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CENTENNIAL CELEBRATIONS OF THE INTERNATIONAL UNION OF GEODESY AND GEOPHYSICS (IUGG): CONTRIBUTIONS FROM INDIA

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Guest Editorial

The International Union of Geodesy and Geophysics (IUGG) is an international non-governmental organization dedicated to the scientific study of the Earth and its space environment using geophysical and geodetic techniques.

IUGG was established in 1919 by 9 founding member countries to promote activities of 10 already-existing international scientific societies dealing with geodesy, terrestrial magnetism and electricity, meteorology, physical oceanography, seismology, and volcanology. During the period 1919 to 1939 the number of member countries increased to 35.

India joined IUGG in 1947. The Indian National Science Academy (INSA) is the adhering body for ICSU (now ISC) and IUGG in India. The affairs of IUGG are the responsibility of the Indian National Committee for IUGG and IGU.

The year 2019 is the centennial year of the formation of the International Union of Geodesy and Geophysics (IUGG). In 2017, a decision was made to bring out a special issue of Proceedings: Indian National Science Academy (P-INSA) to commemorate the centennial year 2019 of IUGG. The purpose of this volume would be to show case IUGG related work having been carried out in India. The members of the IUGG&IGU Indian National Committee took up the responsibility for writing articles corresponding to the 8 constituent International Associations of IUGG. The present volume includes 10 articles, one each for the eight Associations with the exception of International Association of Seismology and Physics of the Earth's Interior (IASPEI) where there are two articles, and a reprint of "Koyna, India, an Ideal site for Near Field Earthquake Observations" from the Journal of Geological Society of India. Contents of the "Encyclopedia of Solid Earth Geophysics" published by Springer in 2011 are also placed in this volume.

International Association of Cryospheric Sciences (IACS)

Baldev Arora and his colleagues in their article "**Himalayan Cryosphere: Appraisal of Climate Glacier Inter-linkages**" have reviewed the growth of cryospheric research in Himalaya, India and its importance in climate change related studies. Examining the snout and mass balance data indicates increased rates of glacier recession during 1970's and 1980's specifically the Central and North-East Himalaya. This is consistent with the global trend. The recession of the glaciers is attributed to increase in anthropogenic emissions of the Green House Gases. Contrary to this trend the glaciers in Karakorum region, Indus Basin are characterized by marginal growth or stagnation. A slowdown in glacier retreat since 1990's is observed along the entire Himalayan arc. An important issue is to forecast the melt water contribution to perennial rivers is of utmost importance for a variety of agricultural, and other social issues. A road map is presented to improve accuracy of anticipated contribution of melt water to the rivers. It is proposed to set up a National Institute of Glaciology to better address glacier related issues, particularly in the Himalayan region.

International Association of Geodesy (IAG)

Srinivas and Tiwari in their article "**Gravity and geodetic studies in India: historical observations and advances during the past decade**" have given a glimpse of how gravity and geodetic work started in India. The Great Trigonometric Survey (1790-1850) defined the geodetic reference frame. Gravity and geodetic observations in the Himalayan region during 1830 to 1843 led to the development of the concept of 'Isostasy', indeed a phenomenal contribution from India. Detailed regional gravity surveys, including pendulum observations started in 1950's. The Survey of India established the Indian national reference gravity station at Dehradun tied up with Potsdam gravity base sometimes in 1948. Taking into account of all the gravity stations in the country, the National Geophysical Research Institute undertook publishing a series of gravity maps of India in 1975. The Geological Survey of India launched National Geophysical Mapping program during 2002/2003 with an objective to generate gravity and magnetic responses in potential areas of mineral exploration. In the recent years detailed gravity surveys including airborne gravity gradient surveys are undertaken to comprehend subsurface mass distribution and mass variability. Other focus area have been refining of the geodetic datum, continental deformation and exploration for resources.

International Association of Geomagnetism and Aeronomy (IAGA)

Manglik in his article "**Research Highlights of the Indian Contributions to Geomagnetism and Aeronomy in the 21st Century**" has provided a historical background of the development of Geomagnetism and Aeronomy globally and in India. Apparently Chinese had discovered existence of magnetism more than two millennium BC. However, the first magnetic compass in China dates back to 1088 AD. In Europe first magnetic compass is reported back to 1190. The first comprehensive description of geomagnetic field was published in 1600. There was quantum jump in magnetism related work in the 19th century. The first magnetic observatory in India was established in Madras in 1792 and the Colaba Observatory at Bombay was established in 1841 ushering the era of continuous observations. In 1904 Alibag Observatory in Bombay was established. Colaba and Alibag observatories provide the longest series of magnetic data anywhere in the world. In the 21st century a considerable amount of work has been carried out on the theory of planetary magnetic field, paleomagnetism, rock and environmental magnetism, equatorial plasma bubble, space weather and geomagnetic storms. In 2014 an IAGA Observatory workshop with 93 observers from 33 countries was organized at the National Geophysical Research Institute, Hyderabad. Magnetic precursors to earthquakes are being investigated through operation of a number of multi-parametric observatories. High resolution heliborne TEM along with magnetics has been used for exploration of ground water and atomic minerals. Future opportunities include Indian space missions for planetary exploration, probing of Indian lithosphere and geo-resource exploration.

International Association of Hydrological Sciences (IAHS)

Arora and Tiwari, in their article "**Hydrological Studies in India during last decade: A Review**" provide a glimpse of the one of the most essential commodity for the survival of humanity: water; variation of water requirements and its availability, large data sets generated and their analyses for appropriate utilization and preservation of this fast depleting water resources.India has a huge hydrological and climatic variability with Thar Desert in Rajasthan getting less than 250 mm rain annually to Mawsynram in Meghalaya getting 11870 mm annually. The demands for water also vary substantially from one region to another. The total annual average rainfall over India and river flow are estimated to be ~1950 km^3, while the utilizable surface water is estimated to be 690 km^3. According to estimates in 2011, the total ground water resources and availability are 433 km^3 and 398 km^3. Some 83% water resources are used for agriculture, 7% for domestic use, 2% for industry, 1% for energy and 7% for all the rest of uses. Using the data from Gravity Recovery and Climate Experiment (GRACE), it is possible to investigate spatio-temporal variations in the total terrestrial water storage and decipher whether in a particular geographical region there is depletion or addition of the water resource. It has been found that north India aquifers are losing, particularly in the Ganga River Basin. "Winning, Augmentation, Renovation" (WAR) is the project launched in 2009 with an aim to find inexpensive methods for converting the saline water into fresh water, harnessing and managing Monsoon water, to manage the flood water and implementing rain water harvesting. In a nutshell, a lot of work has been done in the recent years in India to understand and improve ground water and surface water utilization. In 2009, the National Geophysical Research Institute hosted a very successful Assembly of IAHS at Hyderabad, with the participation of ~1200 scientists from all over the world.

International Association of Meteorology and Atmospheric Sciences (IAMAS)

Maharana and Dimri in their article "**Monsoon: Past present and Future**" have provided an overview of the monsoon related studies in India. They note that summer months contribute to 80% of the total rainfall in India. The spatial and temporal variation of Indian Summer Monsoon (ISM) has deep socio-economic implications for the people living in the Indian sub-continent. Monsoon related investigations got initiated way back in the British era. Better observational facilities, computational facilities, and models have improved Monsoon forecast considerably. However, a lot more needs to be done as an improvement in ISM forecast directly impacts agriculture, flood control, hydroelectric power generation etc. The authors emphasize on collection of better quality data, improvement of model dynamics, use of four dimensional data assimilation, use of better air-sea interaction coupled models and use of ensemble model for improving ISM forecast. They also emphasize on timely dissemination of the forecast.

International Association of Physical Sciences of the Oceans (IAPSO)

Satish Shenoi is the corresponding author of the article "**Physical Sciences of the Ocean: A report to IAPSO/IUGG**" with Prerna, Paul and Francis. To convey the amount of work carried out in IAPSO related work in India in the 21st century, they have put together statistics of publications. In the first 18 years of the current century, around 2300 scientific papers were published involving around 4800 scientists. In these publications collaborative work was carried out with 44 countries. They observe that deployment of Acoustic Doppler Current Profilers (ADCPs) and data from Ocean Data Buoys have helped improving the understanding of Indian Ocean variability and air-sea interaction processes. Indian National Center for Ocean Information Services (INCOIS) set up India's first Operational Ocean Forecast System in 2010. It is very well received. Discovery of Indian Ocean Dipole in 1990's and Equatorial Indian Ocean Oscillation in early 2000's gave an incentive to research on tropical coupled air-sea interaction processes. Potential fishing zone (PFZ) advisories that started in 1990's, have been found very useful by the large fishermen community on the east and west coast of India. Based on sea surface temperatures and chlorophyll content sensed by satellite, the advisories are further improved using ocean circulation and marine ecosystem parameters. The other area commented upon by them is the coastal effects of 2004 Indian Ocean Tsunami and development of the Indian Tsunami Early Warning System.

International Association of Seismology and Physics of Earth's Interior (IASPEI)

There are three articles covering various facets of IASPEI in India. Prakash Kumar in his article **"Recent Seismological Investigations in India"** has discussed seismogenesis and seismotectonics of Himalaya, Burmese-arc, Andaman-Nicobar subduction zone; seismicity of stable continental region (SCR) of India including reservoir triggered seismicity at Koyna, near west coast of India; setting up of the Indian Tsunami Early Warning System (ITEWS), which was established consequent to the occurrence of the 26 December 2004 Mw 9.2 Sumatra earthquakes and the resultant tsunami that claimed over 220,000 human lives. ITEWS was set up in a record 30 months time and was functional by September 2007. It is now considered among the best in the world. Prakash Kumar also discusses the efforts made in India in the recent years to develop an earthquake resilient society. There is also information about the seismological networks in India.

Kalachand Sain has devoted his article "**Controlled Source Seismology in India in the 21st Century**" to the beginning of controlled source seismic (CSS) studies in 1970's in India and how they have progressed over the last ~50 years. Most important geological units of India have been covered by CSS and useful structural details have been highlighted. Investigation for possible Mesozoic sediments that could be petroliferous overlain by the Deccan Volcanic basalt has been pointed out. The results of CSS have been later confirmed by actual drilling. Remarkable success has been achieved in application of CSS in detecting, delineating and assessing the resource potential of gas-hydrates in the off shore regions of India. The estimated amount of gas hydrates is huge: only 10% production of this vast resource in the exclusive economic zone of India can meet energy requirement of the country for the next 100 years.

