kerguelen hot spot (Peirs 1978, Royer et al. 1991). Whitford and Duncan (1978) have analysed trace elements and strontium isotopes to show that the Ninetyeast Ridge basalts and the Rajmahal traps have an origin similar to that of the Kerguelen hotspot and differing significantly from the Indian Ocean spreading center basalts.

4.3 The Andaman-Nicobar island arc-trench system

This arc-trench system which defines a nearly 1100 km long active convergent plate margin where the Indian plate is subducting below the Eurasian/Southeast Asian plate, is one of the prominent morphological feature in the Bay of Bengal (Figure 10). It extends from the eastern Himalayan syntaxis in the north through the western Burma, the western Andaman sea, Sumatra and Java and continues into the Banda arc of eastern Indonesia in a curvilinear manner (Curray, 1989). Behind the forearc, the bathymetry increases significantly related to the development of the forearc basin (Subrahmanyam, 2008).

To the east of the Ninetyeast Ridge, the Andaman trench looks prominent till about 10° N, but further north, similar to the Ninetyeast Ridge, the trench signature diminishes gradually as the Bengal fan sediments fill the trench (Figure 10). But the Andaman arc looks prominent in a curvilinear manner extending
towards north where it merges with the topographic signature of the Burmese Arc. Along the arc, there are pockets of isolated deeps and the island arc displays a prominent concavity between 6° - 8° N. Behind the fore arc, the bathymetry increases significantly related to the development of the fore arc basin (Subrahmanyam et al., 2008).

The Andaman Islands are sub-aerial expressions of the Andaman – Nicobar ridge separating the basin from the Bay of Bengal. The Andaman – Nicobar ridge is believed to have formed in Oligocene – Miocene times due to east – west compression of sediments derived from the Malayan shelf (Rodolfo, 1969; Curray, 2005). The western base of the Andaman – Nicobar ridge lies in the trench that is filled with the sediments of the Bay of Bengal (Curray et al., 1979). The structure along the arc in the Andaman – Nicobar ridge region is dominated by east dipping nappes having gentle folding, while tighter folding and intense deformation is observed off Sumatra (Weeks et al., 1967; Moore and Curray, 1980). Several north – south faults and thrusts have been observed in the Andaman – Nicobar ridge and the adjacent offshore areas.

4.4 85°E Ridge

This is a prominent subsurface basement rise-like feature, approximately parallel to the 85°E longitude between 19°N and 6°N latitudes in the Bay of Bengal (Curay and Moore, 1971, 1974; Curray et al., 1982). Towards south, the ridge takes a curvilinear trend around Sri Lanka and culminates in the Afanasy-Nikitin seamount in the central Indian Ocean. The northward extent of this ridge is however, a matter of academic debate. One school of thought believes that it is connected to the Rajmahal traps via the Bengal basin (Curray and Munasinghe, 1991; Ramana et al., 1997; Gopala Rao et al., 1997) while another group has proposed that the Ridge abuts the east coast of India at 20°N in the proximity of the Mahanadi basin (Subrahmanyam et al., 1997).

In general, the width of the 85°E Ridge varies between 100 and 180 km. The ridge is marked by negative gravity anomalies in the north where the ridge is buried under the thick pile of Bengal fan sediments. Towards South, where the sediment thickness gradually decreases and the volcanic ridge is exposed above the seafloor, the gravity anomalies switch-over to positive values (Subrahmanyam et al., 1999). The negative gravity anomalies observed towards the north seem to be very uncharacteristic as is not expected for an oceanic ridge. Liu et al. (1982) have interpreted the negative gravity anomaly of the 85°E Ridge in terms of a two-stage deformation of the Bay of Bengal lithosphere, the first at the time of loading of the ridge over a weak and young Bay of Bengal lithosphere, and the other, caused by the load of sediments over a lithosphere gaining strength with time. Asymmetric nature of the magnetic anomalies observed over the southern part of the ridge is attributed to the phase shift produced by the northward drift of the Indian plate (McKenzie and Sclater, 1971; Ramana et al, 1997).
CHAPTER 4: DEEP SEA DRILLING IN THE NORTHERN INDIAN OCEAN

Despite a recorded history of extensive maritime activity in the region stretching back to the early part of the modern era, a scientific and systematic study of the seas around India began only during the early 1960s, coinciding with the International Indian Ocean Expedition (IIOE), 1961-65. Spurred on by the emergence of the new revolutionary ideas of seafloor spreading and plate tectonics as well as the development of new technologies, scientific studies of the northern Indian Ocean grew at a steady pace during the early and mid-seventies and accelerated during the eighties and early nineties. Six factors significantly contributed to this accelerated pace in the Indian Ocean Studies:

i. the establishment of premier national institutions dedicated solely to oceanographic research in the country (National Institute of Oceanography);

ii. the development of R&D wings dedicated exclusively to marine scientific research in such established geoscientific institutions as the Geological Survey of India, National Geophysical Research Institute, Physical Research Laboratory, and Space Applications Centre;

iii. the foray of India to Antarctica leading to the establishment of the Department of Ocean Development (the forerunner of the present-day Ministry of Earth Sciences, MoES) by the Government of India and in turn, the establishment of the National Centre for Antarctic and Ocean Research by MoES;

iv. the induction of state-of-the-art coastal research and oceanographic vessels;

v. the increased availability of a scientific talent pool in the country; and

vi. international collaborative ventures at an academic level culminating in the Deep Sea and Ocean Drilling Programs (DSDP and ODP).

