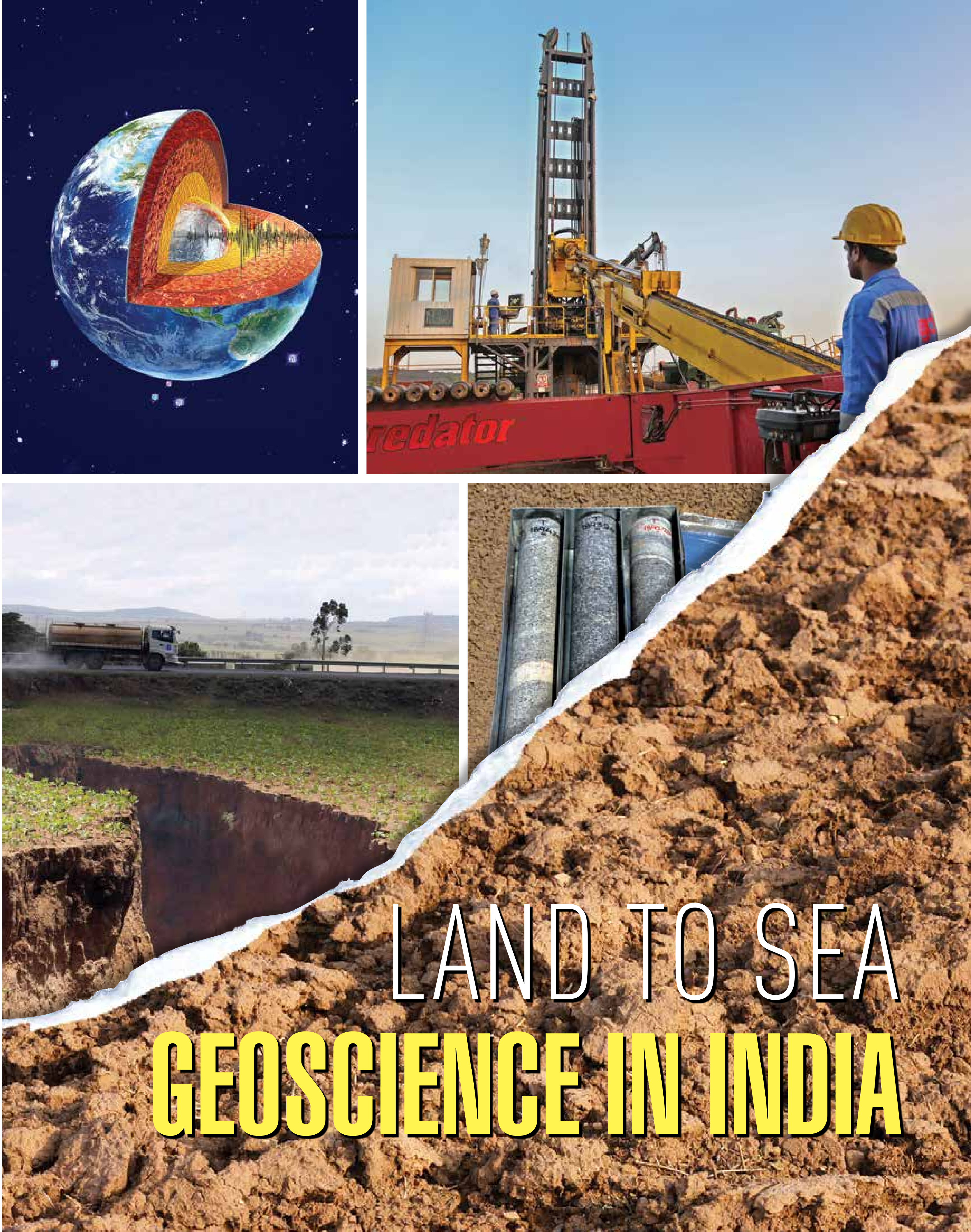

LAND TO SEA
GEOSCIENCE IN INDIA

LAND TO SEA

Geoscience in India

Contents

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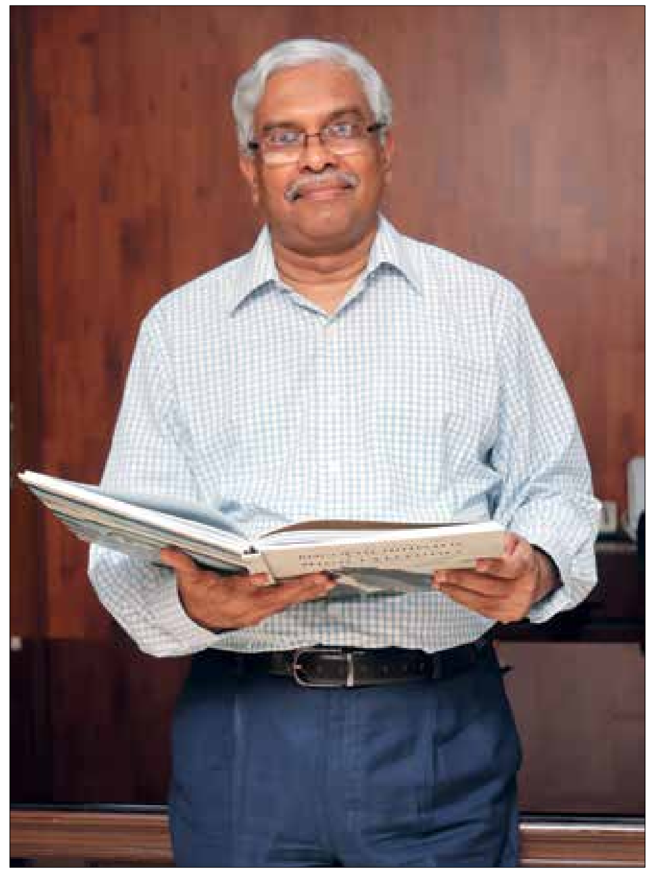
TOWARDS A CLIMATE-RESILIENT TOMORROW

The sustainable protection of our planet's tomorrow is possible only through a dynamic understanding of its different components, their interaction and interdependence; discusses **Dr Madhavan Nair Rajeevan**, Secretary, Ministry of Earth Sciences



In today's age of climate change challenges, how much more relevant has earth science studies become?

The Ministry of Earth Sciences (MoES) ensures an interdisciplinary approach to the study of the planet. Earth isn't uniform; it is made of the atmosphere, lithosphere, hydrosphere, biosphere, cryosphere and each, while unique, is also interlinked in its reactions and well-being. So, if we want to address any issue of the environment – whether pollution or rainfall distribution – we must first gather a very clear understanding of all five systems that make the Earth. Therefore, no doubt, it is of utmost importance today that we have dedicated institutions that study earth sciences. Moreover, in India, the beauty lies in the assimilation of departments. For instance, for weather prediction, IMD (Delhi) and NCMRWF (Delhi) are constantly collaborating to develop models, IITM (Pune) also intervenes and INCOIS (Hyderabad) is roped in for ocean-related information. Further, we are constantly collaborating with the academic community whenever any expertise is sought. Earlier, weather prediction meant a complete dependence on IMD; now, that era has gone and a range of stakeholders are involved.

> To address any issue of the environment, we must first gather a very clear understanding of all five systems that make the Earth

United Nations declared 2020-30 as the 'Decade of Oceans' – how is India approaching this global position?

Oceans cover a majority of our planet but much remains unknown. We know much more about the Moon than the oceans in our planet. They are a most essential resource for a variety of reasons. Most importantly, they assist in regulation of climate while also being rich in resources such as fish, herbs and even minerals. India has already received a nod from the International Seabed Authority (ISA) for two exploration projects, one on polymetallic nodules in the Indian Ocean and the other on hydrothermal sulphides.

Oceans also provide rich sources of clean energy creation. We are trying to advance technologies to better utilise ocean waves and perhaps develop instruments for use in the shipping industry. The other important feature is thermal grading, which can be used for electricity generation and also to convert sea water into potable water through desalination plants. We already have three such plants in Lakshwadeep and six more are underway.

India is also pursuing its Deep Ocean Mission of which, a most significant component is the development of a man-submersible – a pseudo spacecraft that can be submerged into the depths of the ocean. It can carry three people and travel to about 6,000 m for 12 hours. A challenge with the ocean is that its water exerts a great amount of pressure and we need technology to develop an exact, conducive model of the man-submersible. The main element of the submersible will be a titanium sphere of about 8 cm thickness which will host three humans. Building this is quite tricky and only five countries have the technology so far. NIOT (Chennai) is already developing a system.

How can past climate changes lend insight into the possible future?

Past climate lends many clues. By tracing incidents of our near past, we can make robust conclusions about what can be expected in the future. For instance, by drawing correlations between past temperatures and nature of climate – we can estimate what can be dangerous for the future. Manual observations began only 100-150 years back with the use of thermometers, barometers and sophisticated machinery. For a preceding time, we have to observe tree rings and ice cores, especially from Antarctica, to check on the past. In fact, sometimes, by digging the Earth to a few hundred metres we can receive samples from many hundred years back, carrying clues of geophysical conditions then. Many pursue these studies, particularly on the ocean floor. For instance, India's participation in the IODP programme focussed on the Himalayan orogeny through a study of the Laxmi Basin on Arabian Sea to understand how monsoons have changed in the country. The expedition required huge investments and India took a leading role – it was a good experiment!

Earthquakes remain unpredictable. Despite this known impediment, how are we pursuing the future?

Earthquakes aren't predictable and technology too hasn't been developed. Some countries do use early warning where they trace tremors. So, when an earthquake strikes, you have about a few minutes before its reactions affect the surface. This little window can be used in some cases; of course, we can't evacuate people but for top-security services like nuclear plants or oil fields, it is useful. Japan has such a system where its nuclear plants automatically shut down on registering tectonic movement. Such kind of technology we too can adopt but beyond that it's difficult. Especially because the Himalayas make for very tough topography and communication is still limited. Even if some seismic movement is noticed, communicating it to the mainland quickly is difficult.

What is your vision for MoES?

We need huge investments as Earth Science is the need of the hour and constant upgradation has become absolutely necessary. We also need trained people, which is amiss. Since earth science is not a natural science like physics or chemistry, universities hardly teach the subject. So, we have to hire people from mathematics and physics, train them and then they become suitable. We really need huge investment here as getting talented people in the market is nearly impossible. We are trying to encourage universities to begin training students, so in the time ahead, hopefully, we will be even better equipped.

> India is developing a man-submersible – a pseudo spacecraft that can be submerged into the depths of the ocean

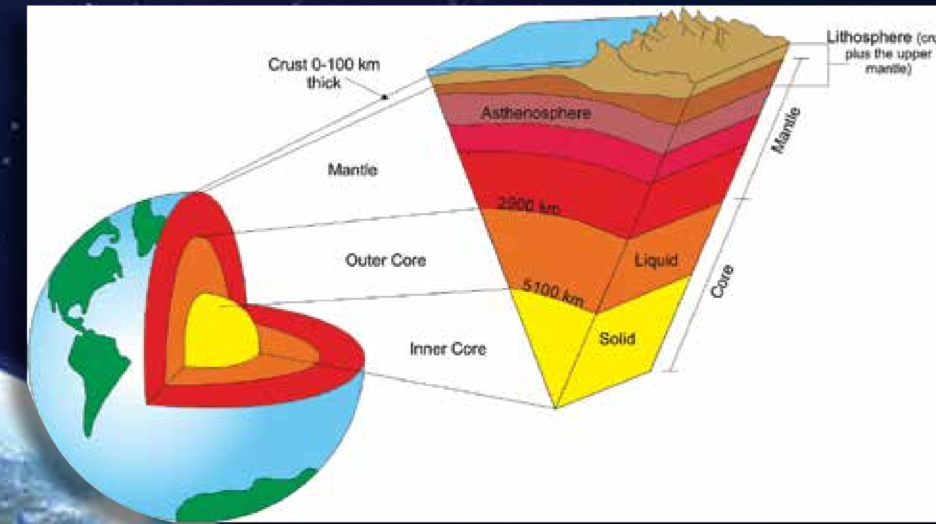
On Land

GEODYNAMICS & SOLID EARTH RESEARCH

UNRAVELLING **EVOLUTION**

The Earth's surface is a treasure trove that lends precious insights into our planet's geological origin and evolution – especially in the subcontinent that is marked by rich variations in topography and outstanding geological anomalies

Graphical representation of Earth's core



A segment of Earth's surface

The lithosphere, comprising the solid surface of our planet, extending from the surface where existence thrives to the uppermost part of the mantle, is a prime component of the Earth's system. Along with atmosphere, hydrosphere and biosphere, it carries properties that allow the sustenance of life and civilisation. Though extending only ~200 km into Earth's interior, the average distance between the surface and Earth's core being 6,371 km, the lithosphere is marked by distinct large-scale activities such as earthquakes, mountain-building,

Deccan traps

sea-floor spreading, etc., that have been pivotal to the origin and evolution of our planet over many billion years. Naturally, to truly understand the scope of our planet's dynamic evolutionary history, conducting solid Earth research has been pivotal. For this, an array of processes and tools has been duly developed – ranging from simple microscopic observation of rock specimens present on the surface to seismic tomographic imaging of deep Earth.

INSIDE THE EARTH

A link between geodynamics and landscape evolution is intrinsic to solid Earth research; and the subcontinent, being a land of varied distinct geological terrains, provides ripe scope for deep enquiry and knowledge creation. Home to a variety of rock formations – with ages ranging from 3,900 billion years to recent – the geological framework of the subcontinent primarily comprises crustal blocks formed under high temperature and pressure (high-grade) surrounding stable cratonic terrains comprising low-grade rocks, deep faults and shear/suture zones that separate these terrains, sporadic igneous intrusions and sedimentary cover sequences. These rocks do not only contain messages delineating our evolutionary history but are also rich reservoirs of minerals and hydrocarbons – a primary source of the subcontinent's celebrated resource-rich identity.

Though the history of specific blocks remains elusive, these formations were also a part of erstwhile supercontinents Columbia, Rodinia and Gondwana that amalgamated at different points of time along the shear/suture zones. The exact nature of these zones is important to propose precise supercontinent configuration but alas, such data remains scarce.

Another remarkable geological feature of the Indian subcontinent has been the formation of Deccan flood basalts. Coinciding with the final rifting and breakup of Gondwana supercontinent, they emerged due to continental volcanism that occurred when the Indo-Australian plate slid over existing mantle plumes in its north-ward journey towards the Eurasian plate. This volcanism led to the formation of a passive margin and adjoining escarpment along the western coast of India that is today known as the Western Ghats. However, robust geophysical observation to delineate the exact nature and process of this passive formation is amiss.

> Another remarkable geological feature of the Indian subcontinent has been the formation of Deccan flood basalts

Finding opportunity in challenge, the National Centre for Earth Science Studies (NCESS), established in 1978, has been passionately pursuing the study of solid Earth research in the south Indian shield to find the missing pieces in the grand jigsaw of the subcontinent's geological becoming. Equipped with a multi-disciplinary approach integrating geological, geochemical, geophysical and geochronological studies, NCESS is pursuing its research with a few specific targets:

- Trace India's position through geological time in global geodynamic continental configurations
- Unravel magmatic and metamorphic processes, petrogenesis and evolution of high-grade metamorphic terrains (and Archean cratons)
- Constrain the evolution of Western Ghats escarpment and elevated passive continental margins
- Investigate interplay of near-surface processes, hazard vulnerability and mechanism of Western Ghat uplift

SCIENCE OF EXCEPTIONS

The conditions on our planet's surface have a complementary expression in its interior, both in the shallow subsurface and deeper parts. For instance, surface processes like upliftment, erosion, subversion will find parallel occurrence in the internal structure, whether in the asthenosphere, upper mantle or plate boundaries. To conduct geophysical studies, a few prominent geological exceptions or anomalies are studied and their corresponding sub-surface expressions are read and researched.

Western Ghats again features prominently in geophysical studies owing to its exceptional escarpment that extends over 1,500 km along the western coast of India. With an average elevation of ~1.2 km, it is a mosaic of distinct geological formations with varied structural and physical characteristics. The Western Ghats primarily covers the Southern Granulite Terrain (SGT), Western Dharwar Craton (WDC) and the Deccan Volcanic Province (DVP). Despite extensive studies with myriad explanations, a conclusive explanation for its evolution remains elusive.

Another important geophysical mystery would be in defining the lithospheric structure across major shear zones. Shear zones emerge as a result of the deformation of a huge volume of rock due to intense accumulation of stress in a region. Predominant at the edges of tectonic blocks, answering fundamental questions on the presence and development of shear blocks is central to our reconstruction of tectonic history.

The Indian Ocean Geoid Low is the greatest oceanic anomaly that lies just to the south of the Indian subcontinent. Registering a low of -106 m, this is the most spectacular and largest such

> Surface processes like upliftment, erosion, subversion will find parallel occurrence in the internal structure, whether in the asthenosphere, upper mantle or plate boundaries

Rock bed in the Himalayas

anomaly, though its origin remains elusive. The study of this geoid low has attracted a number of global scientists and is a key clue to resolving our planet's evolutionary story.

At the forefront of geophysical studies in the country, NCESS has been utilising a range of tools and methodologies including seismology, magnetotellurics, gravity and magnetic methods to answer questions regarding the geodynamic evolution of Western Ghats and overall tectonics of the Indian subcontinent.

THROUGH THE LOOKING GLASS

The Precambrian crustal blocks of south India, commonly known as Southern Granulite Terrain, is home to a wealth of information on multiple episodes of magmatism, metamorphism and melting that have occurred over protracted periods of time since the early-Archean period. A major attraction for petrologists from across the world, these high-end granulite terrains that lend valuable insight into lower crustal processes such as melting, crystallisation and metamorphic time-scales, are considered 'windows into the lower-crust'. The precise timing of each episode of deformation and active metamorphism is discerned from careful field observations at rock outcrops, petrographic observations under the microscope and geochemical and geochronological studies. Alongside, structural mapping of relevant areas is also inevitable. Exploration and petrographic studies under microscopic lens provide information on the formation of minerals and their breakdown reaction textures which consequently provide clues to conditions prevalent at the time of formation.

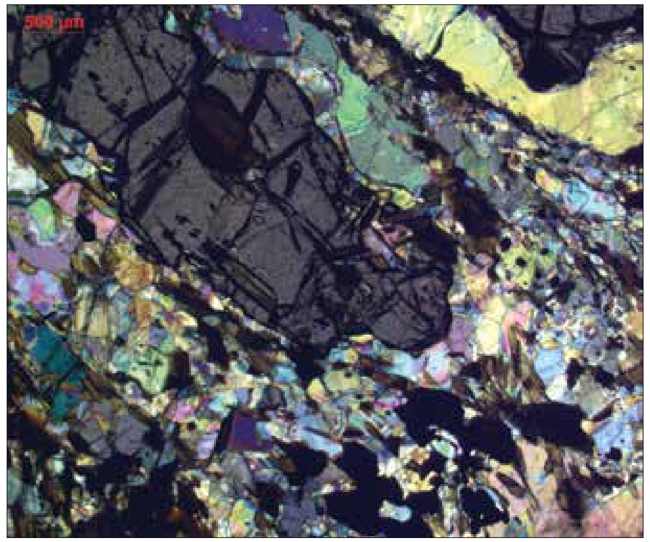
Presently, granulite studies focus on crustal blocks in south India (Madurai, Kerala Khondalite Belt, Nagercoil) and Eastern Ghats Belt (EGB) along the east coast of India. Further, studies on granulite facies rocks in Himalayas (Kumaon & Garhwal) have now been initiated so that comparisons may be drawn between geological phenomenon that have unfolded in peninsular and extra-peninsular India. Recently, an Indian expedition to East Antarctica studied the geodynamic evolution of Princess Elizabeth Land (PEL) and Mac Robertson Land (MRL) — to draw correlations with the Eastern Ghats Belt with which it is believed to share conjugate granulite terrain.

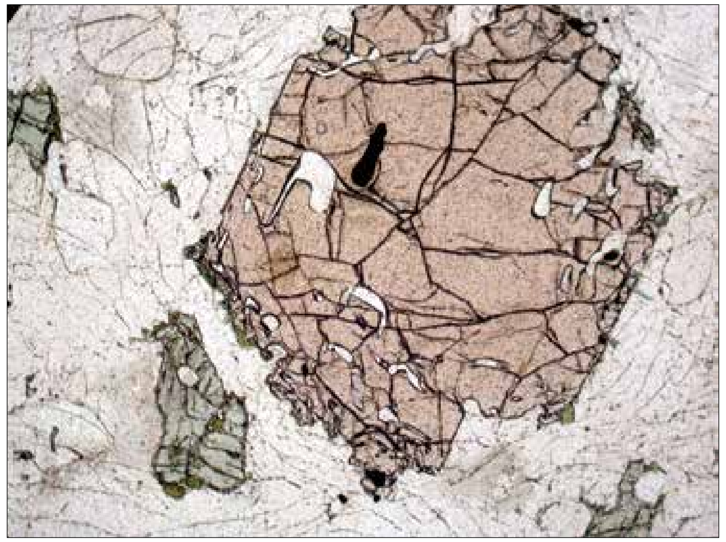
HIDDEN IN SEDIMENTS

The Quaternary Period that

> Presently, granulite studies focus on crustal blocks in south India and Eastern Ghats Belt (EGB) along the east coast of India

Extending landscape of the Western Ghats





Minerals under microscope

commenced some 2.6 million years ago is known to have witnessed exceptional alterations in landforms, climate and sea-levels. These changes have been preserved in sedimentary sequences along the western coast of our country and are a rich source of strategic mineral deposits and potential hydrocarbon reserves. Investigations not only lend insight into resource accumulation but also elucidate paleoclimatic and sea-level changes in the region with predictions on possible future climatic shifts.

NCESS's research in sedimentaries also emphasises the study of paleofluids to understand complete hydrocarbon potential and fluid evolution. It involves petrographic, microthermometric and photoluminescence emission, Raman analysis of fluid inclusions, and evaluation of fluids that interacted with different formations since sedimentary basin development.

ANALYSING CHANGE

The Earth Science System, as has been established, is an amalgam of a number of processes with multiple causative factors that may be visible, such as climate change, or invisible, such as lithospheric evolution. Therefore, to ensure conclusive results, a multidisciplinary approach supported by state-of-the-art equipment will be the most suitable for deriving meaningful observations on the different processes that shape the Earth, its environment and habitat.

The Solid Earth Geosciences program at NCESS has two broad objectives – first, to understand the crust-mantle processes unfolding under the Indian subcontinent and second, to understand the nature of plateau uplift and its surface manifestations along the passive continental margin tectonic environment of Western Ghats escarpment. These two corresponding processes have massively shaped the structure of the Indian landmass and consequently, understanding their composition and evolution is of paramount importance to draw a comprehensive understanding of the geodynamics that define the subcontinent.

HAZARDS

Landslides: Landslide is a most devastating natural phenomenon that occurs particularly on slopes during the monsoons season. Causing rampant loss of life and property, landslides call for more intense understanding and adaptation of strategies to mitigate the ensuing adversity. Running parallel to the western coasts, the 1,500-km-long Western Ghats is fragile and deeply susceptible to landslides and indication of such specific areas is the first step towards mitigation. At NCESS, landslides are studied with a mix of geological, geophysical and geotechnical methods that are deployed across two phases – the pre-disaster and post-disaster phase.

While pre-disaster studies involve landslide inventory mapping and landslide susceptibility mapping, the post-disaster study demands detailed geological field investigations and mapping of various profiles/traverses in Western Ghats to identify potentially unstable profiles. Soil samples are rigorously collected to determine geotechnical properties and shear strength while the Electric Resistivity Tomogoraphy technique has been applied to identify slip surface and hydrological conditions.

Soil Piping: Land degradation due to land subsidence by soil piping (also known as tunnel erosion) has become a common feature of the Western Ghats, especially in Kerala and Karnataka. Soil Piping refers to the subsurface erosion of soil caused by percolating waters that produces pipe-like conduits below the ground, especially in non-lithified earth materials. Common near landslide scarps, it is believed that the build-up of pore water pressure due to clogged soil pipes initiates landslides. In monsoons, these soil pipes carry silt and finer particles and can grow into a tube with a large diameter.

Electrical resistivity imaging is conducted to delineate conducive zones where soil pipes are formed, providing evidence for the formation of a soil pipe. In the wake of extreme events that the highlands of Western Ghats witnessed in 2018-19, plans to intensify scientific investigations studying the factors triggering landslides and subsidence have gained momentum.

NCESS also intends to set-up landslide monitoring stations to understand the behaviour of creep/ lateral spreading in the highlands of Kerala and some parts of Karnataka. If successful, it can be spread out to other vulnerable areas too. These monitoring systems will be used for early warning systems (EWS) as slope instability using acoustic emission monitoring to detect accelerating slope movements and subsequently communicate the warnings to users.

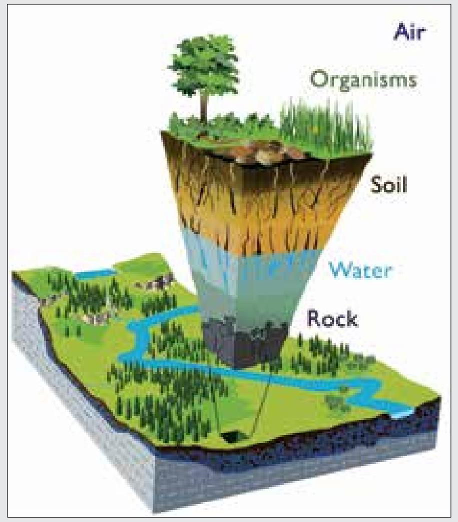
Running parallel to the western coast, the 1,500-km-long Western Ghats is fragile and deeply susceptible to landslides

Landslide in the Western Ghats

Critical Zone Observatories

The narrow near-surface terrestrial environment of our planet extending from the top of the canopies to the lower limits of groundwater aquifers that primarily sustains life is known as the critical zone. Abundant in resources, this zone nourishes conditions most conducive to life on our planet. It is critical to survival and is also under constant pressure from anthropogenic exploitation, misuse and climate change. Consequently, to meet demands of present generations and also ensure sustainability through the future, studying, understanding, predicting and managing this life-sustaining natural capital is of paramount importance.

