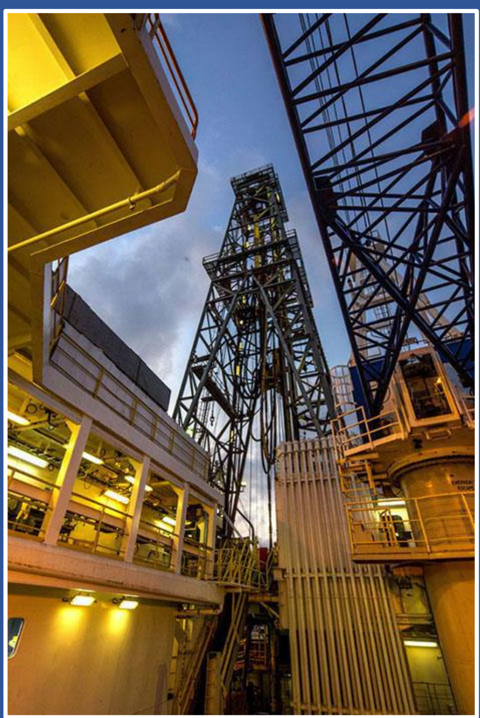
2009-2018

Illuminating the past, present and future

SCIENTIFIC OCEAN DRILLING IN INDIAN OCEAN THROUGH INTERNATIONAL OCEAN DISCOVERY PROGRAM



National Centre for Polar and Ocean Research (NCPOR),
Ministry of Earth Sciences (MoES)

Executive Summary

India, through the Ministry of Earth Sciences (MoES), is an Associate Member of the International Ocean Discovery Program (IODP) – an international consortium committed towards cutting edge global geoscientific research. A detailed IODP Science Plan (2013-2023) has been adopted to steer multidisciplinary international endeavour towards scientific ocean drilling. Through this consortium, scientific drilling at complex geological realms across the globe have been accomplished successfully using unique drilling platforms. Ever since our association to the IODP in 2009, more than 40 young Indian scientists have taken part so far in various IODP expeditions. In the last 5 years (2013-2018), around 27 Indian Scientists from different national institutions with varied specialisations have participated onboard D/v JOIDES RESOLUTION. The unique geological samples acquired by them from the deep seafloor and underneath would provide crucial scientific knowledge about the past history of our planet Earth.

The Nankai Trough (Japan) Seismogenic Zone Experiment (IODP-338) investigated fault mechanism and seismogenesis along subduction forearc and accretionary prism by drilling and coring more than 2000 meters below seafloor (mbsf). The Hess Deep Plutonic Crust (IODP-345) was remarkably successful by recovering the first drilled sections of primitive gabbroic rocks formed at a fast-spreading ridge. Based on the first scientific drilling workshop for Indian Ocean (2011) organised in Goa, six IODP expeditions have been completed successfully in past five years in the Arabian Sea, Bay of Bengal and other parts of the Indian Ocean. IODP Expeditions 346, 353, 354 and 355 were particularly aimed to study the Asian Monsoon along the Japan Sea, Bay of Bengal and Arabian Sea to investigate the tectonic–climatic interactions by documenting the early developments of the Himalaya and Tibet. IODP-359 (Maldives Monsoon and Sea Level) was aimed at investigating the changing ocean currents that affect the Indian monsoon. The Expedition 360 (Southwest Indian Ridge Lower Crust and Moho) explored the nature of lower crust and upper mantle at slow spreading ridges. IODP Expedition 361 (South African Climates) could recover sediment samples having decadal to millennial scale climatic records from the southeast African margin and Southwest Indian Ocean. Expedition 362 (Sumatra Seismogenic Zone) aimed to establish the initial and evolving properties of the North Sumatran incoming sediments and their potential effect on seismogenesis and tsunamigenesis. This expedition was inspired by the 2004 Mw 9.2 earthquake and tsunami that affect the coastal communities around the Indian Ocean. In addition, Expeditions 367 and 368 (South China Sea Rifted Margin) were aimed to address the mechanisms of lithosphere extension during continental breakup. Indian scientists also took part as onshore science party member in Expedition 381 (Corinth Active Rift Development) meant to understand fault formation and strain distribution within the last few million years in a nonvolcanic continental rift of Corinth. Expedition 372 (Creeping Gas Hydrate Slides and Hikurangi LWD) touched a depth of ~750 meters below seafloor to study the slow slip events on subduction faults and actively deforming gas hydrate–bearing landslides. Expedition 374 (Ross Sea West Antarctic Ice Sheet History) recovered 1292.7 m of high-quality sediment cores of early Miocene to late Quaternary which could be a proxy for sensitivity of Antarctic Ice Sheet (AIS) mass balance during warm climates. Among all the recently concluded expeditions, deep sea drilling in the Arabian Sea (IODP-355) requires a special mention as it was one of the major accomplishments with complementary support from the IODP-India (MoES). More than 1700m long cores were retrieved from the Arabian Sea including sampling the igneous basement for the first time in the eastern Arabian Sea. A special volume highlighting major scientific outcomes from this expedition is set to be published shortly in the Geological Magazine.

During these five years, IODP-India has blossomed from a small scientific community to a big family. We are confident that the invested time and resources would provide great scientific dividends in the near future. Early results have already been demonstrated through scientific publications in peer reviewed journals.

Apart from facilitating shipboard participation of Indian scientists, IODP-India also provides financial impetus for their post cruise research and 11 such projects are currently funded under this plan. Taking cues from the scientific drilling outcomes on Indian margins in recent years, IODP-India plans to organize an international workshop to nurture new scientific drilling proposals in the Andamans and surrounding regions in September 2018. We hope that the scientific discussions through such focussed workshops would strengthen our knowledge and understanding about key geological processes along subduction margins in the Indian Ocean.

We are grateful to MoES, India for its whole hearted support to this program. Besides, ever-growing scientific discussions and cooperation from national and international participating organisations are thankfully acknowledged. Last but not the least, I would also like to convey my best wishes to the young and enthusiastic IODP-India team at NCAOR and MoES for their persistence and hard work in driving this program forward. I would also like to appeal to my fellow Indian scientists to take advantage of this unique opportunity and to contribute significantly in solving scientific problems of global importance.

Happy reading...

(M. Ravichandran)
Director, NCAOR, Goa

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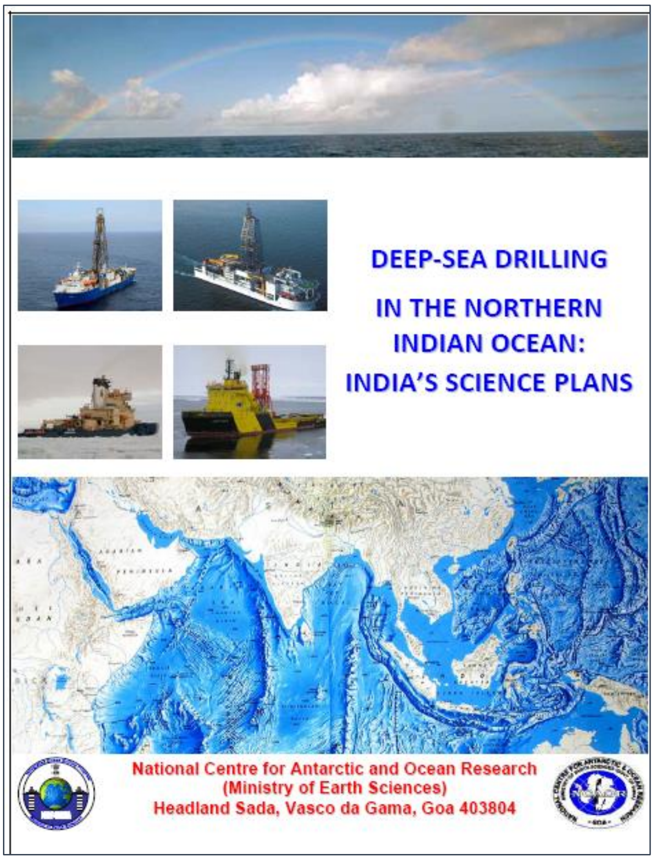
Background

Deep Sea Scientific Drilling in the Indian Ocean in the last decade

The International Ocean Discovery Program (2013-2023) is the new phase of what was formerly known as the Integrated Ocean Drilling Program (2003-2013). Envisioned and nurtured since 2013 as a ten-year Earth science and research program, the new phase of IODP is built upon the outstanding scientific breakthroughs of the Deep-Sea Drilling Project (DSDP) during 1968-1983 and the Ocean Drilling Program (ODP) during 1985-2002 respectively. The cutting edge scientific research catered through this international scientific consortium has received tremendous encouragement. Such recognitions have emanated not only from the global scientific fraternity but also from the United Nations Convention on the Law of the Sea (UNCLOS) towards international cooperation in marine scientific research. Currently, geoscientists from 23 countries collaborate to explore answers to the most challenging geoscientific quests using unique drilling platforms (e.g. JOIDES RESOLUTION and CHIKYU) available with the IODP.

The 10-year Science Plan for the International Ocean Discovery Program aims at *Illuminating Earth's Past, Present, and Future* and is intended to guide multidisciplinary international collaboration on scientific ocean drilling during the period 2013-2023. It was perceived and developed by earth, ocean, atmospheric, and life scientists at the request of international science funding agencies from various funding organizations, representing approximately 75% of the world's economy.

The broad IODP science plan includes objectives from various components of the Earth System Sciences such as flows of mass, energy, and life. Unprecedented records of millions of years of Earth's climatic, biological, chemical, and geological history are buried beneath the ocean floor. Scientific Ocean drilling allows researchers to access these records and explore, analyze, postulate, and test hypotheses that address how our planet evolves on local-to-global spatial scales and on decadal-to-millennial time scales. Over past several decades' scientific ocean drilling has advanced our understanding of Earth's past and has helped us predict its future. This invaluable information derived from cutting edge science help us immensely in decision-making about some of the most significant environmental issues before our society today. IODP also help us build intellectual capacity through the promotion of international scientific exchange.



India @IODP

India joined IODP consortium through its last phase (2003-2013) with an inception of IODP-India at National Centre for Antarctic and Ocean Research (NCAOR), Goa through commitments from Ministry of Earth Sciences (MoES), India. Within the broad ambit of the IODP science plan, IODP-India through a nation-wide consultation process developed its own science plan for 2013-2023. The science plans envisioned key geoscientific challenges, which can be resolved through deep sea drilling around Indian Ocean. Indian geoscientists have contributed immensely to the present knowledge of Indian Ocean evolution. Therefore, association of India to the IODP through MoES is aimed at providing a unique platform for researchers to hypothesize, validate their evolutionary models. India is an Associate member of this consortium through an MoU between MoES and National Science Foundation, USA. This MoU enables Indian scientists exclusive access to NSF owned drilling platform JOIDES RESOLUTION.

Under the MoU with NSF, provisions are made for the Indian scientists and researchers to participate in the regular IODP expeditions around the world onboard JOIDES RESOLUTION as well as European Consortium's Mission Specific Platforms (MSP) and get involved in the active research pertaining to the deep sea drilling. The major scientific objectives within the scope of this MoU include the following:

1. Deep Sea Drilling in the Indian Ocean, especially in the Arabian Sea and Bay of Bengal to understand possible tectono-climatic links between Himalayan orogeny and Indian Monsoon as well as nature of underlying crust.
2. Pursue long-term scientific drilling programs in the Indian Ocean, Southern Ocean and Antarctic Ocean and addressing geoscientific problems of regional as well as global relevance.
3. Capability building, hands-on exposure and building an international collaborative framework at scientists' level through their active participation in various IODP expeditions in different geological domains.

International IODP workshop (2011) for nurturing scientific drilling proposals in the Indian Ocean

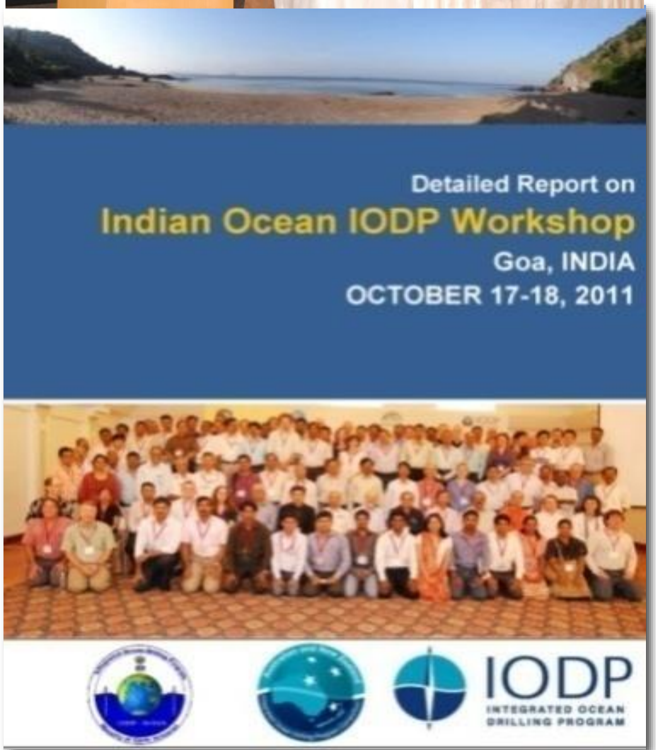
In order to develop new scientific proposals focused on the Indian Ocean sector, an international workshop on IODP was organized by IODP-India in 2011. With more than 100 scientists' participation in this workshop four major themes were evolved.

Themes:

1. Cenozoic oceanography, climate change, gateways & reef development
2. The history of the monsoon
3. Tectonics and volcanism
4. The deep biosphere

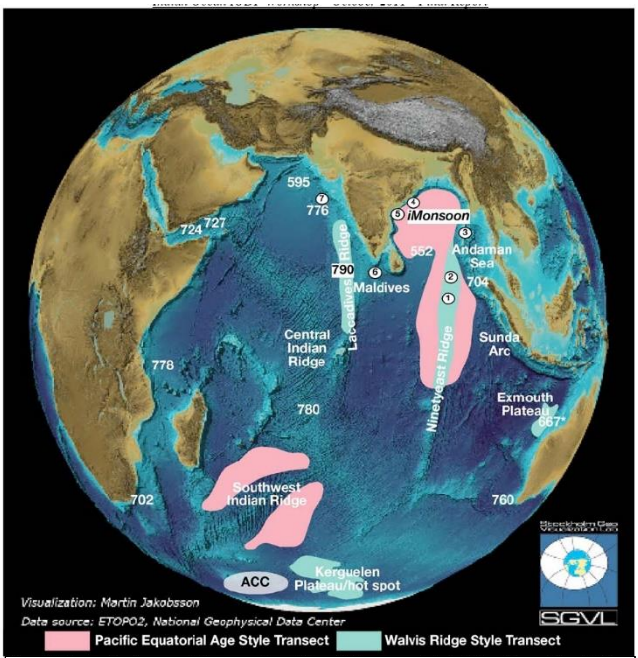
Nurtured proposals

Scientific discussions at this workshop facilitated participants to submit new proposals focussed in the Indian Ocean Sector. Six scientific drilling expeditions were taken up addressing the four themes in the Indian Ocean:



1. Expedition 353 (Indian Monsoon Rainfall)
2. Expedition 354 (Bengal Fan)
3. Expedition 355 (Arabian Sea Monsoon)
4. Expedition 359 (Maldives Monsoon & Sea Level)
5. Expedition 360 (SW Indian Ridge Lower Crust and Moho)
6. Expedition 362 (Sumatra Seismogenic Zone)

Proposal for scientific drilling in the Arabian Sea (Expedition-355)



Illustrative globe showing pre-existing proposals and future drilling prospects in the Indian Ocean

Concaved during the first Indian Ocean IODP workshop (2011), a scientific drilling proposal in the Arabian Sea was nurtured subsequently. A complementary project proposal (CPP) for scientific drilling in the Laxmi Basin, Arabian Sea was submitted involving an international team of scientists from various participating nations.