The third article is a reprint from the Journal-Geological Society of India entitled "**Koyna, India, an Ideal Site for Near Field Earthquake Observations**" written by Harsh Gupta in collaboration with several scientists. Koyna, with a magnitude M 6.3 reservoir triggered earthquake on 10 December 1967 is a unique site of reservoir-triggered seismicity (RTS), where triggered earthquakes got initiated soon after the impoundment of Shivaji Sagar Lake in 1962. RTS has continued till now with the largest RTS event globally in 1967 and several thousand smaller earthquakes including 22 of M $\geq$ 5. Common characteristics of RTS events have been worked out that help them to be discriminated from the normal events (not associated with water reservoirs). A 3 km deep pilot borehole has been completed for near field study of earthquakes. Measurements carried out in and around Koyna are leading to setting up of a 7 km deep borehole laboratory: the first of its kind anywhere in the world.

International Association of Volcanology and Chemistry of the Earth's Interior (IAVCEI)

Ray and Parthasarathy in their article "**Recent Advancement in Studies of Deccan Traps and Its Basement; Carbonatites and Kimberlites - An Indian Perspective in Last Five Years**" have attempted to provide information on the research carried out on Deccan flood basalts, Kimberlites and Carbonatites over the past few years. The issues addressed include origin of Deccan Traps and their composition and age distribution; and origin, disposition, chronology, petrology and geochemistry of Indian Carbonatites. It is inferred that the primary magmas for the Indian Carbonatites originated from sub-continental lithospheric mantle. They have also underlined usefulness of several secondary minerals in Deccan volcanic rocks.

Several senior positions have been held by Indian scientists in IUGG Bureau and Finance Committee. These include K R Ramanathan, President (1954-57); Devendra Lal, President (1983-87); Harsh Gupta, President (2011-15), Vice President (2007-11), Bureau Member (1999-2003 and 2003-07); Vinod Gaur, Member, Finance Committee (1995-99 and 1999-2003); Virendra Tiwari, Member, Finance Committee (2015-19).

In the recent past the National Geophysical Research Institute (NGRI) hosted the International Association of Hydrological Sciences Assembly at Hyderabad in 2009. The joint assembly of IAGA and IASPEI shall be also hosted by NGRI in 2021.

It is indeed a great pleasure to acknowledge efforts of all the members of the Indian National Committee for IUGG and IGU for contributing their articles timely to make it possible to bring this volume in time to coincide with the IUGG General Assembly scheduled at Montreal, Canada in July 2019. Thanks are also to the reviewers, namely Rasik Ravindra, C V Sangewar, M Radhakrishna, Maj Gen (Dr.) B Nagarajan, B R Arora, P Rajendra Prasad, Shishir K Dube, B N Goswami, Dipankar Sarkar, J R Kayal, T Radhakrishna for their comments on the papers, which were very constructive. In the end I would also like to thank Prof Subhash Chandra Lakhotia and Prof Sanjay Puri, Chief Editors of P-INSA. Ms Richa and Ms Seema of Editorial Office of P-INSA are acknowledged for their help in bringing out this volume. Ms. M Uma Anuradha and Ms. K Mallika at the National Geophysical Research Institute, Hyderabad helped me in researching for this review volume.

On behalf of the entire Indian community of geophysicists and geodesists, we wish a very successful centennial year to IUGG and future growth for serving humanity.

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Review Article

The Himalayan Cryosphere: Appraisal of Climate-Glacier Inter-linkages

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The present review takes stock of the growth of crysospheric research in India with reference to glaciers and snow in the Himalaya, which are sensitive marker of the climate change. Overview of the snout and mass balance data indicates accentuated rate of glacier recession during the 1970's and 1980's, particularly in the Central and NE Himalaya. Like elsewhere on the globe, the retreating trends are consistent with the hypothesis of the global warming resulting from the increasing anthropogenic emissions of Green Houses Gasses. In contrast, the Glaciers in the Karakoram region, Indus basin, fed by mid-latitude westerlies, show marginal advancement and/or near stagnation. The climatic influence of temperature and precipitation (monsoon-vis-a-vis-westerlies) combine in complex manner to produce heterogeneous spatial or temporal variations in glaciers, including the slow-down in glacier retreat since 1990's all along the Himalayan arc. From continuously growing monitoring, it is apparent that beside the precipitation and temperature, geometry (wide and narrow), orientation (north or south phasing) of glacier, altitude distribution in accumulation/ablation zones, debris cover, lithology of rock types, process of erosion/weathering, atmospheric chemistry (black carbon) control the variability in glacier mass and hydrology. Quantification of various forcing parameters to allow their use in prediction of melt water contribution to perennial rivers is an important area of future research. Road map of future glacier-climate-hydrology studies, on the lines of ongoing studies in Antarctica-Arctic, is drawn with strong recommendations to establish National Institute of Glaciology.

Keywords: **Cryosphere; Himalayan Glaciers; Climate-Glacier Linkages; Mass Balance; Snout; Hydrology; Arctic and Antarctic**

Background to the Glaciological Research in the Himalaya

Rationale and Perspective

Extensive glaciers and snow that cover the elevated ranges of Hindu Kush-Karakoram-Himalaya together with contiguous Tibet (HKKH-T) represent the important constituents of the cryosphere (frozen water). Since these glaciers and snow cover represent the largest store house of frozen water outside the polar regions, the HKKH-T region has been rightly named as Third Pole on the Earth (Dyhrenfurth, 1995; Qiu, 2008). Such extensive glacier/snow cover in contiguous belt creates its own microclimate and regulates the general climate of the area. In view of their occurrence in the ecologically sensitive high altitudes, they respond too readily to slight change in

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temperature and precipitation conditions, and, therefore, are recognized as a potential proxy for reconstructing the past and present climatic changes. It is now widely accepted that the Earth has witnessed several changes in climate especially during the last 1.6 million years that are exhibited by cyclic expansion and contraction of ice sheet and glaciers (Owen *et al*., 1998; Sharma and Chand, 2016). There are ample scientific observations to suggest that in the past century anthropogenic emissions of Green House Gasses are on the increase and are resulting in gradual enhancement in global mean temperature (IPCC, 2007; 2014). On the assumption that upward trend can have profound influence on the fragile glacial ecosystem by inducing accentuated melting, accelerated rates of recession of glaciers reported from various parts of the world are being attributed to the global warming caused by anthropogenic factors. Melt water released by the glaciers and seasonal snow serves are the perennial source of rivers originating from the Himalaya. These rivers are the life-line of the Indian landmass and several other South-Asian countries, such as Afghanistan, Bhutan, Bangladesh, Nepal, Pakistan, Myanmar. The melt water is source of energy for hydroelectric power plants, used for irrigation of agricultural lands in the command area especially during the summer period when it is most needed, and as well source of potable water for millions of people living in the mountainous and contiguous planes. The scientific study of Himalayan glaciers, therefore, assumes foremost importance for the management of water resources, hydro-power generation, climate/weather prediction and in sustaining the ecological system, particularly in the wake of growing population and compulsions of industrial and technological evolution. The probe into the impacts of climate change, especially due to anthropogenic factors, is high on the agenda of the Government of India. Prime Minister's Council on Climate Change has made the policy decision to create research capacity in knowledge institutions in the country. Dwelling on this subject at a brain storming session, coordinated by the Principal Scientific Advisor, a two-fold action plan was approved for implementation by the Department of Science &Technology (DST). First, "A Study Group on Himalayan Glaciers" was constituted that gathered all the relevant data related to Himalayan glaciers and shared with all the stakeholder organization in the country (Patwardhan *et al*., 2010). Second, a proposal to establish a nodal Institute of Glaciology to undertake multi-disciplinary research on the Himalayan glaciers was agreed upon. In agreement with the proposed time bound program, a Centre for Glaciology at the Wadia Institute of Himalayan Geology (WIHG) was established in 2009, which shall eventually usher the establishment of a dedicated Institute of Glaciology. In the background of these rapid developments, we in this chapter first track in brief the illustrious history of the glaciological studies in the Himalaya allowing assessment of natural water reserve, degree and extent of climate changes on glaciers, melt water contribution to rivers etc. The pace and growth of glaciology research in the 'Third Pole' region is well exemplified in the series of special publications, e.g. Patwardhan *et al*. (2010), DST (2012), Ravindra and Laluraj (2012), Pant *et al*. (2018), Goel *et al*. (2018) among many others. In the background of rich knowledge gleaned from the twentieth century initiatives, we discuss new initiative launched to have deep insight into the factors and physical processes controlling the effects of climate to show case the way forward of Indian glaciology research and its linkage with global research under the umbrella of International Association of Cryospheric Sciences.

Growth Path and Participating Institutions

Earliest information on Himalayan glaciers and snow can be tracked to the records available in the Gazetteers of the erstwhile States during the British. However, the seed of glacier research was sowed with the inception of Geological Survey of India (GSI) in 1851. Organized studies on secular movement of glacier were taken up starting since 1906 and several glaciers of Kuamon, Lahul and Kashmir region were monitored. Later, the studied were extended to encompass Sikkim and Karakoram Himalaya. After independence, during the 'International Geophysical Year (1957-58), 'International Hydrological Decade' (IHD: 1965-74) and later as part of the International Hydrological Programme (IHP) concerted efforts were made to systematize glaciological studies. Subsequently, a separate division on 'Snow, Ice and Glacier' was established by GSI in 1974, which was later rechristened as Glaciology Division. With this development, sustained field observational program on select glaciers expanded both in content and scope to include snout monitoring, mass balance studies, glacier dynamics, glacier-hydrology etc. In addition, meteorological monitoring was added to address issues related to climate-glacier linkage.