Critical Zone Observatories (CZOs) fulfil this role of studying the critical zone but despite international efforts, such an initiative has been amiss in the tropics, despite the monsoon-dominated region's abundance in resources and proclivity to climate and human-induced disasters. India, particularly, witnesses deep threat to its critical zones owing to exploding population levels, high density and rapid economic growth. An absence of adequate



Earth's Critical Zone

number of fully-functional CZOs in India dampens the spirit of achieving sustainable development targets.

Mindful of India's vulnerability, NCESS has initiated a program to establish a network of CZOs in the country under the theme "TERRAIN" (Tropical Ecosystem Research obseRvatories in peninsulAr India). In the first phase, CZOs were set up in Munnar (tropical humid), Attappadi (sub-humid – semi-arid transition) and Thanjavur (deltaic lowlands) in southern peninsular India. The observatories in these distinct locations, equipped with state-of-the-art instruments, will generate data that will lend insight into the controls of resilience, response and recovery that function in critical zones with consequent perturbations in climate, land-use and anthropogenic interference.

NCESS aims to further develop these CZOs into superior quality platforms for advancing critical zone studies. The data and methodology developed here is expected to aid real-time services such as optimum irrigation scheduling and nutrient support for cropping under stress. Thereafter, it will provide reliable scientific support for propulsion of ideas like 'more crop, per drop', as India strives towards achieving complete self-sufficiency in food production.

Continuous profile soil moisture sensor installed in the Attappadi CZO

Coastal Monitoring System

For continuous monitoring of the coast and to derive understanding of the complex beach-surfzone morphodynamics, a pilot project has been initiated at the NCESS. For this, a video-based beach monitoring system has been installed at Valiathura beach in Thiruvananthapuram, Kerala, since September 2016. This demonstration system is the first of its kind in India and a second station has been setup at Kozhikode, north Kerala.

The key component of this system is a remotely-operable video imaging system (along with accessories) which can continuously monitor a chosen coastal area. Further, the software used to process the data comprises tools developed in-house using MATLAB software. The processed data gives vital information regarding the spatial and temporal variations in coastal processes, particularly surfzone dynamics and beach morphology.

The study provides valuable information on the complex coastal processes along the southwestern coast of India which exhibit spatio-temporal variations. The full-fledged coastal monitoring system, after being certified as a tested and proven system, can be used as an effective tool for understanding seasonal changes in coastal processes. The results from site-specific observations can provide valuable inputs for accurate prediction of wave run-up, coastal flooding and also review the adaptability of existing empirical equations for identifying the erosion and accretion processes.

In addition, this facility studies the influence of driving forces that can lead to localised coastal flooding along the country's southwestern coast, especially during the non-monsoon period. Special emphasis has also been laid on societal development activities like providing timely alerts to the coastal communities during adverse weather conditions. Further, the real time data available through the system can be of vital importance to agencies involved in coastal disaster mitigation and management.

Present status

- Two stations established: Valiathura, Thiruvananthapuram (2016) and Kozhikode (2018)
- New codes and algorithms developed for analysis of video imagery – tools to measure beach width, surfzone width, swash zone width, wave run-up, wave parameters
- Experimental studies to test the suitability of thermal camera for observations during night is in progress

Future plans

- Video monitoring network in India for long-term coastal monitoring {initially in SW coast by installing new camera stations at Mangalore, Goa, Varkala and Lakshadweep, and also in Pondicherry (SE coast) during 2019-22}
- Testing and improving algorithms to suit the Indian coast
- Providing information on short-term shoreline changes, hydrodynamics, near-shore bathymetry, sandbar movements, rip currents, etc.

Off the western coast of India

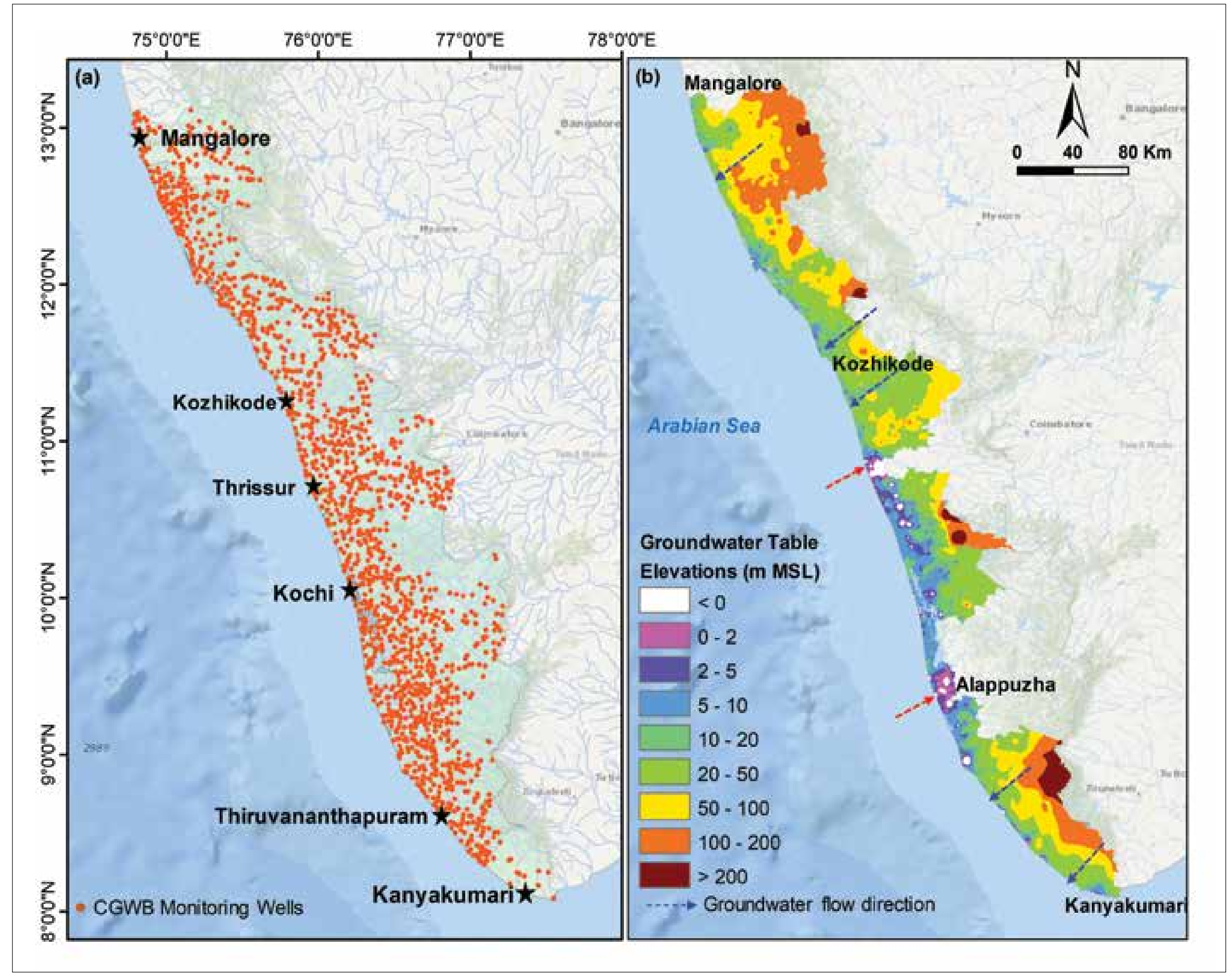
Signature of Submarine Groundwater Discharge at the land-sea interface

In search of freshwater resources

The discharge of groundwater to sea through coastal aquifers or Submarine Groundwater Discharge (SGD) has been recognised as small volumetrically but quite significant ecologically – primarily because SGD offers an important pathway of nutrients, carbon and other geochemical constituents into the ocean. Knowledge of the nature of SGD allows us to estimate optimum extraction levels of potable groundwater and also provides information on feasible waste disposal sites in coastal zones. SGD varies both temporally and spatially as the interaction between multiple forcing mechanisms differs at any given location and time. Thus, site-specific investigation is imperative to comprehensively evaluate the timing, magnitude and importance of SGD in any interface zone between salt water and fresh water. This national-level study is reportedly the first-of-its-kind for SGD flux determination in the world.

In today's time, comprehensive understanding of this component of the water cycle is much more relevant as changing climate is swiftly affecting coastal hydrology. The study focuses on:

- Identification of SGD and saltwater intrusion (SWI) along the coastal zone
- Computation of SGD flux, carbon and nutrient load through submarine groundwater discharge



(L) Locations of groundwater monitoring wells available with the Central Groundwater Board; (R) Indication of coastal groundwater dynamics from archival data

A pilot study has been launched for mapping coastal aquifers and for delineation of SGD segments in designated areas between Kanyakumari (Kothayar basin) in Tamil Nadu and Mangalore (Nevrathi basin) in Karnataka, stretching across 750 km. The study involves:

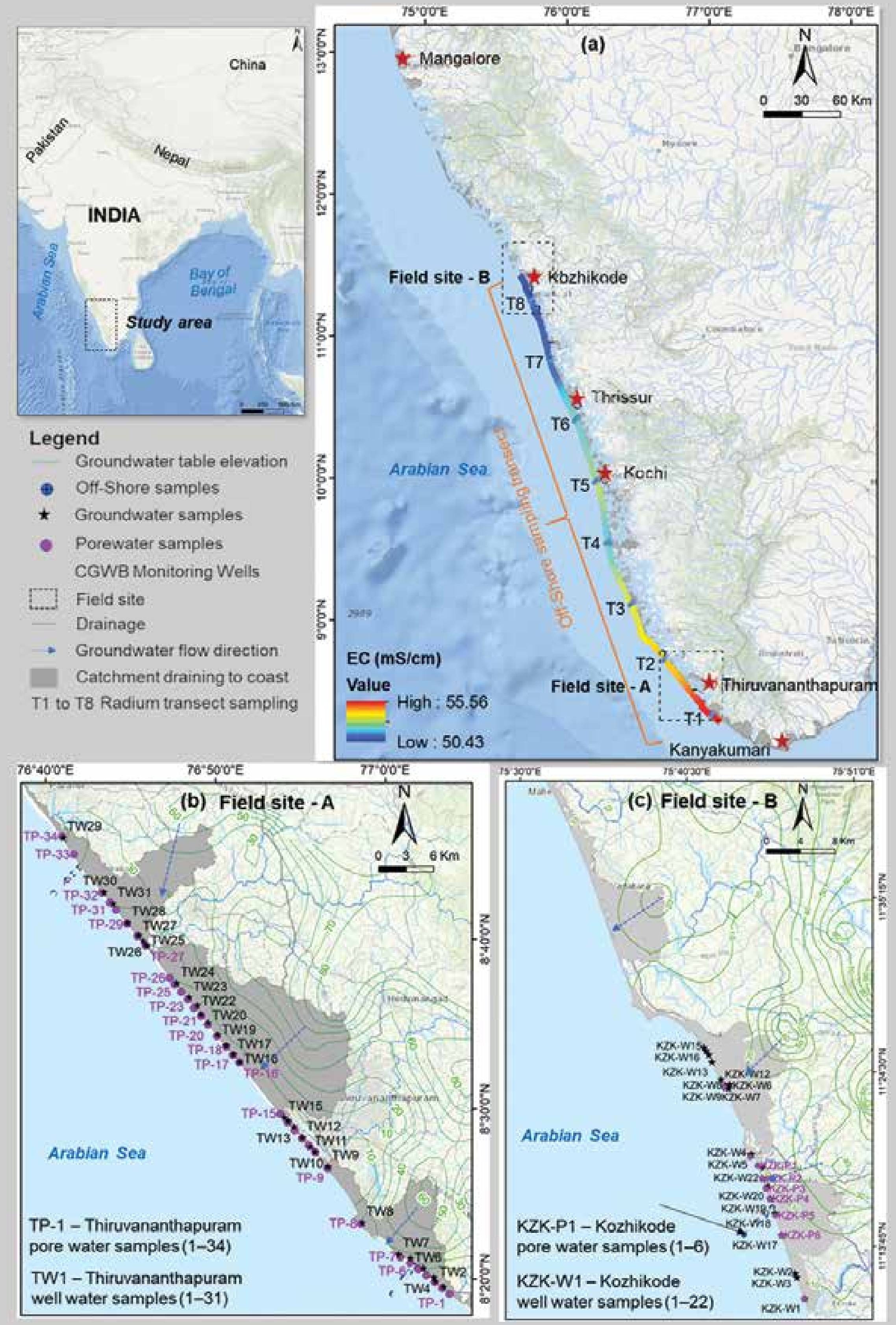
- Computation of SGD flux and nutrient flux in the designated area
- Collection of archival database on coastal aquifers along the eastern and western coasts of the country
- Evaluation of probable SGD segments using thermal image

To investigate the groundwater dynamics in the pilot project area, archival data from the Central Ground Water Board (CGWB) monitoring wells located across the Kerala coast were utilised to generate a groundwater level map above the mean sea level. Data shows that elevated water table positions are more prominent towards the northern Kerala coast in comparison to the south, a reflection of the undulating nature of the topography on the water table. The high hydraulic gradient towards the shoreline provide clues on groundwater discharge to the sea in such segments. Alternatively, potential zones of seawater ingress are also visible.

Satellite thermal infrared imaging has assisted in identifying the location and spatial variability of SGD by exploiting the temperature difference between surface water and groundwater at certain times of the year, particularly in summer. Sea surface temperature derived from Landsat 8 thermal infrared (TIR) imagery of Thiruvananthapuram district in Kerala allowed the mapping of several thermal anomalies related to the outflow of freshwater plumes with temperatures ranging from 22.9°C to 24.06°C. This is lower than the minimum sea water temperature (25-33°C) usually recorded for the area.

After delineation of probable zones of groundwater discharge, fieldwork is essential to collect primary evidence. Water table measurements taken from 120 observation wells along the southern coast of the state identified two segments of SGD zones – Adimalathura and Varkala. Monitoring of water table fluctuation, groundwater conductivity, salinity and groundwater temperature in the beach zone using in-situ water quality data loggers has greatly assisted the study.

Seepage of groundwater from coastal aquifer to sea at Varkala, Kerala



Representation of the alignment of water table in near shore zone as well as sampling locations of pore water, groundwater and sea water — essential for SGD investigations. Electrical Conductivity variation along the coast and disposition of coastal catchments have also been depicted

SCIENTIFIC DEEP DRILLING PROGRAMME

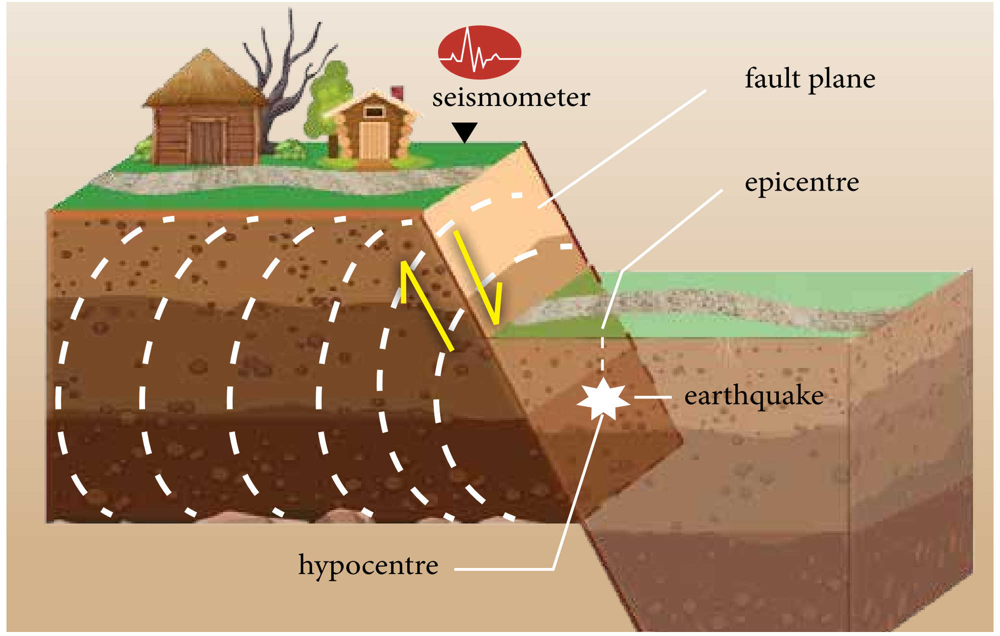
SCIENCE OF EARTHQUAKES

Despite growth in science, progress in earthquake research has been limited. Challenging this paradox, India is swiftly developing its own research capabilities in earthquake science to unravel mysteries that have long perplexed the scientific world

The Indian subcontinent, over the years, has been shaken by a number of large earthquakes – not only in the plate boundaries but also in the plate interiors – causing visible collateral damage to life and property.

With time, an urgent need has been realised to explore deep within the ground and reach the hypocentre, from where the earthquake originates, to gather a more coherent understanding of earthquake-prone zones. While the hypocentre is located deep, the epicentre is the point on the Earth's surface that is exactly above the hypocentre, where the impact of tectonic movement is most accentuated. The distance between the epicentre and hypocentre is

Scientific deep drilling in Koyna



A representational diagram of an earthquake occurring along a fault plane

What is an earthquake?

An earthquake is a sudden release of energy which occurs when two blocks of the Earth slip past one another. The surface where the slip takes place is called the fault plane. The location below the Earth's surface where the earthquake originates is called the hypocentre and the location directly above it on the surface of the Earth where the earthquake is finally experienced is called the epicentre.

understood as the hypocentral depth. Now, with modern advancements, the Ministry of Earth Sciences (MoES) has deployed various mechanisms to study this hypocentral depth and gather a more comprehensive understanding of the fundamental aspects influencing the earthquake process. Consequently, these fresh perspectives have led to the development of a comparatively new branch of science: Earthquake Science.

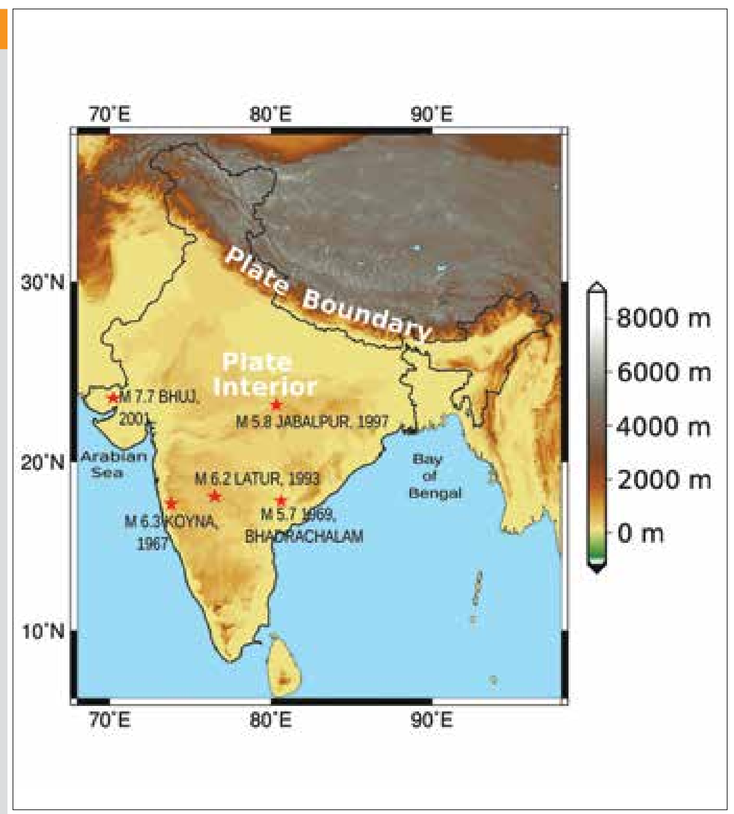
Intraplate earthquakes

Intraplate earthquakes (which occur within a plate interior) are relatively uncommon when compared to inter-plate earthquakes (which take place at the plate boundary) but can be potentially devastating as they occur at least expected locales. The surface features of the intraplate fault systems are often poorly expressed and their genesis too is not well understood. Several major questions about intraplate earthquakes remain unanswered, such as: Why do they occur? Where do they occur? What geological conditions favour their occurrences? Are they likely to occur again?

Intraplate earthquakes, therefore, are often deadly, causing immense loss to life and property.

Recent such events in India

YEAR	LOCATION	MAGNITUDE (M)	LIVES LOST
2001	Bhuj	7.7	~20,000
1997	Jabalpur	5.8	~43
1993	Latur	6.2	~11,000
1969	Bhadrachalam	5.7	-
1967	Koyna	6.3	~200



Recent intraplate earthquakes in India (map not to scale)

Recovery of a 4" diameter rock core from 2,900 m depth in Koyna region

APPROACH WITH A DIFFERENCE

MoES has adopted a two-pronged approach to study the multifaceted aspects of earthquakes:

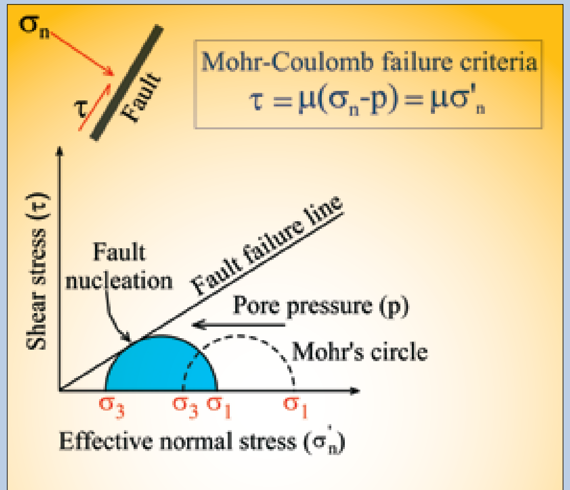
- First, increasing the density of seismic stations across the country
- Second, making advancements in understanding earthquake genesis in select areas

Both these approaches, working complementarily, will yield benefits in not just understanding earthquakes but also tempering the humongous damage caused by unpredictable tremors.

While the National Centre for Seismology (NCS), Delhi, holds the mandate to establish and maintain a national seismic network, MoES has recently established the Borehole Geophysics Research Laboratory (BGRL) at Karad to study certain fundamental aspects of earthquake genesis. In Karad, capabilities in scientific drilling will be leveraged across the seismologically active landscape while elaborately studying the corresponding near field. In this, the deep drilling programme of BGRL is distinctive as it explores changes in physical and chemical properties of rocks in the near field of earthquakes. Near field is best defined as the region close to the hypocentre, under the surface of the Earth, where an earthquake has occurred.

EARTHQUAKE SCIENCE

Earthquake science does not just include seismology; it also involves studies in earthquake geology, geophysics, rock mechanics and study of complex systems. Earthquakes are of diverse kinds, and to build solutions that can limit their consequences, it is essential to understand their genesis.



MECHANISM FOR TRIGGERED SEISMICITY

Reservoir impoundment increases the pore fluid pressure at the hypocentral depth. This reduces the normal stress acting on the fault and triggers an earthquake when the stress level falls below a threshold value

Reservoir triggered seismicity (RTS)

Under certain geologically favourable conditions, artificial water reservoirs trigger earthquakes in pre-existing sub-surface fault(s), either by increasing vertical load because of the weight of water or by decreasing normal stress due to rising pore fluid pressure. Such earthquakes have been reported from over 100 sites globally.

Damaging Reservoir Triggered Earthquakes with Magnitude (M)>6

YEAR	LOCATION	MAGNITUDE
1967	Koyna, India	6.3
1966	Kremasta, Greece	6.2
1963	Kariba, Zambia	6.2
1962	Hsinfengkiang, China	6.1

But, the advancements in this field have been meagre. The possibility of completely predicting earthquakes still seems elusive; but if the underlying mechanism is understood better, seismic hazards can perhaps be addressed more realistically.

KOYNA: A NATURAL LABORATORY

In the Koyna region of Maharashtra, earthquakes have been occurring frequently over the past 56 years, starting soon after the impoundment of the Shivaji Sagar Dam on the Koyna River in 1962. Flowing from Mahabaleshwar southward towards Koyna and then bending sharply towards the east, the river passes through Karad to later join the Krishna River.