The proposal entitled "Deep sea drilling in the Arabian Sea: Discovering the tectono-climatic unknowns (IODP-793CPP)" was primarily aimed at recovering deep sea cores from different sites in the Arabian Sea to:

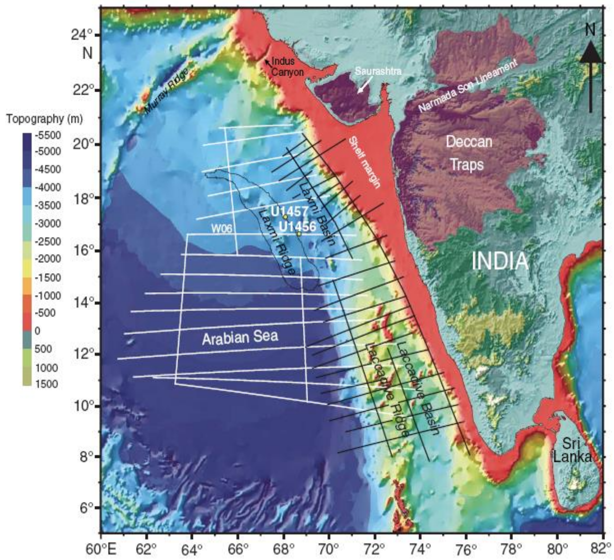
1. Testing whether the timing of the exhumation of the Greater Himalaya correlates with enhanced erosional flux and intense chemical weathering at ~23 Ma.

2. Determining the amplitude and direction of environmental change at ~8 Ma and other times of major climatic variation during the Cenozoic.

3. Dating the age of the base of the fan to constrain the timing of India/Eurasia collision and subsequent uplift of the Himalaya and Tibetan Plateau.

4. Deciphering the nature of the crust in Laxmi Basin (eastern Arabian Sea), which has a significant bearing on paleogeographic reconstructions along conjugate margins in the Arabian Sea and models of continental breakup and rifted volcanic margin formation. After the proposal submission, it was reviewed independently by the IODP through its Science Evaluation Panel (SEP) and Environmental Protection and Safety Panel (EPSP). The proposal, after a rigorous review process, was subsequently recommended for expedition (IODP-355) scheduling using D/v JOIDES RESOLUTION in 2015. However, the review panel also recommended to obtain mandatory Site Survey data prior to the operations to ensure full safety and optimization of proposed objectives.

Site Surveys for drilling proposal in the Arabian Sea

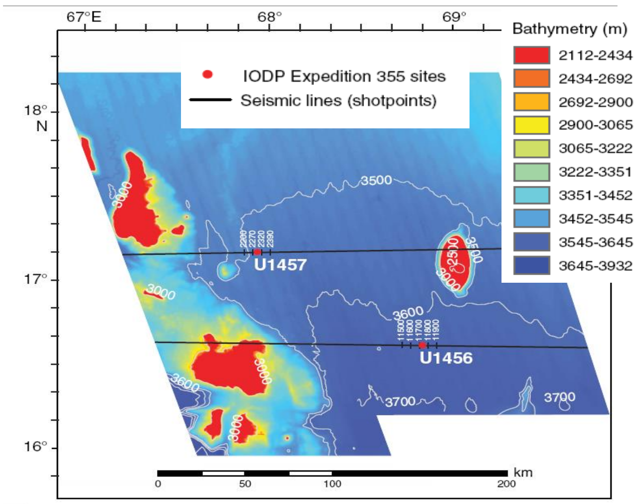


Seismic profiles (white lines acquired by the MoES, Govt. of India; black lines acquired by DGH, India) in the Arabian Sea. Site U1456 is located on Line W06 and Site U1457 is located on Line IODP-04 (not shown).

Swath Bathymetry Surveys (Oct-Nov, 2013)

A two phase operation towards acquiring site survey data for the Expedition 355 was completed in the eastern Arabian Sea. The first phase comprised of swath bathymetry multibeam surveys onboard ORV Sagar Kanya during the cruise SK-306 from 23rd October to 20th November 2013. A total of 7740 km data along the 27 track lines, covering an area of about ~54000 sq km were collected.

Sound velocity and Conductivity, Temperature, Depth profiles were also obtained from 09 stations. This swath bathymetry survey brought out an unprecedented image of the Raman Seamount in the Arabian Sea for the first time (Mishra et al., 2015; Ramesh et al., 2015). In general, the topography of the drilling area was flat despite many prominent volcanic seamounts.



High-resolution multibeam bathymetry data acquired around the Expedition 355 drill sites. Contours (white lines) are in meters below sea level. Black lines are seismic lines with shotpoint numbers around site locations shown in white.

2-D Marine Seismic Data Acquisition (Sept-Oct, 2014)

The second phase of site surveys in the Arabian Sea comprised of 2D multi-channel seismic data acquisition along crossing lines. The multichannel seismic data was acquired onboard chartered vessel R/V Geo Hindsagar from 23rd Sept 2014 to 20th October 2014. Using 6000 m long streamer and ~5000 *cu in* gun volume, a total of 1546-line km seismic data along 5 seismic lines was acquired around proposed drilling sites for the IODP expedition 355. The seismic data beautifully images the subsurface sediment thickness as well as major structural boundaries and seamounts in the region and the data became the basis for the stratigraphic control towards IODP-355 objectives.

Photos of vessel and airgun arrays taken during 2D marine seismic acquisition surveys

IODP Expedition 355

(Arabian Sea Monsoon)

Arabian Sea Monsoon:

IODP Expedition-355 sailed out from Colombo to commence scientific drilling in the Arabian Sea during March 31 to May 31, 2015. A team of 30 international scientists from multi-disciplinary expertise participated in this IODP-355 expedition, including 11 scientists from India. The expedition was jointly led by Dr Dhananjai Pandey (India) and Prof. Peter D. Clift (USA). Dr Denise Kulhanek (TAMU) was the program scientist for this expedition.

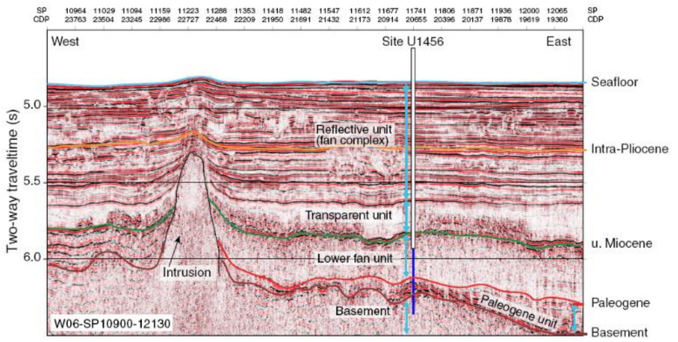
Scientists onboard D/v JOIDES Resolution during Exp 355

During the IODP expedition 355 two sites were drilled in the Laxmi Basin, Eastern Arabian Sea, Indian Ocean. Site U1456, lies within the Laxmi Basin and was cored until the Miocene. However, Site U1457 penetrated to igneous basement in the transition zone between the Laxmi Basin and the Laxmi Ridge. In total ~1700m of sediment and sedimentary rock, as well as 17m of igneous basement was recovered for the first time. All the recovered cores were analyzed and described in details. Based on the onboard analyses of selected samples during the course of expedition 355, major scientific findings were summarized and preliminary report of the IODP 355 was published in August 2015 (Pandey et al., 2015).

Followed by post-cruise sampling at IODP core repository at Texas A & M University, participating scientists were provided core samples to carry out planned scientific objectives. These sediment cores were expected to unravel long term history of Indian monsoon as well as characterizing the igneous basement underneath Laxmi Basin (for the first time).

Recovery of basement sample at Site U1457

The core samples collected during the IODP Expedition-355 was transferred to the IODP Core repository at College Station, Texas, USA for sub sampling. First post cruise meeting "sampling Party Meeting" was held at IODP, College Station, Texas from 24- 28, August 2015. Total of about 15 scientists, including three from India, participated in the sampling Party meeting. During the sampling party meeting more than 18000 sediment samples were sub-sampled.



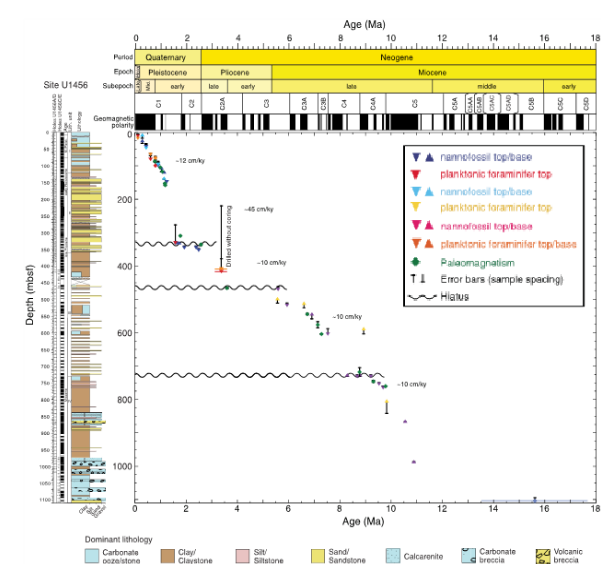
Seismic reflection profile W06 with location of U1456 and main seismically defined horizons described in text. Purple & white bar shows proposed & actual penetration at Site U1456

Salient scientific findings:

Sites U1456 and U1457 provide a basin-wide marine counterpart archives to the Siwaliks on land. Seismic stratigraphy and discovery of thick mass transport deposits (MTD) at IODP Site U1456: Most Likely sourced from continental margin of India at 10.8 Ma.

Sedimentation rate and age-depth Model at Site U1456:

The age model for Site U1456 is based on calcareous nannofossil and planktonic foraminifer biostratigraphy, together with magneto stratigraphy. The succession of bio events indicates that Site U1456 spans the lower to middle Miocene to recent but is punctuated by several hiatuses of varying duration.

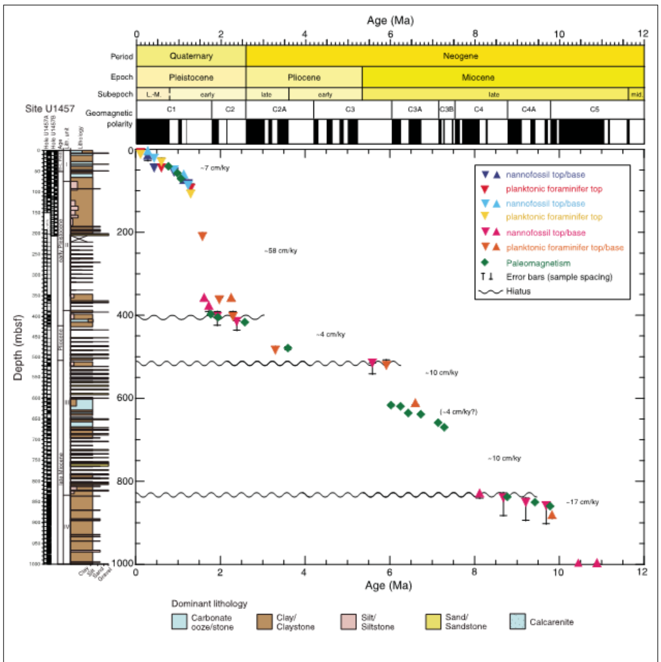


Sedimentation record at U1456

The sedimentation rate appears to have been relatively consistent in the late Miocene at ~10 cm/ky, although deposition was interrupted for ~0.5 million years between ~8 and 9 Ma. Another hiatus spanning ~2 million years encompasses the Miocene/Pliocene boundary. The sedimentation rate in the late Pliocene to early Pleistocene was again ~10 cm/ky. After a 0.45-million-year hiatus, sedimentation rates in the early Pleistocene were much higher (~45 cm/ky) during deposition of Unit II. The sedimentation rate decreased in the late early Pleistocene to recent, averaging ~12 cm/ky.

Sedimentation rate and age-depth Model at Site U1457:

The chronostratigraphic framework for Site U1457 is based on calcareous nannofossil and planktonic foraminifer biostratigraphy, together with magnetostratigraphy. The succession of calcareous nannofossil and planktonic foraminifer events indicates that Site U1457 spans the early Paleocene through recent, albeit with a very long hiatus (~50 million years) between lower Paleocene and upper Miocene sediment. The biostratigraphic framework established at Site U1457 enables identification of three unconformities and an interval of mass transport in the recovered Neogene section. Calculated sedimentation rates at Site U1457 suggest that the sedimentation rate appears to have been relatively consistent in the late Miocene at ~17 cm/ky, although deposition was interrupted for ~0.50 million years around 8 Ma. Sedimentation rates were somewhat lower after sedimentation resumed following this hiatus, averaging ~10 cm/ky during the remainder of the late Miocene. There is some evidence for a short interval dominated by slower hemipelagic sedimentation between ~6 and 7.4 Ma. There is an ~2 million years' hiatus that spans the Miocene/Pliocene boundary and early Pliocene. The sedimentation rate in the late Pliocene to early Pleistocene was ~4 cm/ky. After another ~0.45-million-year hiatus in the early Pleistocene, sedimentation rates for the remainder of the early Pleistocene were much higher (~58 cm/ky) during deposition of Unit II. The sedimentation rate slowed down from the late early Pleistocene to present, averaging ~7 cm/ky.



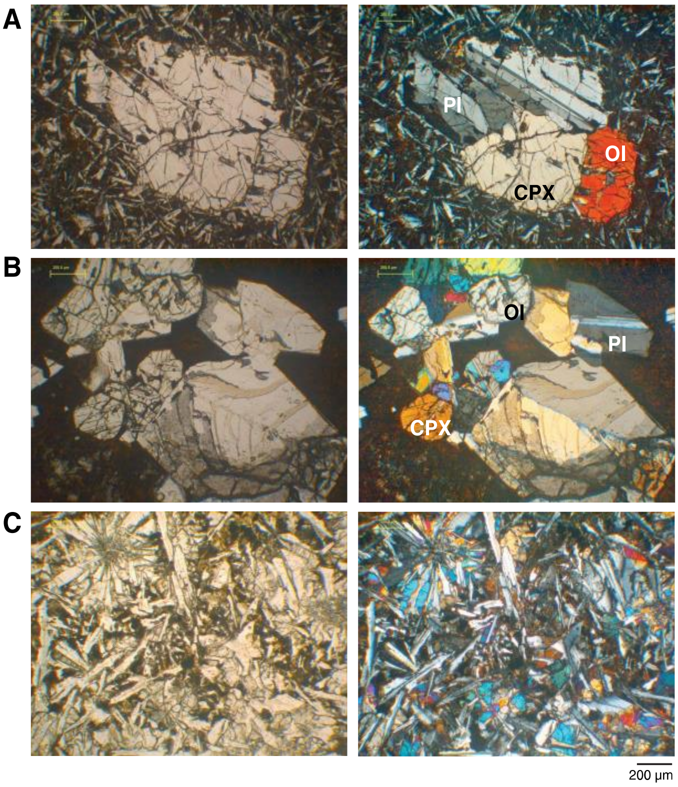
Sedimentation record at U1457


Core recovery of basalt

Recovery of massive basalt and associated volcaniclastic sediment at site U1457 will address the key questions related to rifting and volcanism associated with formation of Laxmi Basin. Geochemical analysis indicates that these are low-K, high-Mg subalkaline tholeiitic basalts and do not represent a typical mid-ocean-ridge basalt. Other observations made at the two sites during Expedition 355 provide vital constraints on the rift history of this margin.