Himalayan Glaciological Programme sponsored by the Department of Science and Technology (DST), Government of India provided fresh thrusts and accelerated the pace of research in glaciology. The program launched in 1985 transformed the level of glacier research from field monitoring to specific theme based research. Under this program wide ranging projects aimed at on reconstruction of past climate, improving our understanding of forcing factors controlling the glacier dynamics, establishing its dependence upon climate, hydrology and environment has been carried out. In this DST program, Space Application Centre (SAC), Indian Space Research Organisation (ISRO) played pioneering role in implementing remote sensing as a powerful tool to monitor glacier dynamics by allowing mass balance and snout movement on large-scale and varied time resolution (Kulkarni, 1992). These studies provided major impetus to climate-glacier interactions. A major merit of the DST program was that it brought number of national research Institutions, e.g. Geological Survey of India (GSI) with its Division of Glaciology, Lucknow and Centre for Arctic and Antarctica Studies, Faridabad, Survey of India, (SOI), Dehradun, Wadia Institute of Himalayan Geology, (WIHG) Dehradun, Space Application Centre (SAC), Ahmadabad, Indian Institute of Remote Sensing (IIRS), Dehradun, Physical Research Institute (PRL), Ahmadabad, National Institute of Hydrology (NIH) Roorkee, India Meteorological Department (IMD), Birbal Sahni Institute of Palaeosciences (BSIP), Lucknow, GSI Sikkim, Central Water Commission (CWC), Jammu Division. Defense Terrain Research Laboratory (DTRL), New Delhi, and National Centre Medium Range Weather Forecasting (NCMRWF), New Delhi under the umbrella of cryosphere research. In addition, numbers of Universities, e.g. Delhi University (DU), Jawaharlal Nehru University (JNU), H. N. B. Garhwal University (HNBGU), Lucknow University (LU) and IITs etc are actively involved in glaciology research. National Center for Antarctica and Ocean Research (NCAOR), Goa, a unit of Ministry of Earth Sciences (MoES), is engaged with glaciology research in Polar Regions. The infrastructure and expertise developed are being used

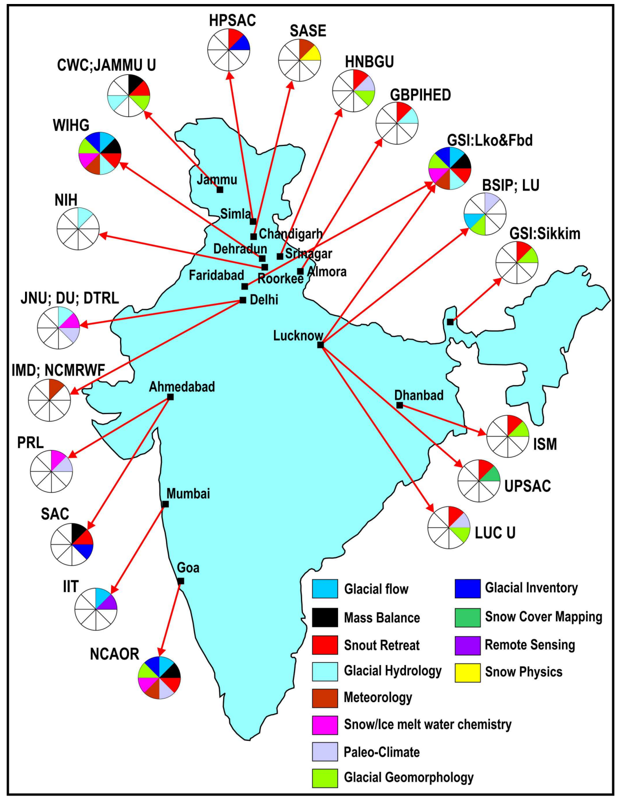

Fig. 1: Location of various organisations engaged in cryospheric research in India

to induct a more integrated approach to the Himalayan glacier studies. Here a multi-component research field station, named "HIMANSH" has been set up for monitoring glaciers of the Chandra basin, Western Himalaya. In addition, seasonal snow cover leading to snow avalanche and glacial lake outburst floods (GLOF) are major glacier related hazard, their monitoring and prediction are the primary subject matter of Snow and Avalanche Study Establishment (SASE), Chandigarh. Fig. 1 shows the geographical distribution of various research and academic organizations that has been engaged in study of frozen mass of water, i.e. glaciers, ice and snow in the Himalaya.

Assessment of Glacier Resources: Inventory

Glacier, ice and snow cover in the Himalaya are perennial source of rivers flowing out from Himalayas to the Indo-Gangetic Plains. To assess their water reserve for proper management and utilisation for agriculture, hydro-power generation etc; the inventory of glaciers, using the guidelines formulated by UNESCO (1970), became a priority theme of investigations. Based on these principles and use of different tools such as topographic maps, aerial photographs and satellite images of different scales and resolution formed the starting point to prepare inventory of Himalayan glaciers by a number of organizations. Incorporating Survey of India (SOI) topographic maps as reference, GSI prepared a preliminary inventory of glaciers incorporating Upper Indus, Chenab and Ravi, Ganga and Sutlej basins, which is included in World Glacier Inventory Status 1988 (IAHS-*(ICSI)–UNEP*–UNESCO, 1989). As noted, inventory compilations were initiated on basin levels, named by the central river. Integrating with the River Systems map published in the National Atlas of India, first edition of 'Inventory of the Himalayan Glaciers' was published by GSI (Kaul and Puri, 1999), which has been upgraded periodically. As per the last publication released in 2009, there are 9575 glaciers in Indian part of Himalaya. Basin wise distribution is given in Table 1. In short, about 17% of the Indian Himalaya area is covered with glaciers and additional area of nearly 30-40% supports the snow cover (Sangewar and Shukla, 2009).

Glacier inventory for the entire Himalaya has also been prepared by SAC with the help of satellite data. Beginning with the compilation of Kulkarni (1992) who using imageries on 1:250,000 scale reported total of 1702 glaciers covering an area of 23,300 sq km in Indian Himalaya. Since then glacier inventory using satellite data on 1:50000 scale has been upgraded for the entire Indian Himalaya (Sharma *et al*., 2008, Ajai *et al*. 2011; Bahaguna *et al*., 2014). More recent updated inventory shows strikingly large numbers of 32392 glaciers, occupying a total area of 71182 sq km (Ajai, 2018 and references there in). The total number and area covered differed greatly from that estimated by the GSI. Determination of precise numbers is uncertain due to terrain and observational difficulties. However, a part differences in the numbers, listed in Table 1, may due to the total area covered in respective exercises. The GSI inventory is confined to the geographical limits of Indian Himalaya whereas the satellite based inventory considers entire contiguous area of the Himalayan mountain belt, invariably trans-passing national boundaries. In addition, fragmentation of large extensive glaciers in to number of smaller glaciers could be major source of ambiguity in determining the precise number of glaciers. Further, use of remote sensing from different season could leads to poor demarcation of glacier boundaries due to fresh snow fall on higher reaches. Validation of different formulations, based on remote sensing vis-à-vis topographic-cum-field investigations over a common basin/sub basin would be helpful to resolve the source of ambiguity and would pave way to prepare more authentic inventory. Despite large differentness in the total count of glaciers, based on the use of remote sensing or field investigations, two distinctive features which emerge are:

Table 1: Basin level distribution of Glacier resources of the Himalaya based on ground verified and satellite data

Sub-Basin	No. of glaciers	Total No. of glaciers	
		GSI	ISRO
Western Himalaya (Indus Basin)			
Ravi	172		
Chenab	1278		
Jhelum	133		
Beas	277		
Satluj	926		
Indus	1796		
Shyok	2658		
Kishanganga	222		
Gilgit	535		
Sub Total		7997	16049
Central Himalaya (Ganga Basin)			
Yamuna	52		
Bhagirathi	238		
Alaknanda	407		
Ghaghra	271		
Sub Total		994	6237
NE Himalaya (Brahmaputra Basin)			
Tista	449		
Subansiri	No data		
Arunachal Part	161		
Sub Total		881	10106
Grand Total		9575	32393

(Source: Sangewar and Shukla, GSI Spl. Pub. 34, 2009 and Ajai, 2018)

(i) Strike-along variation in the concentration of glaciers along the Himalayan arc are apparent in Table 1 when numbers are clubbed for three mega basins, namely the Indus basin, Upper

Ganga basin and the Brahmaputra basins, representing respectively Western, Central and Eastern Indian Himalayan Region (IHR). The concentration is highest in Indus, followed respectively by the Brahmaputra and the Ganga basins. Similar longitudinal variations are also evident in the satellite derived glacier inventory (cf Ajai, 2018). The Indus basin has 16049 glaciers having glaciated area of 32246.43 sq km. The Ganga basin has 6237 glaciers occupying 18392.90 sq km of glaciated area. The Brahmaputra basin has 10106 glaciers occupying 20542.75 sq km of glaciated area.

(ii) Most of the glaciers are situated on the Main Himalayan Range, but other ranges, such as the Pir Panjal, Dhauldhar and Ladakh ranges also support glaciers. There are areas of concentration of high mountains along with the Himalaya and, consequently, they have greater concentration of Glaciers. Some of these areas are the areas of Nanga Parbat, Lolohai, Nunkun, Dibibokri-Chowkhamba-Nanda Devi, Dhaulagiri-Annapurna-Manaslu, Everest Makalu etc.

Glacier Dynamics and Inter-linkages with Climate

Glacier is a dynamic system that flows forward or has flowed at some time in the past under the influence of gravity, controlled largely by the basement bed-rock topography. As it begins to move down the valley, its front making a giant wall of ice is called the snout and generally leis close to the lowest altitude of the glacier. The moving ice (glaciers) is a major erosional agent which sculptures the valley along which it moves and in the process deposits thick pile of assorted sediments. On the assumption that erosion rates respond sensitively to the climate change, geochemistry of the sediments coupled with powerful radiometric dating techniques is used to reconstruct the past climate which can be cross checked with other independent climate sensitive proxies like tree rings and pollen records from lakes and peat logs. Furthermore, the isotopic composition of trapped gases and trace metals in ice layers could be measured. Based on these proxies, it is now possible to reconstruct the climatic fluctuations spanning over several centuries to several millennia. These studies are now routinely carried out under the heading of "Quaternary Climate Change"**.**

Quaternary Climate Changes

Applications of long term proxies has shown that the Earth has witnessed several pronounced oscillations in global climate especially during the last 1.6 million years (Quaternary) that are exhibited in the expansion and contraction of ice sheets and glaciers in Polar Region. These climatic fluctuations have followed a series of distinctive pattern which occurred at regular frequency and are attributed to the changes in solar influx caused due to the sun-earth geometry (orbital forcing). The orbital driven long-term cycles of 100 ka (eccentricity), 41 ka (obliquity) and 21 ka (precession of equinoxes) were superimposed by abrupt climatic events of decadal, centennial and millennial scale and are well represented in the ice-core (GRIP members, 1993), marine (Schulz *et al.*, 1998) and continental records (Gasse *et al.*, 1990), which can be estimated using the isotopic ratios. Long-term climate model so constructed will not only help in identifying the contributory role of various forcing factors but also serve as benchmark against which predictive models of future climate can be evaluated. Such reconstruction studies have shown that most recent period of glaciations is attributed to the Little Ice Age (LIA) that probably terminated during the mid-19th century. Following this, the current phase of warm period is believed to be continuing.