DEEPSEA DRILLING IN THE INDIAN OCEAN SECTOR

The deep-sea drilling activities in the seas around the Indian subcontinent have been primarily the scientific drilling campaigns of Deep Sea Drilling Project (DSDP) in 1972 (Leg 22, sites 211 to 218 over and in the vicinity of the Ninety East Ridge in the Bay of Bengal; Leg 23, sites 219-224 in the Arabian Sea) and its successor, the Ocean Drilling Program (ODP) in 1987-88 (Leg 116, sites 717-719 in the distal part of the Bengal Fan and Leg 121, site 758 over the Ninety East Ridge).

During 2006, the first Indian National Gas Hydrate Program drilling was taken up on board JOIDES RESOLUTION by the Directorate General of Hydrocarbons (DGH) and the United States Geological Survey (USGS). The drilling was
designed to investigate the gas hydrate potential of sites in the Arabian Sea, the Bay of Bengal and the Andaman Sea (Annexure II). The team drilled 39 locations at 21 sites.

The results of the drilled sediments and rock samples have provided most valuable ground truth data for validating the inferences of geophysical investigations, as explained in Chapter 3. However, compared to the exhaustive deep-sea drilling carried out through the world oceans, the northern Indian Ocean sector is marked by very few DSDP/ODP locations (Figure 1). The lack of critical deep ocean sampling has been a major constraint in scientific endeavors towards unraveling the history of the geological and climatic evolution of ocean basins in this part. Availability of sub-seabed cores buried underneath water column of up to 4km deep would certainly enhance our understanding of key geological processes. Moreover, scientific objectives since the early days of ODP/DSDP have increased manifold which require a much more elaborate efforts to drill in this sector than ever before.

Currently there are some IODP proposals to sample the sediments of the Arabian Sea and Bay of Bengal (Figure 2). However, as can be seen, compared to the total number of active proposals world-wide, the proposals concentrated in the Indian Ocean sector are scanty. A theme-wise break-up of the various proposals is shown in Figure 3. The goals of these projects are by and large confined to (1) understanding the millennial scale variations of the monsoon during Pleistocene-Recent times, (2) reconstructing the erosion response of the Himalaya to proposed monsoon strengthening at 8 Ma, and (3) dating the timing of Indus and Bengal Fan initiation and subsequent erosion (Figure 3). Considering the huge thickness of sediment cover in the Bay of Bengal and Arabian Sea, it is not surprising that basement sampling has not been one of the thrust areas. However, as highlighted in an earlier chapter, knowledge of the nature of the basement in these two areas is critical to an understanding of the growth and evolutionary history of the Indian plate. In the following pages, we seek to address this issue.
Figure 2. Proposed drill sites by IODP

Figure 3. Total active proposals as of April 2009 = 113
CHAPTER 5: SCIENCE PLAN

The scientific plan for Indian initiatives in the Integrated Ocean Drilling Program (IODP) has been organized under three major themes:

1. The solid earth and geodynamics
2. Studies of the Andaman-Nicobar subduction zone
3. Large Igneous Provinces
4. Tectonics and climate
5. The deep biosphere

These broad themes have been so chosen as to address some of the key issues of relevance to understanding (i) the evolutionary history of the Northern Indian Ocean, (ii) the monsoonal variations on the Indian subcontinent during Pleistocene-Recent times, and (iii) reconstructing the growth of the Indus and Bengal Fans vis-à-vis the erosional history of the Himalayas. These specific themes may be prioritized depending upon the key scientific questions to be answered and its societal relevance such as climate change, earthquake hazards, biotechnology and natural resource potential etc. These research goals can be modified with the emerging scientific requirements over the years to come.

SOLID EARTH AND GEODYNAMICS

Indian Ocean has often been considered as the most complex of the world’s major oceans. Perhaps, it has also been the least explored in terms of solid earth studies. Considering (i) the immense volume of geophysical data gathered by MoES and other organisations from the continental margin over the years, (ii) the need to understand the geological and tectonic evolution of the Indian plate as well as the role of the various morphological features of the margin (described in an earlier chapter) in the evolutionary history, and (iii) the role of lithospheric processes in modulating global climate over the long term as well as in controlling such catastrophic events as earthquakes, landslides, tsunamis and volcanic eruptions, it is proposed to have two deep-drilling transects, one each in the Arabian Sea and Bay of Bengal. Because of the need to sample up to the basement, the choice of the locations of the drill sites would be dictated by the depth to the basement.

The topics to be addressed by these drill holes would comprise, among other things: (1) lithosphere deformation and structural discontinuities, (2) identification of the continent-ocean transition zone, (3) crustal thinning at the transition, (4) the rifting history and evolution of the Indian margin, (5) offshore extension of the
Deccan volcanics, (6) the nature of the offshore basins of India and their evolution, (7) Characterization of crust at selected locations (eg. Laxmi Basin, west of C-L-R), (8) the nature and origin of C-L-R, the Gulf of Mannar and the 85E Ridge and their relationship to the rifting and drifting history of the Indian plate, and (9) laboratory studies of physical properties of crustal and mantle rocks, where possible.

**STUDIES OF THE ANDAMAN-NICOBAR SUBDUCTION ZONE**

Subduction zones are the flip side of mid-ocean ridges in plate tectonics. Oceanic lithosphere is subducted at convergent plate boundaries leading to its eventual recycling into the deeper mantle and formation of volcanic arcs. Nine out of the ten largest earthquakes occurred in the last 100 years were subduction zone events. Because earthquakes can only occur when a rock is deforming in a brittle fashion, subduction zones can create large earthquakes. If such an earthquake causes rapid deformation of the sea floor, there is potential for tsunamis, such as the earthquake caused by subduction of the Indo-Australian Plate under the Eurasian Plate on December 26, 2004, that devastated the areas around the Indian Ocean.