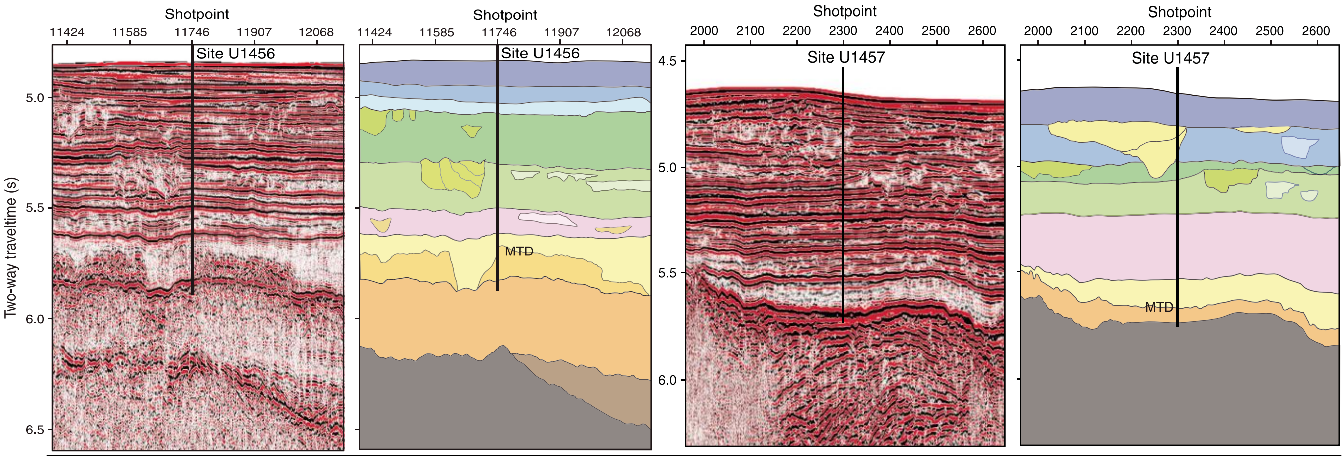
Recovery of Igneous basement for the first time:

Drilling through ~16m of igneous basement rendered ~9m of basalt at Site U1457. No igneous crust was reached on Site U1456. Texture of the basalt ranges from aphyric to phyric. The aphyric material occurs in three intervals and consists mostly of altered glass. Phenocrysts vary from being absent to making up as much as 10% of the rock and are composed of clinopyroxene, plagioclase, and olivine. Phenocryst grain size ranges from 1 to 5 mm, with a mode of ~3 mm. The groundmass is mostly aphyric and may contain mesostasis. The basalt is nonvesicular and massive with calcite-filled veins up to 3 mm in width and of variable lengths. These rocks are classified as clinopyroxene-plagioclase-phyric basalt and plagioclase-clinopyroxene-phyric basalt, with the former the more dominant lithology.



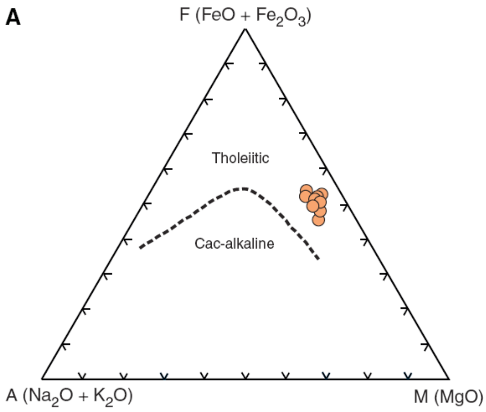
Photomicrographs of basalt samples. (A-B)-Porphyritic texture, phynocrysts of Plagioclase (Pl), pyroxene (Cpx) and Olivine (Ol) are embedded by plagioclase groundmass. (C)-Subophitic inter-growth texture in massive basalt (from Pandey et al., 2016).

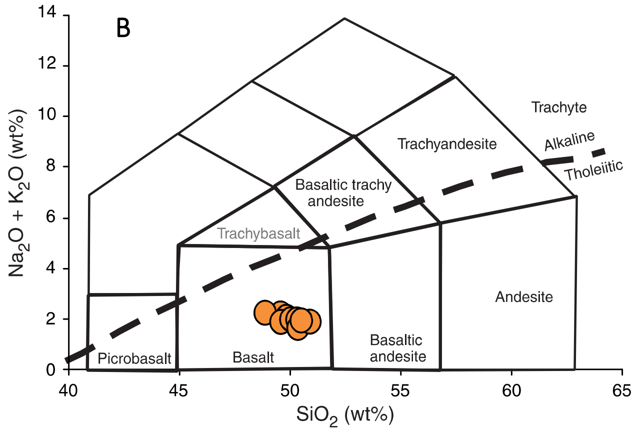
The basalt shows downcore variations in mineralogy, alteration intensity, and grain size. The basalt ranges from aphyric to phyric in texture. The five igneous lithologic units are broadly similar in petrology and range from sparsely to highly clinopyroxene/olivine-plagioclase-phyric, with traces of olivine or clinopyroxene micro-phenocrysts. Most of the basalt is non vesicular to sparsely vesicular. The groundmass is primarily microcrystalline, although it increases to fine grained downhole, and contains plagioclase laths and a large proportion of mesostasis.



Comparison of seismic profile and lithostratigraphy of Site U1456 and U1457 and the major seismic units identified. It is observed that the Mass Transport Deposit (MTD) is much thinner at U1457 compared to Site U1456. The drill site of U1457 appears to cut the edge of one of the large channels in the Pleistocene section, but absent in Site U1456.

Geochemical results of basalt:





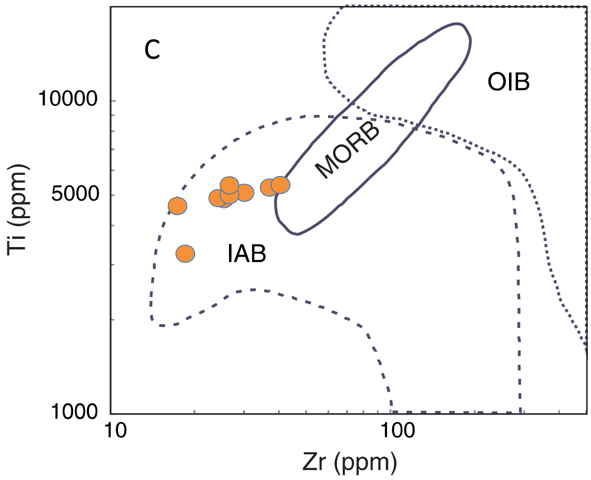


Table 1. Selected incompatible element ratios of Site U1457 basalt compared to average ratios of primitive mantle (PM), mid-ocean-ridge basalt (MORB), ocean island basalt (OIB; Sun and McDonough, 1989), average continental crust (AC; Weaver and Tarney, 1984), and upper crust (UC; Taylor and McLennan, 1981).

	Basement low	Basement high	PM	OIB	MORB	AC	UC
Ti/P	14	17	10.5	5.3	10.7	3.0	3.5
K/P	0.9	2.7	1.5	1.8	0.8	10.7	19.4
Sr/Y	3.8	5.3	5	27	4	36	16
Ba/Y	1.3	2.7	2	13	0.3	51	32
K/Rb	44	142	409	436	830	286	249
Rb/Sr	0.05	0.15	0.03	0.03	0.01	0.12	0.31
Zr/TiO_2	23	47	52	66	63	350	400
Zr/Y	1	2.3	2	7	3	15	11
K/Zr	11	21	23	44	9	83	114
Ba/Sr	0.26	0.62	0.3	0.5	0.1	1.4	2.0

The analysed samples (9 nos.) are fresh or only slightly altered; however, the loss on ignition (LOI) in many samples is high (up to 7.3%). This high LOI may be attributed to the sparsely vesicular character of some of the samples.

Geochemical analysis suggests that the basalt recovered from Site U1457 in Laxmi Basin is Low-K, High-Mg tholeiitic basalt and does not represent a typical mid-ocean-ridge basalt (MORB).

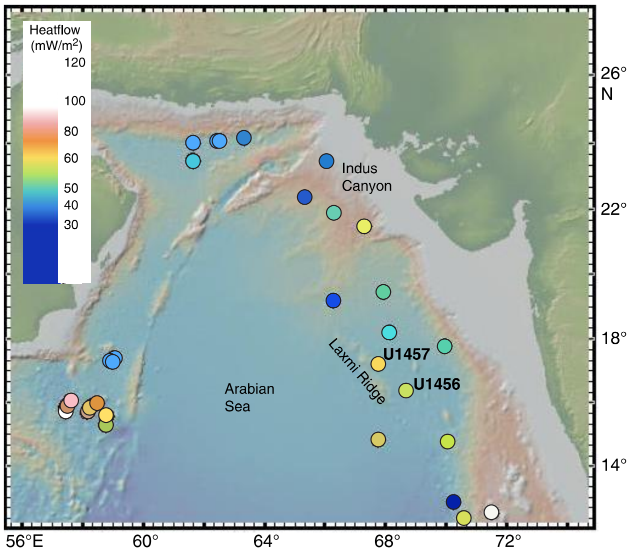
They indicate very limited degree of fractionation. They are characterized by low abundances of large-ion lithophile (LIL) elements (K_2O < 0.13 wt%, Rb < 11 ppm, and Ba < 46 ppm) and closely compare with mantle-derived melts.

Table 1 lists some important ratios (K_2O/P_2O_5, Sr/Y, Ba/Y, Ba/Sr, and K/Zr) in comparison with values of primitive mantle and other ocean crusts. Values of our samples are closely comparable with values of primitive mantle or direct mantle-derived volcanic rocks in an oceanic setting without any affinity toward crustal rocks.

Figure A & B classified basalt samples as subalkaline tholeiitic basalt. In Figure C, basalt plots on the edge of the arc lava field on the discrimination diagram of Pearce (1980) and not in the MORB field. Laxmi Basin is not known to have been in a subduction setting during the Mesozoic and Cenozoic, so this signature may have resulted from the involvement of mantle sources (lithospheric mantle) developed by contributions from an old subduction slab.

Warmer heat flow in Laxmi basin?

Heat flow data measured at each site provide additional constraints to infer the rift history in Laxmi Basin. Average heat flow measured at Site U1456 is 57 mW/m^2, whereas heat flow at Site U1457 is 60 mW/m^2. Comparison with other data from the Arabian Sea shows that Laxmi Basin is warmer than many parts of the Arabian Sea, in particular those regions close to the Indus Delta and the Murray Ridge. Sites U1456 and U1457 also have higher heat flow than those in the eastern and northern sides of Laxmi Ridge.



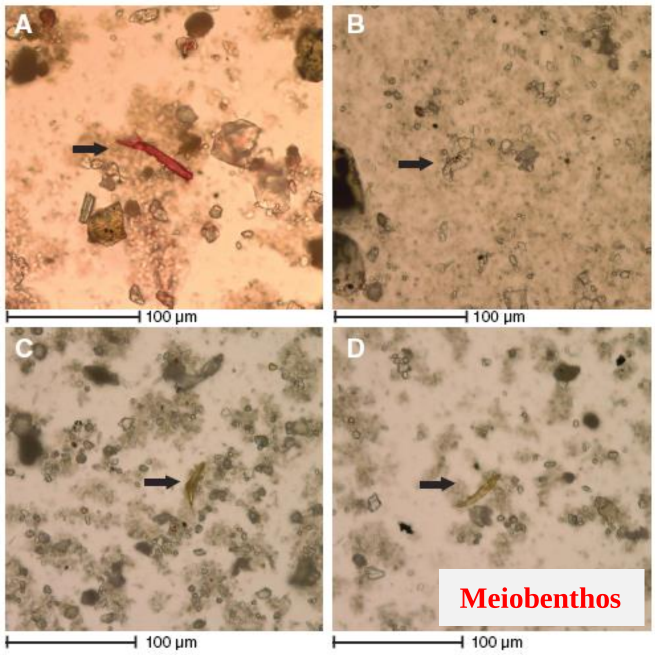
Heat flow map of the Arabian Sea from the compilation of Geo- MapApp, together with the two new measurements derived from Expedition 355.

Stein and Stein's (1992) compilation of oceanic crustal heat flow data indicates that the observed heat flow values at our sites are equivalent to oceanic crust of 76 and 84 Ma age. If the magnetic anomalies interpreted by Bhattacharya et al. (1994) are considered to be a reliable estimate of the timing of extension, then rifting in Laxmi Basin would have occurred between 63 and 84 Ma (Anomalies 28–33). This age would be consistent with the measured heat flow values but requires that no later thermal rejuvenation occurred. However, late-stage intrusions are seen in the seismic profiles, making this assumption somewhat problematic. This is because if the heat flow at our drill sites is normal and oceanic then the lower values in the eastern and northern Laxmi Basin would be anomalous in that they are colder than oceanic crust of corresponding age. This in turn would imply either that the crust in those areas is not oceanic or that the measured locations are positioned in cooler than average regions related to local heat flow patterns.

Discovery of Meiobenthos and Marine fungi within sediments of Laxmi basin

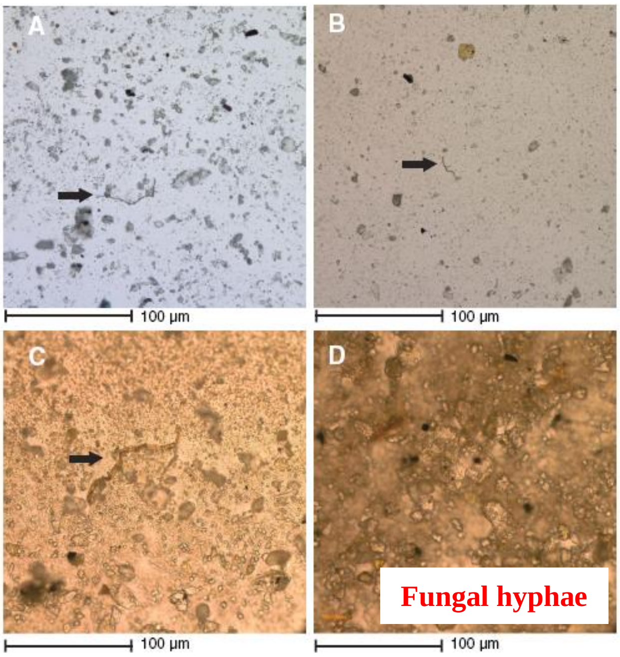
Our measured heat flow is consistent with the theory of extended continental origin for Laxmi Basin.

Meiobenthos (organisms ranging between 1 mm and 45 µm in size) are thought to play a significant role in carbon mineralization, as well as in nitrification and denitrification cycles. We observed presence of several different kinds of meiobenthos in sediments from Hole U1457A. In general, meiobenthos live in aerobic environments; however, some are known to spend part of their life cycles under anaerobic conditions. Recently, Danovaro et al. (2010) were the



first to demonstrate metazoa living under anoxic conditions through an obligate anaerobic metabolism, which is similar to that of eukaryotes. The observation reported here of meiobenthos existing as deep as 105 mbsf in Hole U1457A may be evidence that these organisms can inhabit sub-seafloor environments that were previously thought to be devoid of higher life forms. However, there is also the possibility that these organisms are preserved as organic-walled fossils in sediments.

Deep-sea fungi were also found in sediments from Hole U1457A. Fungal hyphae was identified in several core samples using direct microscopic observations. Preliminary assessment of 12 samples shows the presence of a few fungal morphotypes with single hyphae and branching hyphae. The observation reported here of fungi downhole to 105 mbsf in U1457B is further evidence that these organisms can



inhabit the deep sea, including deep subsurface sedimentary environments. However, there is also the possibility that the fungal hyphae were preserved as organic-walled fossils in the sediment. It was noted that co-occurrence of fungi and meiobenthos in 7 out of the 12 samples surveyed, co-absence in four samples, and just 1 sample where fungal assemblages were detected without meiofauna. This co-occurrence/co-absence suggests a common controlling factor, possibly related to either (1) the control of detritivore abundances by the changing availability of food or nutrient substrates downcore or (2) changing preservational conditions. A further possibility may be that some form of symbioses exists between the fungi and meiobenthos.

Expedition-355 Post-Cruise Science Meeting (25-27 Jul, 2017)

Post cruise Science party group photo

The post expedition science meeting of Arabian Sea Monsoon expedition (IODP-355) was carried out at NCAOR during 24-27 July, 2017. The meeting was aimed to discuss the scientific outcomes so far and the future course of action including scientific collaboration among Shipboard and shore-based participants from all over the world. In total more than 30 scientists from various parts of the world attended this meeting and deliberated upon their scientific progress.

IODP-India provided financial support to three post-cruise science projects (Indian participants) from Expedition-355.