In comparison to polar ice caps, attempts to reconstruct climate records for the geological and historical periods for the Himalayan glaciers using chronometric, stable isotope ratios, geomorphological markers or biotic proxies have begun to appear only recently. Initial studies particularly from the western and central Himalayas suggested that glaciers have fluctuated in response to the Quaternary climate change. The limited chronometric data provides a broad picture of major glaciations occurring around ~70 ka–30 ka, ~17–10 ka, and <5 to 4.5 ka (Sharma and Owen, 1996; Owen *et al.*, 2001; Nainwal *et al.*, 2007). In addition, based on morphology and relative dating technique, a marginal but regional glacier advance was observed during the Little Ice Age (Sharma and Owen, 1996; Mazari *et al.*, 1996; Nainwal *et al.*, 2007). For example, in Lahul-Spiti region, a phase of recession was followed by advancement during the Medieval Warming period and Little Ice Age (LIA) respectively (Mazari *et al*., 1996). In another study, Chauhan (2006) observed phase of glacier recession, caused due to moist climate during 1300 to 750 yrs BP, was followed by re-advancement after 450 years BP due to cold climate. High-resolution pollen and diatom proxies from a peat deposit in the Pindar valley of Higher Central Himalaya indicated prevalence of wetter condition during the last two centuries that exceeded changes recorded over the last three millennia (Rühland *et al*., 2006). Recent tree ring data from Bhagirathi valley have been used to reconstruct high resolution spring precipitation changes since 1731 AD (Singh and Yadav, 2005). During this period, the data suggests highest precipitation during 1977-1986, whereas, lowest precipitation was observed during 1932-1941. Understanding of the Quaternary climatic fluctuations is still evolving (Sharma and Chand, 2016). The cross-validation of such proxies remain an open issue as AWS or meteorological observations in high altitude areas of Himalaya, to record wet precipitation,are still (nearly) not existing. The study of the tree is confined to altitudes below the snow line where trees mark their presence. However, as already pointed higher temperature would result in reduced accumulation of snow and lead to increased wet precipitation that causes mass wasting of glaciers at low altitudes.

Inter-Annual and Inter-Decadal Climate Changes

Glaciers in the ecologically sensitive high altitudes, respond too readily to slight change in temperature and precipitation condition, and, therefore, are projected as a potential proxy for reconstructing the present and immediate past climatic changes. From the current trends in temperature changes, it has been inferred that the mean global surface temperature has risen by 0.85 ± 0.2^{o} C from 1880 to 2012 (IPCC, 2014). Further, there are arguments to suggest that the climate change marked by global temperature increment of even less than one degree Celsius can have profound effect on the fragile glacial and periglacial ecosystem. Noting that increasing global temperature is marked by source level increase in the anthropogenic emission of carbon dioxide in atmosphere as well as by the rising of mean sea levels, wide ranging claims are made to attribute the accentuated recession of glaciers in various parts of the world to the global warming induced by anthropogenic factors. Such extensive glacier/snow cover in contiguous belt creates its own microclimate and regulates the general climate of the area. The observable changes in the onset and durations of seasons, precipitation pattern manifested in water shortages, variability in the biodiversity in some way or other are considered the pointer of changing climate by increasing anthropogenic effects. Adaptability of glaciers to climate change is a topic that is catching global interest with a focus to devise strategies of combating impacts of the change. Direct field observation in the form of snout monitoring and mass balance studies have been in use for deciphering the inter-annual and inter-decadal scale climate-induced changes in glaciers. Isotopic ratios can also provide extremely valuable information on the temporal changes in the atmospheric chemistry, especially the concentrations of certain anthropogenic substances in the atmosphere and, thus, help in understanding the anthropogenic loading particularly after the post-industrial era.

Snout Movement: Proxy to Climate Variability

The rising temperature in the lower periphery (altitude) of the glacier results in higher melting in the ablation zone (due to hot air influx), seen as the retreat of snout. Similarly, if the temperature falls, the snout of glaciers will advance. Hence the monitoring of the snout position, being function of the length and area of the glacier, emerged as pioneering proxy to the changing climate. It received wide acceptance as the World Glacier Monitoring Service (WGMS, 1989) began reporting every five years the changes in the snout position of glaciers from around the world.

Systematic snout monitoring in the Himalaya were initiated by GSI (Vohra, 1981; Raina and Srivastava, 2008). Gangotri glacier has been monitored since 1935. The snout of Gangotri glacier has been receding at least for the last 75 years. The total retreat from 1935-96 is about 1400 m at the average rate of retreat since 1956 is ~31 m/yr (DST, 2012). There was acceleration in the retreat in the mid-seventies and eighties with a marginal slowing down in the nineties. According to Raina (2009), the glacier has almost remained static from 2007-09. Some 50 other glaciers have been brought under the ambit of snout monitoring program of the GSI since the late nineteenth century. Apart from it, snout monitoring at couple of glacier, Chota Shingri, Dokraini and Chaurabari were intiated by WIHG. Fig. 2 depicts the retreat pattern of some of the important glaciers, averaged over different time periods (Vohra, 1981; Raina and Srivastava, 2008). The rates of retreat vary between 5-30 m/yr for different glaciers with different geometries and located in different climatological set ups. Majority of the glaciers in the Central and the Eastern Himalaya are retreating (melting) wherein the rate of retreat increased many folds during mid-seventies to late-eighties, touching avalue of 25m-30m/ year, e.g. the Gangotri glacier. Thereafter, the rate of retreat has slowed down during the last decade of the 20th century or at the start of 21st century (Raina, 2009).

Mass Balance: Proxy to Climate Variability

Mass balance of a glacier is measure of total loss or gain in glacier mass at the end of hydrological year (Paterson, 1994). This is estimated by measuring total accumulation of seasonal snow and ablation of snow and ice over a year, starting from some fixed date, generally 30th September, close to the end of the ablation. In the widely used conventional glaciological method for mass balance, the assessment of winter accumulation is achieved by pitting whereas ablation is by way of stake network over a glacier. Changes in glacier mass balance are considered as the most sensitive indicator of climate change. The annual mass balance studies based on the fixed date system were initiated by GSI in the year 1974 at Gara Glacier, J & K (Raina *et al*., 1977). The network of mass balance studies were further spread by GSI and other research organizations like WIHG and academic groups from JNU and Jammu University under the DST integrated program. Taking stock of mass balance studies, it has been recorded in DST (2012) that in between 1974-2012 only 13 glaciers, representing the varying climatic conditions, were studied with the time span of measurements ranging in length from 2 years to 10 years. The studies have indicated overall negative glacier mass balance during the latter part of 20th century as well as in early 21st century (Gaddam *et al*., 2016, 2017a; Dobhal *et al*., 2008, 2013, Pratap *et al*., 2015; Brun *et al*., 2015). Given that the majority of the glaciers of Himalaya are in state of instability, it has been envisaged that their volume may significantly reduce if the climate stabilizes at its present state (Gaddam *et al*., 2016, 2017a). At present, in-situ mass balance studies are continuing on a few select glaciers, namely, Dokriani and Chaurabari (by WIHG), Hamta (by GSI), Chhota Shigri (by JNU) and Chandra Basin (NCAOR and DU). Long term trend in mass balance at some of these individual stations are discussed later.

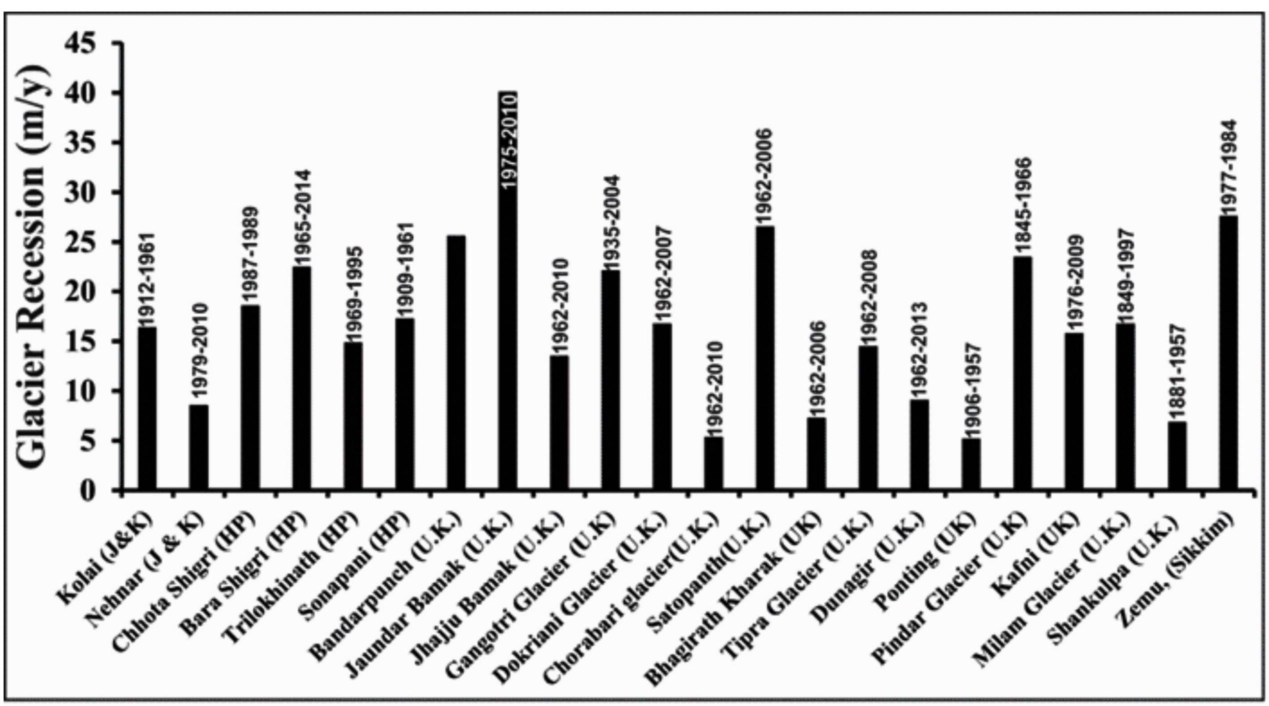

Fig. 2: Snout recession trend of Himalayan glaciers (Modified from Vohra, 1981)