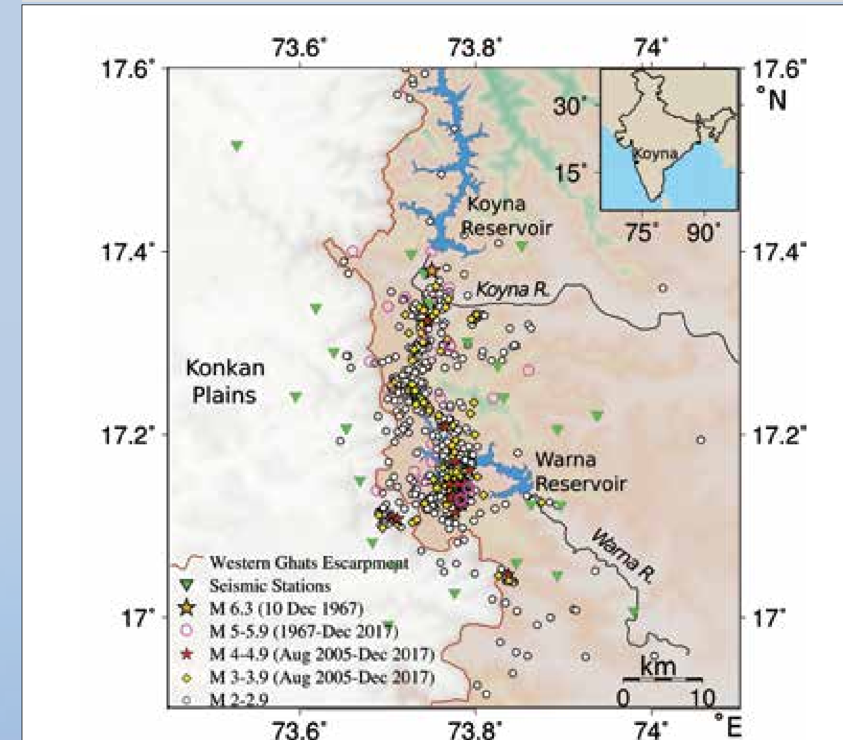
At Koyna, the hydroelectric power plant produces around 2,000 MW of electricity and is one of the largest hydroelectric power projects in the country. But, on the flipside, since the impoundment of this reservoir, seismic disturbance has become typical to the region. Though there exist more than 100 sites globally reporting reservoir-triggered earthquakes, in a majority of these cases, the earthquakes have subsided within a few years of reservoir construction.

In Koyna though, the situation remains unique as earthquakes of varying magnitudes persist even today. The largest earthquake in this region, with a magnitude of 6.3, was recorded in 1967, near the site of the Shivaji Sagar Dam. It raised many questions on induced seismicity while claiming about 200 lives and injuring another 2,000. Since then, almost 20 earthquakes with magnitudes greater than 5 on the Richter Scale have been reported along with at least 200 other events with magnitude between 4 and 5. Besides, more than a thousand earthquakes with magnitude ≤ 4 have also occurred.

The earthquakes in Koyna are distinct as all seismic activity here is restricted to a limited area and majorly confined within 10 km depth. The region

RTS at Koyna-Warna

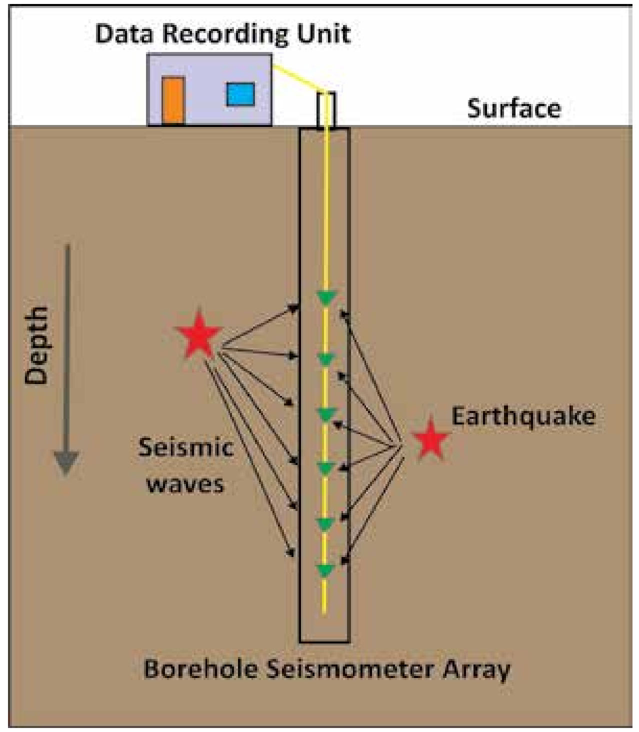
The 1967 M6.3 Koyna earthquake in western Maharashtra is the largest reservoir triggered earthquake, which led to the loss of about 200 lives besides causing damage to property. Understanding the genesis of reservoir triggered earthquakes may lead to better preparedness and also assist in finding safer sites for locating dams for hydropower, irrigation and flood control.



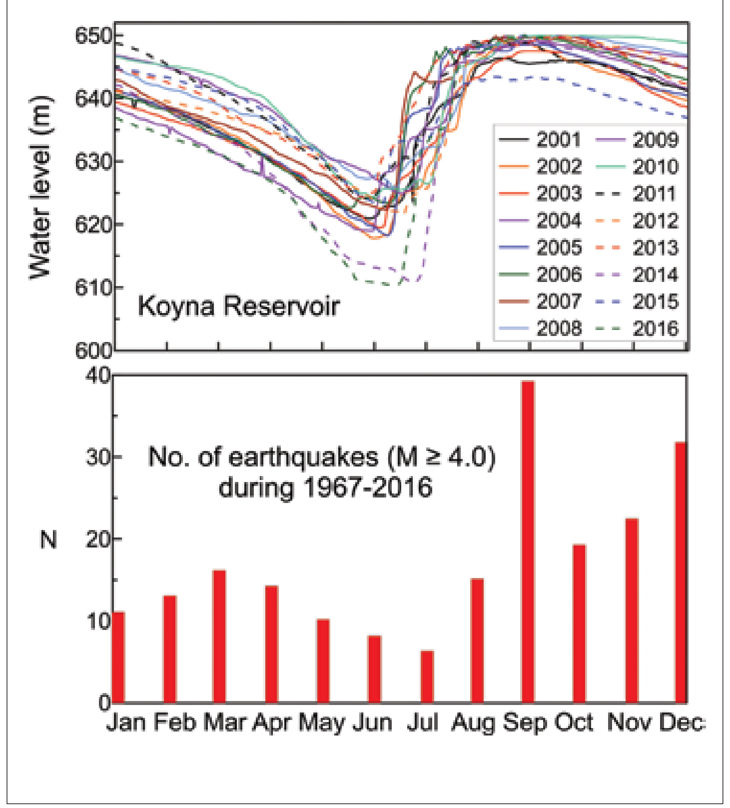
Seismicity map of the Koyna-Warna region

Panaromic view of the pilot borehole (KFD1) site

Borehole instrumentation schematic



Studies in Koyna depict a positive correlation between water levels in the reservoir and occurrence of seismic activity. As water rises in the post-monsoon period, tremors too become more frequent



Diamond impregnated drilling bit

of study is, thus, restricted to an area of 20 km x 30 km. This confined area has been unanimously recognised as a natural laboratory most suitable for the study of reservoir-triggered earthquakes.

BOREHOLE GEOPHYSICS RESEARCH LABORATORY

Pursuing this mystery, a Borehole Geophysics Research Laboratory (BGRL) has been set up at Karad, Maharashtra, which has been serving as the operational centre for conducting research activities pertaining to the scientific deep drilling programme. The laboratory lays primary focus on multidisciplinary research on the science of earthquakes including borehole geophysics, seismology, earthquake geology and rock mechanics.

PARADIGM SHIFT

In Karad, a major national project, *Scientific Deep Drilling in the Koyna Intra-plate Seismic Zone of Maharashtra,* has been undertaken to directly measure the in-situ physical properties of rocks, pore-fluid pressure, hydrological parameters, temperature and other functions that characterise this intra-plate active fault zone in the near field of earthquakes – before,

Lowering a sonde into the borehole KFD1 for geophysical well logging

“With its unique capacity to provide exact, fundamental and globally significant knowledge of composition, structure and processes of the Earth's crust, scientific drilling plays a key role in satisfying society's ever-increasing dependence on natural resources, in meeting its need to remediate existing environmental damage, in learning how to sustain human progress without causing further environmental degradation and in learning how to reduce our vulnerability to natural hazards

INTERNATIONAL CONTINENTAL SCIENTIFIC DRILLING PROGRAMME (ICDP)”

Scientific drilling

Scientific drilling is an indispensable tool of modern Earth Science research as it provides the only means of obtaining direct information on the processes operating at depth. Boreholes drilled at carefully chosen sites are also used as natural laboratories for experiments and as observatories for long-term monitoring of on-going active processes.

Targets of Koyna scientific drilling project:

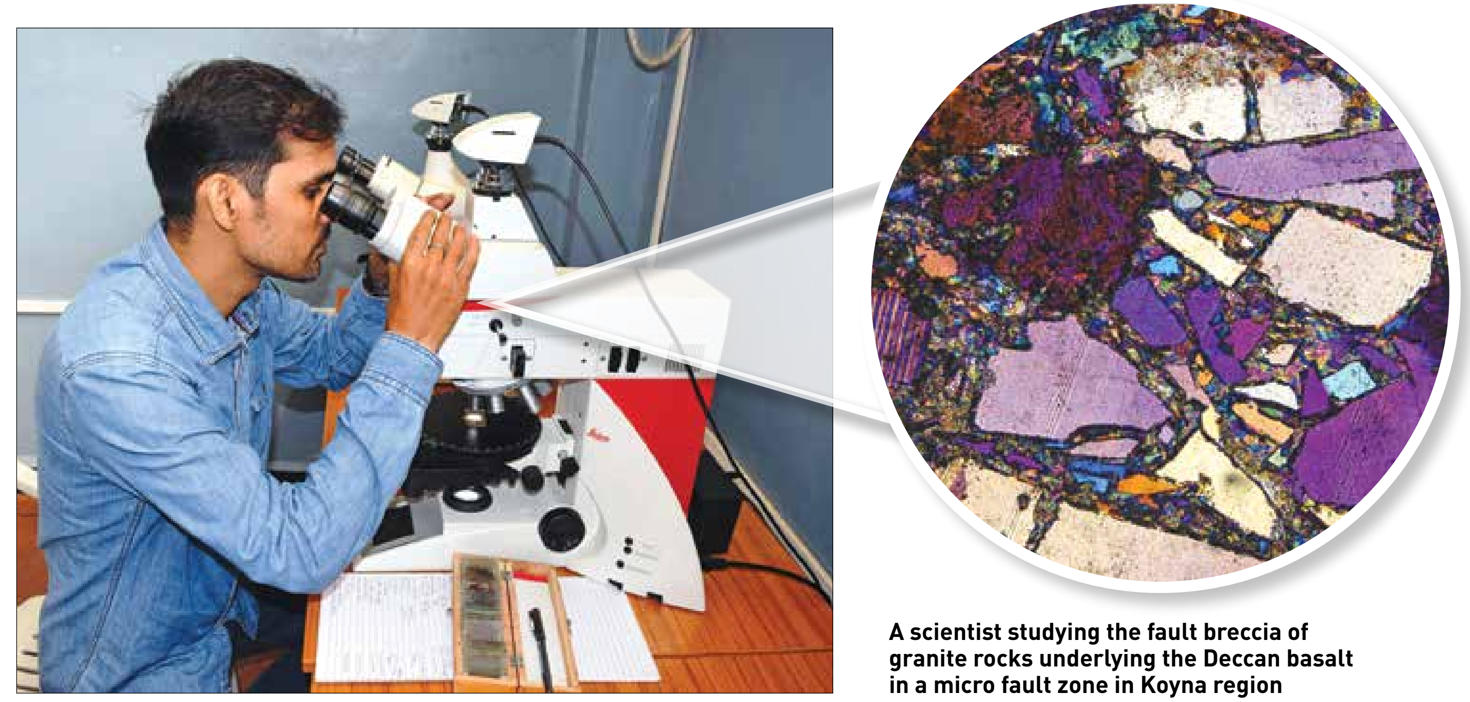
- Reach the depths of earthquakes through scientific deep drilling and set up a fault zone observatory at 5-7 km below the surface
- Sample fault zone materials for multi-disciplinary laboratory studies
- Model earthquake mechanism(s) using direct observations in the near field before, during and after their occurrence

during and after their occurrence (ie., pre-seismic, co-seismic and post-seismic analyses).

While earlier studies utilised surface observations, now, a new approach of scientific drilling investigation has been chosen. In Koyna, conducting investigations in the near field by placing sensors below the Earth's surface in the zone where earthquakes usually nucleate, is taking precedence – marking a paradigm shift from the practice of setting observatories at the surface station, which has been the mainstay so far.

This ambitious venture is being conducted across three well-defined phases – the Preparatory Phase, Pilot Phase and Deep Drilling Phase – to finally culminate in a successful deep borehole observatory located at a depth of 5-7 km in the seismically vulnerable Koyna region. Along with contributions in the study of Earthquake Science, this project will also herald a new era in India's journey of achieving indigenous scientific excellence.

Lowering of a double straddle packer system into the pilot borehole for hydrofrac tests



A scientist studying the fault breccia of granite rocks underlying the Deccan basalt in a micro fault zone in Koyna region

PREPARATORY PHASE

In the preparatory phase carried out by CSIR – National Geophysical Research Institute (NGRI) during 2012-14, various studies, including broadband seismology, magneto-tellurics (MT), airborne gravity gradiometry and magnetics, and LIDAR surveys, etc., have been undertaken. These studies were supplemented by exploratory drilling up to a depth of 1.5 km at nine sites in the vicinity of the seismic zone.

The boreholes pass through the Deccan traps and continue into the underlying granitic basement rocks. Geophysical logging and heat-flow measurements have also been conducted while borehole seismometers have been deployed in six holes. The studies have helped delineate the sub-surface structure in and around the seismic zone that is most suitable for scientific deep drilling and fault zone investigations.

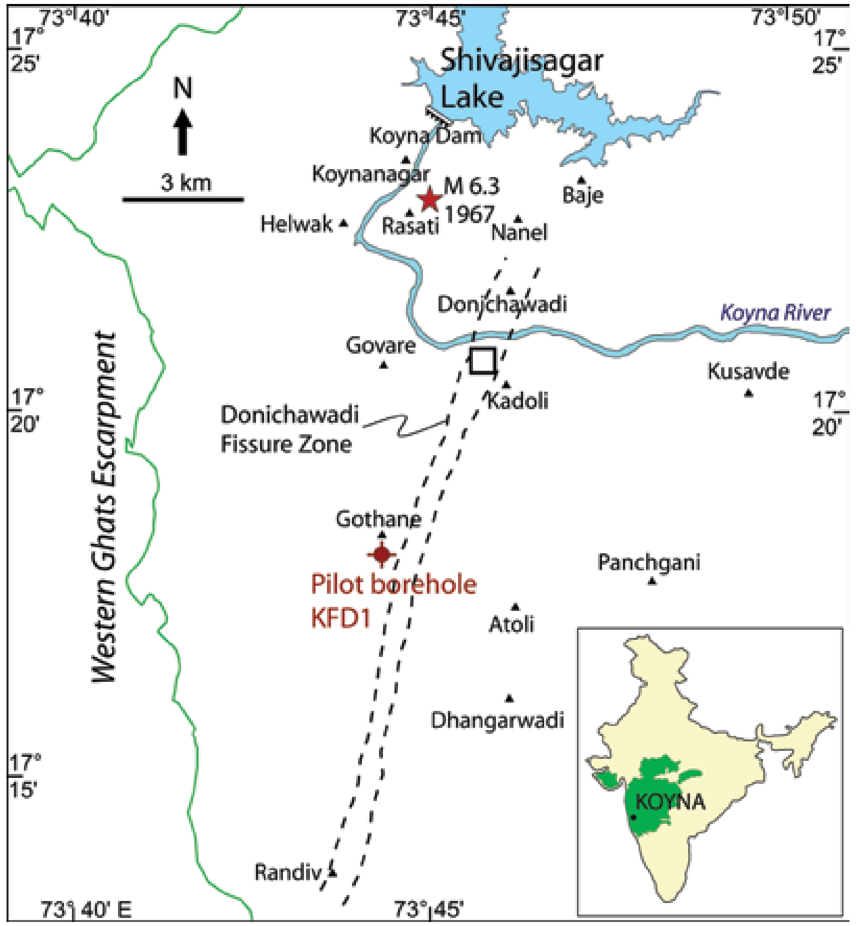
The most significant inferences obtained from the investigations carried out in the preparatory phase and subsequent studies on the borehole core samples at BGRL include:

- The thickness of Deccan traps, which vary from 412 m to 1,250 m
- Absence of infra-trappean sediments
- Presence of granitic basement rocks below the Deccan traps
- Smaller undulations in the basement topography (~100 m) when compared to surface relief of the Western Ghats (600 m to 1,000 m)
- Delineation of co-seismic deformation features in the core samples
- Subsurface temperature of 56°C at 1,500 m depth

DEEP DRILLING: PILOT PHASE

In pursuance of the pilot phase, the digging of a scientific borehole to a depth of 3 km has been completed as a forerunner to deep drilling and setting up of a deep fault zone observatory at depths of 5-7 km. Spudding of the pilot borehole (KFD-1) took place in mid-December, 2016, and the final depth of 3,014 m was reached by the end of

The project provided unprecedented opportunity to develop indigenous capacity both in terms of trained manpower and infrastructure



Location of pilot borehole KFD 1

The borehole, located in a seismically active zone near Koyna, is in close proximity to the Donichawadi surface rupture zone caused by the 1967 M6.3 earthquake

May 2017. The borehole, located in a seismically active zone near Koyna, is in close proximity to the Donichawadi surface rupture zone caused by the 1967 earthquake. While the drilling site was selected after rigorous study of seismological data collected from the dense network of surface broadband stations operating in the Koyna region, the borehole design was optimised on the basis of estimations drawn during the preparatory phase of the programme.

Measurements in the pilot borehole have elucidated:

- The magnitude and orientation of the subsurface stress regime
- Prediction of subsurface temperature (130°C-150°C) at 7 km depth
- Physical and mechanical properties of granitic basement rock formation
- Orientation of fractures and their implications in controlling recurrent seismic activity in the Koyna region

BOREHOLE OF OPPORTUNITIES

The pilot phase drilling project brought several important positives beyond exciting science. KFD-1, so far, is the country's deepest borehole drilled through crystalline rock formations in an active seismic zone. The drilling and associated studies were completed successfully utilising indigenous resources and expertise, with no cost or time over-runs. The project provided unprecedented opportunity for the development of indigenous capacity, both in trained manpower and infrastructure that can be further utilised to address socially relevant geoscience challenges in other parts of the country.

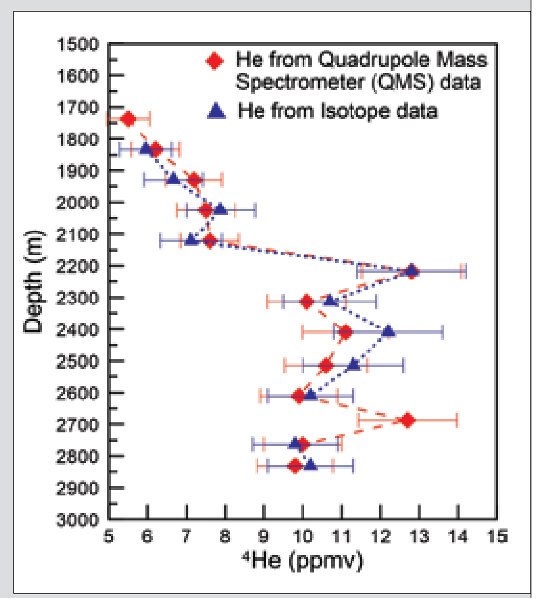
Geophysical well logging: A suite of geophysical probes were lowered in the borehole down to 3-km depth to measure electrical resistivity, self-potential, caliper, natural gamma ray, density, neutron porosity, spectral gamma, temperature and sonic velocities of the rock formations as a function of depth. The variations in physical and mechanical properties bring a clear distinction between fault damage zones associated with seismic activity and relatively unaffected horizons in the subsurface – the former provide targets for further scientific probe.

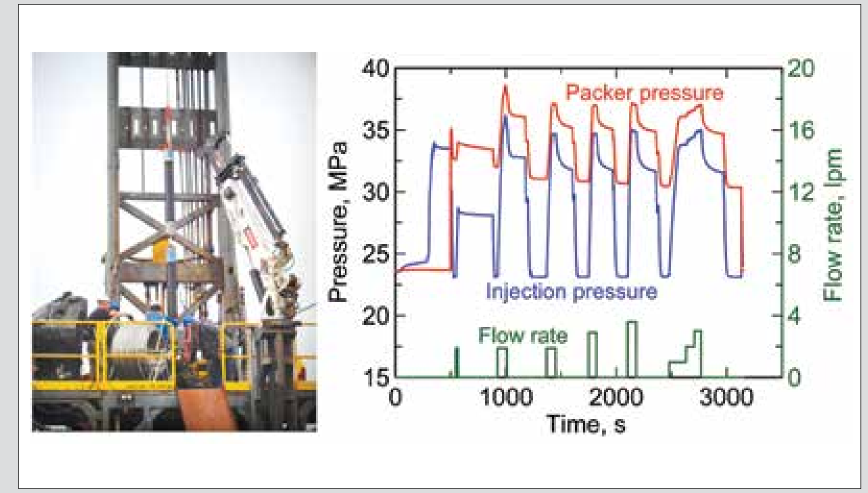
Hydrofrac testing: Stress magnitudes and orientations critically control faulting processes in a region. However, their determination under in-situ conditions is fraught with substantial technological challenges that involve deep drilling through the crystalline basement rocks and establishing stable borehole conditions to carry out hydrofrac tests. Taking advantage of the Koyna pilot borehole, hydrofrac tests were carried out at multiple depths in the granitic basement. The measurements in the deep, crystalline basement rocks in Koyna are the first of their kind in the country and one of only a few made anywhere in the world.

Online gas monitoring & analysis: Another novel experiment was the online gas analysis and sampling conducted during drilling to study the concentrations of gases including CO_2, CH_4, H_2 and He. Here, most significantly, highly anomalous helium gas concentrations have provided strong evidence that the borehole hosts punctured hidden fault zones at multiple depths below 2,100 m.

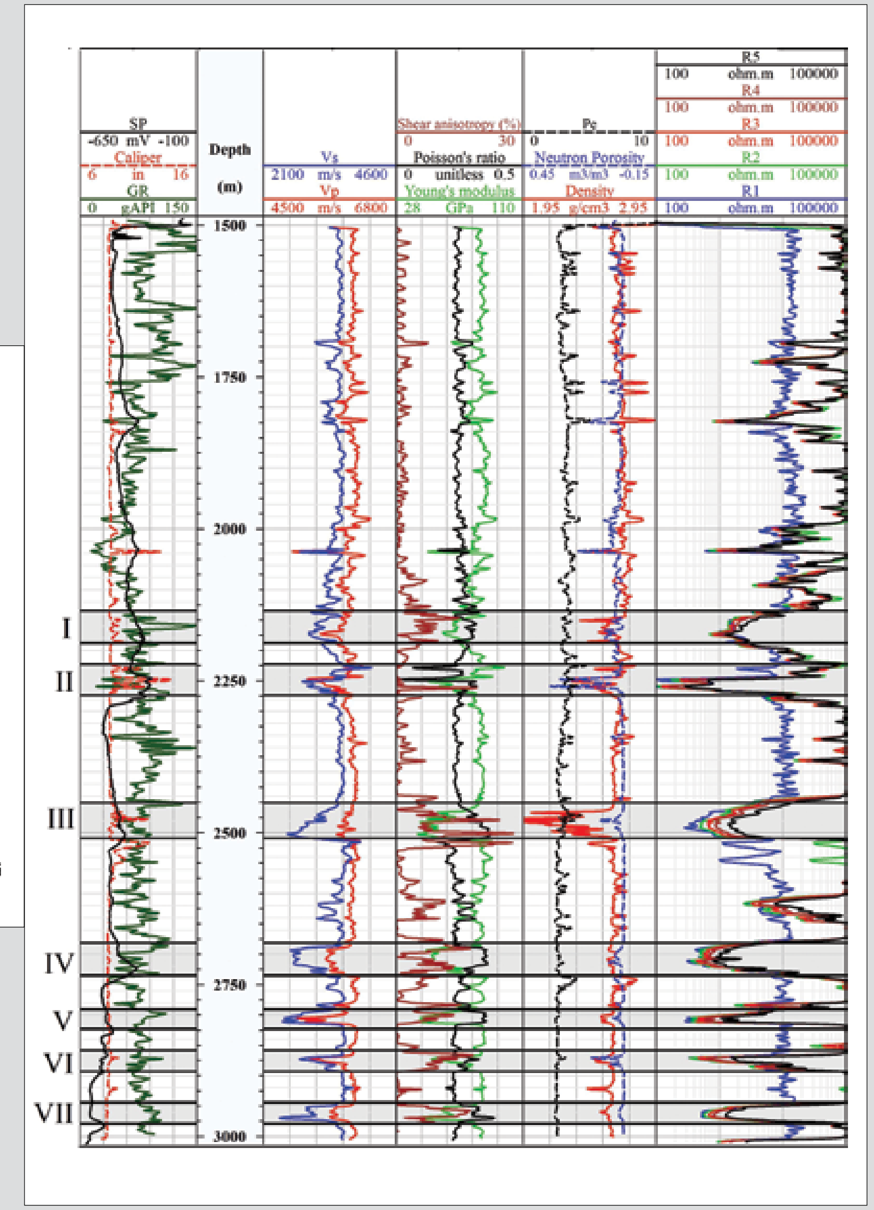
Borehole imaging: High resolution images of the borehole wall have been acquired using both acoustic as well as microresistivity techniques. Analyses of such images provide direct information about fracture types and orientations, fracture density, orientations of in-situ stresses and their variations with depth, and a host of other information.

Geological studies: Rock cores and cuttings recovered from deep drilling have been studied and lithologs have been duly prepared to complement other borehole investigations. Core samples are studied





Instrumentation for hydrofrac testing *(left)* and its results on graph



Right: **Graphical representation depicting fault zones at various depths of the borehole (shaded grey regions), inferred from anomalous rock properties.**
Top: **Measurement of helium, an inert gas, at various depths of the borehole. Anomalous helium escape below 2,100 m depth correlates well with the fault zones**

under the microscope for petrography, microstructures and deformation features associated with seismic activity in the region. The geochemical composition of the borehole samples are being determined to study fault zone characteristics.