![Subduction factory](image)

*Figure 3: A schematic diagram (left) of a typical subduction zone. The overall subduction factory is shown on the right.*

There is a lot to be done in terms of understanding about the internal mechanism within a subduction zone it is unknown whether initiation of a new subduction zone is driven by plate motion or by some other processes (e.g. self-nucleation). The mechanisms and fluxes of major element recycling at subduction zones are still quite uncertain. The depth dependant physical and chemical changes that occur within such seismogenic zones including the release of fluids and volatiles...
require much further attention. The linked growth of continental and arc crusts at convergent margins is an important process yet to be understood in detail.

The Indo-Burmese range and the Andaman arc system in the northeast Indian Ocean define a zone of underthrusting of the Indian plate below the Southeast Asian plate, leading to the formation of a major subduction zone. To learn more about how and why earthquakes and tsunamis occur, the Integrated Ocean Drilling Program (IODP) explores the geology below the seafloor to study Earth processes that evolve over time, ultimately causing violent, unpredictable natural disasters. The first phase of IODP (2003-13) has focused on detailed study of one of the most earthquake prone subduction zones off Japan (The Nankai Trough).

As one of its inaugural activities, IODP had initiated drilling through a seismogenic fault zone (Nankai Trough, off Japan) to characterize the composition, deformation microstructures and physical properties of the rocks at in situ conditions. The Seismogenic Zone initiative of IODP during phase 1 was a comprehensive, multidisciplinary project focused on the behavior of rocks, sediments and fluids in the fault zone region to understand better the nature of this zone and the mechanics of the earthquake cycle. This initiative is to be integrated with studies of earthquake mechanics, past records exhumed from seismogenic zones, laboratory experiments and modeling efforts. In trying to understand how, when and where devastating earthquakes occur, we lack fundamental knowledge of the physical and chemical conditions within the seismogenic zone that change over time and lead up to sudden rupture.

Against the above backdrop, we would like to propose one or two sites for deep drilling in the Andaman subduction zone and in the forearc region.
**LARGE IGNEOUS PROVINCES (ONSHORE/OFFSHORE EXTENSION)**

Large igneous provinces (LIPs) are extremely large accumulations of igneous rocks, either or both intrusive and extrusive, found in the earth's crust. Earth history is punctuated by events during which large volumes of mafic magmas were generated and emplaced by processes unrelated to "normal" sea-floor spreading and subduction. LIPs are best preserved in the Mesozoic and Cenozoic where they occur as continental flood basalts, volcanic rifted margins, oceanic plateaus, ocean basin flood basalts, submarine ridges, and seamount chains. Many LIPs can be linked to regional-scale uplift, continental rifting and breakup, and climatic shifts.

The Deccan Traps are a large igneous province located on the Deccan Plateau of west-central India and one of the largest volcanic features on Earth. They consist of multiple layers of solidified flood basalt that together are more than 2 km thick and cover an area of 0.5 million km². The actual extent of these volcansics however can only be estimated once its offshore extent is also known. Scientists have been working together to determine the offshore extension of the Deccan traps and it is speculated that once confirmed the total amount of volcanic emplacement might even double the present figures. Drilling into the ocean floor offshore Indian margin shall through light on the offshore extent of the Mesozoic lava flows which erupted during the northward movement of India coinciding with the location of the Reunion hotspot.

**TECTONICS AND CLIMATE**

Constraining the processes that control the Earth’s climate system is a primary objective for ocean and earth scientists. While variations in the climate linked to orbital processes have received significant attention, links between climate and solid earth dynamics remain less well studied, in part because we lack the very long duration records required to reconstruct climate, erosion and weathering processes on tectonic timescales. As a result, the effects of mountain building on climate and vice versa are poorly understood. Growth of the Tibetan Plateau, mostly since ~50 Ma, is hypothesized to have intensified the Asian monsoon system. This in turn has a powerful effect in controlling weathering and erosion and thus the exhumation of deep-buried rocks in the Himalaya and other Cenozoic mountains across Asia. Erosion of these mountains has constructed the largest sediment bodies on Earth and buried large volumes of organic carbon, which may, along with the weathering of silicate minerals under the influence of monsoon rains, be a powerful control on atmospheric CO₂, itself a major control on climate. The potential for large feedbacks between tectonic, climatic and weathering and depositional processes is enormous, with possible influence over global climate. However, the timing of initial intensification and subsequent development of the monsoon, as well as the timing and patterns Tibetan-Himalayan surface uplift are still poorly understood and controversial,
and will likely remain so without long-term weathering, erosion and depositional histories.

The Integrated Ocean Drilling Programme (IODP) provides the opportunity to explore these sediment records and reconstruct the history of climatic variations and rate of erosion. Current sedimentation records preserved in the onshore drainage basins (Brahmaputra basin, for example) offer records of more recent sedimentation. The sedimentation records from the Indus and Bengal Fans, both of which can be obtained from IODP cores, should present erosional histories of different parts of the Himalaya. Thus, the Indus Fan should serve as an important repository of the information on the uplift history of western Himalaya. The Bengal Fan’s main feeder rivers, Ganges and Brahmaputra follow the high Himalaya along strike for long distances, and the sediments are mostly derived from the High Himalaya. A comparative study of the isotopic signals, sedimentation rates and sediment characteristics will help develop links between climate, tectonism and erosional history.

THE DEEP BIOSPHERE

EVOLUTION OF HYDROTHERMAL CIRCULATION

Hydrothermal circulation is an intrinsic characteristic of seafloor influencing the accretion and aging of oceanic crust, and impacting tectonic, magmatic, microbial and biogeochemical properties and processes on a global scale. Understanding hydrothermal circulation is fundamental to achieving high priority goals listed under primary themes in the Initial Science Plan (ISP) to IODP. Understanding hydrothermal circulation has societal relevance through its role in fundamental Earth processes and because of the potential for geological sequestration of greenhouse gases within the oceanic crust.