In addition to field based snout and mass balance monitoring, remote sensing data provides information on the areal extent of the glacier and snow cover. In order to obtain climate sensitive index of large number of glaciers, accumulation area ratio (AAR), defined as a ratio between accumulation area and total glacier area, has been widely used (Meier and Post, 1962). Accumulation area is an area of glacier above equilibrium line which coincides with snow line as in temperate glacier the extent of superimposed-ice zone is insignificant. To estimate glacial mass balance, a relationship between AAR and mass balance was developed using field mass balance data of the Shaune and the Gor Garang glaciers (Singh and Sangewar, 1989). The AAR and snout estimates using remote sensing data of different time scale and duration have been extensively used to study the health of glaciers all along the Himalayan arc (Bhambri *et al*., 2011; Kulkarni *et al*., 2011; Ajai *et al*., 2011; Sharma *et al*., 2013a; Bhauguna *et al*., 2014); Kulkarni *et al*. (2011) estimated the glacial retreat for 1868 glaciers spread over 11 river basins of Himalaya. It was found that for the period between 1962 and 2001/2002, the total glacier area reduced from 6332 to 5329 km^2 – an overall de-glaciation of 16%. Further, focusing on the changes in length and area of 82 glaciers in Bhagirathi and Alaknanda basins, Bhambri *et al*. (2011) indicated that glaciated area suffered net loss of 4.6% between 1968 and 2006. It follows that while examining the AAR data for the entire Himalaya as a single unit or individually for the Ganges and Brahmaputra River Basins, representing respectively the Central and NE Himalaya, there is overall reduction in the glaciated area over the prolonged period, mostly post-1962. A major exception to this decreasing trend is witnessed in the Karakoram region, Indusbasin. Here, observations point to advancement or slower rate of retreat of glaciers. For example, a study of 30 glaciers in the centeral Karakorm region during 1997-2001 conclusively showed advancement and/or thickening of tongue by 5-20 m and this heterogeneous behaviour was termed Karakoram anomaly by Hewitt (2005). It is widely recognised that SW and NE Indian monsoon is the dominant source of moisture for the major part of the Himalaya (Khan *et al*., 2018). The Karakoram lies far away from the influence of SW Indian monsoon and the mountain receives a major contribution of the snow through westerlies during the winter (Archer, 2001; Treydte *et al*., 2006). Therefore, the depletion or growth of the Karakorm glaciers are more sensitive to weakening and strengthening of the westerlies.

Identification of Forcing Factors Influencing Health of Glaciers

Synthesis of mass balance and snout movement data indicates that glaciers in the Himalaya, over a period of the last 70-80 years, have responded in contrasting ways. However, the cumulative negative balance observed in large part of the Indian Himalaya is clear pointer that rise in temperature related to global warming is an important forcing factor controlling the health of the glacier. As against the retreating trend of glaciers in Central Himalaya, glaciers in the Karakoram region, Western Himalaya show advancement. It is suggested that the sources of precipitation nourishing the glaciers (monsoon-vis-a-vis westerlies and their contrasting seasonal characteristics) determine the contrasting movement of the glaciers in different basins. Long term ground monitoring of snout have also indicated that rate of glacier recessions in the Ganga basin, including Gangotri glacier, have reduced many folds from eighties to the end of the past century or during the early part of current century (Raina and Srivastava, 2008, Raina, 2009).The monitoring of snout from remote sensing data separately for the two periods of 1989-90 to 2001-04 and 2001-02 to 2010-11 corroborate the slowing down of glacier recession in recent years (Ajai, 2018). During the period of 1989-90 to 2001-2004, 76 per cent of the glaciers have shown retreat, 7 per cent have advanced and 17 per cent have shown no change. As compared to this during the next decade i.e. 2001-02 to 2010-11, only 12.3 per cent glaciers have shown retreat, 86.6 per cent of glaciers have shown stable front and 0.9 per cent have shown advancement. Analogous observation on the rate of glacier retreat are indicated by Ganjoo *et al*. (2014) from the extensive study of snout fluctuations in the Nubra valley, Indus Basin in Western Himalaya. Their study indicated that the glacier in the Nubra valley had vacated 56 km^2 of the area between 1969 and 1989 and only 4 km^2 between 1989 and 2001 suggesting the slowing down in the rate of glacier retreat since 1990. Forcing effects of temperature and precipitation perhaps combine in complex mode to produce contrasting spatial and temporal variability in glacier dynamics. Variations in the rate of snout-recession from one glacier to other in the same basin could be pointer that apart from the temperature-precipitation, other physical factors, debris cover, affect the glacier movements (Sharma *et al*., 2016a). There are also examples when snout recession of individual glaciers differ significantly from those inferred from mass balance studies in the same basin. This necessitates validation of climate induced change deduced from one proxy with other, preferably from the same glacier to derive correct interpretation of cause-effect relation. As a prat of DST integrated program on Himalayan glacier, number of multidisciplinary studies were undertaken by increased participation of institutes with varying expertise. Below, we discuss the results emanating from couple of such integrated studies, which help to identify various forcing factors influencing the dynamics of the glaciers.

Case study of Dokriani and Chorabari Glaciers, Central Himalaya: WIHG

Mass Balance and Snout Variability: Control of Area-altitude Distribution

WIHG has been engaged in monitoring Dokriani (7 km^2) Glacier in Bhagirathi basin and Chorabari (6.4km^2) glacier in the Alaknanda basin for mass balance and snout movement studies over the last one and half decades (Dobhal *et al*., 2008; 2013). Both glaciers exhibit retreating snout as well as negative mass balance trend (Dobhal *et al*., 2013). Curiously, while the snout at Dokriani glacier retreated with average rate of 18.5m/yr, the Chorabari glacier receded at just half of the Dokriani rate, i.e. 9.5m/yr. In contrast to this, Mass balance figures showed reversed trend i.e. for Chorabari glacier loss of mass at the rate of 0.77 m w.e.a^{-1} (ELA, 5060 m) is almost double compared to the Dokriani Glacier i.e. 0.45 m w.e. a^{-1} (ELA 5040 m) during the same study period (Fig. 3). The study apparently suggests that even if a glacier snout has stable fronts (no retreat) for the certain periods, it does not essentially imply that the glacier is not melting or growing.

Critical appraisal of geometrical parameters of the Dokriani and Chorabari glaciers bring home that area-altitude distribution of accumulation and ablation zone in relation to the snowline or equilibrium line altitude (ELA) control the rate of glacier recession/ mass balance. For example, the Dokriani glacier has

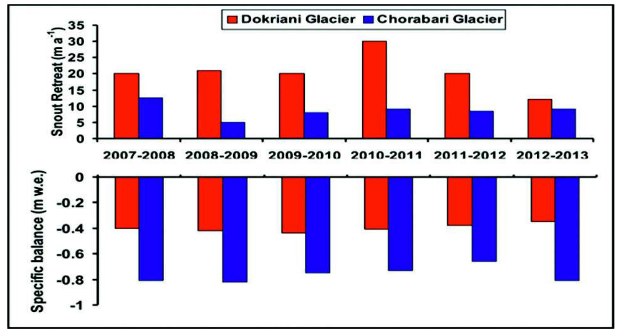

Fig. 3: Variability between mass balance and snout retreat of Dokriani and Chorabari glacier, Central Himalaya

almost 68% area above ELA/snow line altitude and Chorabari has smaller accumulation area (43%). In the case, the glacier has a large accumulation area above the ELA, then the glacier will experience positive or comparatively low negative mass balance. Conversely, the glacier with large ablation area will impart surface melting at faster rate.

Case Study of Chandra Basin, Western Himalaya: NCAOR and JNU

Mass Balance: Influence of Debris Cover

All the glaciers under observation in the Chandra basin in Western Himalaya during the last 4-5 years have shown cumulative negative mass balance (Sharma *et al.*, 2016a; Patel *et al*., 2016), which in terms of retreat are similar to other glaciers elsewhere in the Himalaya, except Karakoram region (e.g. see Section 2.2.2 and references therein). A significant mass wastage was also observed in Baspa basin, Western Himalaya, during last decades and this loss is strongly supported an increasing trend in annual mean temperature and decreasing trend in precipitation (Gaddam *et al*., 2016, 2017a).

The mean vertical mass balance gradient of Western Himalaya during last two years is similar to Alps (Sharma *et al*, 2016a), as well as the Nepal Himalaya (Mandal *et al*., 2014; Azam *et al*., 2012). Mass balance is found to be dependent on solar radiation, debris cover, local and regional precipitation, slope and the shading effect of surrounding steep slopes (Sharma *et al.*, 2016a; Patel *et al.*, 2016). Similar observations were made by some other researchers working on Himalayan glaciers (Azam *et al*., 2016; Venkatesh *et al*., 2012). Winter precipitation and summer temperature are almost equally important for controlling the mass waste pattern of Western Himalayan glaciers at decadal scale (Azam *et al*., 2014; Thayyen *et al*., 2010). Debris cover is one of the significant controlling factors for spatial variability of ablation rate. In contrast to the normal ablation pattern, debris covered glaciers experienced an inverse ablation rate with altitude. Thicker debris protect ice surface efficiently from melting than thin debris (Sharma *et al*., 2016a,b; Patel *et al*., 2016).

Melt Water Contribution to Stream Flows: Seasonal Control

An increasing trend is observed in snow cover in all seasons, except spring, during the last decade which is in variance to earlier deduction that decrease in perennial snow cover area leads to significant decrease in stream flows (Ahluwalia *et al*., 2015; Joshi *et al*., 2015). Irrespective of latitudinal differences, glacier melt contributes up to ~16% of the total discharge in Himalayan glacial basins. Maximum discharge takes place from mid-July to mid-August (Ahluwalia *et al*., 2015; Joshi *et al*., 2015; Thayyen *et al*., 2010) thereafter discharge diminishes drastically from mid of September(Sharma *et al*., 2013b). Runoff contribution from snow melt (81%) seems to be more than from rainfall (11%) and ice melt (8%) during 2000 to 2014 in the Baspa basin, western Himalaya (Gaddam *et al*., 2017b). In Indus basin, glacier melt contributes up to ~44% of the total discharge; however, for Chandra basin it is little higher (Singh *et al*., 2017).

Hydrochemistry of Melt Water: Sources of Suspended Sediments

Hydrochemistry of melt water in Chandra basin is dominated by Ca^{+2} and HCO_3 and shows three dominant composites i.e., the water-rock interaction, atmospheric dust inputs and physico-chemical changes. High molar Ca^{2+}/Na^{+}, Mg^{2+}/Na^{+} and C-ratio indicate that weathering of disseminated carbonates contributes more than silicate weathering to the chemical composition in Chandra basin, Western Himalaya (Singh *et al*., 2017). Mean solute load is only 10-15% of the mean sediment load reflecting solute released from sediment in transit is extremely lower than in proportional of solute derived from subglacial channels and ice rock interface (Singh *et al*., 2017).

Case Study of Chhota Shigri, Lahaul-Spiti Valley: JNU and DU Component

The Chhota Shigri glacier, located in Lahaul and Spiti valley, was selected as a representative glacier in Western Himalaya for the joint expedition lead by WIHG, under a DST program (1986-1989). Since 2002, it has been monitored for the long term annual mass studies. Over the years, Glaciology Laboratory, JNU has added many more field glaciological tools to measure energy balance, hydrology, Hydro-geochemistry, isotope, remote sensing, modelling studies etc.