Expedition 355 Science party

IODP 355 - Key scientific findings

Reconstruction of erosion and exhumation records from the Arabian Sea through the 8 Ma – onset of Lesser Himalaya (MBT). We now have a basin-wide record for this period which can be correlated to those from the Siwaliks.

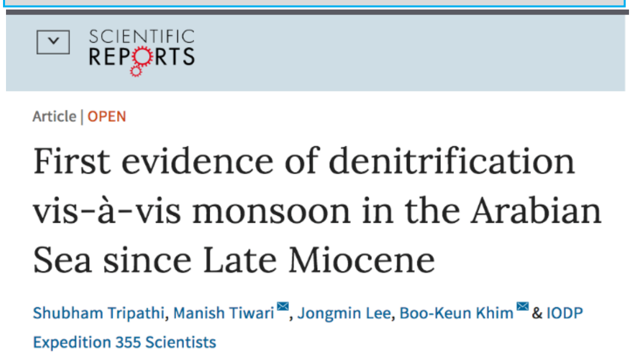
Detrital zircon dating shows a steady increase of flux especially from the Lesser Himalayas since 10 Ma and rules out large-scale drainage capture as previously proposed.

Continuous material to construct a weathering and floral records through the 8Ma transition and Input from the western Himalaya can finally be deciphered.

Cores collected at the two sites constrain Millennial scale variations over several glacial cycles.

Upwelling record has been reconstructed by nitrogen isotopes from the eastern Arabian Sea with particular intensification of the oxygen minimum zone during the Pleistocene apparently disconnected to the terrestrial environment.

Drilling at two sites provides unprecedented records of anomalous subsidence and constrain post-rift evolution of the Laxmi Basin. Evidence of extreme crustal stretching is observed.



SCIENTIFIC REPORTS

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First evidence of denitrification vis-à-vis monsoon in the Arabian Sea since Late Miocene

Shubham Tripathi, Manish Tiwari, Jongmin Lee, Boo-Keun Khim & IODP Expedition 355 Scientists

Initial carbon isotope work suggests an onset of wet conditions on shore at 8.2 Ma followed by continuous drying into the Pliocene.

Bulk sediment provenance work suggests increasing influence from the Himalayas relative to the Karakoram since 10 Ma.

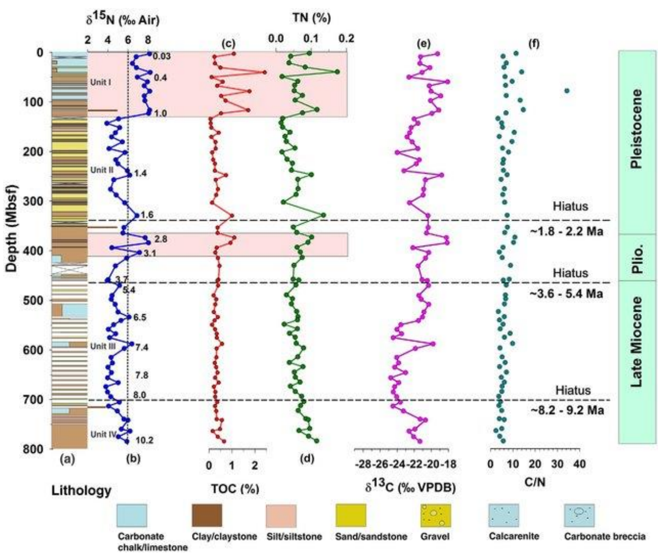
Potential for in-depth study of largest volumes of mass transport deposits on Earth around 10.8 Ma with its geohazard implications.

Recovery of short Paleocene section for the first time in the Arabian Sea at U1457 allows deciphering the dynamics of India-Eurasia collision.

16m long igneous basement recovered from the Laxmi Basin for the first time.

Geochemical analyses of the basaltic rocks recovered from Laxmi Basin characterize it as an arc affinity basaltic crust. Further analyses to examine its geochemical affinity and its age vis-à-vis its relation to the Deccan Flood Basalts is underway.

Links to seismic network allows estimation of mass sediment budget for the first time.



Record of denitrification, surface water productivity, and provenance of the Sedimentary Organic Matter (SOM) in the Eastern Arabian Sea since Late Miocene. (Tripathi et al., 2017)

Indian participation in various Indian Ocean IODP Expeditions

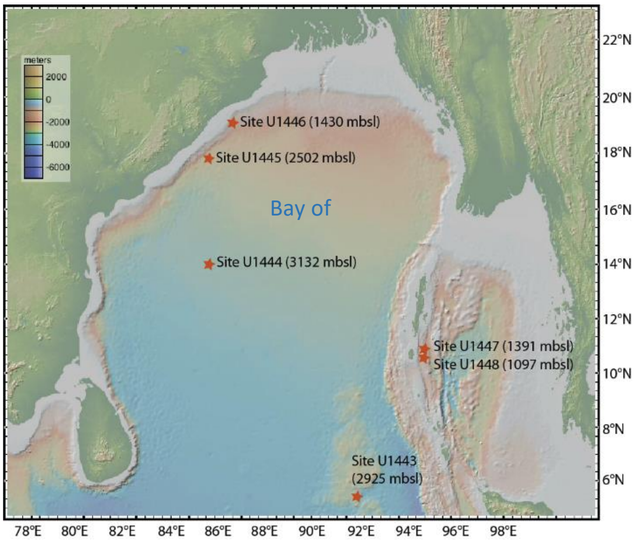
Introduction

By virtue of membership, IODP-India got an opportunity to nominate large number of young researchers from India to facilitate them to start their own research project using the core samples received through ocean drilling. Indian participants have represented the Indian scientific community on various expeditions and have themselves benefitted from participation. Scientific contributions made by the Indian participants in all the expeditions are well recognized by the international ocean drilling community. A list of Indian participation in various Indian Ocean IODP Expeditions are as follows:

IODP Expedition 353: Indian Monsoon Rainfall

International Ocean Discovery Program (IODP) Expedition 353 (29 November 2014–29 January 2015) drilled six sites in the Bay of Bengal, recovering 4280 m of sediments during 32.9 days of on-site drilling. Average core recovery was 97%. The primary objective of Expedition 353 was to reconstruct changes in Indian monsoon circulation since the Miocene at tectonic to centennial timescales. Analysis of the sediment sections recovered will improve our understanding of how monsoonal climates respond to changes in forcing external to the Earth's climate system (i.e., insolation) and changes in forcing internal to the Earth's climate system, including changes in continental ice volume, greenhouse gases, sea level, and the ocean-atmosphere exchange of energy and moisture. All of these mechanisms play critical roles in current and future climate change in monsoonal regions.

It was observed that salinity changes at IODP Sites U1445 and U1446 (northeast Indian margin) result from direct precipitation as well as runoff from the Ganges-Brahmaputra river complex and the many river basins of peninsular India. Salinity changes at IODP Sites U1447 and U1448 (Andaman Sea) result from direct precipitation and runoff from the Irrawaddy and Salween river basins. IODP Site U1443 (Ninetyeast Ridge) is an open-ocean site with a modern surface water salinity very near the global mean but is documented to have recorded changes in monsoonal circulation over orbital to tectonic timescales. This site serves as an anchor for establishing the extent to which the north to south (19°N to 5°N) salinity gradient changes over time.



Map showing drill locations of Exp 353

- ❖ Drilled six sites in the Bay of Bengal, recovering 4280 m of sediments during 32.9 days.
- ❖ Average core recovery was 97%, including coring with the advanced piston corer, half-length advanced piston corer, and extended core barrel systems.
- ❖ Drilling targets between 5°N to 20°N in the Bay of Bengal.

Aditya Peketi and Dinesh Naik (Indian participants)

Objectives:

- ❖ Establish the sensitivity and timing of changes in monsoon circulation relative to insolation forcing, latent heat export from the Southern Hemisphere, global ice volume extent, and greenhouse gas concentrations.
- ❖ Determine the extent to which Indian and East Asian monsoon winds and precipitation are

coupled and at what temporal and geographic scales.

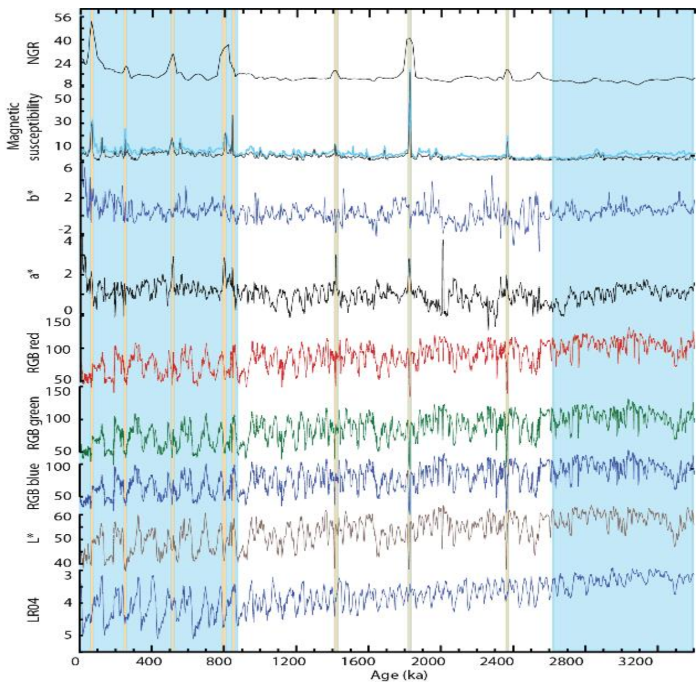
- ❖ Better separate the effects of climate change and tectonics on erosion and runoff.
- ❖ Provide verification targets for climate models, including the rapidly evolving water isotope–enabled, time-dependent models.

Why these sites were chosen?

Changes in rainfall and surface ocean salinity are captured and preserved in a number of chemical, physical, isotopic, and biological components of sediments deposited in the Bay of Bengal. Selected six sites are strategically located in key regions where these signals are the strongest and best preserved.

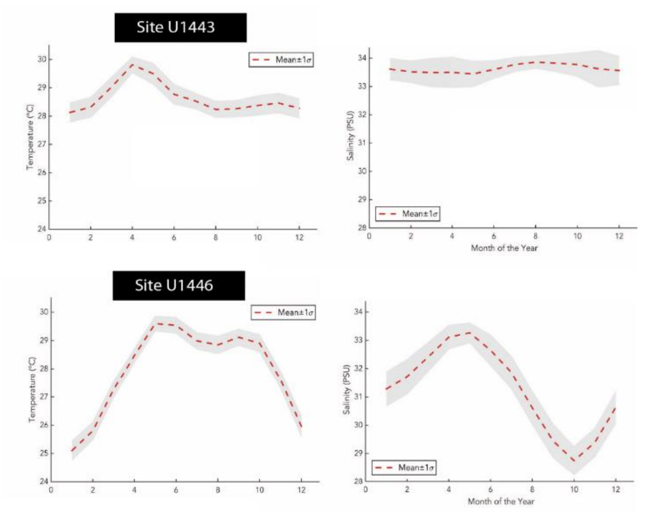
Motivation for drilling in the Bay of Bengal

The three regions chosen for drilling during Expedition 353 (Mahanadi Basin, Andaman Islands, and northern Ninetyeast Ridge) delineate a north–south transect designed to capture past changes in the exceptionally strong salinity gradient observed in the modern Bay of Bengal (19°N to 5°N).



Site U1443 splice RGB, magnetic susceptibility (loop and spot), L, a*, b*, and NGR data tuned to LR04 benthic isotope stack for the last 3.4 My*

The Bay of Bengal/Andaman Sea and surrounding catchments are within the Earth's strongest hydrological regime, impacting billions of people; a solid understnding of the physics behind monsooal climate change is of significant societal relevance.



Estimated monthly G. ruber δ18O derived from monthly salinity and temperature climatologies at (A) 5°N, 90°E and (B) 20°N, 86°E, Bay of Bengal. Monthly mean ±1σ over 1958–2013. Sea-surface temperature (SST) from HadISST data set (Rayner, 2003).

Nearly all proxy records indicate strong coupling between summer monsoon winds and precipitation across the Indo-Asian monsoon subsystems at the millennial scale; this tight coupling is likely attributed to the strong role of the winter westerlies in coupling high- and low-latitude climate change. However, the physical mechanisms behind these links are not fully understood. Changing oxygen content of southern-source intermediate waters creates complication in the interpretation of the OMZ signal as a direct response to atmospheric circulation in the core region of summer monsoon winds (i.e., oxygen drawdown in response to decay of upwelling-produced organic carbon). Precipitation, salinity, and runoff indicators are not influenced by the chemistry of externally sourced intermediate and deep water masses, offering the potential to disentangle the influences of these factors in interpreting monsoon proxy records.

Significant Outcomes:

Freshwater diatoms and phytoliths were abundantly found in marine sediments at site U1445. The strikingly positive correlation between the total diatom concentration and the phytoliths content suggests that the input of land-derived nutrients might have played an important role in driving surface water productivity in the western Bay of Bengal for the interval 3.6-2.5 Ma. The rapid increase of total diatom and phytolith concentration around 3.3 Ma matches, suggest a first strengthening of the Indian Summer Monsoon (ISM) prior to the Northern Hemisphere Glaciation (2.7 Ma). A second major increase around 3.08 Ma roughly corresponds with the end of the mid Picenzian Warm Period. A switch in the amplitudes and the length of variation periods of marine diatoms and phytoliths occurred around 3.1 Ma (Romero et al., 2018)

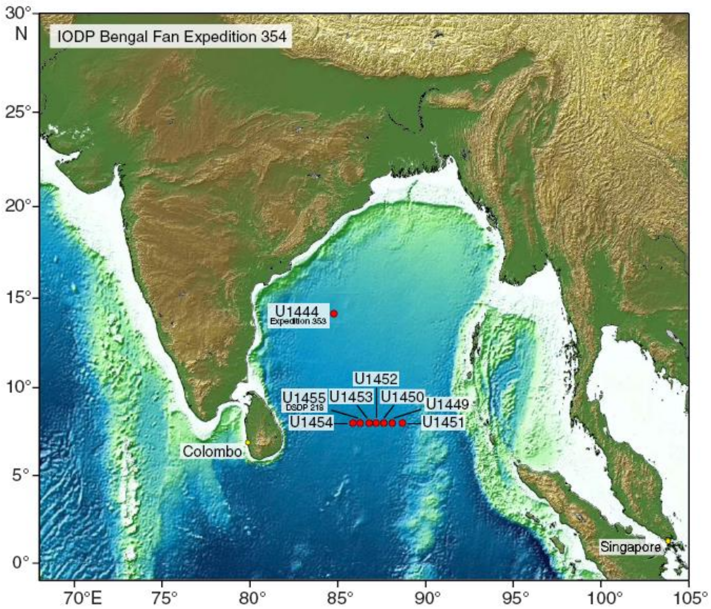
Pore water sulfate concentrations and δ34Sso4 values from Mahanadi (site U1446B) and Andaman (site U1447B) basins were studied. It was found that concentration decreases with depth and reaches to near zero values at ~16 and ~23 mbsf at Mahanadi and Andaman basins respectively. An enhanced slope in the sulfate concentration profile was observed within the depth zones of ~7.3-9.5 and ~4.4 - 6.9 mbsf in Mahanadi and Andaman cores, respectively. Below 6.9 mbsf sulfate concentration profile follows concave down pattern at Andaman site. The difference in the extent of enrichment is possibly because of the variation in sulfate reduction rates and/or nature of sulfate reducing bacteria present in two basins (Peketi et al., 2015).

Planktic foraminifera assemblages were found in core samples from Site U1443, and studied salinity levels. Preliminary ages of the samples were found to be 3.302 Ma to 3.267 Ma. Thus, these samples capture the short-lived M2 glaciation event around ~3.3 Ma. This cooling event may have weakened the Indian monsoon. Typically, during a monsoon event we observed lower salinities due to high levels of precipitation and concomitant freshwater runoff from surrounding terrestrial environments. If our age model is correct, then we observe an overall increase in salinity moving up the section that is indicative of a weakening of the Indian monsoon at the end of Pliocene (Steele et al., 2017).