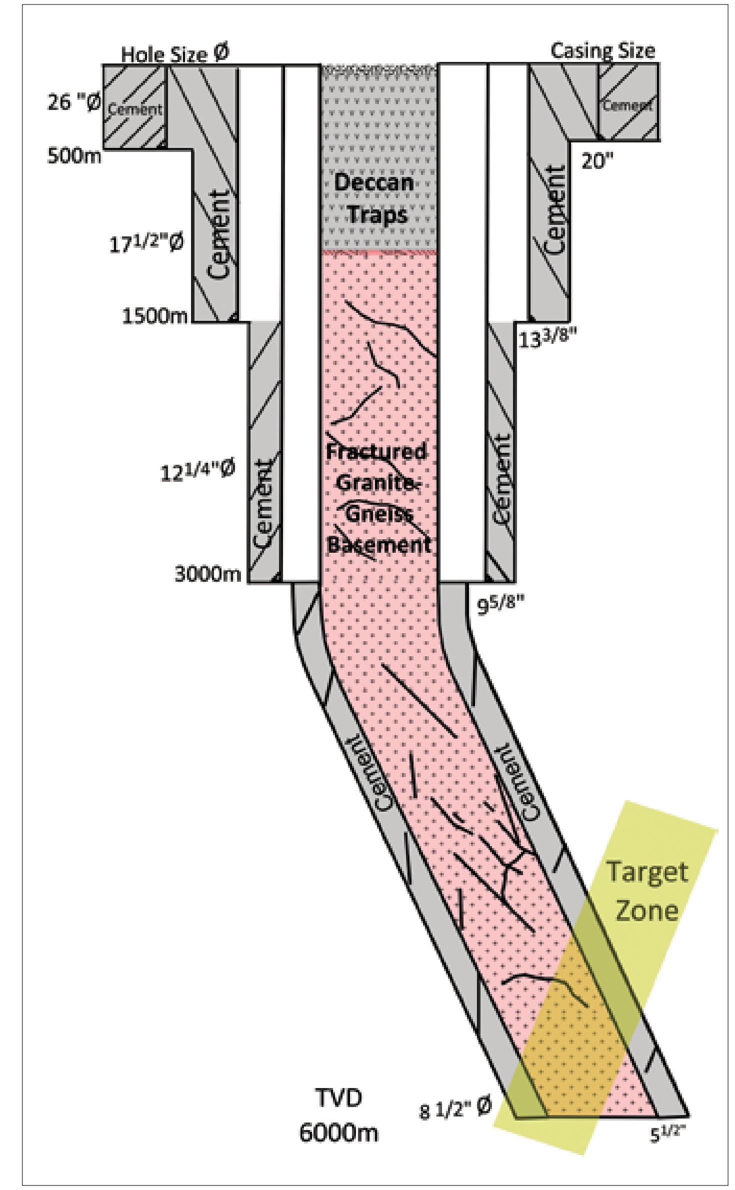
Core curation: Cores and cuttings collected from the borehole are curated at BGRL. A digital core library is also being developed. Whole-round cores from the Koyna Scientific Drilling Project have been optically scanned using a high resolution core scanning system to generate 360° (unwrapped) images, which have been archived in digital form. First-of-its-kind in the country, the digital core library will support scientific studies and facilitate theme-specific sampling for detailed investigations. The cores will be housed in a dedicated core repository, which is under development in Karad.

Borehole seismology: Plans are underway to equip the pilot borehole with a multi-level seismometer array that will complement the existing network of broadband and borehole seismometers in the Koyna region. The improved knowledge of hypocentre locations from such a network will help to delineate the trend of active fault zone(s) in the deep subsurface and guide the trajectory of the main borehole for establishment of a deep, fault zone observatory.

Deep life: Drilling through Deccan basalts to the continental bedrock has provided a unique opportunity in the discovery of microbial life within the deep, hot (~80°C) igneous biosphere. This has shed light on lesser-known processes that they may catalyse many hundred of feet underground. This interdisciplinary research, carried out by a team of scientists from the Indian Institute of Technology, Kharagpur, in collaboration with BGRL/MoES, aims to unravel subsurface microbial diversity and aids the global quest of understanding the limits of life, mechanisms of microbial interaction with inorganic environment, their adaptation and their function in this planet and beyond.

This core sample obtained from drilling shows master fault and pseudotachylite veins in the granite rock underlying Deccan basalt, providing direct evidence of earthquake activity (coin shown for scale)

Core sample showing prominent slickenside with slickenlines observed on a fault surface (coin shown for scale)



Tentative layout of the final deep borehole

Hidden faults delineated from geophysical and geochemical investigations in the pilot borehole provide focussed targets for further seismic monitoring that will be made achievable with the installation of a multi-level seismometer array up to 3 km depth. Further, integration of seismological datasets from the existing six borehole seismic network with pilot borehole observations will guide the design of the deep borehole observatory.

DEEP DRILLING: BOREHOLE OBSERVATORY

Carefully designed deep boreholes drilled in seismically active areas could serve as potential natural laboratories for experiments and as observatories for long-term monitoring of on-going active processes in the near field of earthquakes. The pilot borehole studies provide sound basis to attempt scientific deep drilling down to 5-7 km for establishing a deep fault zone observatory in the Koyna region that can aid studies of temporal changes in physical, mechanical and chemical properties at pre-seismic, co-seismic and post-seismic intervals.

Technical and logistic challenges are most pronounced in deep directional drilling of active fault zones, sampling

Whole-round cores from the Koyna Scientific Drilling Project have been optically scanned using a high resolution core scanning system to generate 360° (unwrapped) images which have been archived in digital form

International workshop conducted during the pilot phase

fault zone rocks for laboratory investigations, selecting sensors that can sustain the high temperature and high pressure environment for several years, installing sensors and ensuring uninterrupted data acquisition. Various possibilities are being analysed to reach the hypocentral depth and approach the fault zone(s) or their immediate vicinity through a combination of vertical and directional drilling techniques. Datasets obtained from the deep borehole observatory and complementary laboratory studies are expected to provide new and fundamental inputs that will aid in comprehending the genesis of recurrent triggered earthquakes in the Koyna region.

The pilot borehole studies provide sound basis to attempt scientific deep drilling down to 5-7 km for establishing a deep fault zone observatory

INTERNATIONAL COLLABORATION

India is a member country of the International Continental Scientific Drilling Program (ICDP) through an MoU with the Ministry of Earth Sciences. BGRL benefits from the pooled expertise of the ICDP Operational Support Group and other member countries in planning scientific deep drilling programmes through meetings and workshops, development of collaborative programmes, capacity building, and drawing technical support for carrying out deep drilling and specialised downhole measurements under challenging conditions.

CAPACITY BUILDING

Capacity building is a key pre-requisite in conducting deep drilling and subsequent investigations. At Karad, BGRL is gearing towards the completion of its fully-equipped brand new campus where a core repository is being set up to provide facilities for core curation and studies of national

Geophysical well logging tools

Outreach programme with the local community at Karad

EDUCATION & **OUTREACH**

An important aspect of conducting research in Earthquake Science is to propel both innovation and awareness. While for the former, giant leaps are being made in acquiring new technology and arriving at new conclusions; for the latter, BGRL is swiftly undertaking community programs to improve the awareness of concerned stakeholders. Education can play a key role in effectively reducing the impact of natural disasters on human life and property. Greater awareness and improved levels of preparedness will also pave the way towards the successful institution of sustainable earthquake-resilient towns.

On field studies during the pilot phase

and international scientists. Advanced facilities for downhole geophysical logging, in-situ stress and geothermal measurements are being established by a group of dedicated scientists and technicians. The MoU with ICDP has provided further technical support, especially in challenging conditions.

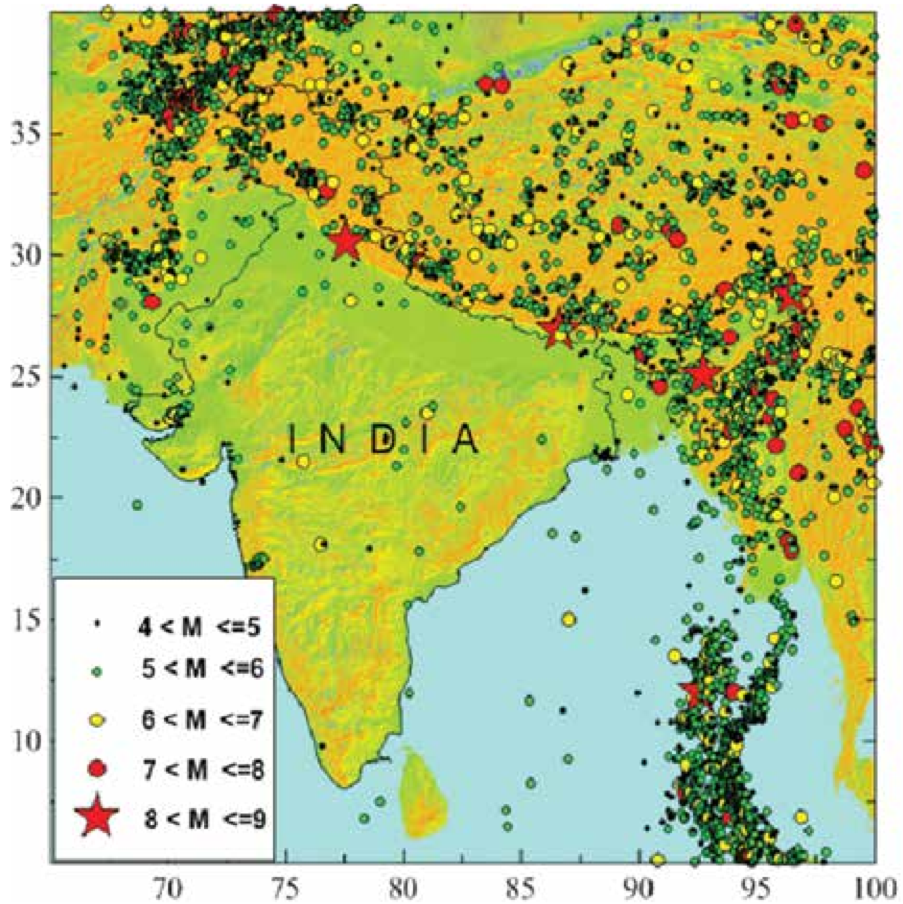
CONCLUSION

As India marches ahead in her mission to address challenging social concerns with the deployment of superlative technology, developing indigenous talent and deepening the country's critical knowledge base gains paramount importance. Natural disasters continue to be a slippery slope for experts across the globe due to their unpredictability and magnanimity. Yet, in the pursuit of knowledge and excellence, the most challenging circumstances only inspire greater innovation.

NATIONAL CENTRE FOR SEISMOLOGY

TRACING **TREMORS**

A broad-based, modern seismological network allows interpretation and analyses of seismic data useful for understanding the Earth's geoscientific intricacies and mitigating risks associated with earthquakes



Events during instrumental era with large earthquakes in India

Occurring sporadically across our planet, earthquakes are a most unpredictable natural hazard. They are also not uniform – some are so weak that their impact evades human cognizance while others are violent enough to uproot whole civilisations. Nonetheless, timely dissemination of earthquake information to concerned state and central government agencies plays a vital role in mitigating post-disaster relief and rehabilitation. Moreover, the loss of life and property caused by earthquakes may be reduced substantially through dedicated planning and implementation of pre- and post-disaster management strategies.

HISTORY OF EARTHQUAKE MONITORING

The history of instrumental earthquake monitoring in India dates back to 1898, when the first seismological observatory of the country was set up at Alipore (Calcutta) on December 1, 1898, in the aftermath of the great Shillong plateau earthquake of 1897. The recurrence of devastating earthquakes such as those witnessed in Bihar-Nepal (1934), Assam (1950) and more, necessitated progressive strengthening of the national network –

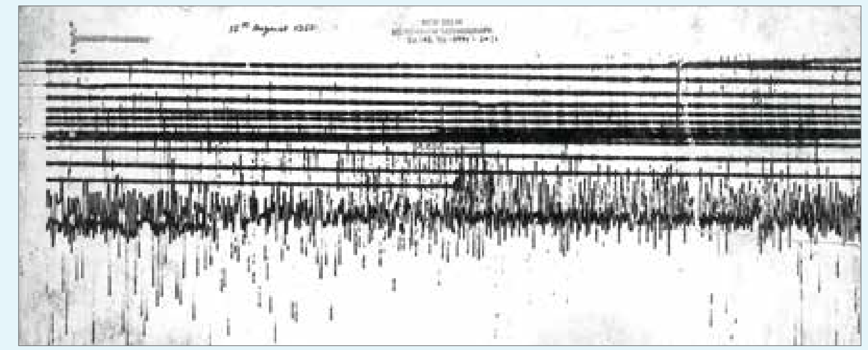
Damages to road and bridge during 1950 Assam earthquake

RECORDS FROM THE PAST

1950 Assam-Tibet earthquake: It occurred on August 15, 1950 with a magnitude of 8.6. The epicentre was located in the Mishmi Hills, east of the Himalayas in the North-East Frontier Agency part of Assam, India. The earthquake was destructive in both Assam (India) and Tibet (China), killing approximately 4,800 people. The earthquake is notable as the largest recorded quake caused by continental collision and is also remembered for the loud noises produced by the quake throughout the region.

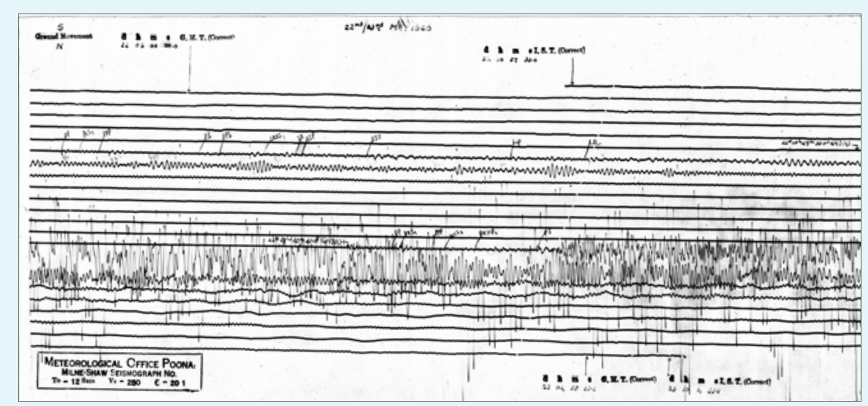
1956 Anjar earthquake: It took place on July 21, 1956, causing maximum damage in the town of Anjar located in Kutch, Gujarat, India. It came with a magnitude of 6.1 on the surface wave magnitude scale and a maximum perceived intensity of IX on the Mercalli intensity scale.

1960 Great Chilean earthquake: Occurring on May 22, 1960, it is the most powerful earthquake ever recorded. Various studies have placed it at 9.4–9.6 on the moment magnitude scale. It occurred in the afternoon (19:11 GMT and 15:11 local time), and lasted approximately 10 minutes. The resulting tsunami affected southern Chile, Hawaii, Japan, the Philippines, eastern New Zealand, southeast Australia, and the Aleutian Islands.

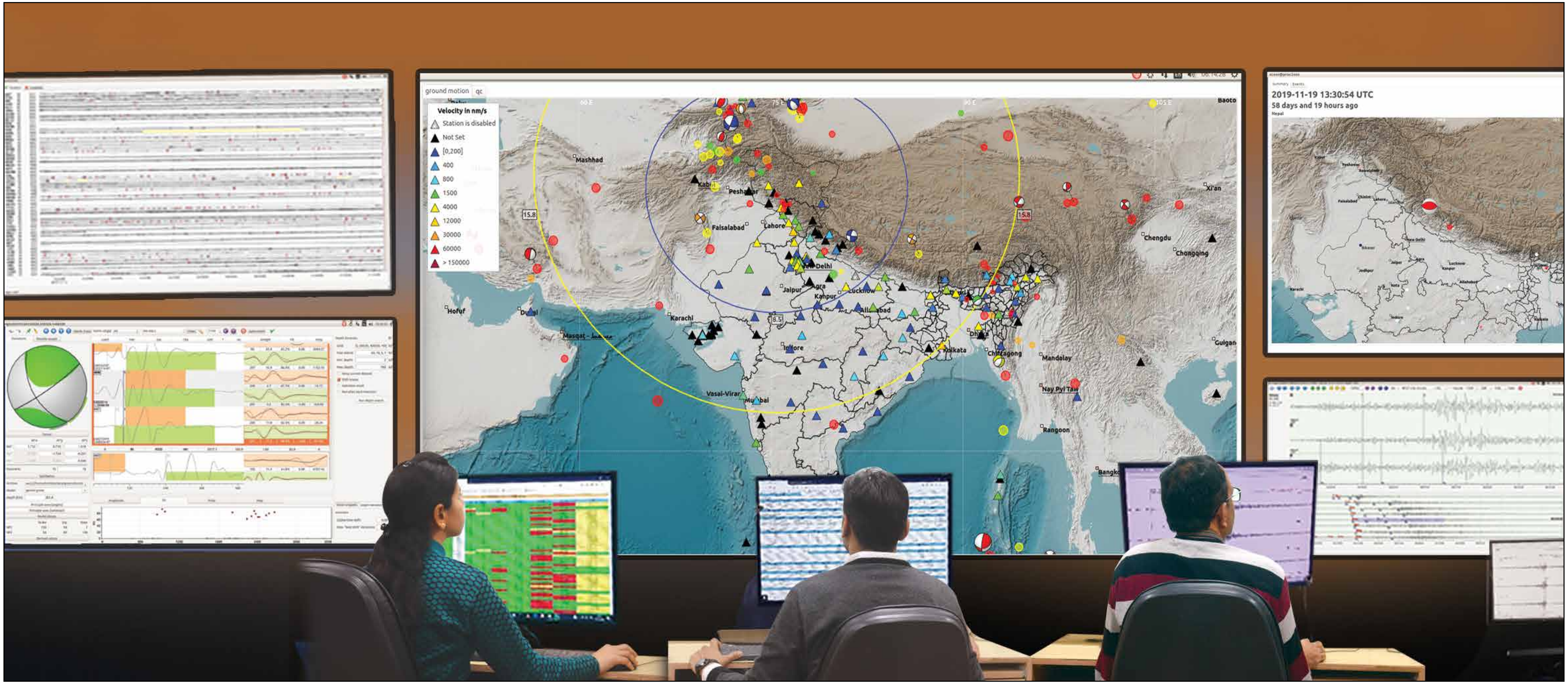


The 1950 Assam-Tibet earthquake RECORDED AT NEW DELHI

The 1956 Anjar earthquake RECORDED AT SHILLONG



The 1960 Great Chilean earthquake RECORDED AT POONA



Scientists at work at the Central Receiving Station

Analogue smoke paper type seismograph

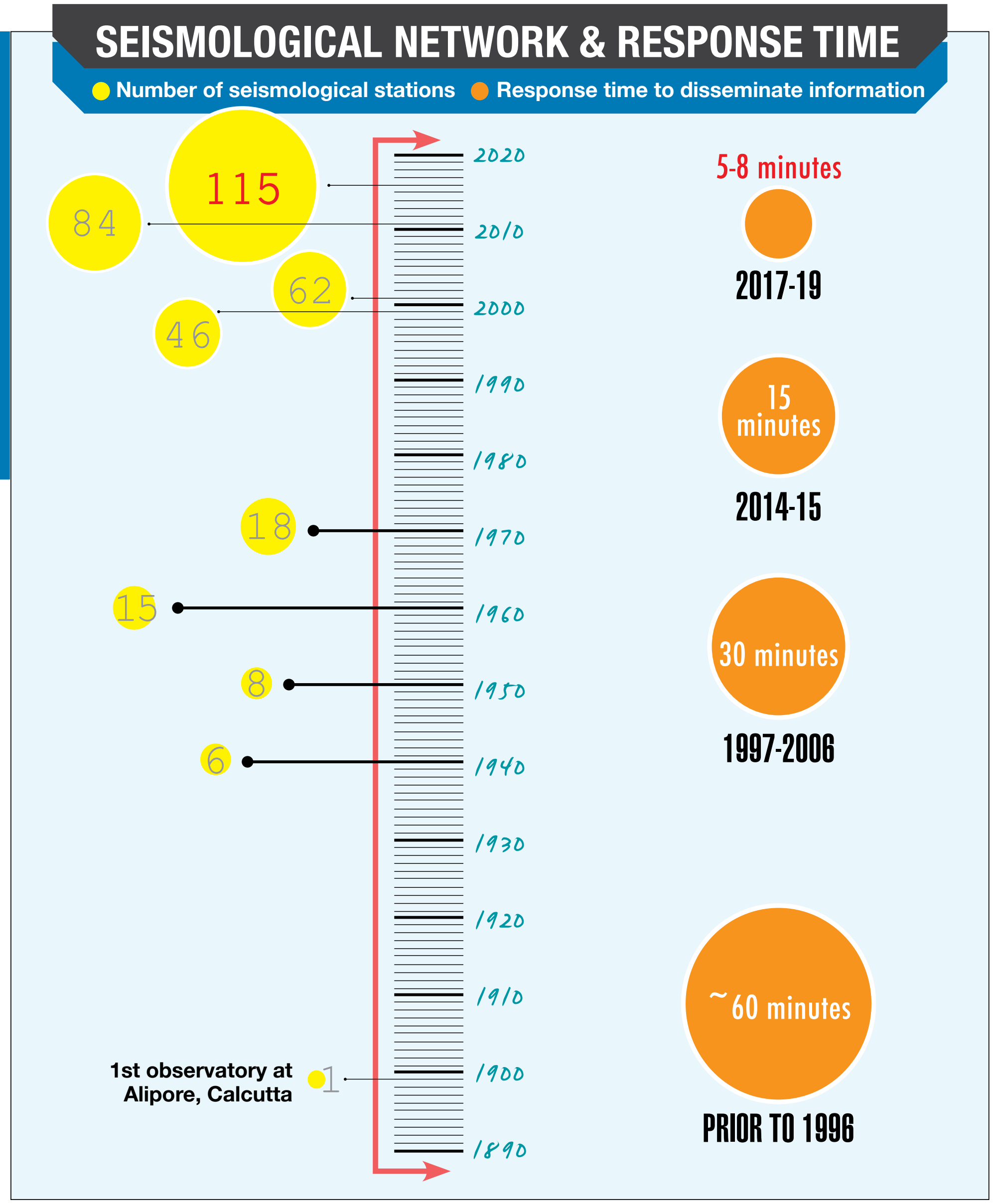
from a paltry six in 1940 to eight in 1950, 15 in 1960 and 18 in 1970.

With the establishment and global functioning of the WWSSN (World Wide Standardised Seismic Network) stations, the early-1960s marked a landmark in the history of seismic monitoring. During 1962-1963, four stations located at New Delhi, Shillong, Pune and Kodaikanal became a part of WWSSN with the installation of matched 3-component short-period and long-period seismograph systems.