Hydrothermal chemical exchange between the crust and oceans is a basic component of global geochemical cycles, affecting the composition of the crust, oceans and, through subduction, the mantle. Seawater chemistry reflects the balance between hydrothermal and sedimentary fluxes to and from the oceans. Since the magnitudes of these fluxes depend on key global geologic processes including plate tectonics, climatic conditions, and biological processes, temporal variations in seawater chemistry can provide insights into fundamental Earth processes. However, reconstructing reliable records of past seawater chemistry and deconvolving the processes responsible for temporal variations in such records remain major challenges.

Many aspects of hydrothermal circulation and its impacts on crustal evolution remain poorly understood. For example:
• How long does geothermally and geochemically significant flow continue through the oceanic crust and what controls the waning of this flow?

• What is the nature of the transition between ridge-axis and ridge-flank hydrothermal circulation?

• Are these two systems isolated, or are mass, heat, solutes, and microbiological material exchanged between ridges and flanks?

• What are the characteristic geometries of ridge flank hydrothermal circulation, including typical lengths, depths, and orientations of flow?

• What controls the nature, extent and intensity of hydrothermal alteration and its temporal evolution as the crust matures?

• How do microbial communities in the crust evolve – functionally and genetically – as a function hydrothermal circulation?

• What are the geochemical flank fluxes into and out of the crust and what is their impact on global geochemical budgets?

• To what extent can changes in ocean chemistry and consequently the wider Earth system processes be resolved from the record of crustal alteration?

Answering these questions requires drilling into basement to provide access to rock samples and opportunities for high-resolution downhole observations and experiments, coupled with detailed transects of closely spaced heat flow measurements, pore-water geochemical analyses and environmental information from seismic and swath mapping.
CHAPTER 6: IMPLEMENTATION PLAN

A three tier management level can be developed for the functioning of the IODP related activities:

- **Science steering and evaluation committee**
- **Program Planning Group**
- **Drilling proposal**

Overall management of program
Proposal development & ranking
Program specific roles
### CHIKYU DATA

What ship is D/V CHIKYU? We will fully introduce the data of D/V CHIKYU from the ship size to number of crews.

<table>
<thead>
<tr>
<th>Event</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Keel-laying ceremony</td>
<td>April 25th, 2001</td>
</tr>
<tr>
<td>Naming</td>
<td>January 18th, 2002</td>
</tr>
<tr>
<td>Launching ceremony</td>
<td>January 18th, 2002</td>
</tr>
<tr>
<td>Delivery</td>
<td>July 29th, 2005</td>
</tr>
</tbody>
</table>

#### General

<table>
<thead>
<tr>
<th>Clarification (or Class)</th>
<th>NK (Nippon Kaiji Kyokai)</th>
<th>Onboard Scientific Facilities/Equipments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Navigation area</td>
<td>Ocean going area (Worldwide)</td>
<td>• 3D X-ray CT Scanner</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Multi sensor core logger (MSCL)</td>
</tr>
<tr>
<td>Length</td>
<td>210 m</td>
<td>• MSCL-W (whole), -S (split), -Image, -Color</td>
</tr>
<tr>
<td>Breadth</td>
<td>38.0 m</td>
<td>• X-ray Fluorescence Core Logger (XRFCL)</td>
</tr>
<tr>
<td>Height (from ship bottom)</td>
<td>130 m</td>
<td>• Penta-pychnometer</td>
</tr>
<tr>
<td>Depth</td>
<td>16.2 m</td>
<td>• Electric Balance</td>
</tr>
<tr>
<td>Draft</td>
<td>9.2 m</td>
<td>• Thermal Conductivity</td>
</tr>
<tr>
<td>Gross Tonnage</td>
<td>57,087 tons</td>
<td>• Thermal Conductivity (Whole core and pieces)</td>
</tr>
<tr>
<td>Range</td>
<td>Approx. 14,800 nautical miles (Full load condition, 10knots)</td>
<td>• X-ray Diffraction</td>
</tr>
<tr>
<td>Complement</td>
<td>150 people (Crew: 100, Scientist: 50)</td>
<td>• Gamma-ray Attenuation Density</td>
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<tr>
<td>Propulsion system</td>
<td></td>
<td>• Natural Gamma Radiation</td>
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<tr>
<td></td>
<td></td>
<td>• Cryogenic Magnetometer System</td>
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<tr>
<td></td>
<td></td>
<td>• Spinner Magnetometer</td>
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<tr>
<td></td>
<td></td>
<td>• Gas Chromatograph (ECD)</td>
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<tr>
<td></td>
<td></td>
<td>• Refractometer (Salinity)</td>
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<tr>
<td></td>
<td></td>
<td>• Titrator (pH, alkalinity, Chloride)</td>
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<tr>
<td></td>
<td></td>
<td>• Ion Chromatography</td>
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<tr>
<td></td>
<td></td>
<td>• ICP-AES (major cation, silicate, major elements)</td>
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<td></td>
<td></td>
<td>• ICP-MS (trace cation, silicate, trace elements)</td>
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<tr>
<td></td>
<td></td>
<td>• Spectrophotometer (UV-VIS) (ammonium, silicate)</td>
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<td></td>
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<td>• CNHS/O Analyzer</td>
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<td></td>
<td></td>
<td>• Carbonate Analyzer (coulometer)</td>
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<td></td>
<td></td>
<td>• Gas Chromatograph (GC)</td>
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<td></td>
<td></td>
<td>• Gas Chromatograph (FID)</td>
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<tr>
<td></td>
<td></td>
<td>• Gas Chromatograph (NGA)</td>
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<td></td>
<td></td>
<td>• Rock Eval</td>
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<td></td>
<td></td>
<td>• Magnetic Susceptibility (MS2B)</td>
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<td></td>
<td>• Liquid Chromatograph (HPLC)</td>
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<td></td>
<td></td>
<td>• Kappabridge</td>
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<tr>
<td></td>
<td></td>
<td>• Scanning Electron Microscope/ Energy Dispersive Spectroscopy</td>
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<tr>
<td></td>
<td></td>
<td>• Impedance Analyzer</td>
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<tr>
<td></td>
<td></td>
<td>• Multi-Wavelength Particle Analyzer with Micro Volume Module (MVM) System</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• X-ray Fluorescence Spectroscopy (XRF)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Laser Ablation ICP-MS</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Digital Microscope</td>
</tr>
</tbody>
</table>