Mass and Energy Balance: Seasonal Control

Fig. 4 provides the long-term seasonal and annual mass balance series of Chhota Shigri glacier. Over last 13 years, 2002-2015, the Chhota Shigri glacier has lost mass with a cumulative glaciological mass balance of -6.88 m w.e. (water equivalent), corresponding to a mean annual glacier-wide mass balance of –0.53 m w.e. a^{-1} (Azam *et al*., 2016; Mandal *et al*., 2014). However, for short intervals, i.e. 2004-05, 2008-2011, the glacier experienced positive mass balances. The highest negative melting throughout the entire measurement period (since 2002), with a cumulative value of ~50 m w.e., is observed in the lower ablation part close to 4425 m a.s.l. (excluding debris-covered area). Over the debris covered part, melting at the lowest part of the ablation zone is reduced by –1 to –2 m w.e. a^{-1} regardless of its altitude. This is attributed to the "debris effect" that protects the ice beneath the debris-cover from direct solar radiation and surface atmosphere (Mandal *et al*., 2014). The studies also found that the summer snowfall on Chhota Shigri glacier has a significant impact on the annual mass balance. If a significant snowfall happens during summer, it reduces the surface melt by increasing albedo of glacier surface resulting in a significant amount of melt reduction and ultimately annual mass balance is towards positive or slightly negative in the particular years, e.g. 2010 and 2011 (Azam *et al*., 2014).

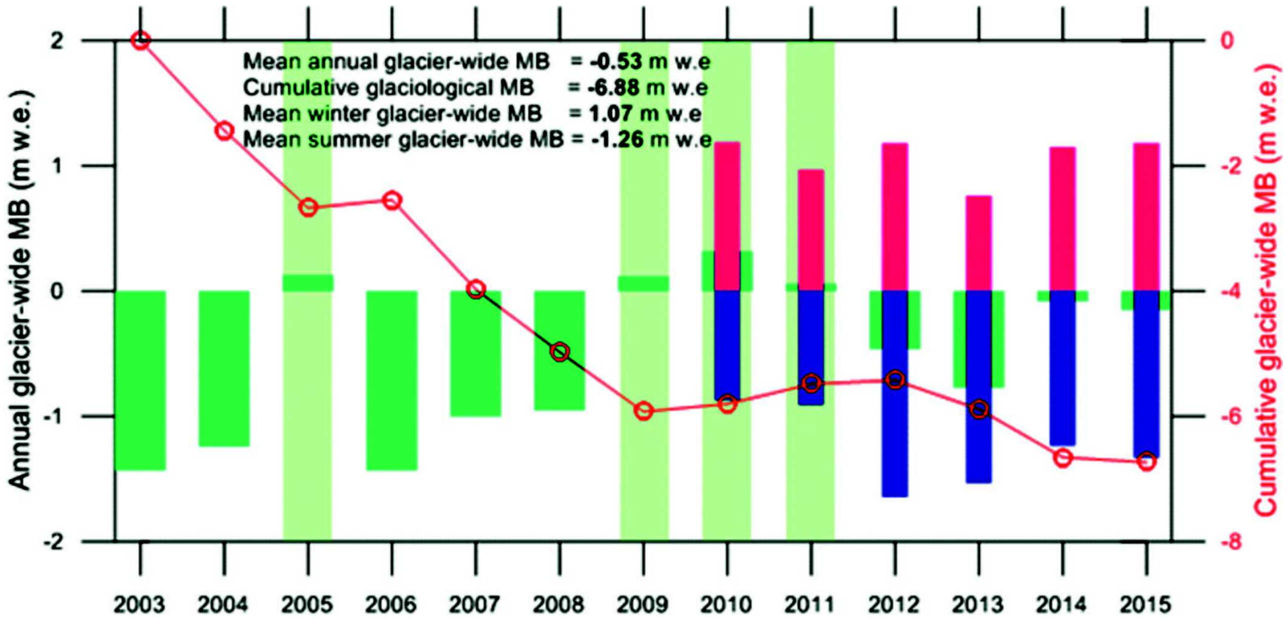

Fig. 4: The annual (green histograms) and cumulative (line with red circles) glacier-wide MBs of Chhota Shigri glacier between 2002 and 2015. Light greed shads are the years with positive (+) glacier MB. Also shown are the seasonal (winter (purplish-red histograms) and summer (deep blue histograms)) glacier-wide MBs between 2009/10 and 2014/15 hydrological year. The figure is adopted from Mandal (2016)

Glacial Hydrology, Hydrochemistry: Discharge Rates and Sediment Mass

JNU Glacier Research Group included hydrology and hydrochemistry in their study plan and also expanded activities on various Central and Western Himalayan glaciers such as Chhota Shigri, Patsio, Gangotri, Bara Shigri, Batal glaciers etc. Velocity area method was used for discharge measurement. Ion Chromatograph and standard analytical methods (APHA 2005) were used for the hydrogeochemical study.Temporal variations in the concentrations of major cations, major anions, TDS and discharge are shown in Fig. 5A-C (Singh and Ramanathan, 2017). Distribution of melt water runoff from the Chhota Shigri glacier shows increasing trend from June onward and attains to its maximum value in July and August and after that, it starts declining. Based on the daily mean daytime and night time discharge, study shows strong storage characteristics of melt water during the early part of ablation period, which reduces with the progress of melt season. Diurnal variations in discharge show that minimum runoff occurred in the morning (0700-0900h) and maximum runoff occurred in the afternoon and evening (1500-1800h). The time lag between melt water generation over the surface of Chhota Shigri glacier and its emergence as runoff is higher in the early ablation period as compared to the peak ablation period. A strong relationship was observed between suspended sediment concentration and the discharge of Chhota Shigri, Patsio and Batal glaciers. In addition, the hydrological variation of melt water is mainly controlled by the temperature of the study area. The investigations also indicate that suspended sediment concentration in the melt water of Gangotri and Bara Shigri glaciers are higher than the Chhota Shigri glacier. Such type of results may be due to high melt water runoff, more availability of rock debris and large size of these glaciers as compared to the Chhota Shigri glacier. The sediment yield from the catchment of Chhota Shigri glacier was lower as compared to the Gangotri glacier, which may be due to low glacial runoff, lithology and lower physical weathering rates in the Chhota Shigri glacier (Engelhardt *et al.*, 2017; Singh *et al.*, 2016; Singh and Ramanathan, 2017).

Melt water draining from Chhota Shigri, Bara Shigri, Gangotri and Batal glaciers is slightly acidic in nature, whereas melt water of Patsio glacier is nearly neutral in nature. Bicarbonate is the dominant anion in the melt water of Chhota Shigri, Bara Shigri and Patsio glaciers, whereas Sulphate is the dominant anion

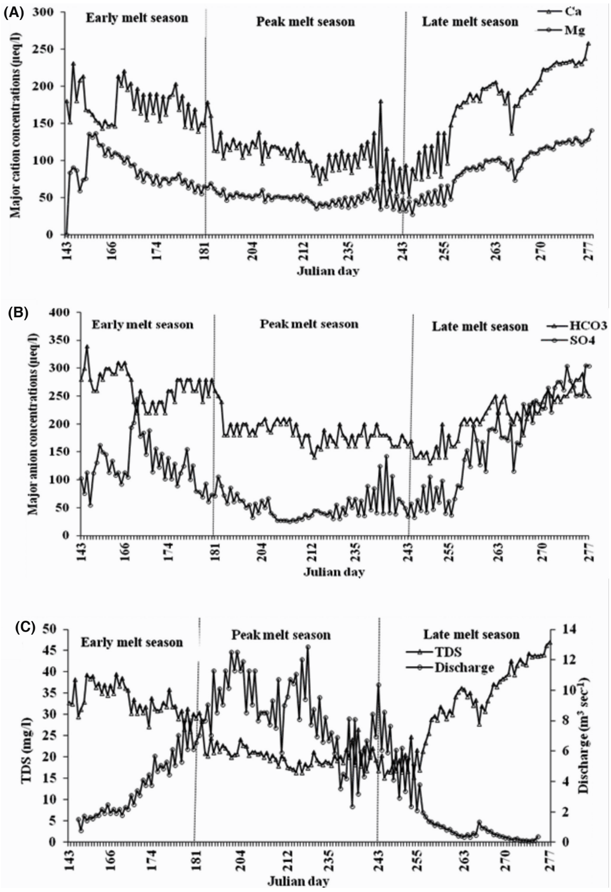

Fig. 5: Temporal variations in the major ion concentration with discharge in Chhota Shigri Glacier (Adopted from Singh and Ramanathan, 2017)

in the melt water of Gangotri, Chaturangi and Batal glaciers. Calcium is the dominant cation in all studied Central and Western Himalayan glaciers. High contribution of (Ca+Mg) vs the total cation and high equivalent ratios of (Ca+Mg) vs (Na+K) for the studied Himalayan glaciers melt water show that hydro-geochemistry of these studied glaciers was mainly controlled by carbonate weathering followed by silicate weathering. The average ratio of Na/Cl and K/Cl in the melt water of Chhota Shigri, Bara Shigri, Patsio, Chaturangi, Gangotri and Batal glaciers melt water was much higher than the sea aerosols, showing the low atmospheric contribution of these ions to the total solute budget of these glaciers. A trace amount of NO^3 and PO^4 was reported from the Central and Western Himalayan glaciers melt water, showing palatability of melt water. Seasonal variations in the TDS concentration of melt water was inversely correlated with discharge, which means their concentration was minimum during the peak melt period (July and August) and maximum during the end of ablation period (September and October) in the Chhota Shigri glacier. Dissolved load, cation and chemical weathering rates and associated CO_2 consumption rate due to silicate, carbonate and chemical weathering are higher during the peak melt period because of more runoff and lower during the late melt period due to low discharge from the Chhota Shigri glacier. The annual CO_2 drawn down by the Chhota Shigri glacier is much lower than the Gangotri glacier, which may be due to low discharge and smaller basin area as compared to the Gangotri glacier (Sharma *et al*., 2013b; Singh *et al*, 2016; Singh and Ramanathan, 2015).