Before the 1990s, seismological networks primarily consisted of conventional analogue seismograph systems with photographic/ smoke/ink recording devices and separate short-period and long period sensors to record near and distant events. Following the deadly Latur earthquake of 1993, the Seismology Division of India Meteorological Department (IMD) (now National Centre for Seismology), upgraded 10 of its analogue observatories that were located mostly in the peninsular

WWSSN seismograph

As the number of seismological stations expanded from 1 (in 1898) to 115 (since 2016), response time fell sharply – what demanded over an hour before 1996 can now be achieved in brisk 5-8 minutes



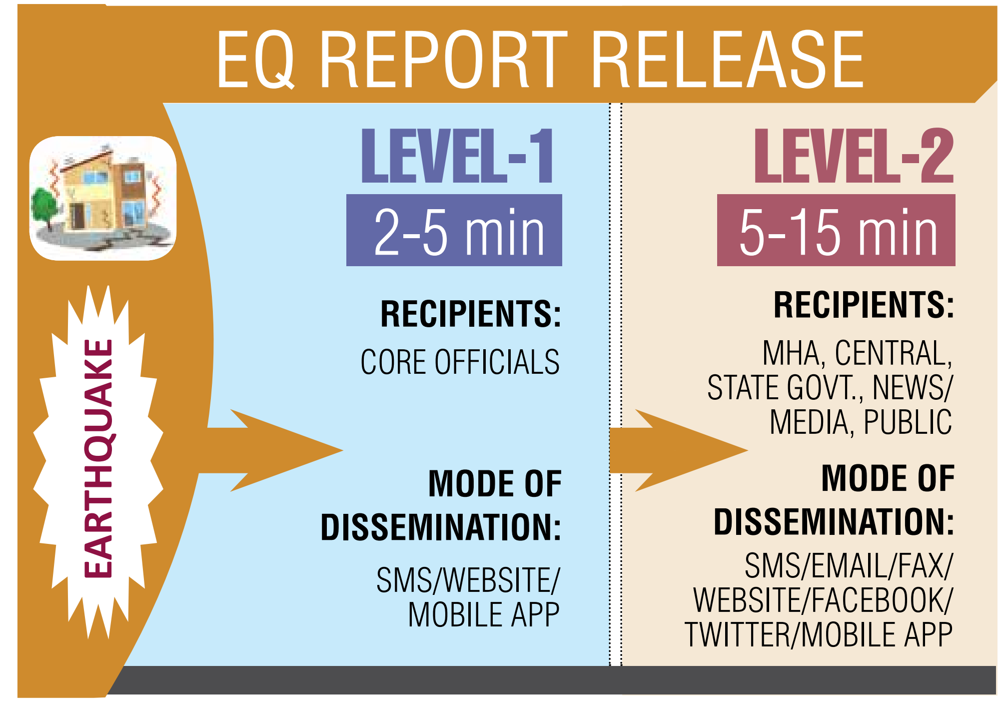
The new facilities will not just help India but would also provide other nations with research inputs to minimise the damage incurred

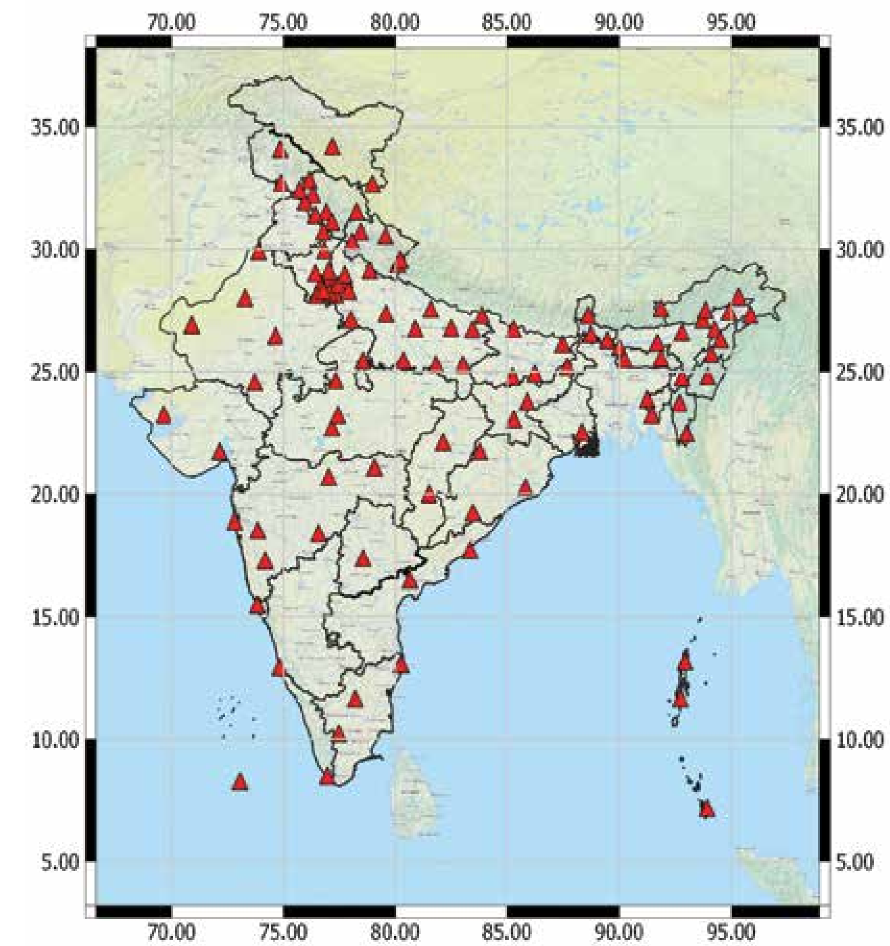
shield region, to match the standards of the Global Seismograph Network (GSN). These were the first series of digital seismographs inducted in the National Seismological Network (NSN). Subsequently, 14 more analogue observatories of the national network were upgraded with similar digital broadband seismograph systems during 1999-2000. While there are a few thousand observatories operated by various universities/institutions/ organisations for specific scientific research and engineering studies, NSN is operated and maintained by the National Centre for Seismology (NCS). NCS is the nodal agency of the Government of India for monitoring earthquake activity in the country through its NSN and round-the-clock monitoring centre.

NATIONAL SEISMOLOGICAL NETWORK

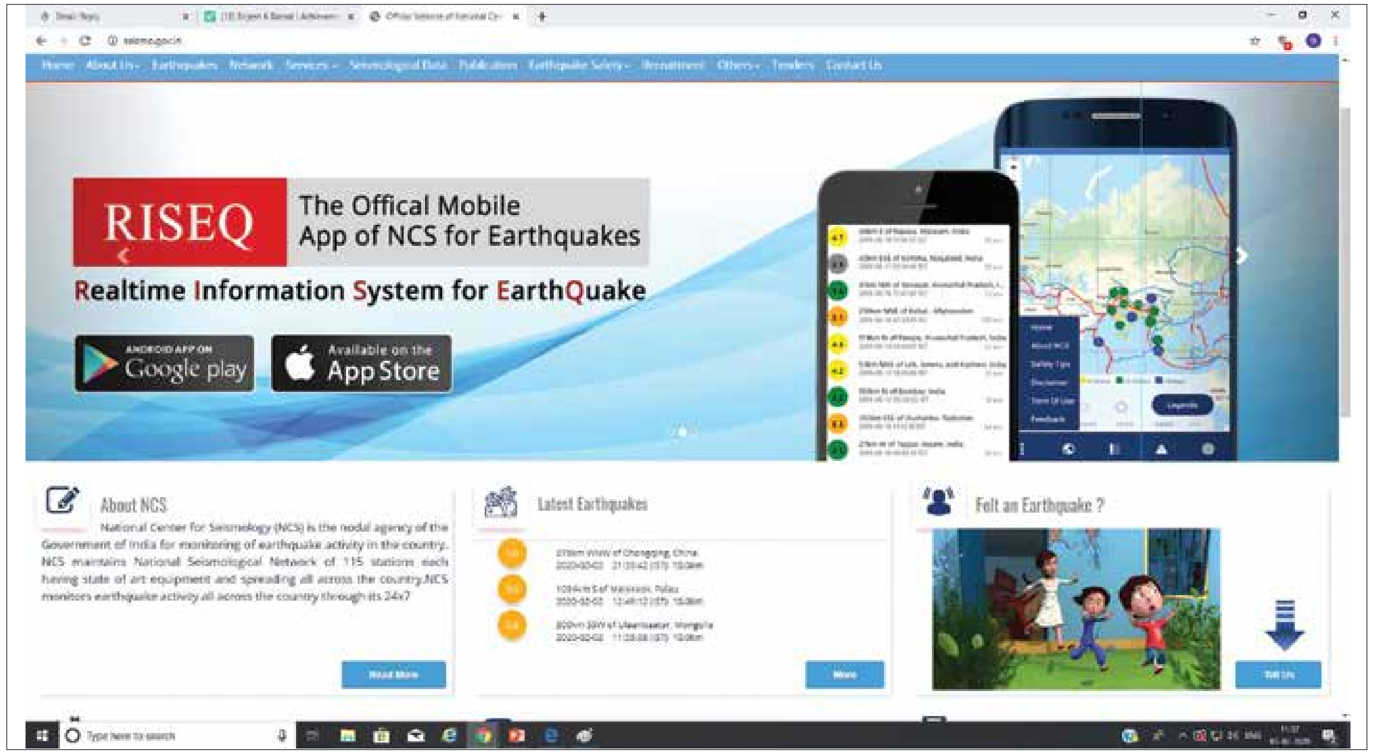
Presently, NCS maintains the National Seismological Network (NSN) consisting 115 observatories that are spread widely across the country. Each station is equipped with state-of-the-art seismic broadband velocity sensor, accelerometer and data acquisition systems. The broadband velocity sensor (or seismometer) is used to record weak ground motion resulting from local as well as distant earthquakes of different magnitudes. On the other hand, low-gain accelerographs are used to record strong ground shaking at nearby stations caused due to larger earthquakes likely to cause more damage. The ground motion data recorded at all field stations are transmitted in real-time by the VSAT communication systems to the Central Receiving Station (CRS) located at NCS, New Delhi.

A control room/monitoring centre with state-of-the-art facilities for data collection, processing and dissemination of earthquake information functions round-the-clock at New Delhi. The centre employs an advanced auto-location software, called SeisComp3, to make swift (within a few minutes) preliminary estimates of earthquake source parameters immediately after the occurrence of an earthquake. The source parameters include the time of occurrence, location (region), magnitude and focal depth



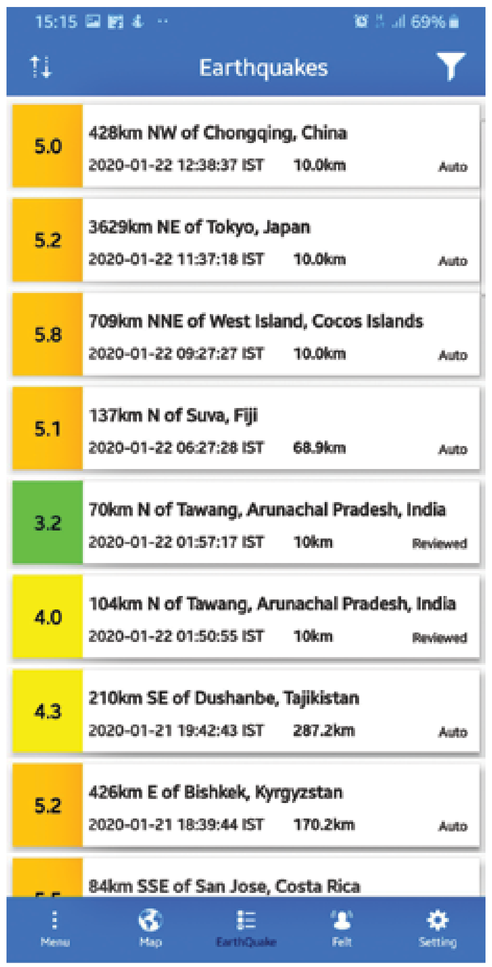


National Seismological Network



Website: www.seismo.gov.in

Mission: Building a seismic resilient society
Vision: Understanding earthquake source processes and their effects through earthquake monitoring and seismological research for the cause of earthquake–safe society



Mobile App: RISEQ

of the earthquake. As the automatic results are not always accurate, the incoming data is reviewed by a seismologist on duty.

The earthquake information is then disseminated to concerned user agencies through various modes of communications, such as mobile app (RISEQ), SMS, Fax, Email and published with value-added products on NCS's website *www.seismo.gov.in*. The network can detect earthquakes with magnitudes 3.0 and above for most of the country.

TEMPORARY NETWORK

NCS is also involved in monitoring earthquake swarms and aftershocks by deploying a temporary network of field observatories in the affected region. The available seismological data from all the network stations, including those operated by other agencies, are compiled, processed, analysed and archived systematically at the data centre managed by NCS. The data centre has capabilities such as storing continuous waveform data in standard SEED format, retrieval as per user criteria, SeedLink protocol for connectivity with auto-location software, etc. All the data collected at New Delhi is mirrored at the Indian National Centre for Ocean Information Services (INCOIS), Hyderabad.

Waveform data from all stations relating to earthquakes occurring in India and its neighbourhood, along with significant earthquakes in any part of the world, are analysed routinely in detail. Thus, Monthly National Seismological Bulletins containing the phase data and the processed information on source parameters of all earthquakes located by the seismological network are prepared and published.

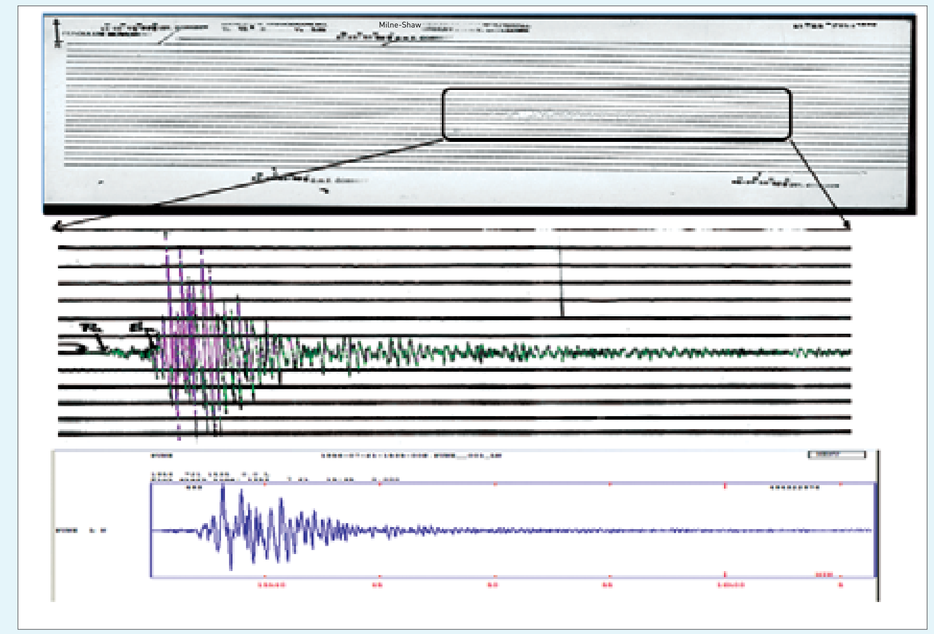
India, represented by NCS, is a permanent member of the International Seismological Centre (ISC), UK. Seismological bulletins of NCS containing information on earthquakes occurring across the Earth are shared regularly with the global research community.

DIGITISATION

Over the past 100 years or so, a wealth of seismological data has been generated from across the seismological network — these historical, analogue seismic charts number more than a million. These charts, containing ground motion records, are made on photographic, smoke recording and heat-sensitive recording devices. Raster scanning of one lakh historically significant analogue charts and vector digitisation of 5,000 significant earthquake waveforms has also been completed. The aim is to achieve long-term preservation of invaluable information contained in these historical charts in an electronic form to bolster research opportunities for the seismological community.

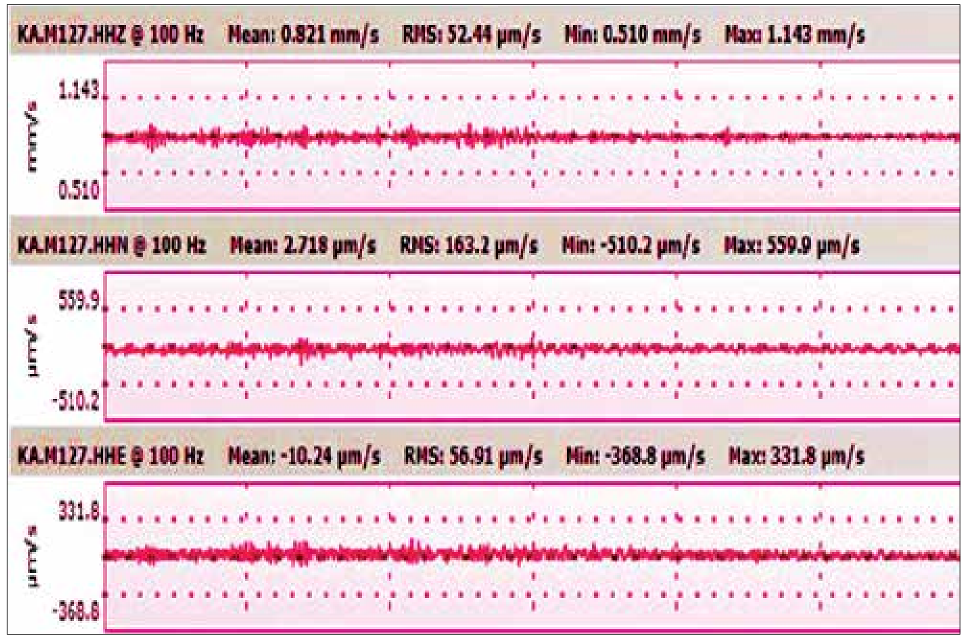

Instrumentation set-up for digitising analogue charts:

- 5-scanners (each of A0 size, 600dpi / 800dpi)
- Raster scanning of 1 lakh charts containing significant events from year 1927 onwards


A depiction of how the 1956 Anjar earthquake was digitised from the analogue seismic chart

WAY FORWARD

In the near future, the National Seismological Network will be strengthened with the addition of more observatories. This will assist greatly in improving earthquake detection capabilities down to a magnitude threshold of 2.5. Further, a stronger mechanism for dissemination will also be conceived so that the public can receive timely information, and loss to life and livelihood can also be reduced.



Field survey related to acquisition of microtremor data for seismic microzonation

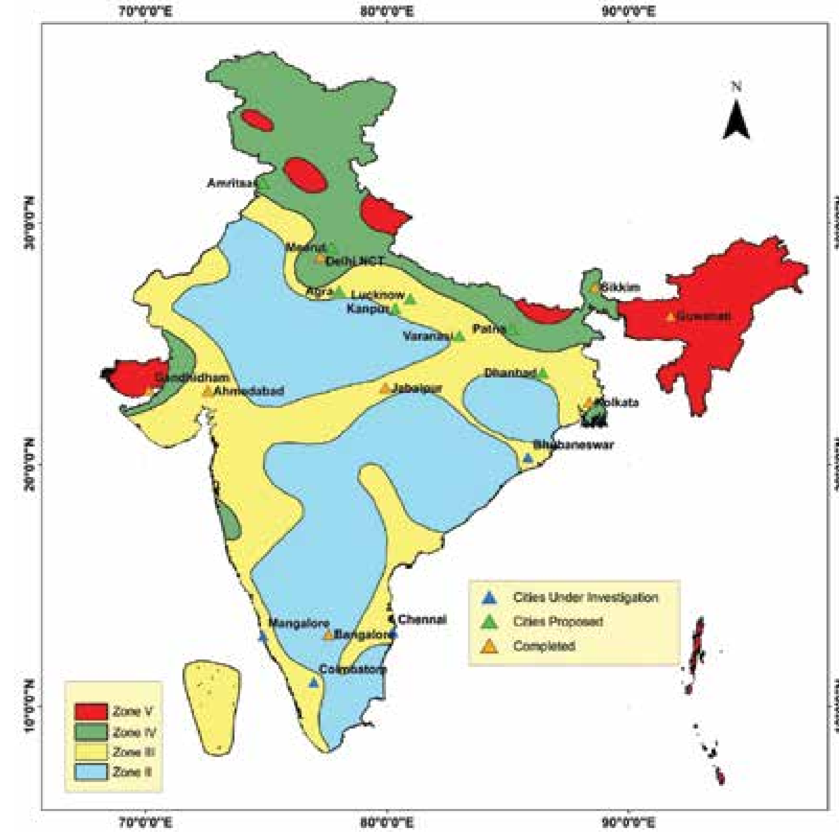
SEISMIC MICROZONATION

MICRO PERSPECTIVES TO **A MACRO PROBLEM**

Studying the specific details of geoscientific, geotechnical and seismological inputs that characterise the influence of tectonic processes, seismic microzonation has emerged as a viable process that embraces a more enhanced study of earthquake-prone regions by subdividing them into smaller zones of equal hazards, thus, allowing more efficient urban planning

The entire Indian subcontinent is susceptible to unexpected tectonic shocks; however, some regions of the country have emerged as more vulnerable than others. While the Deccan syneclise is relatively stable, the hilly Himalayan terrain is home to frequent tremors, landslides and earthquakes. This uneven distribution of tectonically-sensitive pockets, which is a common phenomenon across the globe, has demanded introspection and study of the micro components – such as geophysical characteristics, parent rock, soil composition, etc. – that make a particular region more vulnerable.

The process of seismic microzonation provides an attractive solution to unravel the unpredictability inherent in the functioning of earthquakes that can thereby, assist in the process of urban planning and development.



Microzonation of Indian urban centres

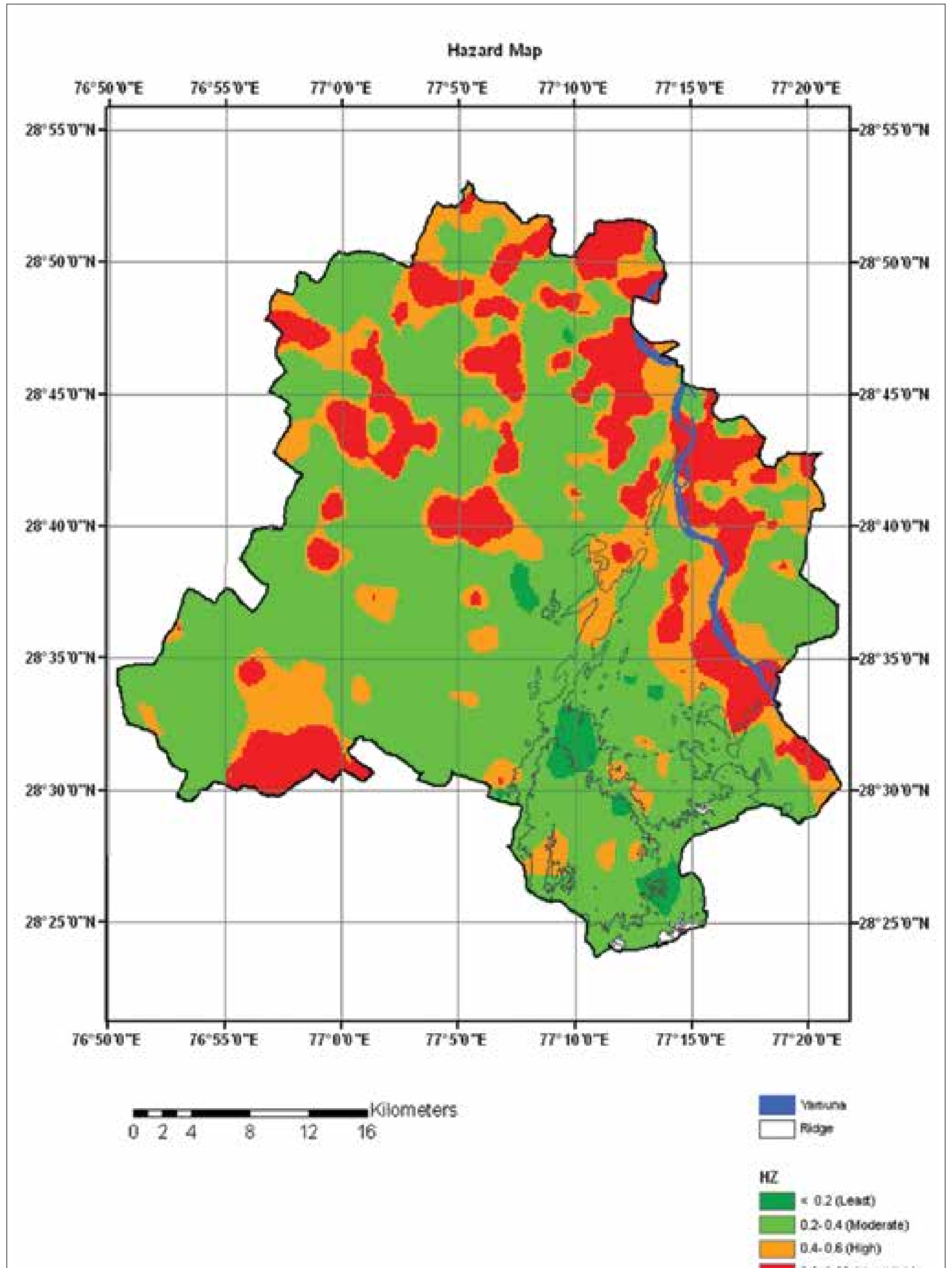
DIMENSIONS OF SEISMIC MICROZONATION

As the name suggests, the process of seismic microzonation requires the subdivision of a region into further smaller areas – depending on the various local potential sources harbouring hazardous earthquakes along with an analysis of the soil dynamics and groundwater scenario which can together irreversibly impact the peripheral infrastructure and people. With a long lens that scans minute specifics, microzonation provides detailed information of site-specific hazards on a much larger scale.

As an initial step in risk mitigation studies, seismic microzonation demands a multidisciplinary approach with active interactions between geological, seismological, geophysical and geotechnical parameters. Some key features of seismic microzonation study are:

- Identifying the tectonic and geological formations essential for determining seismic sources
- Establishing realistic earthquake hazard models
- Conducting detailed field investigations to evaluate hazards – most effective in delineating spatial variations in seismic hazards
- Assisting in evaluation of peripheral risk scenarios
- Saving heritage structures from future major earthquakes
- Seismic microzonation maps assist urban planning by assessing the impact of future earthquakes

Globally, countries are often classified into two, three or more seismic zones that have complementing seismic design requirements. Sustainable urban planning requires a strict study of possible potential hazards – tectonic susceptibility, among which, is a prime concern. Therefore, seismic microzonation plays a most crucial and relevant role in assisting urban planners to construct cities that can avert the risk of collapse.



Seismic microzonation based hazard index map of NCT-Delhi

SEISMIC MICROZONATION: THE INDIAN CHAPTER

The uneven distribution of earthquakes in India brings wide variation in the intensity of ground motion and spectral acceleration even within a defined seismic zone. Initially, Bureau of Indian Standards (BIS) categorised the entire country into five broad seismic zones from Zone I (safe) to Zone V, in increasing vulnerability to earthquakes. This was later modified after the Kilari earthquake (M6.2) of 1993 when Zone I was consequently dropped, as no region within the subcontinent could any longer be proclaimed as completely safe. Thus, in the second stage of seismic zonation, regions were marked from Zone II to Zone V. This map was widely used by builders, architects and urban planners to develop India in tandem with the underlying geophysical structure.

Over time, the second map too proved inadequate as differences in tectonic receptivity could be noticed even within one definite zone. Subsequently, there arose a need for analysing zones within zones by studying each specific area from the perspectives of geology, geophysics, seismology, geotechnology, etc. Seismic microzonation thus, is a site specific study that provides a more realistic and reliable representation of the ground motion characteristics in a given area. Especially since predicting earthquakes is almost impossible, studying specific subsurface soil dynamics can aid our efforts of reducing the impact of natural disasters, like earthquakes, on human life and livelihood.