IODP expedition 354: Bengal Fan

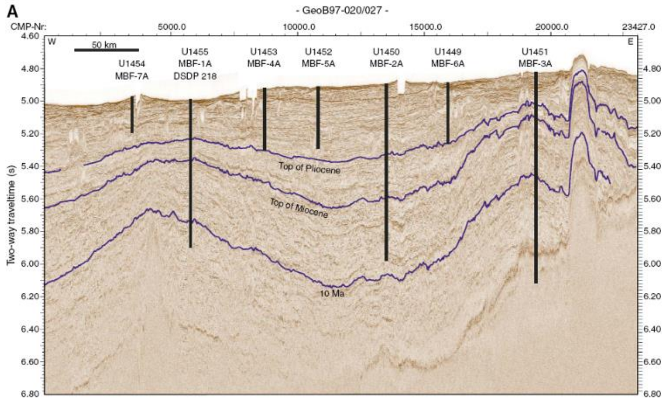
International Ocean Discovery Program (IODP) Expedition 354 took place from 30 January to 31 March 2015 in the Bay of Bengal. Seven sites (U1449, U1451, U1452, U1454 and U1455) along an east-west 320 km transect at 8° N across the Bengal Fan were drilled during the expedition. Three deep-penetration and an additional four shallow holes were drilled to obtain a spatial overview of the primarily turbiditic depositional system that comprises the Bengal deep-sea fan. Sediments recovered from the holes show comprehensive variability in internal facies, and document changes in the depositional system through geologic time, tectonic and climate history.

The organic biogeochemistry research team at Presidency University led by Dr. Das, and comprising two MSc students and one PhD student performed stable isotope and lipid biomarker analyses of IODP samples received by the research team. The research established marine source of the hemipelagic sediment from the core collected from the hole U1452 (Fig. 1), and showed glacial-interglacial scale variation in marine primary production in Bay of Bengal (Fig. 2). Outcome of the research was published, submitted to peer reviewed international journals, and contributed to symposia (see below).



Map showing drill locations of IODP 354

To reconstruct the near bottom current strength variability sortable silt analysis is carried out for the Pleistocene sediments. The excellent relationship between $\overline{SS}$ and SS% is consistent with the sediment being sorted by a variable current with no significant extraneous influence such as unsorted gravel or sand. The variability of coarse silt is most significant in



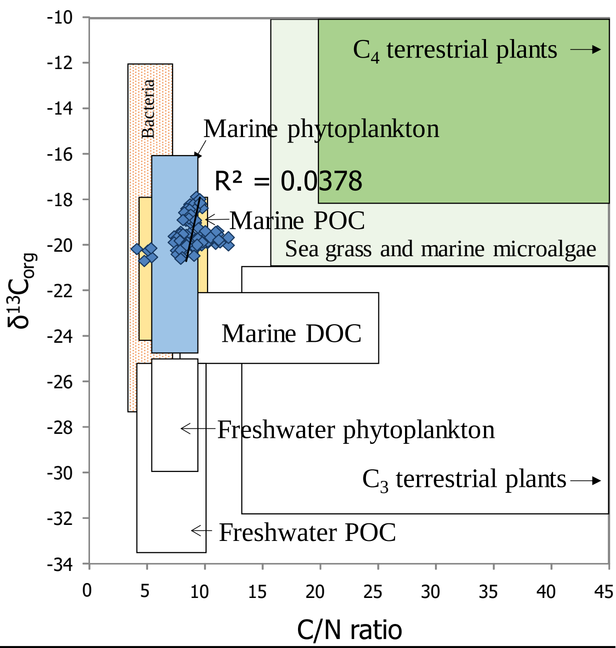
Seismic Profile showing the positions of Expedition 354 drill sites in relation to regional fan architecture. The tops of the Pliocene and Miocene, as well as the 10 Ma horizon, are traced through the profile based on results from DSDP Site 218 (Moore et al., 1974).

controlling the overall mean and shows positive correlation with both the mean and sorting index. Turbiditic interventions can be traced in this section of the core with increased mean and standard deviation as well as poly-modal grainsize distribution pattern.

M.C. Manoj (Sedimentologist, India) working in the Core Laboratory. (Credit: Petra Dekens & IODP)

Supriyo Das (Organic Geochemist, India) conducting analysis in the Chemistry Laboratory. (Credit: Sonja Storm, IODP JRSO)

Maximum values are observed during the glacial periods and certain intervals of interglacial period. The increased $\overline{SS}$ could be attributed to increased bottom current activity. The increased values of $\overline{SS}$ at the studied site are could be influenced by the AABW and also by the monsoonal variation.

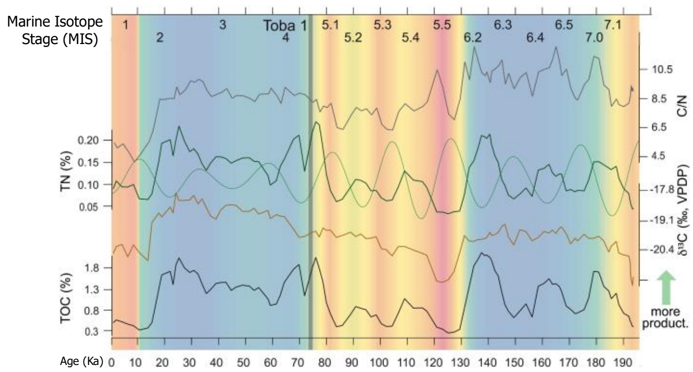


Stable isotope of organic carbon ($\delta^{13}C_{org}$) versus total organic carbon (TOC) to total nitrogen (TN) ratio (C/N) of sedimentary organic matter in hemipelagic material from core collected from the hole U1452C. Boxes indicate typical sources of organic matter according including dissolved organic matter (DOC) and particulate organic matter (POC) (Weber et al., 2018).

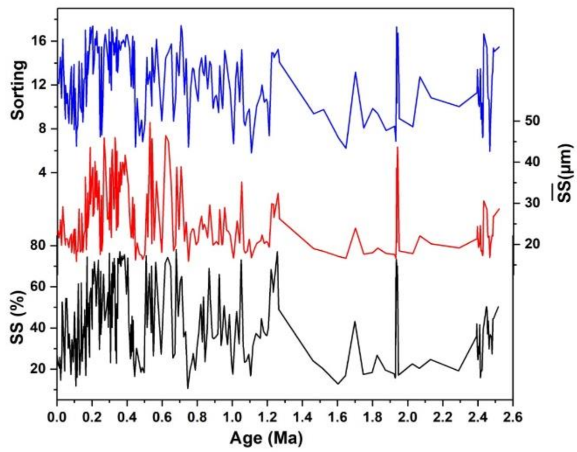
Why this expedition?

Approximately 80% of the material eroded from the Himalaya is deposited in the Bay of Bengal, which therefore hosts the most complete record of erosion and weathering in millennial timescale. This expedition was planned to track and understand these records and its impact on the global carbon cycle. Successfully, Miocene shifts in terrestrial vegetation, sediment budget, and style of sediment transport were able to track. This Expedition has extended the record of early fan deposition by 10 Ma into the late Oligocene.

Besides, Australasian microtektites are found within a foraminifer-rich calcareous clay layer beneath the Matuyama-Brunhes (M–B) magnetostratigraphic boundary (in core-U1452).



200,000-year record of marine paleoproductivity in core collected from the hole U142C reflected by TOC, TN, C/N and $\delta^{13}C_{org}$ with superimposed summer insolation for 20 ° N (Weber et al., 2018).

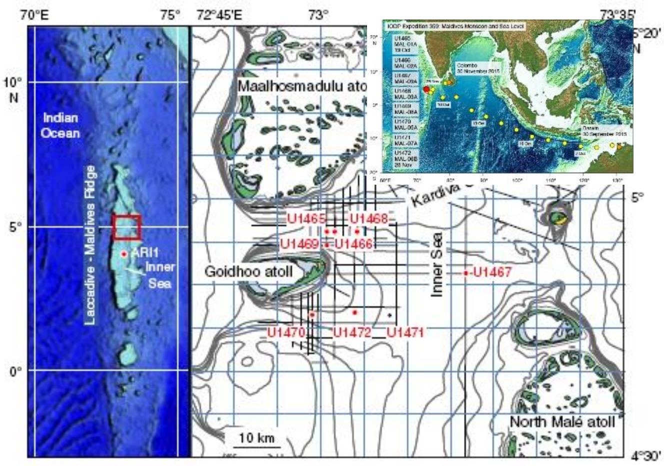


The $\overline{SS}$, SS% and sorting variability from the core U1451 up to Pleistocene

IODP Expedition 359: Maldives Monsoon and Sea Level

International Ocean Discovery Program (IODP) Expedition 359 (30 September to 30 November 2015) was designed to address sea level, currents, and monsoon evolution in the Indian Ocean by drilling in the Maldives carbonate platform. Carbonate platforms are very few in the Indian Ocean, and the Maldives carbonate platform is ideally situated in the equatorial Indian Ocean to learn about the Indian monsoon. And this carbonate edifice bears a unique and mostly unread Indian Ocean archive of the evolving Cenozoic icehouse world.

The seismic stratigraphic framework was already available with the Hamburg Sedimentology group, with which they have constructed a model for the evolution of this carbonate bank, showing the role of changing sea level and ocean current patterns in shaping the bank geometry. The bank growth seems to have occurred in pulses of aggradation and progradation that are controlled by sea level fluctuations during the early and middle Miocene, including the mid-Miocene Climate Optimum.



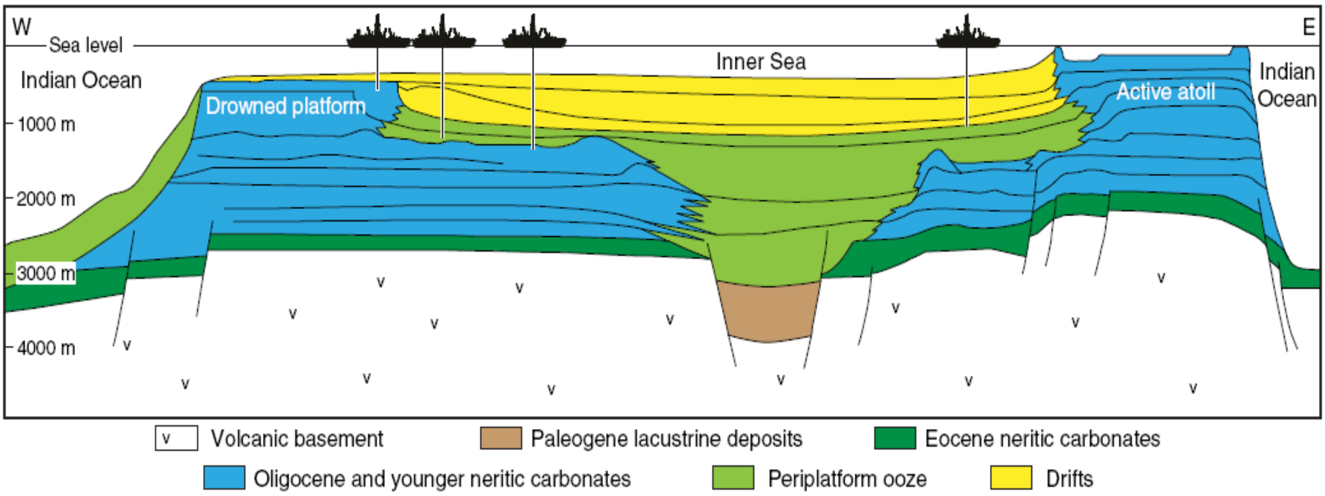
It was interpreted that a sea level–controlled development of the carbonate edifice has shifted to a predominantly current-controlled system, the onset of currents possibly related to the evolving Indian monsoon. This phase led to a twofold configuration of bank development: bank growth continued in some parts of the edifice, whereas in other places, banks drowned. Drowning steps seem to coincide with onset and intensification of the monsoon-related current system and the Expedition 359 intended to date of these drowning steps to reconstruct the evolution of monsoon-driven current system. This is in a way a unique way of interpreting the monsoon evolution since earlier monsoon reconstructions were either based on upwelling proxies (in the NW Indian Ocean) or through Himalayan erosional pulses (NE Indian Ocean). This reconstruction was achieved by drilling eight sites aligned into two transects covering shallow to deepwater deposits. Sites U1465, U1466, and U1468 were drilled to recover a sedimentary sequence encompassing a carbonate platform to drift succession (Oligocene to Pleistocene). Sites U1467, U1470, U1471, and U1472 recovered a Miocene to Pleistocene carbonate drift succession.

The Role of Indian participant:

The work in progress by the Indian participant (*B. Nagender Nath*) on the drill cores U1467 and U1468 was to reconstruct (1) the Neogene changes in ocean pH and linkage with carbonate ion concentration (2) the evolution of OMZ and denitrification changes for the last 13 Myr, and (3) the productivity and bottom water oxygenation changes for the last 13 Myr in the drift sequence. These 3 aspects will contribute to our understanding of the evolution of Indian monsoon system in the equatorial Indian Ocean.

The shipboard scientific data of Expedition 359 had provided two main contributions. The first was to date precisely the onset of the current system that is potentially in concert with the onset or the intensification of the Indian monsoon and coincides with the onset of the modern current system in the world's ocean. The second important outcome of Expedition 359 is ground trothing the seismic-stratigraphy based hypothesis that the dramatic, pronounced change in style of the sedimentary carbonate sequence stacking was caused by a combination of relative sea level fluctuations and ocean current system changes.

The first paper using the shipboard scientific data- "***The abrupt onset of the modern South Asian Monsoon winds"*** *was* published in the *Scientific Reports.* It was shown that the onset of the south Asian Monsoon wind-driven currents in Maldives dates back to 12.9 Ma. It was an abrupt event evolving from a sea-level dominated system. This coincided with the Indian Ocean Oxygen Minimum Zone expansion as revealed by geochemical tracers and the onset of upwelling. Proxies of dust deposition fluxes has also helped in identifying a weaker 'proto-monsoon' which seems to have existed between 12.9 and 25 Ma. In addition, a new calcareous sediment



Sketch of the Maldives carbonate platform stratigraphy (after Betzler et al., 2013a). The volcanic basement is overlain by Eocene and Oligocene neritic carbonates. During the Oligocene, the platform areas shrank and two north-south–trending carbonate banks developed. During the Miocene, shallow-water carbonate banks partly drowned, whereas other platform areas grew further on. Contemporaneously, the carbonate platform was affected by an inten-sification of currents, as registered by the onset of widespread drift sedimentation in the Inner Sea of the Maldives. The research strategy for Expedition 359 was to drill two transects of sites from the inner part of the drowned platforms toward the Inner Sea, coring the platforms and the drifts.

drift type with sigmoidal clinoform geometry deposited under a current-controlled regime in deep to shallow water setting with an aerial extent of 342 to 384 km^2 and a depositional relief of approximately 500m was identified based on seismic and IODP Leg 359 data. The timing of sealevel and current controlled deposition are assessed by dating resultant sedimentary alterations that mark stratigraphic turning points in the Neogene Maldives platform system. The first four turning points during the early and middle Miocene are related to sea-level changes. Phases of aggradational platform growth give precise age brackets of long-term sea-level high stands during the early Miocene and the early to middle Miocene Climate Optimum that is dated between 17 to 15.1Ma. The subsequent middle Miocene cooling coincident with the eastern Antarctic ice sheet expansion resulted in a long-term lowering of sea level that is reflected by a progradational platform growth. The change in platform architecture from aggradation to progradation marks this turning point at 15.1Ma.

An abrupt change in sedimentation pattern is recognized across the entire archipelago at a sequence boundary dated as 12.9–13 Ma. At this turning point, the platform sedimentation switched to a current-controlled mode when the monsoon-wind-driven circulation started in the Indian Ocean. The similar age of the onset of drift deposition from monsoon-wind-driven circulation across the entire archipelago indicates an abrupt onset of monsoon winds in the Indian Ocean. Ten unconformities dissect the drift sequences, attesting changes in current strength or direction that are likely caused by the combined product of changes in the monsoon-wind intensity and sea level fluctuations in the last 13Ma. A major shift in the drift packages is dated with 3.8 Ma that coincides with the end of stepwise platform drowning and a reduction of the oxygen minimum zone in the Inner Sea.