| Length                   | 210 m                   |
| Breadth                  | 38.0 m                  |
| Height (from ship bottom)| 130 m                  |
| Depth                    | 16.2 m                  |
| Draft                    | 9.2 m                   |
| Gross Tonnage            | 57,087 tons             |
| Range                    | Approx. 14,800 nautical miles (Full load condition, 10knots) |
| Complement               | 150 people (Crew: 100, Scientist: 50) |
| Propulsion system        | Side thruster 2,550 kW (3,470PS) × 1 (the bow) |
|                         | Azimuth thruster 4,100kW(5,710PS) × 3 (the bow), 3 (the stern) |
|                         | Diameter of propeller: 3.8m |
| DPS                      | NK DPS-B                |
|                         | Wind speed: 23 meters pre second surface current : 3-4 knots |
|                         | Wave height: 4.5 meters |
| Max cruising speed       | 12 knots                |
**JOIDES Resolution Scientific Ocean Drilling Vessel**

- **Official Number**: 6151
- **Port of Registry**: Monrovia, Liberia
- **Year Built**: 1978
- **ABS Class**: 41 T Drilling Unit AMS ACCU
- **Ice Class**: 1B
- **Converted at**: Halifax, Nova Scotia, Canada
- **Last Upgrade**: 2008; turning Shipyard Singapore
- **Operated by**: Transocean

**Capabilities**
- **Maximum water depth**: 22,000 ft
- **Minimum water depth**: 300 ft
- **Total hanging drill string length**: 30,000 ft
- **Panama Canal capable (height and width)**
- **Time at sea without repositioning**: 75 days

**Drilling/ Tubular Storage Capacity**
- **Drill pipe**: 46,500 ft (5 in. and 56 in.)
- ** Drill collar**: 2,300 ft (6 in. and 6 9/16 in.)
- **Casing**: 7,500 ft (6 1/2 in., 10 3/4 in., 11 3/4 in., 10% in.)

**Power**
- **Engines/Generators**: 2 x EMD 6-cylinder diesel
  - 5,600 kW (7,500 hp)
  - 2 x 3,500 kW (4,700 hp)

**Propulsion**
- **Main screw**: 2 x 750 hp thrusters (10 retracted, 2 fixed)
- **Main shafts**: 2 x 9,000 shp

**Liquid Capacities**
- **Diel fuel (MGO)**: 950,000 gal (3,500 m)
- **Drill water**: 324,386 gal
- **Ballast water**: 205,208 gal
- **Potable water**: 173 t

**Mud/Cement**
- **Mud pumps**: 2 x Oilwell 1700 FT (triple Liquid mud)
  - **Bulk capacity**: 13,000 cu ft
- **Cement unit**: Halliburton 40 FT

**Heave Compensation System**
- **Western Gear model 800-17-20**
  - **Lift capacity**: 300,000 lb (136,000 kg)
  - **Total stroke**: 20 ft
  - **Max. operating conditions**: 15 ft heave
  - **750 sec**

**Core Retrieving Winch**
- **Model**: Deco 147 ft
- **Height above water line**: 205 ft
- **Ratings**: 1,020,000 lb static, 800,000 lb dynamic

**Derrick**
- **Model**: Oilwell E3000
- **Motors**: 2 x EMD M99 - ALB x 1200 hp on
  - **Liner**: 1 in. thick
- **Brakes**: Dual banker Frisco model 760B

**Drill String Support**
- **Type**: Dual elevator handler (no slips, no protect pipe)
  - **Model**: Vaco DHE8/471
- **Reach**: 60 ft (horizontal), 36 ft (vertical)
- **Inertial trim**: 250 or 100 tons, modified side door

**Drill String Bearing Restraint**
- **Model**: Stoker guide haven (no tier support)

**Iron Roughneck**
- **Model**: Vaco IR 2300
  - **Pipe size**: 4 in. 8% in.
  - **Make up torque**: 60,000 ft-lb
  - **Breakout torque**: 75,000 ft-lb

**Top Drive**
- **Model**: Vaco TDSI
  - **Motor**: EMD M99, electric, 1000 hp
  - **Continuous torque**: 80,000 ft-lb
  - **Intermittent torque**: 40,000 ft-lb
  - **Breakout torque**: 60,000 ft-lb
  - **Maximum speed**: 250 rpm

**Rotary Table**
- **Model**: Oilwell A340-12
  - **Motor**: EMD D 79 MB
  - **Maximum speed**: 425 rpm

**Cranes**
- **Type**: Bucyrus Erie Pedestal type
- **Model**: 2 x MK60; 70 ft and 80 ft booms
  - **1 x MK 35 with 80 ft boom**

**Pipe Racks**
- **Type**: Horizontal racking (triples)
  - **Manufacturer**: Western Geco/PMV
  - **Capacity**: 24,700 ft of 5 in. drill pipe
  - **5,900 ft of 5 1/2 in. drill pipe**

**ASR System**
- **Manufacturer**: National Monilex
- **Model**: SO32 (single rotor)
- **Type**: Intermediate baseline
  - **Capabilities**: 2% of water depth
  - **Signal**: beacon primary, GPS secondary