So far, the microzonation study has been completed for a number of cities/states in India, including, Jabalpur, Guwahati, Sikkim, NCT Delhi, Kolkata, Bangalore, Gandhidham and Ahmedabad with the use of available geological map scales of 1:25,000 or 1:50,000. Importantly, microzonation of NCT Delhi has been completed on a much higher resolution (1:10,000 scale) geological map. In addition, similar studies for other cities, namely, Bhubaneswar, Coimbatore, Chennai, Mangalore, Agra, Amritsar, Dhanbad, Kanpur, Lucknow, Meerut, Patna and Varanasi have been initiated.

ZOOMING INTO ZONES

The study of microzonation involves the curation of extensive, specific maps along different themes that

Umedpur crater surface

Seismic microzonation may help engineers in refining the building codes across the country to attain sustainable usage and long life of buildings

Liquefaction susceptibility – a key component of seismic microzonation

Microzonation is a site specific study that provides a more realistic and reliable representation of ground motion characteristics

are superimposed on a Geographic Information System (GIS) to build a wholesome integrated seismic hazard map of a region showing low, moderate and high hazard micro-zones. These specific maps study a wide array of characteristics such as:

- **Geological and Geomorphological features:** Older alluvium is more stable than newer geological formation including geomorphic features
- **Site response characterisation:** By analysing the criterion of predominant frequency and peak amplification
- **Peak ground acceleration on ground surface:** The horizontal impact of seismic waves
- **Engineering bedrock depth configuration:** As overlying sediment column is vulnerable to earthquakes
- **Site class:** Soil classification based on shear wave velocity (Vs 30)
- **Liquefaction:** Studying soil behaviour on the passage of seismic waves due to presence of ground water in underlying soil strata

The microzonation process, thus, includes rudimentary assessments of existing regional level hazard estimations along with seismotectonic as well as other micro level geo-scientific and geotechnical studies. A general methodology for conducting seismic microzonation is based on comprehensive modalities detailed in the microzonation handbook and seismic manual developed under the guidance of MoES.

Damage to buildings after the Bhuj earthquake of 2001

USAGE IN URBANISATION

Many developing nations are situated in zones of high seismicity where even small tremors can cause significant loss to property and life. Consequently, the use of seismic microzonation maps depicting micro-zones of equal hazard and other relevant ground surface parameters are gaining ground and developing rapidly. In the process of microzonation, site specific design response spectra and spectral acceleration for different periods at different locations are also generated, which are the most useful parameters for engineers while designing earthquake-resistant structures.

Anticipating a disaster-resilient city is primarily dependent on proactive disaster mitigation planning and preparedness, which can positively assist reduction of corollary damage. Earlier, plans of building residential areas were quite inadequate. Microzonation, however, has paved the way for identifying areas with varying seismic hazard potentials with the capability to generate adequate maps to serve urban planning and land use management. Comprehensive planning is imperative and will assist in building the necessary infrastructure and determining the risk in the processes of urbanisation.

WAY AHEAD

As population rises and demands for equipped and resilient cities expand, it has become necessary to widen the scope of microzonation. Expansion of cities is related to the vital installation of risk-resilient structures that can be conceived most efficiently based on the outcomes of microzonation studies.

An important intervention in the times ahead could witness as improvement in the scale of microzonation studies. This would facilitate the generation of various thematic and integrated seismic hazard maps on a higher resolution. Nevertheless, accomplishing the ongoing microzonation study in 12 cities, as mentioned earlier, is the next immediate goal.

As population rises and demands for equipped and resilient cities expand, it has become necessary to widen the scope of microzonation

NATIONAL FACILITY FOR GEOCHRONOLOGY

WORLD-CLASS **R&D**

By establishing a dedicated facility for geochronology, MoES has reinstated its commitment to look back in the past to study the system of Earth sciences

Compact ^{14}C Accelerator Mass Spectrometer extended for ^{10}Be and ^{26}Al (XCAMS) facility at IUAC

Qudurpole Inductively Coupled Plasma Mass Spectrometry (Q-ICPMS) facility

Automated Graphitization Equipment (AGE)

Geosciences has witnessed a paradigm shift in the past few decades – from being an observational science to becoming a more rigorous multidisciplinary science with a strong quantitative data base. Important new developments have been particularly witnessed in geochronology at the micro phase and single grain levels. India too is in the process of developing such facilities.

The Facility of Geochronology at the national-level in the country is equipped with a full spectrum of instrumentations including two major equipment, the High Resolution Secondary Ionization Mass Spectrometry (HR-SIMS) and Accelerator Mass Spectrometry (AMS). Importantly, both these instruments are first-of-their-kind in India. This facility by the Ministry of Earth Sciences (MoES) will enable the geoscience community in India to undertake cutting-edge on-field research. The facility is being set up at the Inter-University Accelerator Centre (IUAC) and will function as a community centre for geochronology that will permit high-quality geochronological data including relevant characterisation at the highest international level. HR-SIMS & AMS, the two end members of the facility that are complemented by a number of other active facilities, are capable of dating the geologically youngest and oldest formations/rocks/sediments in Earth's history. They will provide improved quantitative understanding of the evolution of the Indian lithosphere and the regolith. The facility emphasises on:

- Understanding reasons and time scales for the formation of symmetric geo-patterns that arise on all spatial and temporal scales
- Quantification of the role of climate in surface processes
- Understanding role of ecology on surface processes
- Development of paleo-records of landscape evolution
- Unravelling early solar system processes

This facility is equipped to conduct front-line research in geological diversity, climate change, paleoclimate, global carbon cycle, oceanographic parameters, etc.

STUDYING GEOCHRONOLOGY

The geochronology facility holds the objective of developing an internationally-competitive centre for geochronology and isotope geochemistry that will permit measurement of quality isotopic data for geochronological and isotopic fingerprinting including relevant characterisation. Geochronology, or the science that studies the age of rocks, fossils, sediments, seeks to answer a number of perplexing scientific questions. Advancements in modern trends of research have established the importance of isotopic composition (stable and radiogenic) of geological material in understanding geological processes in time and space, i.e., studying geochronology. High precision isotopic measurements require equally sophisticated instrumentation and laboratory conditions.

The Accelerator Mass Spectrometry (AMS) analysis attempts to answer some scientific problems in erosion rates, dating of seismic events, sediment provenance studies, quantitative Earth surface processing studies and more. The establishment of AMS dating facility will also provide means to explore new isotopes like ^{32}Si, ^{36}Cl, ^{41}Ca, with potential applications in hydrology, glaciology and ocean circulation studies.

The High Resolution Secondary Ion Mass Spectrometer (HR-SIMS), which is under installation and will be operational soon, tries to answer questions on dating of elements such as zircon and several other accessory minerals such as monazite, titanite, sphene and apatite at a high spatial resolution to decipher complex growth histories in processes that led to crust formation and continental dynamics. It also conducts elaborate isotopic analyses in deep Earth processes and those related to cosmochemistry.

AMS and HR-SIMS are two most relevant facilities capable of dating an entire geological age spectrum from the youngest to the oldest

Technology in chronology

The existing Facility for Geochronology in IUAC is operational round-the-clock and has started contributing towards capacity building programs. Many facilities like X-ray Diffractometer (XRD), X-ray Fluorescence spectrometer (XRF), Quadrupole–ICPMS (Q-ICPMS), Femtosecond Laser Ablation High Resolution Inductively Coupled Plasma Mass Spectrometer (Fs-LA-HR-ICPMS) and Field Emission-Scanning Electron Microscope (FE-SEM) with cathodoluminescence and EDS detectors along with necessary sample preparation equipment have been installed and are in regular operation.

A compact ^{14}C accelerator mass spectrometer extended for ^{10}Be and ^{26}Al (XCAMS) has been installed. A sample preparation laboratory having three automated graphitization equipment and one carbonate handling system has also been set up.

A large geometry High Resolution Secondary Ion Mass Spectrometer (HR-SIMS) has been added for performing U-Pb geochronology at few micron resolution and extended applications like measurement of various tracer isotopic composition (O, B, Li, Fe, Ca, Mg, Hf and Os-Re) of geological importance. In the next phase, an Ion Accelerator for medium and heavy ion AMS measurements is also on the cards that will facilitate study of many other heavier radioisotopes.

X-Ray Diffractometer (XRD) facility

X-Ray Fluorescence (XRF) spectrometer facility


At Sea

SAFETY AT **SEA**

The state-of-the-art Tsunami Early Warning Centre at Hyderabad has made remarkable strides in effectively monitoring Indian seas, tracking tsunamigenic occurrences and consequently, reducing potentiality of exigencies

Tsunami buoy onboard *Sagar Nidhi* cruise

Prime Minister Narendra Modi paying homage at the Tsunami Memorial in Car Nicobar, December 2018

The Indian Tsunami Early Warning Centre (ITEWC), housed at Indian National Centre for Ocean Information Services (INCOIS), Hyderabad, is India's official tsunami tracking and warning centre. It was formally inaugurated and established in 2007 but has been informally functioning since 2005.

GENESIS

The 2004 tsunami that occurred off the coast of Sumatra, Indonesia, was a wake-up call to the world that was hitherto unprepared to deal with tsunamis. In fact, the word 'tsunami', meaning 'harbour waves' in Japanese, was only nascently known. Prior to this massive earthquake measuring 9.1 magnitude that claimed about 2,30,000 lives, active information centres on tsunamis were numbered and consequently, preparedness to deal with exigencies was also limited.

After 2004, UNESCO called an all-party meeting to prepare for risk management and, in the process, established the Intergovernmental Coordination Groups (ICGs) to develop an Indian Ocean Tsunami Warning and Mitigation System (IOTWMS). Tsunami Early Warning (TEW) is provided across all ocean regions and India earned a Tsunami Service Provider (TSP) tag in 2011 after meeting several targets and fulfilling many more norms. The Tsunami Early Warning generated in India is provided to all 25 Indian Ocean rim countries.

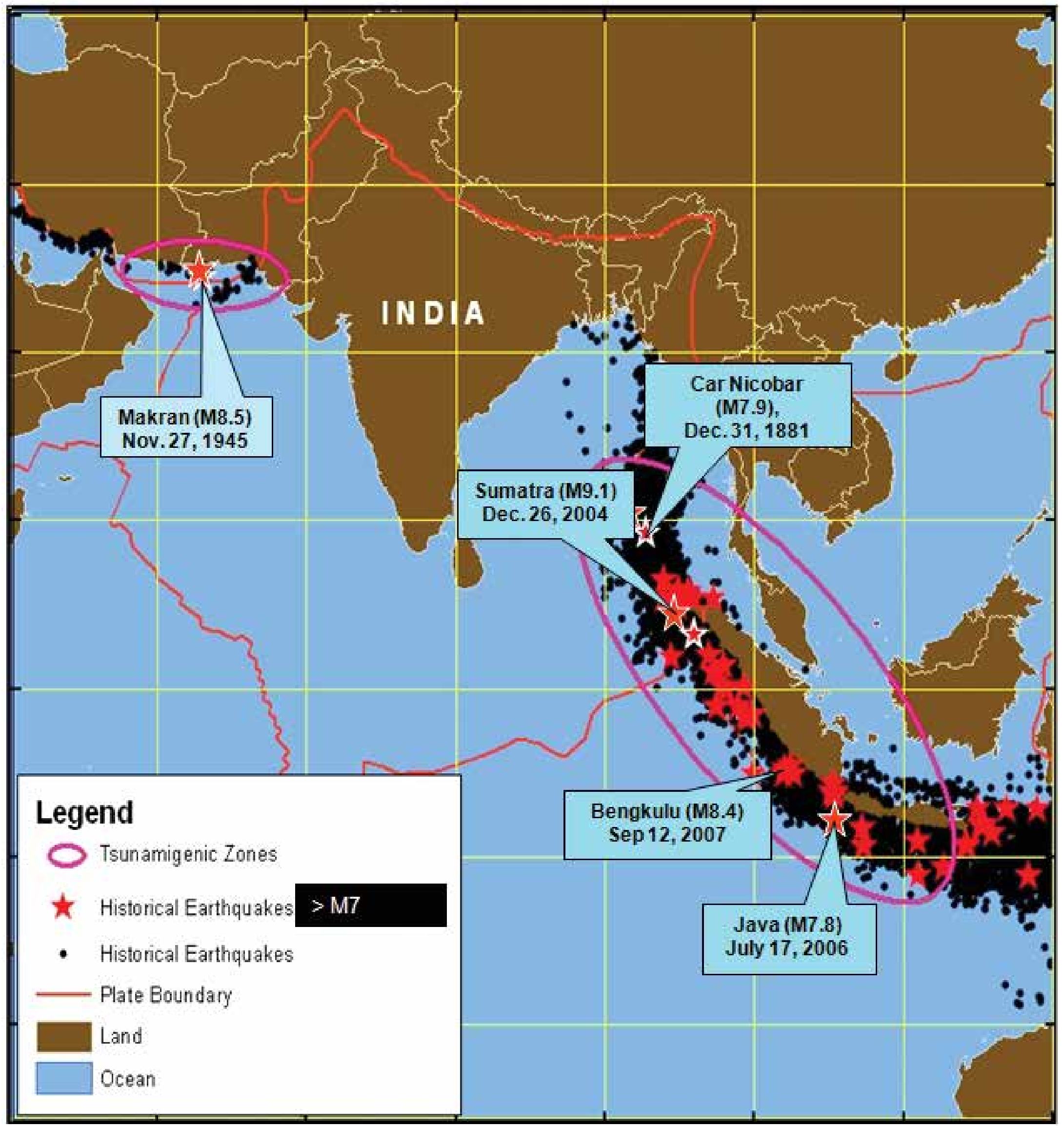
EARTHQUAKES & TSUNAMIS

The biggest cause for tsunamis is the occurrence of earthquakes on the ocean floor. Exceptions though are present; for instance, two tsunamis occurred last year in Indonesia under unconventional circumstances and warnings could not be duly issued. Near Java Island, the Anak-Krakatau volcano erupted, causing a flank to collapse into the ocean which then

2004 TSUNAMI

- The worst tsunami in recorded history occurred on December 26, 2004
- It lasted for 10 minutes (longest lasting earthquake in history)
- Approximately 2,30,000 lives lost
- More than $7 billion damage

Representation of the Makran and Andaman-Sumatra subduction zones



Tsunami characteristics

Length & Time Period

» Long wave length (of several 100 km)

» Periods of a few minutes to about an hour

Speed proportional to square root of water depth

» 500 to 1,000 km per hour in deep ocean

» About 30 km per hour near shore

Height of Tsunami Wave

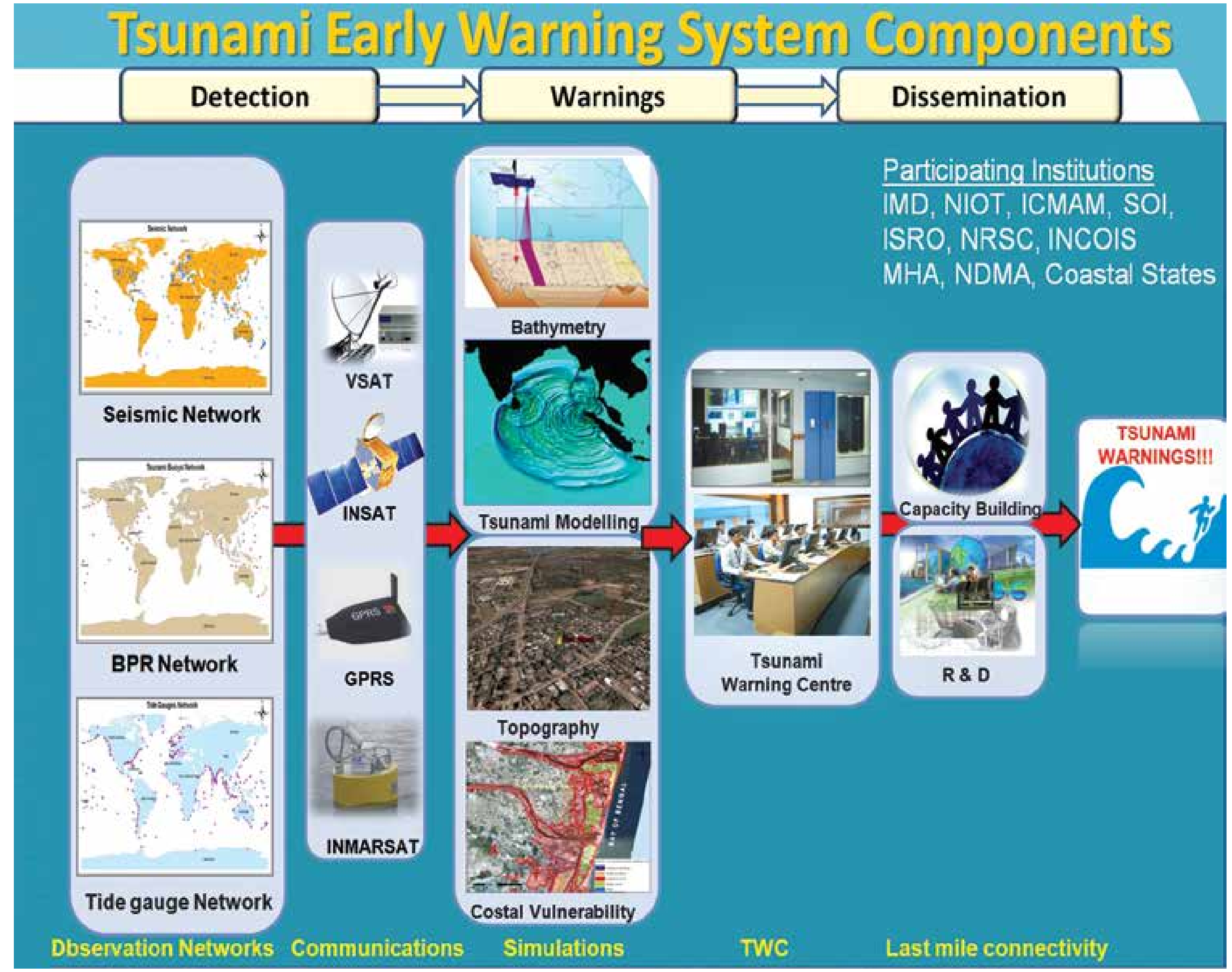
» In the deep ocean, waves are less than a metre as tsunami waves have long wavelength, small amplitude and travels fast

» As it approaches the shore, it slows and since energy is conserved, the amplitude builds up and waves grow to tens of metres

triggered a near-shore tsunami; whereas in Palu, a submarine landslide provoked a near shore tsunami — giving little response time for evacuation and rescue measures alongside causing widespread damage.

Other than freak instances or rare occurrences of earthquake very close to the shoreline where not enough time is left between tectonic disturbance and ocean reaction, the Indian Tsunami Early Warning Centre has proven to be most effective in issuing notifications and then allowing evacuation prior to tsunami waves hitting the shoreline.

Depending upon the earthquake location (Makran or Andaman-Sumatra subduction zones), the response time for evacuation of coastal population could range between 10 minutes to a few hours. As Andaman & Nicobar Islands is situated right on the subduction zone, the available response time is very short. For instance, if an earthquake occurs at the Makran subduction zone, travel time to the nearest Indian Coast (Gujarat) is between two and three hours; whereas, if an earthquake occurs at Nicobar Islands, travel time to the nearest coast (Andaman & Nicobar Islands) is less than 10 minutes and for the Indian mainland, the travel time ranges between two and three hours.



Diagrammatic representation of the Tsunami Early Warning process

TIMELY WARNINGS

The Tsunami Early Warning System (TEWS) constantly monitors seismic data from 450 seismic stations, operated by various global as well as national agencies – allowing the detection of an earthquake within five to six minutes of its occurrence. Further, only when seismic signals are detected by multiple stations in the network is an earthquake officially declared

The goal of ITEWC is to publish bulletins at the earliest instance of the occurrence of an earthquake on the ocean floor, depending on whether such an earthquake can translate into a tsunami. Therefore, earthquakes of greater than 6.5-magnitude which have occurred within 100 km of the surface, are considered most susceptible to trigger potential tsunamis and for such earthquakes, the first bulletin must be sent out within 10 minutes, confirming an earthquake occurrence.

Bulletin 1 (within 10 minutes): Confirm earthquake occurrence with details of magnitude, location and depth.

Bulletin 2 (within 15-20 minutes): When an earthquake is greater than 6.5 magnitude, numerical models are used to derive specific information in tandem with the earthquake. Such models convert the earthquake into potential impacts relating to how much water it

The goal of ITEWC is to publish bulletins at the earliest instance of the occurrence of an earthquake on the ocean floor

Deployment of Bottom Pressure Recorder (BPR) in Bay of Bengal

TSUNAMIS IN INDIA

DATE	ORIGIN	MAX RUN-UP HEIGHT (m)
December 26, 2004	Sumatra	30
November 27, 1945	Makran	17
June 26, 1941	Andaman	1.25
August 27, 1883	Krakatoa	2
December 31, 1881	Car Nicobar	1.2
April 12, 1762	Bay of Bengal	>2

New Decision Support System 2016

Dash Board

» Captures real-time earthquake information from multiple sources and displays earthquake location with focal mechanism

Situation Analysis

» Access to Open Ocean Propagation Scenario Database (OOPSDB) with complete optimisation

» Near real-time tsunami model launch with available focal mechanism for open ocean propagation results

Observation Analysis

» Real-time access to all national and international sea-level station data

» Real-time calculations of residual data

» Sea-level inversion to get slip distribution of tsunamigenic source

can displace, wave propagation, how it will approach the coasts, etc. Based on these models, the second bulletin is sent with information in four colours – Red, Orange, Yellow, Green.

Red indicates the areas that are most vulnerable and where evacuation must be carried out right away without delay. Orange is for areas where disaster management authorities are advised to be on high alert, take people to higher grounds from beaches and low-lying areas and be cautious of any potentiality. Yellow is for areas where disaster management authorities must keep a cautious watch and wait for further updates of emergency or otherwise. Green is for no threat areas.

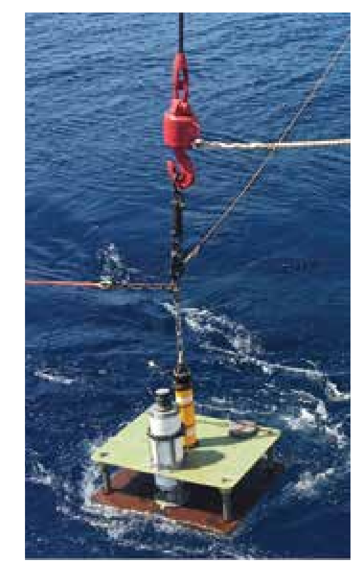
Tsunami arrival time and wave height is also provided in this bulletin.

Bulletin 3 (consequent bulletins): After the preliminary warning, as more data is received from sea level gauges such as Open Ocean Tsunami Buoys and tide gauges located at 36 locations along the coasts, it is matched with generated bulletins to check accuracy and further updates are provided to regions, warning them of exigencies or otherwise.

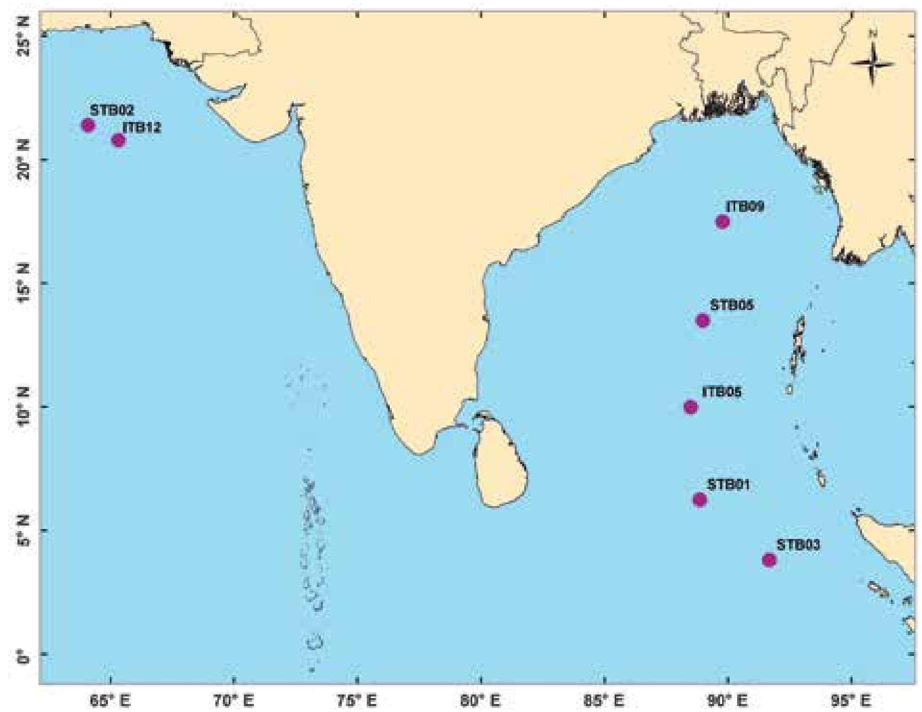
These bulletins are provided to all disaster management officials, those registered with INCOIS via mobile, website, Email, MHA, MoES, NDMA, etc.