Indian scientist Dr B Nagender Nath, from National Institute of Oceanography (NIO) Goa observing core samples with fellow scientists retrieved during Exp 359

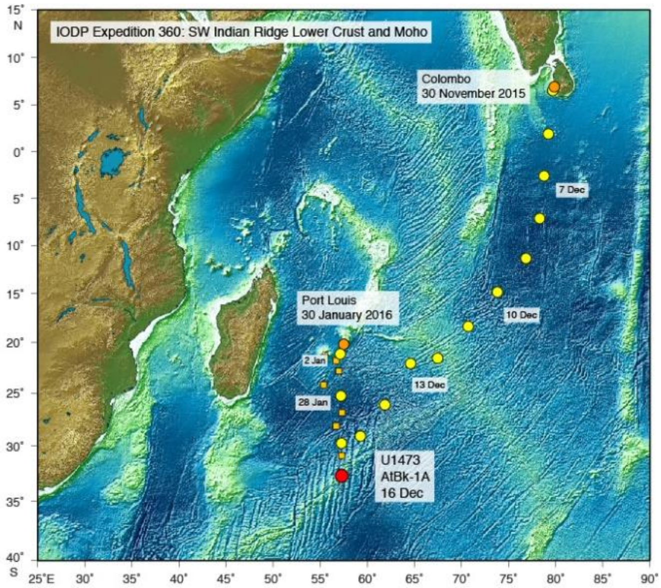
IODP Expedition 360: SW Indian Ridge Lower Crust and Moho

Expedition 360 (30 November 2015 - 30 January 2016) was the first leg of Phase I of the SloMo (The nature of the lower crust and Moho at slower spreading ridges) Project, a multiphase drilling program that proposes to drill through the outermost of the Mohorovicic seismic discontinuity (Moho).

Specific aims of Expedition 360 were to determine the interaction between tectonism and magmatism in accommodating the seafloor spreading, how magnetic reversal boundaries are expressed in the lower crust, the role of lower crust and shallow mantle in global carbon cycle, and the extent and nature of life at deep levels within the ocean lithosphere.

A single hole (Hole U1473A) was drilled on the summit of Atlantis Bank, an 11–13 My old elevated oceanic core complex massif adjacent to the Atlantis II Transform on the Southwest Indian Ridge, an ultraslow spreading ridge. This is the deepest hole ever drilled from the seafloor into the oceanic crust during a single expedition. A primary objective of IODP 360 was to correlate the lateral variability of the stratigraphy established in earlier holes with Hole U1473A. Preliminary assessment indicates that these lower crustal sections are constructed by repeated cycles of intrusion.

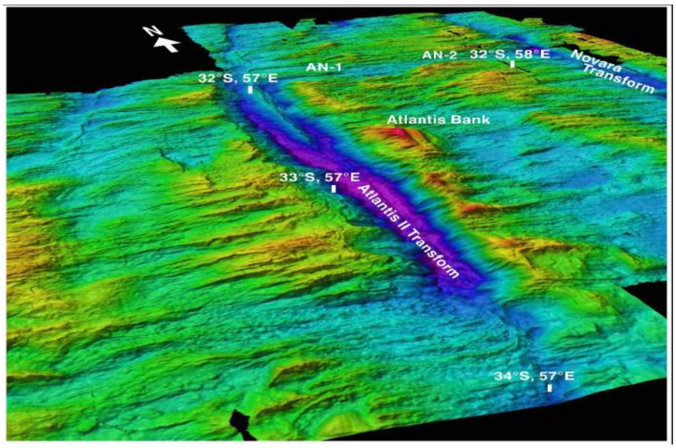
Participants onboard D/v JOIDES Resolution during Expedition 360



A variety of gabbroic lithounits were obtained from Hole U1473A, which include relatively primitive olivine gabbro (olivine+ plagioclase+ clinopyroxene, none of which has modal % <5) to evolved oxide gabbro (modal oxide> 5%); olivine gabbro being the most dominant one (76.5%). Felsic rocks represented by veins or patches are recovered from Hole U1473A. Igneous interlayering defined by modal- and grain size-variation is observed throughout the borehole. Contacts between these layers are commonly subparallel; irregular contacts are found though. The dominant olivine gabbro is largely coarse grained, but shows local variability ranging from fine to very coarse grained.

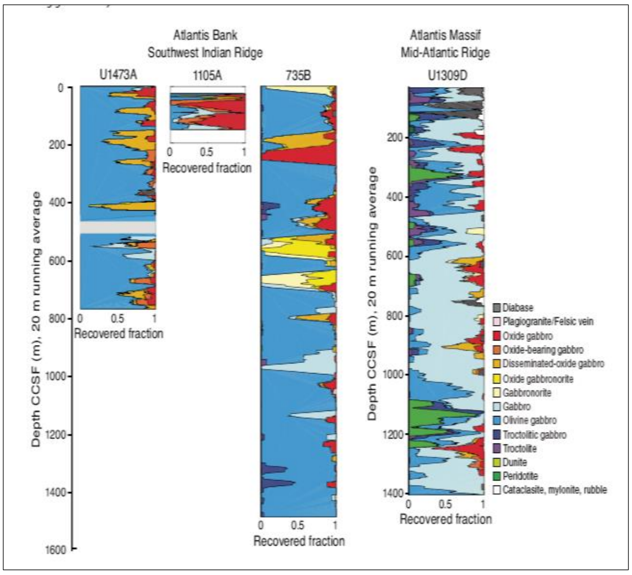
Various petrogenic indicators viz. Mg#, Ca#, Cr, Ni content show major discontinuities at ~60-90, 300, and ~700 CCSF. These discontinuities delineate upwardly evolving units of magma in individual intrusive events. Four carbonate-rich samples contain inorganic C upto a range of 0.5%, which is similar to the range reported for clay-rich alteration of glass on the seafloor and may be related to clay alteration in the gabbros.

Three distinct modes of alteration have affected the Hole U1473A gabbroic rocks: (i) static hydrothermal alteration, (ii) alteration associated with crystal-plastic deformation, and (iii) cataclastic deformation. Wide variation in mineral assemblage is observed, ranging from high temperature granulite to amphibolite facies assemblage, lower temperature green schist to zeolite facies, and very low temperature alteration including carbonates, clay and mixed-layer smectites. Felsic veins are typically more altered than the host gabbros. This variation is associated with the transition from crystal-plastic to brittle deformation.



3-D perspective view of the Atlantis II Transform, looking north-northeast. Source: Dick, H.J.B., MacLeod, C.J., Blum, P., and the Expedition 360 Scientists, 2017.

The internal structure of the Hole U1473A cores is the manifestation of interaction between magmatic and tectonic processes that span a broad range of temperatures, ranging from high-temperature crystal-plastic deformation to late low temperature brittle faulting. Hole U1473A gabbros show a 600m thick zone of intense crystal-plastic deformation which is cut by a later brittle high-angle fault zone. This represents high-temperature deformation related to the formation of Atlantis Bank oceanic core complex and associated detachment fault zone.



Hole U1473A lithostratigraphic variations compared with lithostratigraphic columns for other holes drilled at Atlantis Bank (Holes 735B and 1105A) and Atlantis Massif (Hole U1309D).

Undeformed portions of the Hole U1473A lithology preserve weakly developed magmatic fabric. Microbiological sampling during Expedition 360 focused on exploring evidence for life in the lower crust and hydrated mantle using culture-based and culture-independent approaches, microscopy, and enzyme assays. Adenosine triphosphate (ATP) was quantified from the samples collected for microbiological analysis. It ranged from below detection level to 5 pg/cm3 (mostly <1 pg/cm3), indicating the presence of a subsurface biosphere in Atlantis Bank.

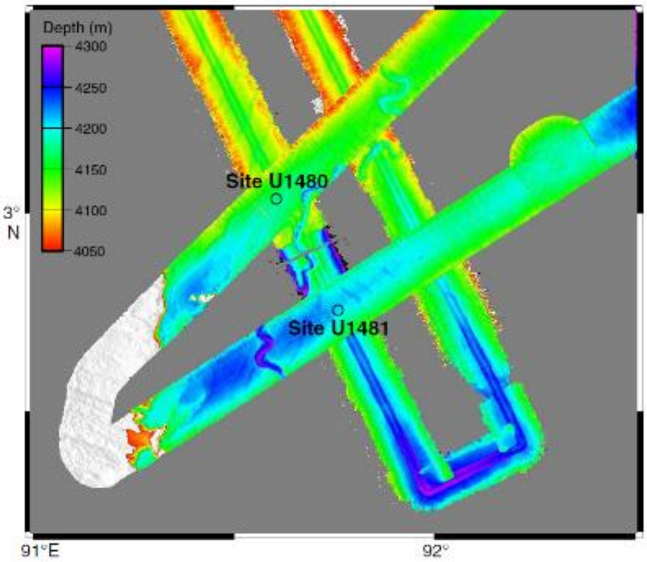
Microbiological sampling evidenced for life in the lower crust and hydrated mantle. Adenosine triphosphate (ATP) was quantified from core sample. It indicates the presence of a subsurface biosphere in Atlantis Bank.

IODP Expedition 362: Sumatra Subduction Zone

The 2004 Mw 9.2 earthquake and tsunami that struck North Sumatra and the Andaman-Nicobar Islands devastated coastal communities around the Indian Ocean, killing more than 250,000 people. This earthquake was caused by an unusual shallow megathrust slip in Sumatra subduction zone. Therefore, Expedition 362 (06 August 2016 - 06 October 2016) aims to establish (1) the initial and evolving properties of the North Sumatran incoming sediments and (2) their potential effect on seismogenesis, tsunamigenesis, and forearc development for comparison with global examples.

It is important to mention that the December 2004 earthquake was followed by the Mw 8.7 Nias earthquake in March 2005 and by others in 2007 and 2010 on the margin. These earthquakes all ruptured megathrust sections between the Indo-Australian and Burma-Sunda plates.

To address these objectives, two drill sites (U1480 and U1481) were drilled to sample and log the oceanic plate input succession of the southern portion of the 2004 earthquake rupture zone. The succession is composed of the distal part of the trench wedge, the Bengal-Nicobar Fan succession, the pre-fan pelagic succession, and the top of basaltic basement. Combined operations at the sites were planned to sample the complete sedimentary succession, sediment/basement interface, and oceanic crustal basalt. The two sites were designed to test for local variations in stratigraphy, lithology, physical properties, thermal state, and fluid geochemistry at



two neighbouring but different locations. The sedimentary succession includes lithologic horizons that may develop into the plate boundary decollement for the north Sumatran margin.

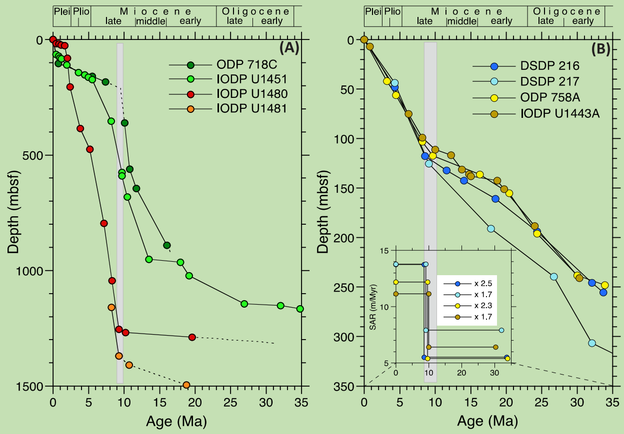
Preliminary highlights of the scientific achievements of Expedition 362

Basement characterization

At Site U1480, a range of igneous lithologies was cored at the base of the section, including basaltic, often altered, flows; an intermediate composition sill; and oceanic crustal basalt. Volcaniclastic sediments containing volcanic glass and discrete ash layers are an important component within the pelagic succession underlying the submarine fan deposits. Glass shards include both mafic (likely proximal source) and felsic (likely distal source) compositions and have undergone significant levels of alteration. According to Hupers et al., (2017), glass alteration had inevitably contributed to clay composition and potentially to pore water chemistry in the deeper part of the stratigraphic section.

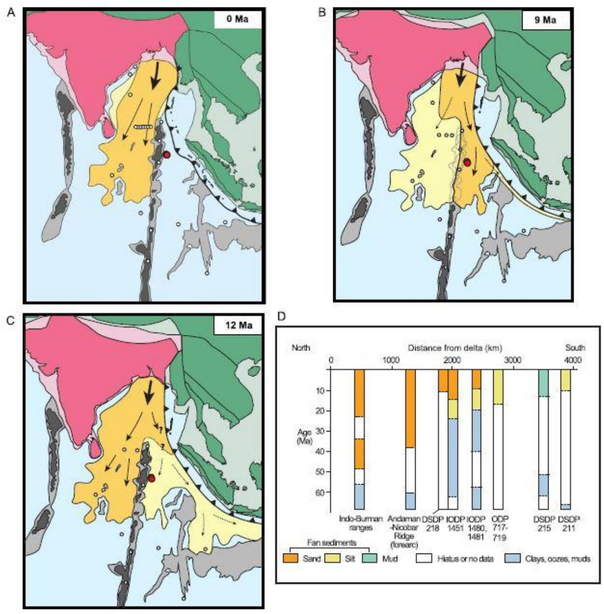
Depositional history

Sampling of the full sedimentary section at Site U1480 and partial section at Site U1481 enabled identification of principal lithologies, grain compositions, depositional environments, sediment accumulation rates, and diagenetic and lithification state. The observed mineral assemblage of the sediment gravity flow deposits is consistent with a general provenance from Himalayan rivers (e.g., Garzanti et al., 2004), and the succession is interpreted to represent different stages of fan development.



Biomagnetostratigraphic age-depth relationships (McNeill et al., 2017)

- The initial provenance data (zircon U-Pb ages) indicated a Himalayan-West Burman source from the north.
- Increase in sediment accumulation rate (SAR) between 9 and 10 Ma.
- Nicobar Fan holds a significant component of the sedimentary record in the Indian Ocean, ~9-2 Ma.



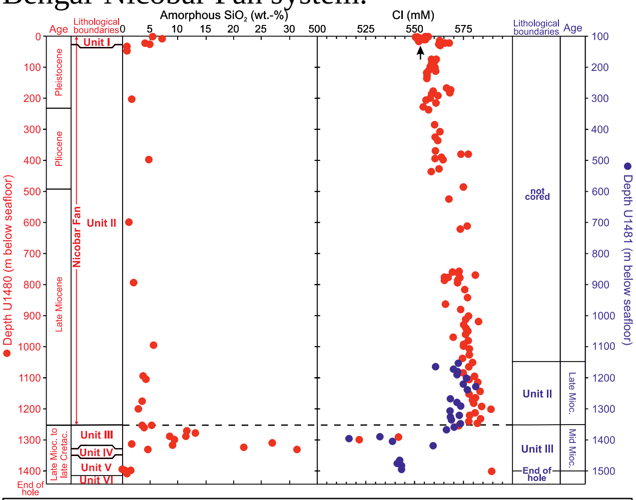
Conceptual model of Bengal–Nicobar Fan system history

- Bengal-Nicobar fan sedimentation diverted to east ~10-9 Ma.
- Change in sediment routing coincides with uplift of Shillong Plateau (E Himalaya) and westward progradation of Indo-Burmese wedge.