**Personnel Complement**
- **Capacity**: 135

**Scientific Spaces**
- **Square footage**: 18,000 ft²
- **Refrigerated core storage**: 20,250 cu ft

**Normal Fuel Consumption**
- **Crating**: 33-47 m/day
  - **DP (3 engines)**: 16.5-19.5 m/day
  - **DP (2 engines)**: 12-13 m/day

**Transit Speed**: 10-15 kts (optimal)

**Helideck**: Sikorsky S-61 capable

**Moopool**: 22 ft diameter
**SODV Science Services**

**Survey Capabilities**
- Navigation system
- Bathymetry system
- Seismic sound source and acquisition systems

**Drilling and Coring Capabilities**
- Drilling and Coring Capabilities
  - Soft sediment: Advanced Piston Corer (APC)
  - Hard sediment: Extended Core Barrel (XCB)
  - Hard rock: Rotary Core Barrel (RCB)
  - Borehole recovery capabilities
- Recovery of cores at in situ pressure
- Recovery of in situ formation fluid
- Drilling Parameters
- Rig Instrumentation System

**Formation Measurement Capabilities**
- IODP and Third-Party Tools
- Formation temperature
- Formation pressure
- Resistivity at the bit
- Formation Logging
  - Resistivity
  - Gamma ray attenuation density and lithology
  - Natural gamma radiation
  - Neutron porosity
  - Acoustic velocity
  - Bottom-hole check shot
  - Vertical seismic profiling
  - Borehole temperature
- Long-term Observatories
  - Circulation Obviation Retrofit Kit (CORK)

**Shipboard Analytical Capabilities**
- Geological Analysis of Core Samples
  - Lithology structures, fossils, etc.
  - Microscopy
  - X-ray diffraction mineralogy
  - Stratigraphic correlation
  - Heat flow analysis
- Physical Properties of Core Samples
  - Digital imaging
  - Moisture and density analysis
  - Magnetic susceptibility
  - Gamma ray attenuation bulk density
  - Natural gamma radiation
  - Resistivity
  - Thermal conductivity
  - Spectral reflectance
  - Magnetotacticity and rock magnetism
  - Acoustic velocity
  - Sediment strength
- Chemistry and Microbiology
  - Hydrocarbon and natural gas chromatography
  - Organic carbon analysis
  - Pyrolysis hydrocarbon content characterization
  - CHNS analysis
  - Total organic carbon analysis
  - Carbonate carbonate analysis
  - ICP-AES elemental analysis
  - Ion analysis in aqueous samples and extracts
  - Halogenated compound detection
  - Microbiological microscopy
  - Sample mass measurement
  - Gas analysis
  - Radiometric sample for sample preparation

**Curation, Data, and Publication Services**
- Shore-based, secure, refrigerated core storage
- Shore-based analytical equipment
- Janus relational database
- Production of state-of-the-art publications since 1986

**Network and Communications**
- High-capacity data server and -7 TB storage system
- Wireless network available in laboratory areas
- Network connections available throughout ship
- Over 20 Mac and ~50 Windows workstations
- Over 20 Windows instrument hosts
- Laboratory Information Management System
- Printer throughout labs and large-format plotters
- Video distribution system
- 24/7 ship-to-shore communications
- Digital Asset Management System

**Staff Support**
- Drilling and coring technical support
- Laboratory and logging technical support
- Information Technology technical support
- Curatorial and data management support
- Publications and Web support
### Mission Specific Plateforms - MSP

The US and Japanese ships, JOIDES Resolution and Chikyu, are dedicated drilling vessels fitted out with permanent drilling, laboratory and offshore core repository facilities, MSPs are platforms especially chosen to fulfill particular scientific objectives. In most cases this requires modifications to the most appropriate platform (which may be a ship, drilling rig, etc).

<table>
<thead>
<tr>
<th>Image 1</th>
<th>Image 2</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1.png" alt="Image 1" /></td>
<td><img src="image2.png" alt="Image 2" /></td>
</tr>
</tbody>
</table>

Due to the time required to identify, contract and modify the most suitable platform, scientists selected for MSP expeditions need to have a flexible approach to their timing and participation. Whereas other drillships have expedition schedules agreed sometimes years in advance, the date that any MSP expedition starts can vary. The schedule may change at relatively short notice because of unforeseen delays in the platforms commitments prior to coming on contract, to technical challenges connected with fitting out the platform or to adverse weather conditions.

### Riser/Riser-less vessels

A riser is a metal tube (pipe) that extends up from the seafloor to a drilling platform, such as a drillship’s rig floor. Its inner diameter is large enough to let pass the drillpipe, the drillbit, logging tools, additional casing strings and any other devices that scientists may want to place in the hole. The top end of the riser must be attached to the drillship and the ship must bear the weight of the device. The bottom end of the riser must be firmly attached to the top of the drillhole in the seafloor. This connection is made to a casing string, which lines the upper part of the hole and is cemented into the seafloor. After the casing is set, the riser is lowered to the casing and the two tubes are locked together by a riser connector. A “blow-out preventer” (BOP) is an automated shut-off device placed at the seafloor between the casing and the riser. It provides protection against unintentional release of high-pressure fluids and gases into the surrounding seawater.

The riser provides a way to return drilling fluid and cuttings, the ground up bits of rock, from the drillhole to the drillship. Removing cuttings from the hole is essential for drilling holes deep into the sediment and crust. The JOIDES Resolution currently uses seawater as its primary drilling fluid, which is pumped down through the drillpipe. This pumping cleans and cools the bit and lifts
cuttings out of the hole, piling them in a cone around the hole. The seawater also tends to wash out of the sides of the hole as it rises to the seafloor.