TECHNOLOGY

A sophisticated three-tier technology system is used by ITEWC. At the first level, seismic sensors installed at



Deployment of BPR before being released in the ocean



Network of tsunami buoys

Network of tide gauges

Performance of ITEWC

ITEWC monitored 595 earthquakes (M≥6.5) during September 2007 to May 2019

Region	No. of earthquakes (M≥6.5)
Indian Ocean (IO)	97
Other than Indian Ocean (GO)	498

various locations detect an earthquake while the Bottom Pressure Sensors that are placed at 3,500-4,000 m depths on the ocean floor are triggered with tectonic movement. The sensors then send information via sound waves to buoys that are anchored and are floating on the ocean surface. These buoys then transfer information to satellites through microwaves and this satellite confirms information to the Indian Tsunami Early Warning Centre at Hyderabad. These readings are consequently read by the Centre, which interprets, sends bulletins and informs concerned parties of the occurrence of an earthquake, a possible tsunami and its extent.

In areas more prone to tsunamis, like the Andaman & Nicobar Islands, electronic display boards have been set up which are linked to very-small-aperture terminal (VSAT) that allow communication even when all networks are snapped due to bad climate, unruly winds, etc. These VSATs ensure that information on the INCOIS website can be accessed irrespective of network and those in vulnerable areas registered with INCOIS too are able to receive instantly generated bulletins and updates.

ITEWC has deployed five tsunami buoys on the East Coast and two on the West Coast (total seven). Additionally, there are 36 tide gauges, which provide real-time sea-level data at coasts and confirm the generation of a tsunami. The same is then published in bulletins. The tsunami buoys are deployed in such a way that it can confirm the occurrence of a tsunami well within 30 minutes.

ZONES

India is primarily concerned with two subduction zones — Makran subduction zone and Sumatra subduction zone. The tsunamis in this region, as elsewhere, are caused primarily by earthquakes, landslides, volcanos. 80-90 per cent tsunamis are caused due to earthquakes and thus, extensive tracing of tectonic movements assists the tracking of tsunamis. Earthquakes are tracked up to 200 km from the coast and the average detection time is about 5-6 minutes. In Andaman & Nicobar Islands, an earthquake will trigger a tsunami within 10-15 minutes – depending on the magnitude, distance and depth.

The devastated district of Banda Aceh in Indonesia's Sumatra island in the aftermath of the massive December 2004 tsunami

CAPACITY BUILDING

Capacity building is an important parameter for ITEWC to enhance performance and further mitigate impacts of a disaster. For this, several workshops, training programmes (national and international) and exhibitions are organised. The most important aspect of capacity building is to empower the local populace residing near vulnerable coastal areas in responding to earthquake and tsunami warnings. Additionally, coastal administrators, disaster management officials and general public are taught about Standard Operating Procedures, use of tsunami inundation maps and other technical aspects. In secondary and high schools, knowledge on disaster awareness and response to related occurrences is also provided.

Each year, tsunami mock drills are conducted along with test runs to check that all channels of dissemination to various disaster management organisations and participating agencies are in place and functioning properly. The processes and procedures are evaluated and organisational decision-making skills are further honed. The drills also provide an opportunity to identify proper communication methods that could be used to notify and instruct the public and also assess the lapse time between occurrence and distribution of information. These mock drills are done at the district level involving at least two villages and assist immensely in validating the level of community awareness, preparedness and response.

Further, ITEWC operates the Indian Ocean Tsunami Ready (IOTR) programme, which is a community performance-based programme that aims to strengthen tsunami preparedness of coastal communities through a structural and systematic approach and by fulfilling a few best-practice indicators set by ICG/IOTWMS. The main objective of the IOTR programme is to improve the coastal

India is primarily concerned with two subduction zones – Makran and Sumatra

A woman in a tsunami-damaged village in Tamil Nadu waving for assistance from a hovering helicopter, December 31, 2004

community's preparedness for tsunami emergencies and to minimise the loss of life and property. In India, IOTR has been implemented in six tsunami prone villages of Odisha on a pilot basis. One village in each tsunami prone district has been chosen and the Odisha State Disaster Management Authority has implemented the programme.

The most important aspect of capacity building is to empower the local populace residing near vulnerable coastal areas

WAY FORWARD

Currently, the predicted height of ocean waves is calculated on a model which can work only up to a depth of 30 m, this is a shortcoming that is now being addressed.

Before ITEWC began its complete functioning, only Level 1 service of potential announcements was provided. After UNESCO set up TEWCs with upgraded technology that provide localised data, Level 2 of providing services was achieved.

Now, we are moving towards Level 3 service where not only will expected wave height be provided, but the information system will also detail extent of inland inundation and its possibilities. This inundation will be computed in real-time using advanced numerical models. These inundation models will utilise Digital Elevation Models (DEMs) developed by National Remote Sensing Centre (NRSC) of ISRO which has deployed CartoSAT-1 as well as Air-borne Laser Terrain Mapper (ALTM) along coasts to derive topographic details and make consequent graphs of how the ocean water is expected to gush in and inundate.

These graphs are extremely detailed, showing even street lights, and is based on Multi Hazard Vulnerability Maps created at 1:25,000 resolution across the coast of India to identify the most vulnerable areas. Currently, such mapping has been deployed in Puri, Kakinanda, Machhilipatnam, Chennai, Cuddalore, Kochi, Allepey, Rameshwaram and Tuticorin. This 3D GIS mapping is done very intricately across levels and is known as the Digital Shoreline Analysis System. Tsunami markings have been done extensively on the eastern coast and partially on the western coast.

Upgradation has also been achieved in developing methods to translate seismic occurrence into data. Currently, data recorded by nearby broadband seismometers gets clipped for higher magnitudes, limiting proper estimation of an earthquake in time for tsunami early warning. For instance, in 2011, in Tohoku, near shore earthquakes occurred, allowing very little time for mitigation. The first warning said that the magnitude was 7.9 and preparations were being made accordingly. However, consequently, this information was updated to 8.2 then 8.6 then 9 – indicating a massive

IOWave mock drill conducted by ITEWS

India as Tsunami Service Provider

Indian Tsunami Early Warning Centre (ITEWC) serves not only as a national tsunami warning centre but also as a Tsunami Service Provider (TSP) for the Indian Ocean region. ITEWC is consequently playing a major role in UNESCO/IOC Tsunami Warning Initiatives:

- Indian scientists played a major role in designing the Indian Ocean Tsunami Warning and Mitigation System (IOTWMS)
- India had been Founding Chair of Intergovernmental Coordination Group (ICG) for the IOTWMS
- India first to initiate exchange of earthquake information (SL-1) in 2008
- In 2011, India started exchanging model-based advisories (SL-2)
- On October 12, 2011, UNESCO handed over the responsibility of Indian Ocean tsunami advisories to the TSPs of India, Australia, Indonesia
- As a TSP, India is providing bulletins to 25 Indian Ocean rim countries, i.e. Australia, Bangladesh, Comoros, France (La Réunion), India, Indonesia, Iran, Kenya, Madagascar, Malaysia, Maldives, Mauritius, Mozambique, Myanmar, Oman, Pakistan, Seychelles, Singapore, South Africa, Sri Lanka, Tanzania, Thailand, Timor Leste, UAE and Yemen

Boats topple as tsunami waves land off the southern coast of India

earthquake. Receiving this information late caused many hiccups and more lives would have been saved had the extent been known earlier.

To avert this trouble, India is now using Global Navigation Satellite System (GNSS) receivers that will measure the displacement and quickly derive magnitude. So, when an earthquake occurs, it quickly studies the position of the receiver and how much it has displaced from its original position, and then transfers that data through VSAT to INCOIS — this is quicker than waiting for unclipped data from distant seismometers in case of a large earthquake. 35 GNSS receivers have been placed in Andaman & Nicobar Islands for quicker translation of information.

A large portion of Indira Point, India's southern-most tip, submerged after the 2004 tsunami

Currently, information to India also arrives from Indonesia and Australia and the ICG at UNESCO coordinates all incoming information. To other countries, ITEWC provides earthquake parameters and tsunami forecast information, while the rest (inundation, impact, etc.) is prepared by the home countries. But ITEWC at home provides much more detailed mapping and information. For this, two bulletins are prepared: one for national use and one for other countries. Day-to-day updates are provided inside the country while the information from INCOIS is coordinated with NDRF and NDMA.

Since 2004, after fortunes of Indian Ocean rim countries drowned in unexpected 'harbour waves', India has come a long way in building and improving its tsunami warning centre. As earthquakes still remain largely unpredictable, scope for improvement in technology with more enhanced results is still a possibility.

Tsunami buoy deployment team aboard SN-138 cruise

Tsunami notification

- Notification messages are issued in text format
- Bulletins are generated in both text and HTML formats on the websites
- Graphics are generated in jpg or png format on the websites
- Spatial data is also available in dbf format on the websites

International level

All 25 Indian ocean rim countries

National level

MHA, NDMA, MoES, NDRF, IMD & CWC

State level

Relief commissioners and State Disaster Management Authorities of Andaman & Nicobar Islands, Andhra Pradesh, Gujarat, Goa, Karnataka, Kerala, Maharashtra, Odisha, Tamil Nadu, West Bengal, Lakshadweep and Puducherry

District level

District Disaster Management Authorities and Emergency Officers of all coastal districts

Institutional

1-10 NDRF Battalions, all control rooms of A&N Islands, HQWNC, HQENC, HQANC, HQSNC, NOIC Tamil Nadu, Gujarat, West Bengal, NPCIL, Mumbai, Madras Atomic Power Station, Tarapur Atomic Power Station (1&2, 3&4), Kudankulam Atomic Power Unit, SHAR, MRCC, Coast Guards, Port Officers, Coastal Industries (Reliance) media & public subscriptions.

Deep Ocean

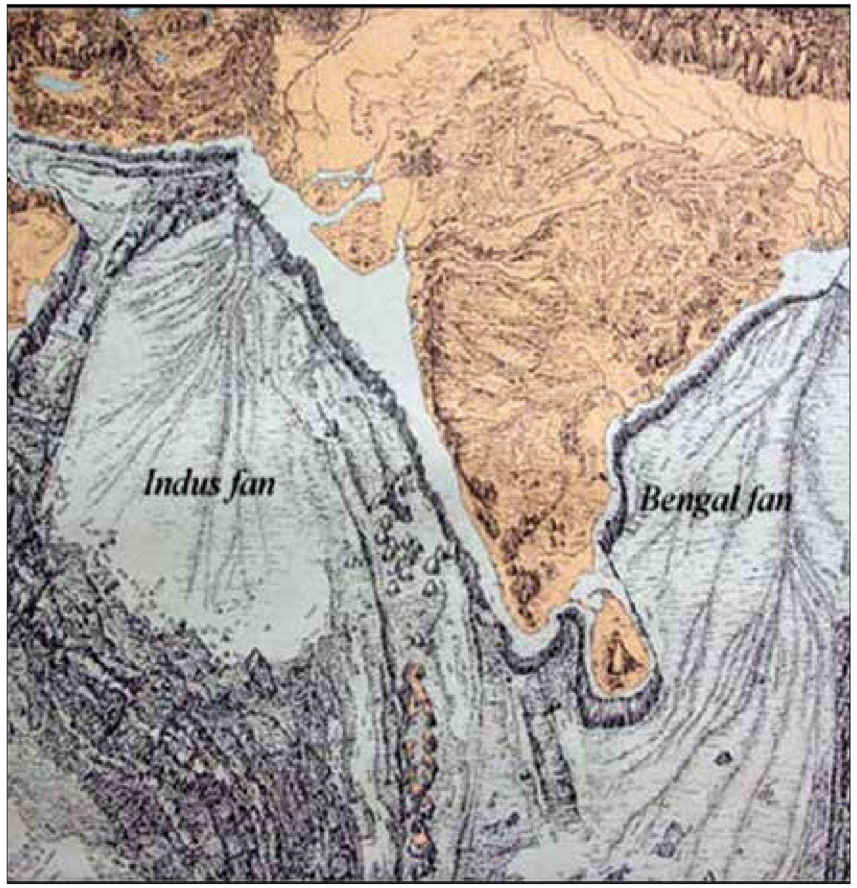
CLAIMS **ON SEA**

By pursuing its claim of an extended continental shelf, India is seeking to expand its horizons in deep sea research – to trace the region's dynamic geological past and also attempt sustainable resource extraction

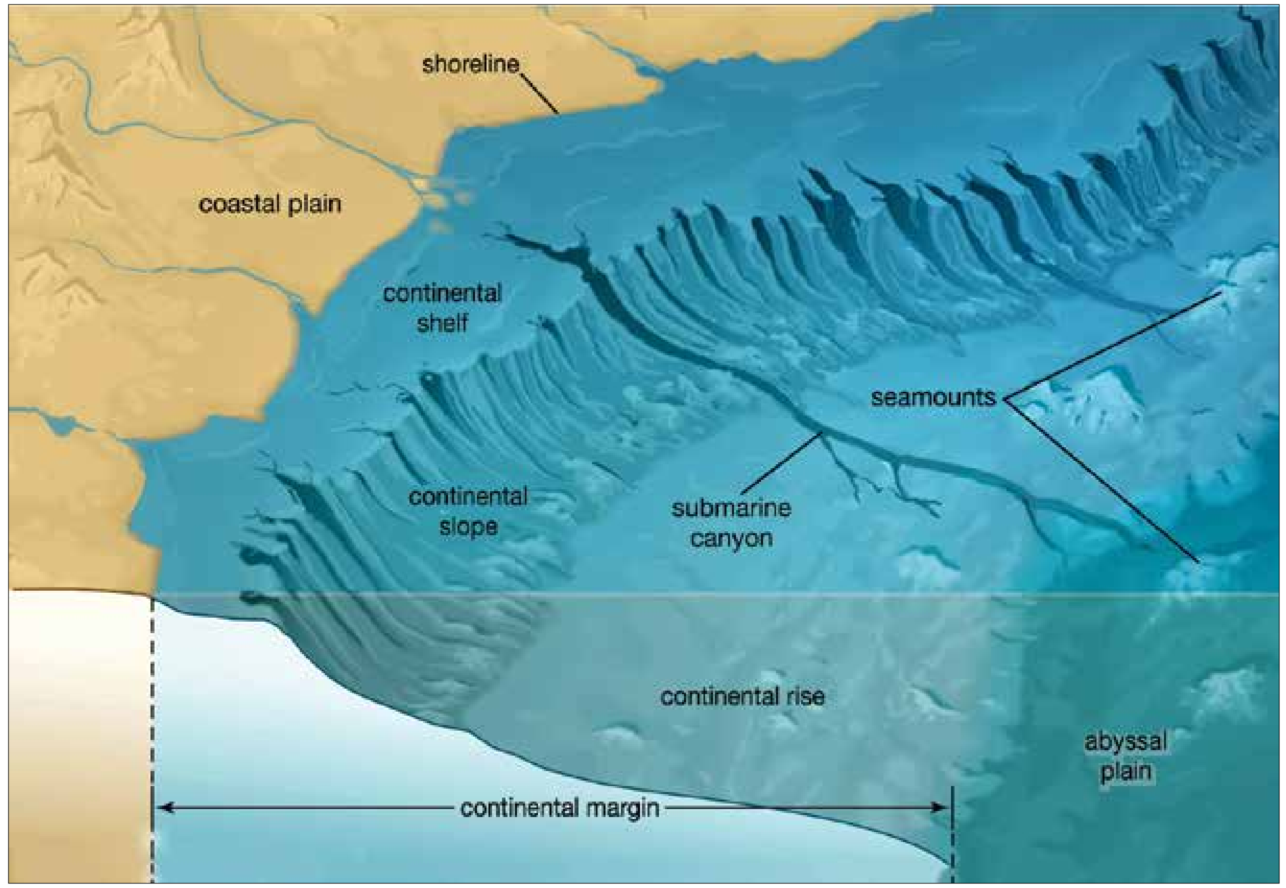
India's claim to an extended continental shelf has been resting with the United Nations for a while and, if granted, would open many new avenues of crustal exploration for the country's scientific community. The continental shelf is the submerged extension of land territories in coastal areas, and is defined and governed by the United Nations Convention on Law of the Sea (UNCLOS).

As defined by UNCLOS, the continental shelf comprises the seabed and subsoil of submarine areas in a coastal state that extend beyond the territorial sea through natural prolongation of its land territory to the outer edge of the continental margin (comprising the geological shelf, slope and rise), or to a distance of 200 nautical miles (NM) from the territorial sea baseline where the outer edge of the continental margin does not extend up to that distance.

The western coast of India



Location of the Indus Fan and Bengal Fan – two extensive submarine canyon systems



Structure of the continental shelf

In one of the largest marine geophysical surveys conducted by India, over 31,000 line km of multichannel seismic reflection, gravity and magnetic data together with bathymetric information were acquired along 42 pre-determined profiles

Now, a coastal state which intends to establish the outer limits of its continental shelf beyond 200 NM has to submit particulars of such limits to the United Nations Commission on the Limits of the Continental Shelf (CLCS) along with supporting scientific and technical data within a specific time frame. CLCS – a 21-member UN body of experts on geology, geophysics and hydrography – will consider the data and other material submitted by the coastal state and provide consequent recommendations.

INDIA & CLCS

Considering that India's natural continental shelf extends beyond 200 NM from the territorial sea baseline, the Ministry of Earth Sciences (MoES) undertook a major multi-institutional national programme of collecting, processing, analysing and documenting the requisite scientific and technical information for delineating the outer limits of the continental shelf in the Arabian Sea and Bay of Bengal, including the western offshore areas of the Andaman & Nicobar Islands. The task was implemented by the National Centre for Polar and Ocean Research (NCPOR), an autonomous institute of MoES, with close participation of the Ministry of External Affairs, Naval Hydrographic Office of Ministry of Defence, National Institute of Oceanography, National Geophysical Research Institute of Council of Scientific and Industrial Research, Geological Survey of India, Directorate General of Hydrocarbons, and Oil and Natural Gas Corporation.

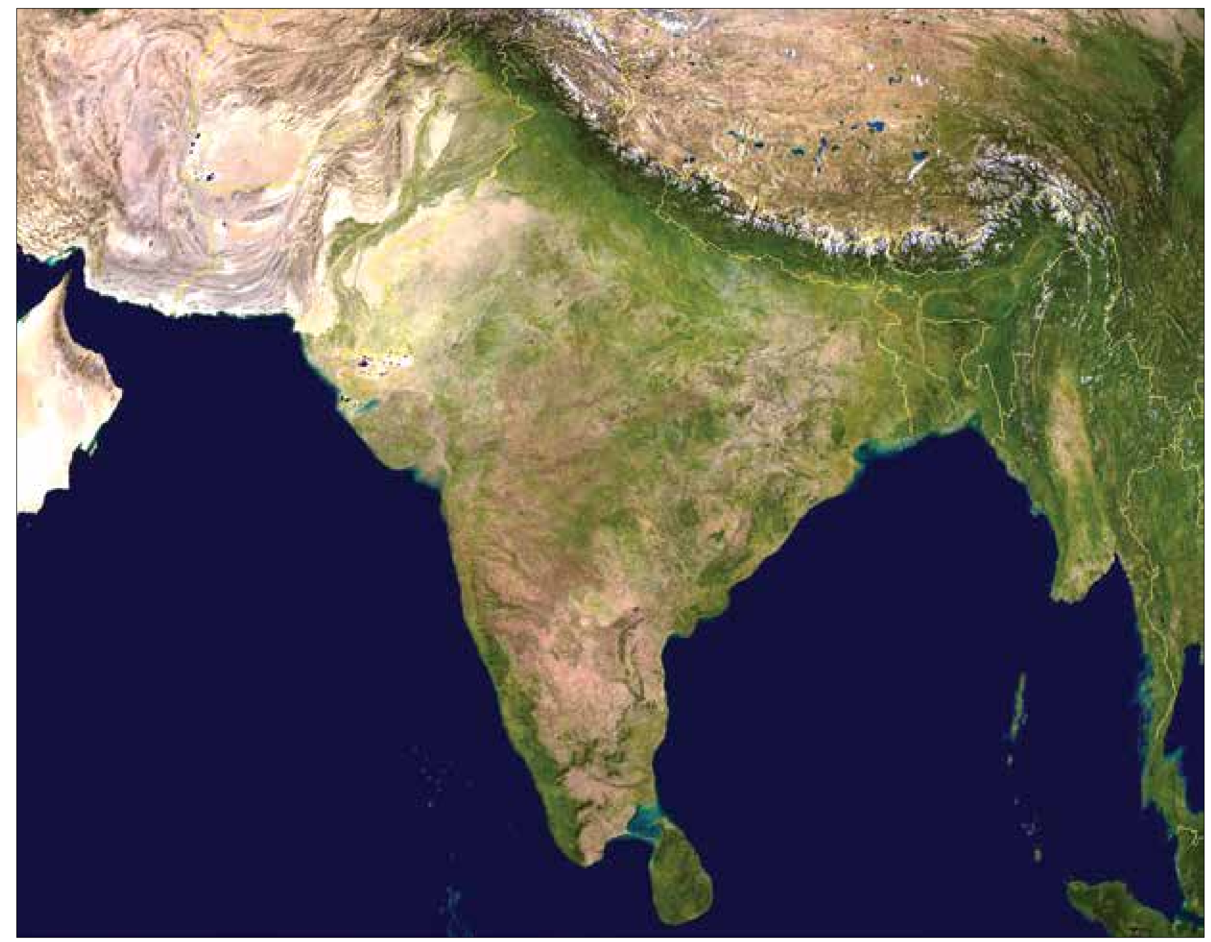
In one of the largest marine geophysical surveys conducted by India, over 31,000 line km of multichannel seismic reflection, gravity and magnetic data together with bathymetric information were acquired along 42 pre-determined profiles. Additionally, 100 Ocean Bottom Seismometers (OBS) were deployed with a significant retrieval rate of 92 per cent, while data from high-quality wide angle seismic reflection and refraction were obtained at critical locations.

The entire data acquisition programme that unfolded across 11 phases was implemented during the period of 2002-2004. Over 40 Indian scientists along with officials from seven national organisations and institutes participated actively during the exercise of data collection. This was followed by data processing,data interpretation with rigorous quality checks and analyses which were carried out concurrently at three national institutions over a period of over two years.

WEALTH IN THE OCEANS

The studies conducted by Indian scientists have provided a wealth

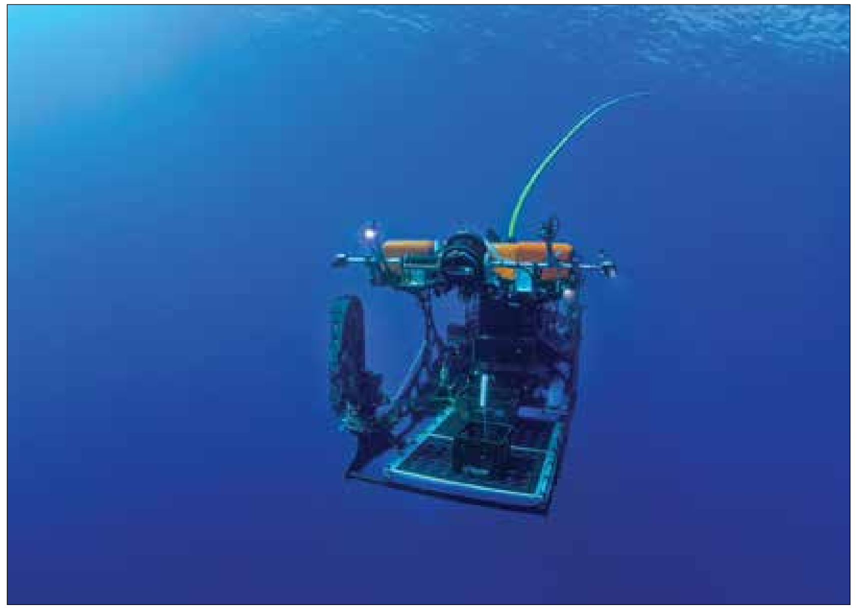
The studies conducted by Indian scientists have provided a wealth of scientific data that lends critical insight into the nature of the seabed and sub-seabed in and off the Indian Exclusive Economic Zone



As a peninsula, India boasts of a 7,516.6 km coastline

Oil exploration on Indian seas

of scientific data that lends critical insight into the nature of the seabed and sub-seabed in and off the Indian Exclusive Economic Zone (EEZ). The existence of two of the world's thickest accumulations of sediments on the seabed – the Indus Fan in the Arabian Sea and Bengal Fan in the Bay of Bengal – that culminated from the Himalayas along with a complex geological setting in the western offshore of Andaman & Nicobar islands has made data interpretation challenging in a multitude ways.



A glimpse of deep sea mining

While scientific and technical information have admirably served their primary purpose of delineating the outer limits of India's continental shelf beyond the 200 NM mark, the surveys have also furnished invaluable data that could form the cornerstone of the country's planned endeavours in the oceanic realm. Further studies of the data collected are expected to provide answers to long-debated questions on the history and geological evolution of the seas and offshore sedimentary basins around us, the origin and evolution of enigmatic features such as the 85° East Ridge in the Bay of Bengal, the Laxmi and Laccadive Ridges in the Arabian Sea, the Gulf of Mannar, the offshore extent of the Deccan volcanics, the reasons for the association of gravity lows in the Bay of Bengal with structural highs, the development of the fans vis-à-vis the origin and growth of the Himalayas, etc.

The studies have also opened a new vista in the exploration of hydrocarbons in the offshore areas of the extended continental shelf beyond 200 NM. This is particularly relevant to the country's growing energy needs. In addition, the data gathered is expected to provide specific insights related to areas such as marine ecosystems, unconventional energy, mineral resources and hazards resulting from extreme events, such as earthquakes and tsunamis.

APPEALS

On May 11, 2009, India filed an appeal to CLCS, her first partial submission under the provisions of Article 76 for a continental shelf extending beyond 200 NM from the Indian baselines.