- Pattern of sedimentation along the Bengal Fan system from proximal to distal indicated absence of simple fan progradational pattern.
- Pulse of sediment led to increase in forearc growth since late Miocene and potentially to development of the plateau

Geochemistry and fluids of the input section

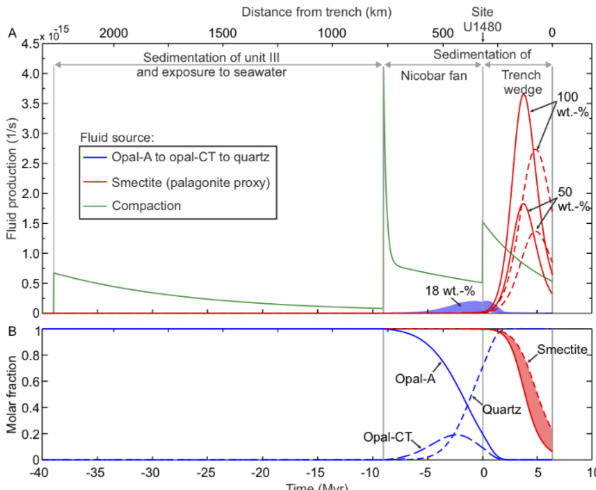
An extensive pore fluid sampling identified two fluid chemistry anomalies of the sedimentary inputs to the subduction zone. The first is the presence of two phosphate peaks in the upper 150 mbsf at Site U1480. Both peaks span ~20 m intervals: the shallower peak is near the seafloor, and the magnitude is small, controlled by organic matter diagenesis; the second peak is sharp and large and may be controlled by a regional flow system. Similar phosphate peaks were observed in the shallow pore fluids sampled during IODP Expeditions 353 and 354 elsewhere on the Bengal-Nicobar Fan system.



Mineral diagenesis linked to shallow plate boundary slip (Hüpers et al., 2017)

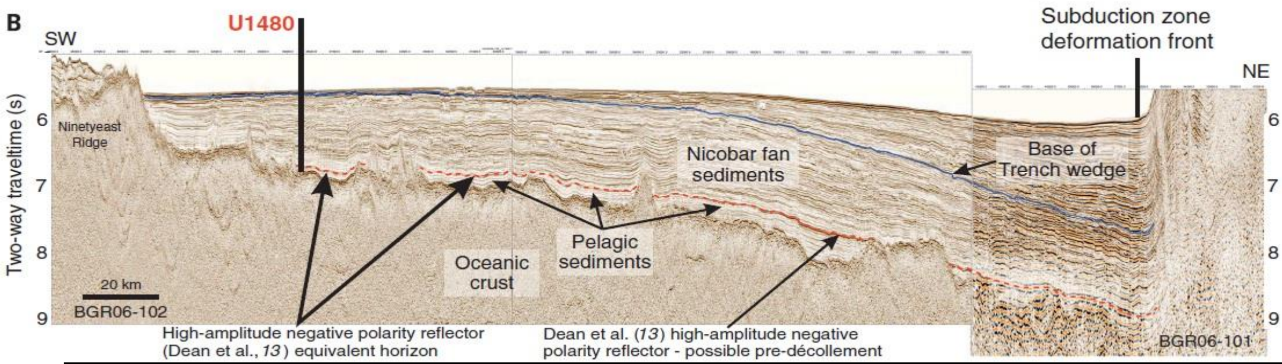
The second pore fluid anomaly was observed deeper in the section, within Unit III where pore fluid freshening was observed.

- Chloride freshening anomaly within Unit III interval, suggesting mineral dehydration
- Linked to an interval in Unit III of altered volcanic, amorphous silicate-rich (palagonized, tuffaceous mudstone), and increased porosity
- Interval coincides with the seismic horizon - high amplitude-negative polarity - candidate horizon for décollement development
- Fluid production has been modeled using burial and thermal history



Modeling results of time-temperature-dependent reaction kinetics

- Predicts complete dehydration of opal and palagonite/smectite before the deformation front
- Reveals that diagenesis before subduction may have driven shallow slip which might have resulted in one of the major earthquakes



Seismic profile of the North Sumatran subduction inputs in the area of the drill sites

Post Cruise Research Support

In order to support the advancements in science based on the sediment samples obtained by Indian scientists post their participation, IODP-India supports several Indian scientists with extramural grants. The support is provided based on their scientific proposals submitted to IODP-India which go through a peer review process. List of grants provided till date is given below:

Project Title: "Paleoclimatic and magmato-metamorphic history of Wilkes Land, East Antarctica: constraints from accessory minerals in oceanic sediments"

PI of the Project	: Dr. N C Pant
Organizations	: University of Delhi
Project Duration	: Three years
Date of Sanction	: 26 Nov 2012
Status	: Completed

Project Title: "Millennial to centennial scale variability in the Asian summer monsoon: Foraminiferal perspective from the East China Sea"

PI of the Project	: Dr R. K Singh
Organizations	: IIT, Bhubaneswar
Project Duration	: Three years
Date of Sanction	: 22 Dec 2014
Status	: Completed in June 2018

Project Title: "Mediterranean Outflow Water (MOW) paleoceanography and its impact on global climate during the last 3 MY"

PI of the Project	: Dr. A. D Singh
Organizations	: BHU, Banaras
Project Duration	: Two (+1) years
Date of Sanction	: 14 Feb 2013
Status	: Completed

Project Title: "Study of seismically induced slope failure of sediment and subsurface fluid flows in the Costa Rican seismogenic zone using long sediment cores drilled during IODP Expedition 334"

PI of the Project	: Dr.Yatheesh Vadakkeyakath
Organizations	: NIO, Goa
Project Duration	: Two (+1) years
Date of Sanction	: 26 Nov 2012
Sanctioned Grant	: Completed

PI of the Project	: Dr Supriyo Kumar Das
Organizations	: Presidency University, Kolkata
Project Duration	: Two years
Date of Sanction	: 23 Feb 2017
Sanctioned Grant	: Ongoing

Project Title: "The nature of the lower crust at slow spreading ridges: constraints from gabbroic samples recovered from IODP Expedition 360, Southwest Indian Ridge"

PI of the Project	: Dr Biswajit Ghosh
Organizations	: University of Calcutta, Kolkata
Project Duration	: Two years
Date of Sanction	: 23 Feb 2017
Sanctioned Grant	: Ongoing

Project Title: "Quantifying Late Pleistocene-Holocene seawater temperature and runoff changes from the northeastern Arabian Sea to understand ocean-climate linkage"

PI of the Project	: Dr Rajeev Saraswat
Organizations	: NIO, Goa
Project Duration	: Two years
Date of Sanction	: 23 Feb 2017
Sanctioned Grant	: Ongoing

Project Title: "Evolution of pCO_2 and Indian monsoon from the Miocene to Pleistocene"

PI of the Project	: Dr Sushant Naik
Organizations	: NIO, Goa
Project Duration	: Two years
Date of Sanction	: 23 Feb 2017
Sanctioned Grant	: Ongoing

Project Title: "Sediment provenance and palaeo weathering studies of Mahanadi basin"

PI of the Project	: Dr Aditya Peketi
Organizations	: NIO, Goa
Project Duration	: Two years
Date of Sanction	: 23 Feb 2017
Sanctioned Grant	: Ongoing

Project Title: "Reconstructing variability of Indian Monsoon since the Late Pleistocene using a marine sediment core (U1446) recovered from the Mahanadi Basin during the expedition 353"

PI of the Project	: Dr Netramani Sagar
Organizations	: NIO, Goa
Project Duration	: Two years
Date of Sanction	: 23 Feb 2017
Sanctioned Grant	: Ongoing

Project Title: "Palaeoclimate and palaeoceanography of the Lower Bengal Fan from late Paleogene to present – IODP Expedition 354"

PI of the Project	: Dr Manoj MC
Organizations	: BSIP, Lucknow
Project Duration	: Two years
Date of Sanction	: 23 Feb 2017
Sanctioned Grant	: Ongoing

Project Title: "Probing the Evolution Of Late Miocene Bottom Water Oxygenation: A Stable Metal Isotope Constraints (PELMO-SMIC)"

PI of the Project	: Dr Gurumurthy GP
Organizations	: BSIP, Lucknow
Project Duration	: Two years
Date of Sanction	: 08 May 2017
Sanctioned Grant	: Ongoing

Project Title: "Geochemical records in the South china Sea: Implications for its Evolution"

PI of the Project	: Mr. N. Lachit Singh
Organizations	: NCAOR, Goa
Project Duration	: Two years
Date of Sanction	: 26 September 2018
Sanctioned Grant	: Ongoing

Project Title: "Impact of climate change on Microbial communities in Ross Sea, Antarctica during the periods of Pliocene, Pleistocene and Holocene"

PI of the Project	: Dr. Shiv M. Singh
Organizations	: BHU, Varanasi
Project Duration	: Two years
Date of Sanction	: 26 September 2018
Sanctioned Grant	: Ongoing

Project Title: "Gas hydrates characterization and assessment from seismic and log data in the Hikurangi margin, New Zealand"

PI of the Project	: Dr. Uma Shankar
Organizations	: BHU, Varanasi
Project Duration	: Two years
Date of Sanction	: 26 September 2018
Sanctioned Grant	: Ongoing

Project Title: "Reconstruction of long term climate variability and depositional environments from sediment cores of South China Sea"

PI of the Project	: Dr. Devleena M Tiwari
Organizations	: University of Hyderabad
Project Duration	: Two years
Date of Sanction	: 26 September 2018
Sanctioned Grant	: Ongoing

Project Title: "Understanding the role of mineral hydration driving tectonics and its effect on climate during Neogene

PI of the Project	: Dr. Prosenjit Ghosh
Organizations	: University of Hyderabad
Project Duration	: Two years
Date of Sanction	: 26 September 2018
Sanctioned Grant	: Ongoing

Selected major publications derived from the IODP expeditions participated by the Indian Scientists & Outreach by IODP-India

SCIENTIFIC REPORTS

Article | OPEN | Published: 21 February 2017

First evidence of denitrification vis-à-vis monsoon in the Arabian Sea since Late Miocene

Shubham Tripathi, Manish Tiwari, Jongmin Lee, Boo-Keun Khim & IODP Expedition 355 Scientists

ELSEVIER

Earth and Planetary Science Letters
Volume 475, 1 October 2017, Pages 134-142

Understanding Himalayan erosion and the significance of the Nicobar Fan

Lisa C. McNeill [a], Brandon Dugan [b], Jan Backman [c], Kevin T. Pickering [d], Hugo F.A. Pouderoux [e], Timothy J. Henstock [a], Katerina E. Petronotis [f], Andrew Carter [g], Farid Chemale Jr. [h], Kitty L. Milliken [i], Steffen Kutterolf [j], Hideki Mukoyoshi [k], Wenhuang Chen [l], Sarah Kachovich [m], Freya L. Mitchison [n], Sylvain Bourlange [o], Tobias A. Colson [p], Marina C.G. Frederik [q], Gilles Guèrin [r], Mari Hamahashi [s, 1], Brian M. House [t], Andre Hüpers [u], Tamara N. Jeppson [v], Abby R. Kenigsberg [w], Mebae Kuranaga [x], Nisha Nair [y], Satoko Owari [z], Yehua Shan [l], Insun Song [aa], Marta E. Torres [ab], Paola Vannucchi [ac], Peter J. Vrolijk [ad], Tao Yang [ae, 2], Xixi Zhao [af], Ellen Thomas [ag]

nature
International journal of science

Letter | Published: 01 December 2013

Primitive layered gabbros from fast-spreading lower oceanic crust

Kathryn M. Gillis, Jonathan E. Snow, Adam Klaus, Natsue Abe, Álden B. Adrião, Norikatsu Akizawa, Georges Ceuleneer, Michael J. Cheadle, Kathrin Faak, Trevor J. Falloon, Sarah A. Friedman, Marguerite Godard, Gilles Guerin, Yumiko Harigane, Andrew J. Horst, Takashi Hoshide, Benoit Ildefonse, Marlon M. Jean, Barbara E. John, Juergen Koepke, Sumiaki Machi, Jinichiro Maeda, Naomi E. Marks, Andrew M. McCaig, Romain Meyer, Antony Morris, Toshio Nozaka, Marie Python, Abhishek Saha & Robert P. Wintsch - Show fewer authors

SCIENTIFIC REPORTS

Article | OPEN | Published: 20 July 2016

The abrupt onset of the modern South Asian Monsoon winds

Christian Betzler, Gregor P. Eberli, Dick Kroon, James D. Wright, Peter K. Swart, Bejugam Nagender Nath, Carlos A. Alvarez-Zarikian, Montserrat Alonso-García, Or M. Bialik, Clara L. Blättler, Junhua Adam Guo, Sébastien Haffen, Senay Horozal, Mayuri Inoue, Luigi Jovane, Luca Lanci, Juan Carlos Laya, Anna Ling Hui Mee, Thomas Lüdmann, Masatoshi Nakakuni, Kaoru Niino, Loren M. Petruny, Santi D. Pratiwi, John J. G. Reijmer, Jesús Reolid, Angela L. Slagle, Craig R. Sloss, Xiang Su, Zhengquan Yao & Jeremy R. Young - Show fewer authors

ELSEVIER

Palaeogeography, Palaeoclimatology, Palaeoecology
Volume 505, 15 September 2018, Pages 187-197

The last 1 million years of the extinct genus *Discoaster*: Plio–Pleistocene environment and productivity at Site U1476 (Mozambique Channel)

Deborah N. Tangunan [a], Karl-Heinz Baumann [a, b], Janna Just [b], Leah J. LeVay [c], Stephen Barker [d], Luna Brentegani [e], David De Vleeschouwer [a], Ian R. Hall [d], Sidney Hemming [f], Richard Norris [g], the Expedition 361 Shipboard Scientific Party [1]

nature geoscience

Article | Published: 20 August 2018

Rapid transition from continental breakup to igneous oceanic crust in the South China Sea

H. C. Larsen, G. Mohn, M. Nirrengarten, Z. Sun, J. Stock, Z. Jian, A. Klaus, C. A. Alvarez-Zarikian, J. Boaga, S. A. Bowden, A. Briais, Y. Chen, D. Cukur, K. Dadd, W. Ding, M. Dorais, E. C. Ferré, F. Ferreira, A. Furusawa, A. Gewecke, J. Hinojosa, T. W. Höfig, K. H. Hsiung, B. Huang, E. Huang, X. L. Huang, S. Jiang, H. Jin, B. G. Johnson, R. M. Kurzawski, C. Lei, B. Li, L. Li, Y. Li, J. Lin, C. Liu, C. Liu, Z. Liu, A. J. Luna, C. Lupi, A. McCarthy, L. Ningthoujam, N. Osono, D. W. Peate, P. Persaud, N. Qiu, C. Robinson, S. Satolli, I. Sauermilch, J. C. Schindlbeck, S. Skinner, S. Straub, X. Su, C. Su, L. Tian, F. M. van der Zwan, S. Wan, H. Wu, R. Xiang, R. Yadav, L. Yi, P. S. Yu, C. Zhang, J. Zhang, Y. Zhang, N. Zhao, G. Zhong & L. Zhong - Show fewer authors

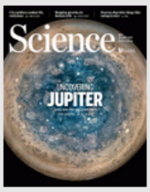
REPORTS

Release of mineral-bound water prior to subduction tied to shallow seismogenic slip off Sumatra

Andre Hüpers[1,*], Marta E. Torres[2], Satoko Owari[3], Lisa C. McNeill[4], Brandon Dugan[5], Timothy J. Henstock[4], Kitty L. Milliken[6], Katerina E. Petronotis[7], Jan Backman[8], Sylvain Bourlange[9], Farid Chemale Jr.[10], Wenhuang Chen[11], Tobias A. Colson[12], Marina C. G. Frederik[13], Gilles Guèrin[14], Mari Hamahashi[15], Brian M. House[16], Tamara N. Jeppson[17], Sarah Kachovich[18], Abby R. Kenigsberg[19], Mebae Kuranaga[20], Steffen Kutterolf[21], Freya L. Mitchison[22], Hideki Mukoyoshi[23], Nisha Nair[24], Kevin T. Pickering[25], Hugo F. A. Pouderoux[26], Yehua Shan[11], Insun Song[27], Paola Vannucchi[28], Peter J. Vrolijk[29], Tao Yang[30], Xixi Zhao[31]

[1]MARUM–Center for Marine Environmental Sciences, University of Bremen, Post Office Box 330 440, D-28334 Bremen, Germany.

[2]College of Earth, Ocean and Atmospheric Sciences, Oregon State University, 104 CEOAS Administration Building, Corvallis, OR 97331-5503, USA.