Forcing Effects in Average Annual Precipitation: DU

Among all the hydro-meteorological parameters, precipitation (snowfall and rainfall) is the most difficult to predict due to its inherent variability in time and space (Guenni and Hutchinson, 1998), particularly for a complex mountainous terrain like Himalaya. Poor network of *in situ* rain gauges particularly in mountainous region, inaccessible terrain, high altitude variation and significantly large size of basins forces adaption of remote sensed based (TRMM-342) estimation of average annual precipitation. Recently, Khan *et al*. (2018) investigated precipitation patterns for the Indus, the Ganga and the Brahmaputra basins by using satellite based Tropical Rainfall Measuring Mission (TRMM-3B42) data and validated it with APHRODITE and IMD interpolated gridded precipitation data (Fig. 6). The entire basin areas within the geographic limits of India were considered. Derived from a ten-year TRMM-3B42 data set, the average annual precipitation for the Indus, the Ganga and the Brahmaputra basins is estimated as 413 mm, 1081mm and 1460 mm respectively. Validation of TRMM-3B42 data with the rain gauge IMD data correlates well particularly for the Ganga basin as unlike Indus and Brahmaputra basins, more than 80% part of the Ganga basin lies within the Geographical boundary of India (Khan *et al*., 2018). Consideration of data not covering the entire basins is inferred as the cause of high variability for the other studied basins. Reported precipitation variability for the Indus basin is more than 250%, for the Ganga basin it is 100% and for the Brahmaputra basin it is more than

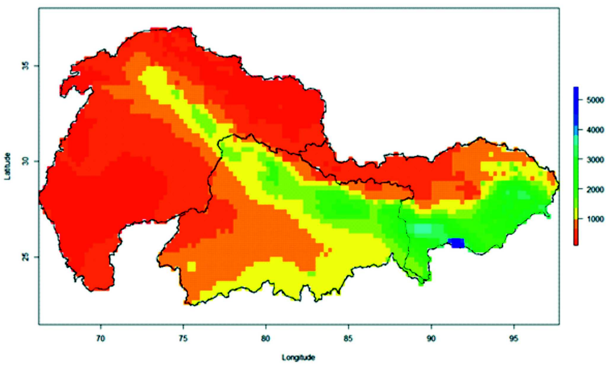

Fig. 6: Ten years (2001-2010) average annual precipitation map of the Indus, the Ganga and the Brahmaputra basins derived from TRMM-3B42 (From Khan *et al.*, 2018)

240% (Immerzeel *et al.*, 2010; Jain and Kumar, 2012). Khan *et al*. (2018) further showed that the precipitation broadly follows an east-west and north-south gradient control, i.e. the eastern most Brahmaputra basin has the highest amount of precipitation followed by Ganga and western most Indus basin has least precipitation. The precipitation is highest on the higher elevation than at lower elevations of the basins. The contoured distribution of precipitation indicates the orographic control as the primary factor on the summer monsoon precipitation in the Ganges and the Brahmaputra basins. Indus basin behaves independent of the Indian summer monsoon.

Estimation of Glacial Melt Fraction: DU, NIH and GSI

Bhagirathi and Alaknanda basins in the upper Ganga valley have been studied for estimation of glacial melt fraction. The Gangotri glacier which constitutes nearly a fifth of the glacierized area of the Bhagirathi basin represents one of the fastest receding, large valley glaciers in the region which has been surveyed and monitored for over sixty years. Availability of measurements over a long period and relatively small glacier-fed basin for the Bhagirathi River provides suitable constraints for the measurement of the glacial melt fraction in a Himalayan river. Calculations of existing glacial melt fraction ~30% at Rishikesh (Maurya *et al*., 2011) are not consistent with the reported glacial thinning rates (Dong *et al*., 2013). It is contended that the choice of unsuitable end-members in the three component mixing model causes the overestimation of glacial melt component in the river discharge.

Khan *et al*. (2017) applied three component mixing model by using oxygen isotope and electrical conductivity. The fundamental assumption is that the liquid (water) and solid (snow) precipitation will distinctly fractionate the light and heavy isotopes of oxygen. Since the precipitation of snow is altitude dependent, snow (and also ice) is likely to contain less amount of heavier (^{18}O) isotope compared to liquid precipitation. The oxygen isotope composition is expressed in the form of a ratio expressed as parts per thousand or parts per million (ppm) in reference to a standard composition. In the context of a Himalayan river it can be assumed that the river discharge comprises three components, namely (i) Surface runoff due to summer rainfall, post monsoon interflow and winter snow melt from the catchment area (R), (ii) Glacier ice melt (I), and (iii) Ground water (G).

Pre- and post-monsoon samples reveal a decreasing trend of depletion of ä^{18}O from upstream to downstream. By careful selection of end members, Khan *et al*. (2017) have estimated ~12% glacial melt fraction in the Bhagirathi basin and ~ 9% glacial melt fraction in the Alaknanda basin and at Rishikesh. Glacial melt fraction decreases from the upstream to downstream during the pre-monsoon and the post-monsoon period, whereas surface run off in the form of snow melt is the major fraction during the pre-monsoon and in the form of rainfall during the post monsoon period in the upper Ganga basin. Ground water contribution varies significantly from 39% during pre-monsoon to around 17% during post-monsoon in the Bhagirathi basin. Their estimated glacial melt fraction matches closely with the reported thinning rates of the Himalaya.

Snow Cover Fraction: JNU, SAC

Major Indian Rivers and their tributaries originating in the Himalayas depend upon seasonal snow cover melt during crucial summer months. In addition, accumulation and ablation of the seasonal snow cover are important parameters to assess snow-climate interactions, snow hazard prediction modeling (IPCC, 2007; Konz *et al*., 2010). Due to rugged and unapproachable terrain and harsh weather conditions in situ snow and ice observation is one of the limitations. This data gap has been bridged by usages of remote sensing with suitable image processing techniques (Arora *et al*., 2011; Brun *et al*., 2015). Though there are still inherent problems due to resolution and validation, but they can provide a benchmark detailing for the estimates (Hasson *et al*., 2014). Based on remote sensing techniques, snow-covered areas in the Himalaya/Tibet region is reported to have decreased by one-third at the rate of ~ 1% a^{-1} during 1966-2001 (Rikiishi and Nakasato, 2006). During 1986-2000, the western Himalayan snow-cover showed a synchronous decline with an increase in snow melt data from 1993 onwards (Kriplani *et al*., 2003). During 1990-2001 an annual snow cover decline of ~16% over the entire Himalayan region is reported (Menon *et al*., 2010). Past snow accumulation/snow-fall rates derived from the ice-core studies suggest a decline since mid-20th century (Thompson *et al*., 2000) while others show an increase (Kaspari *et al*., 2008). The difference in these records are attributed to differences in moisture trajectories, ice-flow dynamics and inaccuracies in identifying the annual layers (Kaspari *et al*., 2008). However, most of these studies have been carried out in Tibet (Thompson *et al*., 2000), very few in Himalayas (Kaspari *et al*., 2008). Some trends on the seasonal snow cover, specifically for the Indian Himalayan region (IHR) were reported by Kulkarni *et al*. (2010) using Advanced Wide Field Sensor (AWiFS) of Indian Remote Sensing Satellite (IRS). Snow cover products were generated individually for the 28 sub-basins extending over Indus, Chenab, Ganga and Yamuna basins Satuj basins. These products were used to estimate snow extent at an interval of 10 days from October 2004 to June 2005 using the Normalized Difference Snow Index (NDSI) algorithm. The distribution of snow in an individual basin was combined to estimate the overall snow cover for the Western and Central Himalaya. In the winter of 2004 and 2005, for a period between October and mid-December, snow cover was less than 50 percent and increased to 82 % by the end of January. Snow extent remained more than 80% till beginning of April. Then snow ablation and retreat of snow cover continued till end of June and residual snow cover remains was only 37 % (Kulkarni *et al*., 2010).

As monitoring has gained pace, some clear trends are witnessed in annual averages. Increasing/decreasing snow-cover trend over the entire Hindu Kush Himalaya was reported during 2000-2010 (Gurung *et al*., 2011). During same period increasing/decreasing snow cover trend over the Indus, the Ganga and the Brahmaputra basins is reported (Singh *et al*., 2014). Statistically insignificant contrasting increase of approximately 2% of snow cover in three sub-basins of Alaknanda and Bhagirathi and 1% for Yamuna sub-basin is reported (Rathore *et al*., 2015) whereas Mukhopadhyay (2013) has shown approximately ~32% increase of snow cover over sub-basin during 1980-2010 which remained stable during 2000-2010.

Recent studies have found that the snow albedo, which depends largely on the SLA (Snow Line Altitude) and snow cover state, has been declining suggesting the darkening and shrinking of snow cover (Ming *et al*., 2012; Yasunari *et al*., 2010; Brun *et al*., 2015). Darkening of snow cover leading to decreased snow albedo has been largely linked with deposition of black carbon (BC). Simulation studies have reported that the enhanced black carbon (BC) over Indian subcontinent contributed 4 36% to the decline in snow cover between 1990 and 2000 (Menon *et al*., 2010). Improved modeling studies have led to the understanding that the BC is instrumental in causing snow retreat and effects are manifested simultaneously through a threefold process: (i) direct atmospheric heating, (ii) darkening of the snow surface, and (iii) the snow albedo feedback leading to the elevation dependent warming (Xu *et al*., 2016). High-resolution climate model simulations from 1861 to 2100 reveal a stable snowfall trend for western (supporting the ‘Karakoram anomaly’) while a decreasing trend is found for central and eastern Himalayan regions (Kapnick *et al*., 2014). They suggest a meteorological mechanism for the observed and projected regional differences in the snow-ice shrinkage to climate warming.

Peep into Cryospheric Studies in Antarctica: NCAOR

The research directions and emerging results in Antarctic cryospheric studies by Indian scientists can be grouped into following 3 topics.

Ice Core Palaeo-Climatology

Ice core based reconstruction of past climate by the Indian scientists revealed significant changes in Southern Hemispheric climate during the past several hundreds of years (Laluraj *et al*., 2014; Thamban *et* *al*., 2011, 2013; PAGES 2k Consortium, 2013, 2017; Rahaman *et al*., 2016). Nitrate (NO_3^-) profile in a core revealed a close relationship with the Antarctic ^{10}Be record (solar proxy), suggesting the influence of external solar forcing on the circulation pattern over the Antarctica (Laluraj *et al*., 2011). The oxygen isotope ($\delta^{18}O$) records of a core supported significant changes in temperature during periods of solar activity as well a warming trend of 2.7°C for the past 470 years, with an enhanced warming during the last several decades (Thamban *et al*., 2011, 2013). Ice core based temperature reconstructions during the past five centuries also revealed substantial warming by 0.6-1°C per century, with greatly enhanced warming during the last few decades (~0.4°C per decade) (Thamban *et al*., 2013).