A riser returns the drilling fluid and the cuttings to the ship via the space between the riser and the drillpipe (annulus). Because most of the drilling fluid can be reused when drilling with a riser, it is possible to use drilling mud rather than seawater as the primary drilling fluid. Drilling mud, because of its greater density and viscosity, is much better than seawater as a drilling fluid when certain drilling problems arise, such as slow penetration, hole instability or a buildup of heavy cuttings.

Figure 2: Riser (left) versus Riserless (right) drilling platforms currently employed by IODP consortium. These platforms correspond to ‘Chikyu’ and ‘JOIDES Resolution’ respectively.
ANNEXURE II

White Paper: WG6.6 – INVEST Meeting, Bremen, 2009

A long-term drilling program for understanding of tectono-climatic evolution of northern Indian Ocean

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(Ministry of Earth Sciences, Government of India)

Goa, INDIA 403804

Abstract:

Compared to the exhaustive deep-sea drilling carried out through the world oceans, the northern Indian Ocean sector is marked by very few DSDP/ODP locations (Fig. 1). The lack of critical deep ocean sampling has been a major constraint in scientific endeavours towards unravelling the history of the geological and climatic evolution of ocean basins in this part. Availability of sub-seabed cores buried underneath water column of up to 4km deep would certainly enhance our understanding of key geological processes. Under these circumstances, as an associate member of the Integrated Ocean Drilling Program (IODP), India would like to draw attention of the international scientific community towards making appropriate steps for IODP boreholes in this region.

Since the northern Indian Ocean covers a vast area and is largely under-sampled region in terms of ocean drilling activities, a long-term, multi-leg project is favoured. Considering that the INVEST meeting would provide an ideal opportunity to discuss the scientific aspects of this sector, it is felt that the next science plan could be guided to cover the already active (#552, 595, 605, 618, 704, 744 etc.) future IODP proposals in the northern Indian Ocean. It is also perceived that the wide-range of geological and climatic processes over the extensive zone justify our attempts to prioritize this region.

For detail paper please visit:
http://www.marum.de/INVEST_Submitted_WP.html

INVEST
IODP
New Ventures in Exploring Scientific Targets
Wireline Coring and Analysis under Pressure: Recent Use and Future Developments of the HYACINTH System

by Peter Schultheiss, Melanie Holland, and Gary Humphrey


Introduction

The pressure of the deep sea and of deep earth formations has subtle effects on all aspects of physics, chemistry, and biology. Core material recovered under pressure, using pressure cores, can be subjected to sophisticated laboratory analyses that are not feasible in situ. Though many fields of study might benefit from pressurized cores, most obviously, any investigation on gas- or gas-hydrate-rich formations on land or under the sea certainly requires pressure coring.

Downhole Pressure Coring and HYACINTH

Scientific investigations of marine gas hydrate formations have provided the impetus for all wireline pressure core development apart from proprietary oilfield technology, including the HYACINTH (HYAe In New Tests on Hydrate, 2001) system. The first scientific wireline pressure core, the Pressure Coring Barrel, was developed by the Deep Sea Drilling Project to capture gas hydrate. It was used by Kvenvolden et al. (1983) in depressurization and gas collection experiments to quantify gas hydrate within cores. The Ocean Drilling Program (ODP) later developed the Pressure Core Sampler (PCS; Pettigrew, 1992; Graber et al., 2002), and the Pressure-Temperature Coring System (PTCS) was developed for Japan Oil, Gas and Metals National Corporation (JOGMEC; formerly Japanese National Oil Company, JNOC; Takehashi and Tsuji, 2005). Both of these systems were used almost exclusively for gas hydrate research. The HYACE (HYdrate Autoclave Coring Equipment, 1997) and the subst-

quent HYACINTH programs (Schultheiss et al., 2006; Schultheiss et al., 2008a), funded by the European Union, were also driven by the need for gas hydrate research.

The HYACINTH vision of scientific pressure coring encompassed not only coring tools but also an array of downstream core processing equipment and capabilities. The two coring tools, the Fugro Pressure Corer (FPC) and the Fugro Rotary Pressure Corer (FRPC; previously HYACE Rotary Corer, HRC), were designed to recover high-quality cores in a complete range of sedimentary formations. The combined suite of equipment (the HYACINTH system) enables these cores to be acquired and transferred in their core liners from the pressure cores into chambers for non-destructive testing, sub-sampling, and storage as required.

The HYACINTH system has continuously improved over the ten years since its inception. ODP and the Integrated Ocean Drilling Program (IODP) have played major roles in this development, allowing the tools to be initially tested (ODP Legs 194 and 201) and then used on both recent gas hydrate expeditions (ODP Leg 204, Hydrate Ridge, offshore Oregon; Tréhu et al., 2005; IODP Expedition 311, Cascadia Margin, offshore Vancouver Island, Canada; Riedel et al., 2008). Since that time, further improvements to the performance and capabilities of the coring and analysis assemblies have been made, and the system has allowed new scientific insights into the structure of natural marine gas hydrate deposits.

Recent HYACINTH Expeditions

Since the completion of IODP Expedition 311 in 2005, the HYACINTH system has been used on four major gas hydrate expeditions for quantification of gas hydrate and detailed measurements on gas-hydrate-bearing sediments. The need to assess the nature, distribution, and concentration of gas hydrate in the marine environment has multiple driving forces. Scientific interest in gas hydrate craters on carbon cycling and climate impact, but to the oil and gas industry, hydrate is an irritant geohazard, and to national governments it is a potential resource ripe for exploitation. Political climate change has made national energy independence a high priority for governments, and in the last few years, the biggest financial input into marine gas-hydrate-related drilling expeditions has come from national governments and their associated national energy and geological organi
izations. Of the four recent expeditions since IODP Leg 311 on which the HYACINTH coring and analysis system has been used, one was to define geohazards related to oil and gas production, and three were to quantify resources for the governments of India, China, and Korea.