Science
Vol 356, Issue 6340
26 May 2017

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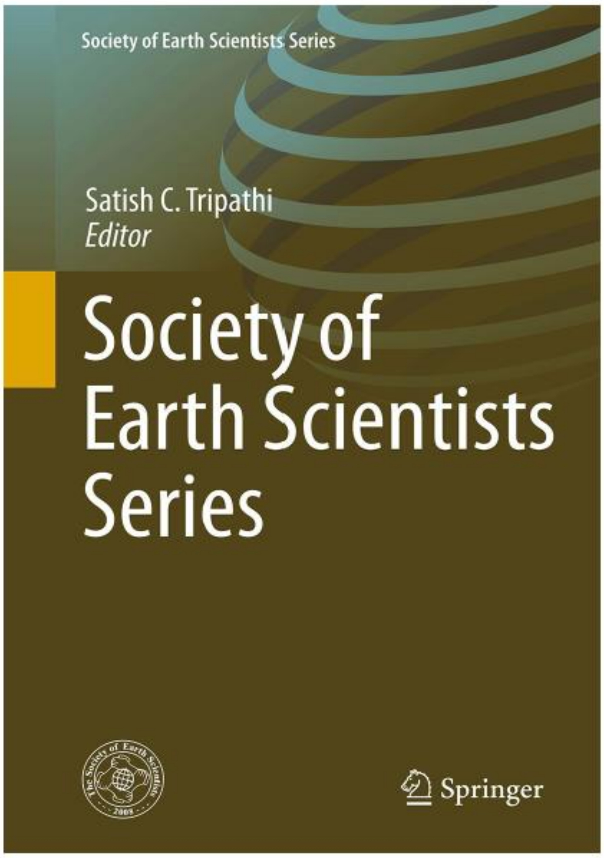
Special volumes for research emanating from IODP expeditions

IODP 355: Special Volume in Geological Magazine:

Based on the scientific outcomes of IODP Exp 355, a special volume of Geological Magazine with 15 scientific papers is being rolled out later this year. The volume is co-edited by DK Pandey, Peter Clift and Denise Kulhanek.

Society of Earth Scientists (SES) Series: Springer

To commemorate the 10 year-long journey of IODP India (2009-2019), a special volume in Springer – Society of Earth Scientist Series is planned to be published by 2019. The volume will be co-edited by DK Pandey, M Ravichandran and Nisha Nair.



List of publications emanated from IODP

1. Larsen, H. C. et al., (including **Ningthoujam, L.** and **Yadav, R.**) (2018). Rapid transition from continental breakup to igneous oceanic crust in the South China Sea. Nature Geoscience. (Accepted and in Press) [IF=13.9]
2. Liu Ruixuan, Lu HuaYu, Wang Yao, Yu Zhaojie, Zhaokai Xu, Fen Han Rong Hu and IODP Expedition 355 Scientists (including all the **Indian participants**) (2018) Grain size analysis of a depositional sequence in Laxmi Basin (IODP 355 U1456A, Arabian Sea) unravels Indian monsoon shift at the Middle Pleistocene Climatic Transition. Quaternary Sciences (in Press). [IF=2.9]
3. **Prerna R., Pandey D.K.**, and Mahender, K. (2018) Longitudinal Profiling and Elevation-Relief Analysis of the Indus. Arabian Journal of Geosciences, Springer. Vol 11:343. DOI 10.1007/s12517-018-3657-5. [IF=0.8]
4. **Nisha Nair**, and **Pandey, D.K**., (2018) Cenozoic sedimentation in the Mumbai offshorebasin: Implications for tectonic evolution of western continental margin of India. Journal of Asian Earth Sciences, 152, 132-144, doi.org/10.1016/j.jseaes.2017.11.037 [IF=2.8]
5. Weber M.E., Lantzsch H., Dekens P., **Das S.K.**, Reilly B.T., Martos Y.M., Meyer-Jacob C., Agrahari S., Ekblad A., Titschack J., Holmes B., Wolfgramm,P. (2018) 200,000 years of monsoonal history recorded on the lower Bengal Fan - strong response to insolation forcing. Global and Planetary Change 166, 107–119. [IF=3.9]
6. McKay, Rob, **Pandey, D. K.** et al. (2018) Developing community-based scientific priorities and new drilling proposals in the Southern Indian and Southwest Pacific oceans. Scientific Drilling [IF=1.2]
7. Das, M., **Singh R. K.,** Vats, N., Holbourn, A., Mishra, S., Farooq, S.H., **Pandey, D.K.** (2018) Changes in the distribution of Uvigerinidae species over the past 775 kyr: Implications for the paleoceanographic evolution of the Japan Sea. Palaeogeography, Palaeoclimatology, Palaeoecology. (In Press) [IF=2.3]
8. McKay, R.M., De Santis, L., Kulhanek, D.K., and the Expedition 374 Scientists (including **Shiv M. Singh**) (2018). *Expedition 374 Preliminary Report: Ross Sea West Antarctic Ice Sheet History*. International Ocean Discovery Program, 374. https://doi.org/10.14379/iodp.pr.374.2018
9. Pecher, I.A., Barnes, P.M., LeVay, L.J., and the Expedition 372 Scientists (including **Shankar, U.**), (2018). *Expedition 372 Preliminary Report: Creeping Gas Hydrate Slides and Hikurangi LWD.* International Ocean Discovery Program. http://dx.doi.org/10.14379/iodp.pr.372.2018
10. **Pandey, D.K., Nair, N., Pandey, A.**, Gullapalli, S., (2017) Basement tectonics andflexural subsidence along western continental margin of India. Geoscience Frontiers,8, 1009-1024; DOI: 10.1016/j.gsf.2016.10.006 [IF=4.0]
11. Mc Neill, L.C., Dugan, B., Petronotis, K.E., and the Expedition 362 Scientists (**Nair, N.**), 2017. Sumatra Subduction Zone. Proceedings of the International Ocean Discovery Program, 362: College Station, TX (International Ocean Discovery Program). https://doi.org/10.14379/iodp.proc.362.2017
12. McNeill et al., (including **Nair, N.)** (2017). Understanding Himalayan erosion and the significance of the Nicobar Fan. Earth and Planetary Science Letters, 475, 134–142. doi:/10.1016/j.epsl.2017.07.019 [IF=4.5]
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16. Hall, I.R., Hemming, S.R., LeVay, L.J., and the Expedition 361 Scientists, (including **Lathika, N.**) (2017) South African Climates (Agulhas LGM Density Profile). Proceedings of the International Ocean Discovery Program,

361: College Station, TX (International Ocean Discovery Program). http://dx.doi.org/10.14379/ iodp.proc.361.2017

17. Carter, S.C., Griffith, E.M., Scher, H.D., and the Expedition 355 Scientists (including **Pandey, D.K., Gurumurthy, G.P., Kumar, A., Kumar, A.G., Mishra, R., Radhakrishna, T., Saraswat, R., Saxena, R., Sharma, G.K., Singh, A.D.,** and**Tiwari, M.**) (2017) Data report: 87Sr/86Sr in pore fluids from IODP Expedition 355 Arabian Sea Monsoon. In Pandey, D.K., Clift, P.D., Kulhanek, D.K., and the Expedition 355 Scientists, Arabian Sea Monsoon. Proceedings of the International Ocean Discovery Program, 355: College Station, TX (International Ocean Discovery Program). https://doi.org/10.14379/iodp.proc.355.201.2017
18. Tripathi, S., **Manish Tiwari**, J. Lee, B.K. Khim, IODP Expedition 355 Scientists (2017). First evidence of denitrification vis-à-vis monsoon in the Arabian Sea since Late Miocene. Nature Scientific Reports,7, 43056, doi: 10.1038/srep43056 [IF=4.2]
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Outreach

IODP-India participated in an outreach program at the 2018 Association of Exploration Geophysicists, India meeting held at Indian Institute of Technology, Mumbai during Oct 31-Nov 3, 2018. Young minds from various schools as well as young scientists benefitted from interactions with NCPOR scientists at the booth during this workshop.

Interactions during AEG 2018 at IIT, Mumbai with NCPOR scientists

IODP Forum meeting held at Goa during 19-21 Sep, 2018

The annual IODP Forum meeting 2018 was hosted by IODP India (NCPOR, Goa). During this three day meeting, scientists from various IODP member countries deliberated upon the progress made so far about their respective activities as well as forthcoming initiatives. IODP-India (NCPOR) also shared the progress and future plan of IODP-India office at the Forum, emphasising on greater participation of young minds as well as potential outreach.

Group photo and presentations made during IODP Forum Meeting 2018

Future Plans

International Workshop: 17-18 September, 2018

SPADE (Scientific Proposals for Andamans Drilling Endeavour)

The purpose of this workshop was to develop scientific proposals for drilling and investigating the Indian Ocean near Andaman subduction zone. For a long time, Indian scientists have wanted to expand their understanding of the Indian Ocean but due to the paucity of data and ship time, these scientific objectives remained unexplored. As a combined international effort, scientists from all over the world with similar research interests were invited. A workshop was organised at the NCPOR on 17-18 September, 2018 to have brain-storming discussions among scientists, to understand pros and cons, and finding out possible sites for drilling. Efforts were made to lead this program by team India, and we are hopeful that this will enable us to explore the Andamans and surrounding regions under the water.

The workshop was supported by various scientific bodies.

Total of 33 scientists talked about their science plan for possible drilling.

Earth scientists, marine biologists and climatologists, from India and foreign, had come for discussion. Final draft of the proposal is due to be out.

Ministry of Earth Sciences Government of India
ESSO

European Consortium for Ocean Research Drilling
ECORD EUROPEAN CONSORTIUM FOR OCEAN RESEARCH DRILLING

U.S. Science Support Program (USSSP)
U.S. SCIENCE SUPPORT PROGRAM

Integrated Ocean Discovery Program (IODP)
IODP INTERNATIONAL OCEAN DISCOVERY PROGRAM

National Centre for Polar and Ocean Research
NCPOR

IODP-India

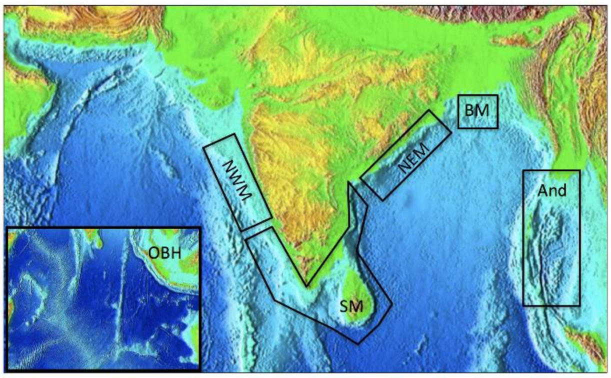

Figure: Paleoceanography and Paleoclimate regions of proposal interest including northwest margin (NWM), southern margin (SM), northeast margin (NEM), Bangladesh Margin (BM), Andaman (And), and oceanic bathymetric highs (OBH).

Why Andaman drilling?

- Unusual back arc opening system.
- Heavily sedimented subduction zone; which may affect the nature of subduction, earthquake and the climate.
- Why mantle composition of Indian Ocean is so different from other oceans?

The first Indian Ocean drilling workshop held in Goa in 2011 culminated in successful drilling through six IODP expeditions in the Indian Ocean since 2015. The next phase of Indian Ocean drilling (anticipated to begin sometime after 2023), will build on results from these previous expeditions and address key regions never before targeted by scientific drilling.

Recently, IODP-India (NCPOR), hosted a second international IODP workshop in Goa during September 17-18, 2018 to identify and improve understanding of several geological paradoxes in this region. The primary goal of this workshop was to discuss, deliberate and nurture new scientific drilling proposals in the northern Indian Ocean (refer Figure). About 50 international scientists took part over two intensive days of plenary and breakout sessions, supported by Ministry of Earth Sciences, India, US Science Support Program (USSP) and European Consortium for Ocean Research Drilling (ECORD).

The workshop was focused around three main themes: 1) **Tectonics of oblique convergence in the Andaman subduction zone** – understanding the convergence-transpressional transition, the generation and propagation of seismicity, the effect of subduction of large sediment piles on slab processes, history of volcanism in Andaman arc, growth of continental crust beneath the arc, the timing and nature of back-arc spreading and the relationship between the thermal structure of the oceanic crust and the development of magnetic anomalies. 2) **Recovering Asian monsoon archives from the Andamans and Indian margins -** long-term, high resolution records of Indian monsoon circulation from the Paleogene to present, including the influence of the Himalayan orogeny and its consequential signatures of uplift, weathering, erosion, sediment deposition. 3) **Recovering depth-transects from open ocean bathymetric highs** – assessment of dust transport pathways, timing of gateway restrictions and surface, intermediate, and deep water circulation over time. Full abstracts of ideas discussed at the workshop are available at http://www.ncaor.gov.in/iodps.

During the workshop, scientists emphasized the necessity of international collaboration in writing innovative drilling proposals that will reveal the wealth of tectonic, climatic, geochemical and oceanographic information archived in the crustal rocks and overlying sediments of the Indian Ocean, advancing the community's goals of the meeting as well as the high-priority science objectives of the IODP long-range science plan. Wide consensus exists among participants that the three broad themes discussed have potential to meet these objectives. Participating scientists formed operational working groups to communicate with each other electronically in the coming months and years and to promote increased participation by interested scientists unable to attend the workshop.

Feedbacks from IODP participants:

Dr. Raj kumar Singh
(Assistant Professor, IIT BHubaneshwar)

Expedition 346 helped me to work with reputed international academicians. Post cruise funding helped me to establish my new laboratory at IIT Bhubaneshwar.

Dr. Nisha Nair
(Scientist - B, NCPOR, Goa)

My expedition enabled me to initiate scientific collaboration with national and international geoscientists. Thankful to IODP-India for giving me a platform to gain hands-on experience

N. Lathika
(Scientist - B, NCPOR, Goa)

Participation in IODP expedition had given me scientific exposure through collaborations and learning new techniques.

Dr. Supriyo Das
(Asst. Professor, Presidency Univeristy, Kolkata

IODP Expedition allowed me to collect rare samples from under-represented area of the world. Post cruise funding helps me in sample analysis and 2 students are engaged. I hope it will continue to promote university researchers for future participation.

Dr. Yatheesh Vadakkeyakath
(Senior Scientist, NIO, Goa

IODP expedition gave me great experience of working with international team. Post-cruise funding helps in data analysis. Inspired by this program, a proposal for drilling in the Andaman Sea was presented in the Australasian Regional Planning Workshop held at the University of Sydney.

Dr. K.S.V. Subramanyam
Sr. Technical Officer, NGRI, Hyderabad

I was immensely benefitted by the exchange of scientific thoughts and research with international scientists on board, during Expedition-340. I am grateful for the kind support and opportunity given by the IODP-India and MoES.

Dr. Nagender Nath
(Retired Scientist, NIO, Goa

IODP Expedition has benefitted me immensely. Every marine Geologist needs to participate at least once to keep abreast with the latest tools used in marine geology, and equip our ships with such tolls and plan domestic expeditions.

Dr. Manish Tiwari
Scientist-E, NCPOR, Goa

It provided opportunity to work on long sediment cores spanning past several million years and also helped in forging new collaborations that would not have been possible otherwise. It also helped in obtaining high-impact factor publications.

Dr. Rajeev Saraswat
Senior Scientist, NIO, Goa

IODP has fulfilled a long cherished dream of working on marine records (covering large part of Pleistocene) from the monsoon dominated regions in the Indian Ocean.

Dr. Gurumurthy GP
Scientist-B, BSIP, Lucknow

Post-cruise funding helped me hire a JRF who is registered for PhD at BHU. The fund covers analytical charges. IODP-India encourages us by conducting periodic monitoring of post-cruise projects.

Prof. AD Singh
Dept. of Geology, BHU,Varanasi

Students got opportunity to work on IODP samples. Enabled to bring out good publications. It makes easy to have collaborative work with internationally reputed institutions.

The *JOIDES Resolution* at sunset. (Credit: Shuhao Xie & IODP)

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