MARINE GEOPHYSICAL DATABASE

Considering the huge volume and intrinsic value of geoscientific data collected for the CLCS programme, a marine geophysical data centre has been established at NCPOR. The data centre allows for a web-based geospatial database of marine geophysical and bathymetric information pertaining to the Indian continental shelf. The metadata functionality of the database describes the primary details in terms of when and how the data was collected, nature of the data, how the data was processed, necessary supporting information that went into the processing, etc. The database also facilitates customised GIS-based interface for easy retrieval of data from Network Attached Storage (NAS), queries based on different scientific inputs, and web-based input/output interface to facilitate the application to run on internet/intranet with login authentication. The database format is also flexible, allowing both vertical and lateral growth.

Like the rest of coastal India, Andaman Islands are rich in floral and faunal diversity

The data centre allows for a web-based geospatial database of marine geophysical and bathymetric information pertaining to the Indian continental shelf

> With the International Ocean Discovery Programme, India is conducting superior geoscientific research to study the planet's evolutionary history and envisage a more sustainable future

Members of the Indian Navy use a rigid bottom inflatable boat (RIB) to meet with the JOIDES Resolution captain and science management team of Exp 355

INTERNATIONAL OCEAN DISCOVERY PROGRAMME

IN PURSUIT OF THE **UNREVEALED**

Scenic shot of the bow on Exp 359

The International Ocean Discovery Program (IODP) is an international marine research collaboration that explores Earth's history and dynamics using ocean-going research platforms to recover data recorded in seafloor sediments and rocks, and to monitor sub-seafloor environments. The broad goal of IODP has been to gain perspective on changes observed over time (millions of years) on Earth's oceanic crust that would, in turn, lend perspective into possible outcomes that could occur in the future. The current phase of IODP (2013-23) has identified the present five-year scientific plan as 'Illuminating Earth's Past, Present, and Future'. Key highlights of the current project include:

- Climate and Ocean Change: Reading the Past, Informing the Future
- Biosphere Frontiers: Deep Life, Biodiversity, and Environmental Forcing of Ecosystems
- Earth Connections: Deep Processes

A collage of the dance of whales seen on Exp 356

- and their Impact on Earth's Surface Environment
- Earth in Motion: Processes and Hazards on Human Time Scales

PALEOCLIMATOLOGY

Paleoclimatology or the study of past climates is vital to IODP explorations. The past lends important markers for the future, and paleoclimatology is one such sphere of study that checks past trends in climate to influence future decisions. It is impossible to go back in time and observe physical changes; therefore, we must locate proxies that will provide a glimpse into events that have unfolded in the past. Long-time climate evolution is particularly important today as we look for ways to sustain in an age when drastic climate alterations are occurring at a more accelerated rate.

IODP involves the use of advanced technology to drill deep into the ocean's surface and collect geological samples that have been preserved naturally without human interference. These samples, which are largely sediments, lend insight into how climate behaved over periods of time. Alongside climate, IODP also studies plate movements and tectonic shifts to understand the course of evolution — of our planet and its climate.

> IODP involves the use of advanced technology to drill deep into the ocean's surface and collect geological samples that have been preserved naturally without human interference

Two albatross spotted at sea during Exp 360

A fast-moving red tailed tropic bird spotted during Exp 356

AN OCEAN OF SECRETS

The oceans and seas of our planet have proven to be rich repositories of knowledge that predate human existence. This has been possible due to the sea's essential character of maintaining continuity over time – making it less susceptible to human or other meteorological changes and consequently, making the search for untampered evidence of what could be our planet's story less hassling.

A crucial finding from the oceans has been in reaching the roots of Himalayan orogeny, which is believed to have occurred some 50 million years ago and seems to have nurtured the Indian monsoon. Prior to this, monsoon was not typical to the Indian subcontinent. Just as the Himalayas were forming and monsoons began in the subcontinent, large amounts of sediments that comprised the structure of these fold mountains were washed down the land surface into the Bay of Bengal and Arabian Sea. These washed deposits carry crucial evidence of the time that preceded formation of the Himalayas and even after. They have also assisted in tracing the climatic and tectonic changes that the subcontinent experienced in the period when the Indian plate collided with its Eurasian counterpart.

INDIA & IODP

India became an Associate Member of the IODP consortium in 2009 through an MoU between Ministry of Earth

The sun sets on the horizon during Exp 362

A sedimentologist subsamples microbiology whole-round samples in the geochemistry lab cold room during Exp 374

A scientist prepares an archive-half section for imaging during Exp 374

A logging and physical properties specialist examines the downhole logging data from drill hole of Exp 355

Sciences (MoES), Government of India, and National Science Foundation (NSF), USA. Since then, every year, Indian scientists have participated in various IODP expeditions for scientific research. The National Centre for Polar and Ocean Research (NCPOR) has been designated as the nodal agency to act as IODP-India and Program Management Office (PMO). IODP-India has been delegated with the responsibility of coordinating all scientific activities conducted by Indians pertaining to this program.

In the current phase of IODP (2013-23) India has signed an MoU with NSF, USA, with the following objectives:

- Indian participation to global IODP expeditions
- Exclusive access to core samples within moratorium period
- 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 the underlying crust
- Develop long-term scientific drilling programs in the Southern and Antarctic Oceans and address regional as well as global scientific challenges
- Capacity building, hands-on exposure and international collaboration

Apart from facilitating shipboard participation of Indian scientists, IODP-India also provides financial impetus for post-cruise research support to Indian researchers and 11 such projects are currently funded under this plan.

Ever since India's association with IODP in 2009, more than 40 young Indian scientists have participated in different IODP expeditions on board D/V JOIDES Resolution. IODP has provided a major breakthrough to Indian scientists who received access to cutting-edge technology and also connected with experts from across the globe with similar interests in studying geosciences. Prior to this, India's involvement with global technology was limited. 40 scientists sailed on these high-end vessels for the first time to study sediment core and base coring.

LAXMI BASIN

The Laxmi Basin, a geophysical anomaly on Arabian Sea, will assist in delineating the long-term consequences of changing climate patterns and also provide potential links to periods of missing data. The basin is a most significant geological spot where crustal movement appears to have occurred both in convergence and divergence. This makes Laxmi Basin vital to paleoclimatic studies, particularly to understand changes in the Himalayan orogeny.

The most number of drillings were done in 2015, with five being conducted around Laxmi Basin. A major geophysical myth was busted with this drilling.

Scientists had largely believed that the Himalayas peaked some 8-15 million years ago, marking the most intense period of the mountain's span. However, sediment studies around Arabian Sea prove otherwise. It appears that this period of high intensity was more recent than previously estimated.

Subsea camera system being lowered into the cyan blue waters of the moonpool during Exp 355

Major physiographic features in the Arabian Sea and adjoining areas. The existing Deep Sea Drilling Project and Ocean Drilling Program locations are marked with red stars. Expedition 355 proposed drill sites lie in the Laxmi Basin area; Yellow circles – primary sites, white circle – alternate site

Scientists in discussion onboard Exp 355

A sedimentologist takes a small amount of sediment from a core section to examine the microscopic constituents of the sediment

Scientists checking in to ascertain the latest results from smear slides

Recording the lengths of core sections before they are entered into the shipboard database, during Exp 355

> IODP involves the use of advanced technology to drill deep into the ocean's surface and collect geological samples

This knowledge provides crucial links into the subcontinent's geophysical temperament.

Studying plate movements and tectonic shifts helps us understand fundamental changes on Earth's surface, locate resources in deep seas and also assists in predicting disasters so that their impact on human life can be minimised. With links from IODP, observatories can be set up in vulnerable locations that provide real-time updates on events unfolding inside Earth's crust – furnishing important hints on what could occur soon.

IODP explorations are not just conducted in Laxmi Basin but across Bay of Bengal and Arabian Sea, particularly to understand the evolution of orogenic rainfall since the emergence of the Himalayas.

The Himalayas, in fact, did not just birth changes in India but across Asia. The spectrum of Asian monsoons appears to be influenced significantly by the formation of the Himalayas.

TECHNOLOGY

Scientific drilling is performed through highly specialised and unique drilling platforms available before the international scientific community, namely – JOIDES Resolution (USA), Chikyu (Japan) and Mission Specific Platform (MSP) (Europe).

At present, there are 23 representative nations, whose scientists are selected to staff IODP research expeditions conducted throughout the world's oceans. India deployed JOIDES Resolution at Laxmi Basin, off the western coast on the Arabian Sea during Expedition 355.

JOIDES Resolution

It is a US-based vessel, second of only two vessels available in the world that are capable of extensive drilling and stand well-equipped with scientific laboratories. The other is Chikyu owned by Japan.

JOIDES Resolution measures 143 m in length and 21 m in width with a derrick (lifting device) of 62 m above the water line. The rig suspends up to 9,150 m of drill pipe to an ocean depth as great as 8,235 m. This is about the equivalent of six miles. 12 computer-controlled thrusters and a main propulsion system are used to position the vessel exactly at the drilling site with the help of crew.

Near the centre of the research vessel is the 'moon pool', a 7 m-wide hole through which the drill string is lowered into the ocean. Each piece of pipe is about 28 m and weighs about 874 kg. The drill crew lowers the drill bit through this hole. It takes about 12 hours in 5,500 m of water to touch the first layer of the sea floor. A motorised system is used to rotate the entire drill string and core on the seafloor.

Drills

In IODP, different drilling methods are deployed, depending on the nature of underwater sediments and rocks. The Advanced Piston Corer (APC) is feasible for unconsolidated sediments, while Rotary Core Barrel (RCB) is useful for consolidated sediments and hard rocks.

APC is crucial for high-resolution climate and paleoceanographic studies. It is a hydraulically-actuated piston corer designed to recover relatively undisturbed samples from very soft to firm sediments. Such sediments cannot be recovered well by rotary coring.

RCB is a rotary coring system designed to recover core samples from firm to hard sediments and igneous basement. It has a longer bit survival, greater coring depths and fewer mechanical failings.

Underwater camera

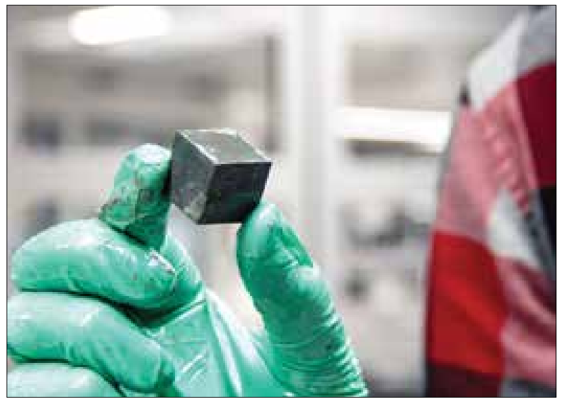
Without an underwater camera, a driller's job would be almost impossible – trying to do anything with a drill pipe in deep water, while blind, is incredibly tricky.

In the dark old days, science drilling ships relied on their sonar to locate the borehole in relation to the drill, and it could take days to enter and re-enter

Scientists carrying a retrieved core for further studies

The rig floor during coring operations

Working with the sediment of the core catcher during Exp 361



A perfect paleomagnetic cube sample from Exp 382

End of the Mill Guide showing the core a few inches inside from Exp 360

JOIDES Resolution at sea

funnels. Now, JOIDES Resolution comes equipped with advanced Vibration Isolated Television (VIT) underwater camera. The footage can be recorded and replayed in standard and high definition too if needed.

The VIT is lowered and raised using a very strong cable, called an umbilical, that has four optical fibres as well as two sets of twisted pair copper electrical wires that can carry electrical power to the cameras and sensors, and also return a lot of data back-up to the ship. The umbilical is about 7,000 m long, although only about 5,000 m is deployed for safety reasons.

SUSTAINABLE EXPLORATION

IODP is an exploration programme, not one to exploit Earth's resources. Before commencing any process of drilling, thorough reconnaissance is conducted of the ocean floor. Now, oceans are among the most sensitive ecosystems that are already suffering under the agony of climate change. For these programmes, therefore, ensuring sustainability becomes key. Typically, areas around coasts are home to coral reefs and other sea ecosystems; the deeper sea, on the other hand, where most IODP activities are conducted, is bereft of these treasures. Nevertheless, since IODP is directly impinging upon natural ecosystems, receiving clearance is mandatory. Every IODP project takes at least five years to fulfill protocols, receive clearances, build proposals etc., before the project can finally commence. An IODP project lasts for five years, and every five years, a new MoU is signed with IODP, confirming India's participation.

A glimpse of the rig tower from the helideck during Exp 356

INDIAN OCEAN GEOID LOW

MISSION INDIAN OCEAN

The Indian Ocean geoid low, one of the world's greatest geological anomalies, demands exploration and research as it appears to conceal many secrets of our planet's evolution

The scientific team deploys an Ocean Bottom Seismometer from the deck of ocean research vessel *Sagar Kanya*

The study of the Indian Ocean Geoid Low (IOGL) has irked curiosity across the global scientific community. The geoid is typically considered as a hypothetical equipotential surface that explains the geometrical irregularities on Earth. It is a mathematical abstraction that levels seas and rivers across the planet, giving birth to a mean sea level.

Deviations of the geoid from an idealised hydrostatic ellipsoid are known as geoid anomalies. Uneven mass distribution in the Earth's interior is predominantly attributed to geoid variations from place to place in terms of highs (positive) and lows (negative). Extreme geoid anomalies (either positive or negative), thus, imply a significant shift in the subsurface geodynamic conditions. The National Centre for Polar and Ocean Research (NCPOR) is the ideating and implementing body for the study of IOGL.

The IOGL program was started in 2014 as a part of 12th Five Year Plan, consequent to which, funds were received in 2016-17 and work began soon after. The first fleet of Ocean Bottom Seismometers (OBSs) was sunk in 2018 and has been retrieved recently, in August 2019, by a team of geoscientists. Subsequently, the same fleet of OBSs was redeployed to trace events for the succeeding one year. The ocean research vessel (ORV) *Sagar Kanya* vessel has been used for this deployment.


The scientific team assembling an OBS system on board ORV *Sagar Kanya*


The team washes an OBS system on deck after retrieval

THE INDIAN OCEAN ANOMALY

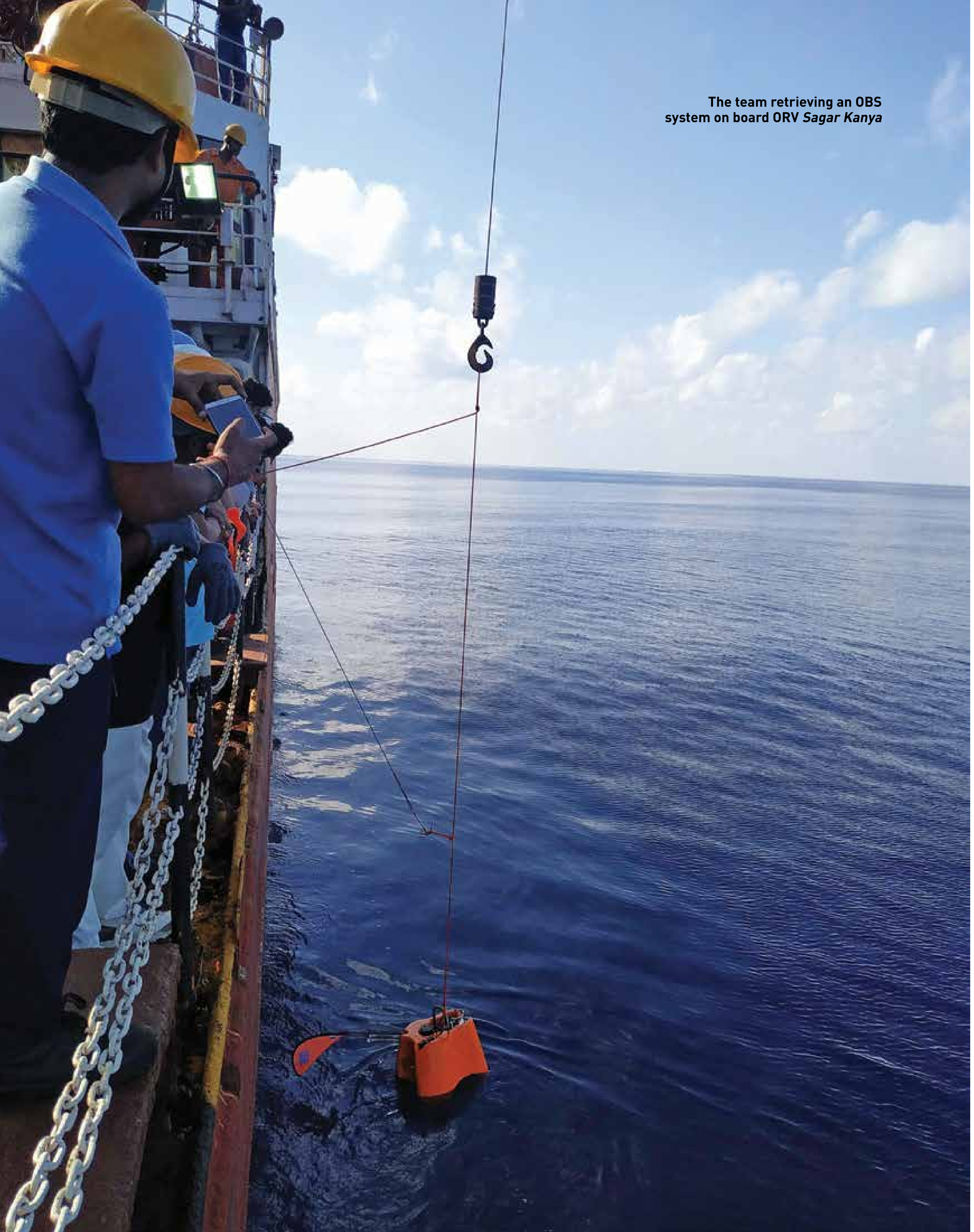
The India Ocean Geoid Low (IOGL) is the largest low in the world, displaying a ~106 m deficit. Usually, geoids are influenced by gravitational pull and volcanic structures, along with other technicalities. But the Indian Ocean geoid shows no such typicalities and yet is the deepest in the world. Some of the dominant hypotheses put forth were based on seismological investigations and visco-elastic modelling. The anomalous lower mantle convection has been understood as the most plausible cause for large geoidal undulations and is weakly coupled with shallow crustal plate motions. In addition, distinct theories such as the structural undulation in the core-mantle boundary, seismic low-velocity anomalies in the upper mantle and subduction of the oceanic origin slab-graveyard in the lower mantle during the Mesozoic period have been attributed to IOGL's very existence. In case of IOGL, numerical modelling supported by the global tomographic result provides new insight on the possible source and mantle geodynamics beneath the Indian Ocean. Another view indirectly relates geoid anomalies with intraplate deformation zones that are surface manifestations of mantle convection processes.

STUDYING IOGL

The IOGL study commenced with the broad goal of understanding the nature of the geoid, tracing its evolution (if possible) and also utilising its characteristics to sense possible changes that could occur from such a geological sink. Due to inherent methodological limitations and almost no offshore seismological observations from this region, secrets of this perplexing anomaly still remain outstanding. Under the IOGL program, plans are underway to achieve a comprehensive understanding of the nature, source and cause of the geoid anomalies in the region through integrated interpretation, and to develop a better understanding of the region's geodynamic evolutionary history, mantle processes, etc. To achieve these objectives, NCPOR has initiated a long-term plan for acquisition of various marine geophysical data which includes multichannel seismic data, wide-angle seismic data, deep ocean seismological data, etc.

The IOGL study commenced with the broad goal of understanding the nature of the geoid, tracing its evolution and also utilising its characteristics to sense possible changes that could occur from such a geological sink


The SK-360 scientific team just before deployment of the last OBS unit deep in the Indian Ocean



The team retrieving an OBS system on board ORV *Sagar Kanya*

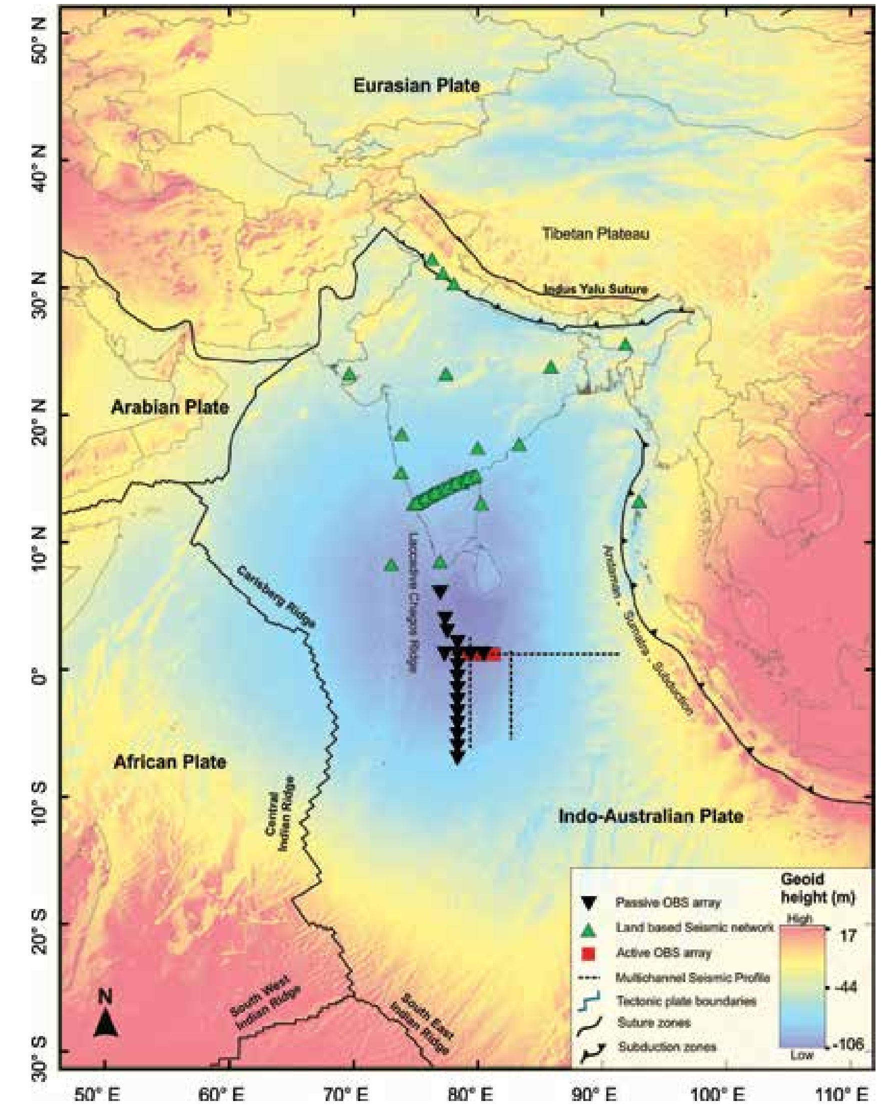
TECHNOLOGY

Ocean Bottom Seismometers (OBSs) are deployed in the geoid region to understand the depths of its sources and other associated changes. The regions where several plates are intertwined and deformed witness several minor earthquakes. The OBS systems are used to measure ground movements on the ocean floor caused by natural sources like earthquakes, landslides, underwater currents, etc. This system is equipped with a three-component broad-band seismometer and a high-tech broad-band hydrophone. The OBS is sunk into the geoid region for a period of one year, after which it is retrieved with remote sensing technology. Thereafter, all readings of the OBS are etched out to study the seismological events that could have occurred over a one-year period and gather deeper understanding of the Earth's deep structure. Such studies lend insight into the nature of this geoid and the possibilities it posits.

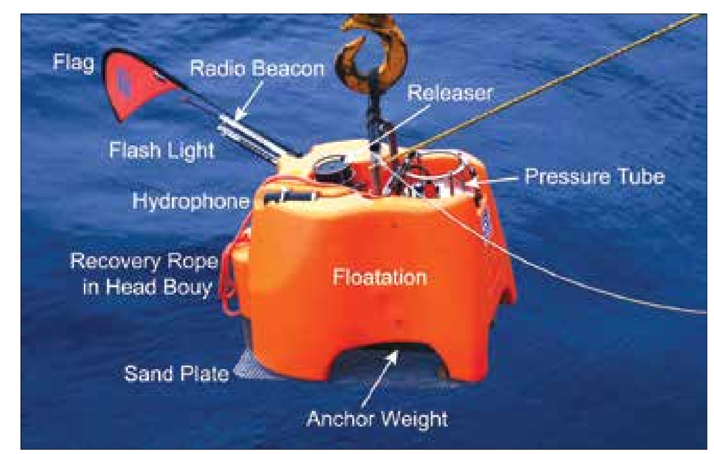
In August 2019, NCPOR retrieved seismological data of more than a year from the IOGL Ocean Bottom Seismometer Array (IOBSA) comprising 17 OBSs, and also deployed all the OBS units in the Indian Ocean during the cruise SK-360. It aims to image the earth's mantle structure, understand it and reduce the gap between dynamics of materials beneath the surface and its surface manifestation as the Indian Ocean geoid anomaly.

In addition to these primary purposes, the OBS data can be used to study tidal phenomenon and other very low frequency signals like infragravity waves, calls of marine mammals, etc. This paves the way for conducting multi-disciplinary studies through long-term deployments of such broad-band OBSs.

The broad philosophy of IOGL is to study the seismic activities that are occurring at the margins and intraplate deformation regions so that we can gain enhanced perspective into IOGL sources and the consequences those activities can have on our landmass.



IOBS array (black triangles) in a large geoid anomaly (blue area) in the Indian Ocean. Black lines represent major tectonic boundaries; green triangles and red squares represent other regional seismological stations around the IOGL region



A NAMMU OBS system used in the mission

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At Sea

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LAND TO SEA: GEOSCIENCE IN INDIA

2020