India, 2006

The first Indian National Gas Hydrate Program drilling expedition (NGHP-1; Fig. 1) took place on the drillship JOIDES Resolution in the summer of 2006, led by the Indian Directorate General of Hydrocarbons (DGHI) and the United States Geological Survey (USGS). It was designed to investigate the gas hydrate resource potential of sites around the Arabian Sea, the Bay of Bengal, and the Andaman Sea (Collett et al., 2006). This was an ambitious program, lasting 113 days, involving over a hundred scientists and technical staff from India, Europe, and the United States, and drilling thirty-nine locations at twenty-one distinct sites. It was a largely successful program, collecting more gas-hydrate-bearing cores than any previous expedition and describing in detail at multiple scales one of the richest gas hydrate accumulations ever discovered (Collett et al., 2008).

As part of the coring program, forty-eight pressure cores were recovered under pressure and analyzed at sea and postcruise. These included IODP PCs cores as well as HYACINTH FPC and HRC/FRPC cores. The onboard pressure core analysis included routine core measurement of all pressure cores in the HYACINTH Pressure Core Analysis and Transfer System (PCATS). All nondestructive data was collected at in situ pressure. The analytical portion of the PCATS is designed to measure continuous profiles of P-wave velocity and gamma density at in situ pressure and temperature conditions on HYACINTH pressure cores, as well as collect high-resolution 2D X-ray images (Fig. 2).

To perform these analyses, the PCATS extracts the lined cores from the HYACINTH corer autoclaves under pressure and moves them past the sensors. The PCATS was modified to accept PCs corer autoclaves. As the PCs core could not be extracted under pressure, only gamma density and X-ray images could be collected on these cores and at a reduced resolution.

The X-ray images collected from pressure cores taken in the Krishna-Godavari Basin showed hydrate structures with remarkable complexity and unprecedented detail (Fig. 2A). Cores were rotated in the PCATS to understand their three-dimensional nature. Less dense (lighter) patches in the original X-ray (Figs. 2A, 2C) are dipping veins of gas hydrate when seen from a perpendicular view (Fig. 2D). The P-wave velocity and gamma density profiles also reflect this anisotropy. In the first data set (Fig. 2C), the profiles were taken perpendicular to through the major gas hydrate veins, and a slight lowering of density and a smooth increase in P-wave velocity is seen in the area of greatest gas hydrate concentration (Fig. 2C). In the second data set (Fig. 2D), the...
profiles are taken parallel to (along) the major gas hydrate veins, showing low-density zones and a complex P-wave velocity profile. Some extreme values are artifacts caused by pulse interference effects from hydrate structures.

A decision was made to hold five of these cores for additional, more detailed shore-based investigations. The morphology of the gas hydrate within this clay-hosted deposit is worth extended study, not only to explain the mechanisms of gas hydrate growth in fine-grained sediments but also to predict the sediment behavior during gas hydrate dissociation. Models predicting the behavior of such gas hydrate-bearing sediments during dissociation, whether for well bore stability, geohazard assessment, or potential methane gas production, are certainly dependent on the small-scale spatial relationship in the sediment. X-ray computed tomography (CT) scans showed that the fine-grained sediments hosted a complex gas hydrate vein network (Fig. 2B). The pressure cores were individually transferred into the Instrumented Pressure Testing Chamber (IPTC; Yun et al., 2006) using the PCATS. Measurements of P-wave velocity, S-wave velocity, electrical resistance, and strength of the sediments were made at regular intervals along the three pressure cores. Cores were then sub-sampled under pressure with the HYACINTH PRESS system (Parize et al., in press) or rapidly depressurized and placed in liquid nitrogen for further analyses at various laboratories.

The rest of the pressure cores had been depressurized onboard the ship directly after PCATS analyses to determine the exact methane content and hence the gas hydrate saturation (Fig. 2E). Pressure cores are the “gold standard” for gas hydrate quantification and are used to calibrate other methods of gas hydrate detection. The slow, isothermal release of pressure from a pressure core allows gases to escape from pore fluids and allows gas hydrate to dissociate. Measuring the quantity of gas, its composition, and its evolution relative to time and pressure provides information on the quantity, composition, and surface area of gas hydrate (Kvenvolden et al., 1983; Dickens et al., 2006; Millet et al., 2004). The fundamental number obtained through these experiments is the nominal concentration of methane in the pore fluids, assuming all methane is in solution. If this nominal concentration is greater than the calculated methane saturation, gas hydrate (or free gas, depending on the thermodynamic conditions) is assumed to be present, and the amount can be quantitatively calculated. Data that shows the sediment is under-saturated in methane is equally important, as careful pressure core analysis is the only technique that can confirm the absence of gas hydrate. Figure 2E shows pressure core methane data from the same site as the core shown in Figs. 2A–D. All pressure cores taken above the base of gas hydrate stability were oversaturated in methane, allowing calculation of the exact quantity of gas hydrate contained in the cores.

The text continues with further details and figures, including:

- Figure 3: (A) Gas hydrate saturation from porewater freshening (blue circles) and from depressurization experiments and methane mass balance from pressure cores (red circles) at Site 912 in the Shenhua area, South China Sea (Wu et al., in press). (B) Example of gas hydrate-bearing sediments from 204 mbsf at Site 912. Though the core has a gas hydrate saturation of approximately 30% by pore volume, no gas hydrate was visible to the naked eye. (C) A gas hydrate-bearing pressure core is slowly depressurized to release methane. A ROV compositional test is sometimes performed before gas chromatographic analysis.