The dust record of IND-25/B5 ice core showed dust deposition in East Antarctica following the Southern Hemispheric climate change, which has doubled during the 20th century (Laluraj *et al.*, 2014). Strong positive correlation observed between ice core dust flux and the Southern Annular Mode (SAM) revealed that the positive values of the SAM index are indicative of increase in dust deposition over East Antarctica, through strengthening of westerly winds. Interestingly, the timing and amplitude of the insoluble dust flux matched remarkably well with the trace metal fluxes of Ba, Cr, Cu, and Zn, confirming that dust was the main carrier of airborne geochemical tracers to East Antarctica in the recent past (Laluraj *et al.*, 2014). The observed doubling of dust and associated trace metal deposition in East Antarctica have wide-ranging implications for understanding the factors driving the inter-continental transportation of impurities and their environmental impact on Antarctica. Proxy records of sea ice (sea-salt sodium (ss-Na^+) and methane sulfonic acid (MSA)) and moisture (deuterium excess (d-excess)) variability of IND-25/B5 ice core also revealed the history of moisture transport and sea ice condition during the last century (Rahaman *et al.*, 2016). This study suggested that moisture source and sea ice variability in annual-decadal scale in Antarctica seems to be largely influenced by SAM and its teleconnection to ENSO.

The ice core studies by NCAOR also contributed to the Past Global Changes (PAGES 2k) consortium aimed at reconstructing global temperature database for the past 2000 years (PAGES 2k Consortium, 2013). Integrating the 692 proxy climate records from 648 locations spreading across all continents and oceans, the study revealed an overall cooling trend across nearly all continents during the last two thousand years. This cooling trend was reversed by distinct warming, beginning in some regions at the end of the 19th century. This database provides a vital resource for climate researchers interested in how the climate has changed from 1 AD to the present (PAGES 2k Consortium, 2017).

Dynamics and Stability of Ice Shelves and Ice Rises

Ice shelves of Antarctica are rapidly changing and could largely affect the Antarctic ice sheet stability. Ice rises, grounded ice domes, affect ice-shelf stability and are useful sites to investigate the proxy records of Antarctic climate variability. Dronning Maud Land (DML) is characterized by small ice shelves that are punctuated by ice rises. To fill the knowledge gap and to undertake a detailed study of ice shelves and ice rises of coastal DML, an Indo-Norwegian project named MADICE (Mass balance, dynamics, and climate of the central Dronning Maud Land coast, East Antarctica) was initiated between NCAOR and the Norwegian Polar Institute (NPI). MADICE project investigated the ice dynamics, current mass balance, and millennial-long evolution in the coastal region of the central DML coast as well as the past changes in atmospheric and sea ice dynamics in this region, using remote sensing data, geophysical field measurements, and ice core based climate reconstruction.

During the 2016-17 and 2017-18 seasons, joint Indo-Norwegian field campaigns were under taken within the Nivlisen Ice Shelf and adjacent ice rises (Djupranen, Leningradkollen and Kamelryggen). During the 2016-17 campaign, the glaciology team conducted a range of geophysical surveys over five weeks on the Nivlisen Ice Shelf and adjacent Djupranen and Leningradkollen Ice Rises, to examine their dynamics and evolution in the past millennia. The team first made kinematic GPS surveys for 1900 line kilometers over the two ice rises to precisely measure surface elevations. Two types of ice-penetrating radar were deployed to map bed topography and ice stratigraphy. The radar operations were made for 500 line kilometers of deep-sounding radar and 270 line kilometers of shallow-sounding radar over the two ice rises, as well as the ice shelf. Along these survey lines, 90 markers were installed and their initial positions were measured using GPS. The campaign successfully collected a range of glaciological data using GPS and radar, and recovered two ice cores at the summits of the ice rises (depth 122 and 51 m, respectively). The second MADICE campaign is currently underway.

Glaciochemical Processes and Biogeochemistry

To understand the fundamental air-snow transfer processes in Antarctic ice sheet and to improve the utility of the ice cores as reliable climate archives, field measurements and spatially distributed snow sampling along strategically placed transects are also initiated. First results show that unlike the common perception, Antarctica is not chemically pristine as there is supply of various chemical species like the reduced sulfur species such as dimethyl sulfide, oxidizing chemicals such as NO*x*, nitrate ions, formaldehyde, ozone and hydrogen peroxide as well as halogen-containing compounds due to various atmospheric and oceanographic processes. Chemical and mass concentrations of aerosols revealed that mass concentrations of coarse aerosols increase towards the Antarctic coast (Thakur and Thamban, 2014). While anthropogenic impact is evident within the fine mode aerosols, the marine influence dominated the coarse mode aerosols. Study on the distribution and source pathways of environmentally critical trace metals in coastal Antarctic snow revealed that while contributions from natural sources are still dominant in Antarctica, anthropogenic contamination related to the ever increasing logistic activities is locally significant (Thamban and Thakur, 2012).

Glaciochemical studies on Antarctic snow for the first time also demonstrated the influence of the degree of slope of the ice sheet on the distribution of sea salt ions in Antarctic snow (Mahalinganathan *et al*., 2012). Among the large variety of particulates in the atmosphere, calcic mineral dust particles have highly reactive surfaces that undergo heterogeneous reactions with nitrogen oxides contiguously. The association between Ca^{2+}, an important proxy indicator of mineral dust and NO_3, in Antarctic snow, studied using 41 snow cores (~1m each) along two coastal-inland transects from the Princess Elizabeth Land and central Dronning Maud Land (cDML) in East Antarctica, revealed the formation of calcium nitrate in Antarctic atmosphere. The study helped in discovering a strong relation between calcium and nitrate in Antarctic snow and provided clues on the genesis of calcium nitrate in Antarctic snow and ice (Mahalinganathan and Thamban, 2016). Southern South America was identified as the main calcic mineral dust source to the East Antarctica. The study revealed an association between calcium and nitrate occurs due to the formation of calcium nitrate during the long range airborne transport from South America to Antarctica that may significantly influence the total nitrate deposited in Antarctic snow.

Microbial Ecology and Crybiological Processes

Cryobiological studies carried out by Indian scientists included diverse fields such as: i). Studies on taxonomy and diversity of microbial communities (bacteria, algae, bryophytes, lichens, fungi etc.) in supraglacial environments; ii). Mechanisms of adaptation to extreme environments and response to environmental stress; iii). Search for novel bioactive molecules and novel microbes; iv). Biogeochemical cycling in supraglacial ecosystems. In recent years, research in the field of cryobiology and biogeochemistry in India has gained momentum with new studies focusing not only on the diversity and physiology of cryospheric life forms but also how cryospheric microbial communities might drive the biogeochemical cycles in these regions. Recently, several microbial species have been isolated from Antarctic cryospheric habitats such as snow (Antony *et al*., 2011) and ice (Antony *et al*., 2012, Shivaji *et al*., 2013) and their physiological and metabolic properties studied. Antioxidant enzyme production was observed in an Antarctic bacterium in response to cold stress (Chattopadhyay *et al*., 2011). Studies at the biochemical and genetic level have provided important insights into the adaptive strategies employed by microorganisms to survive in the extreme habitats characteristic of cryospheric ecosystems (Kulkarni *et al*., 2014, Singh *et al*., 2014, Chattopadhyay *et al*., 2011, Antony *et al*., 2012). Recently, the draft genome sequence of several microbes from Antarctica such as Psychrobacter aquaticus strain CMS 56^T (Reddy *et al*., 2013), Leifsonia rubra Strain CMS $76R^T$ (Pinnaka *et al*., 2013), and Arthrobacter gangotriensis Strain $Lz1y^T$ (Shivaji *et al*., 2013) have been published. Active microbial communities associated with snow and ice sheet surfaces have been found to play an important role in the biogeochemical cycling in supraglacial systems. The scientific studies being carried out by Indian scientists in the realm of cryospheric sciences will contribute significantly to the global community's ongoing efforts to better understand the functioning of cryospheric systems and how they might respond to future changes as a result of climate change.

Biochemical and microbial characteristics of various supraglacial ecosystems such as, snow, melt-water streams, blue ice and cryoconite holes together with their role in biogeochemical cycling on the glacier surface was systematically studied during the past decade. The studies on cryoconite hole and surface snow samples collected from coastal Antarctica has shown that in addition to abundant and diverse microbial populations, supraglacial environments contain a substantial reservoir of organic carbon with inputs from microbial, marine and terrestrial sources (Antony *et al*., 2014; Samui *et al*., 2017). In addition, microcosm experiments involving cryoconite hole samples showed that resident microbial communities have good potential to metabolize organic compounds found in the cryoconite hole environment, thereby influencing the water chemistry in these holes.

Research Leads in Cryospheric Studies in Arctic: NCAOR

The Arctic region is currently one of the fastest warming regions and the pace/magnitude of environmental change are greater in the Arctic than at any other location on the Earth. Moreover, the ocean and sea ice in the Arctic are a crucial part of the global climate machinery, influencing atmospheric and oceanographic processes, and biogeochemical cycles beyond the Arctic region. Considering the importance of a better understanding of the Arctic, the Government of India initiated expeditions to Arctic region in 2007 with significant major long-term scientific initiatives in the Svalbard archipelago. India's permanent research base named 'Himadri' at Ny-Ålesund in Svalbard is operational since 2008. The thrust areas of the research in the Arctic from India are: (a). Atmospheric sciences with special emphasis on the study of aerosols and precipitation; (b). Cryosphere studies on the mass balance of glaciers and chemical characterization of snow; (c). Biogeochemical studies in fjord systems (with respect to long-term monitoring of climate change studies).

The cryospheric studies by Indian scientists in Arctic mainly focus on the sea ice studies, dynamics and mass budget of Arctic glaciers in the context of climate change as well as the microbiological diversity and ecology in the Ny-Alesund region in Svalbard. Estimation of thin ice thickness for coastal polynyas in the Chukchi and Beaufort Seas using the Advanced Microwave Scanning Radiometer-EOS revealed the model error is 1.3 cm within the thickness range of 1-10 cm (Singh *et al*., 2011). Recently, several microbial species have been isolated from various cryospheric habitats such as snow, ice, and permafrost and cryoconite holes in Svalbard (Singh and Singh, 2011; Srinivas *et al*., 2012). Many of the isolated strains have been shown to have biotechnological potential (Hatha *et al*., 2013). For example, observations related to substrate utilization by Arctic fungi indicate their potential to produce industrially important enzymes such as pectinase, phosphatase, protease, urease, esterase, cellulase and amylase (Gawas-Sakhalkar and Singh, 2011).

To better understand the nitrogen and sulphur chemistry at the Arctic air-snow interface, air and snow measurements were carried Ny Alesund, Svalbard using a particulate sampler equipped with denuders and filter packs for simultaneous collection of trace gases (HNO_3, NO_2, SO_2 and NO_y) and aerosols. The findings provided useful information on the variability of the fundamental chemical processes at the air-snow interface with the changing meteorological conditions (Thakur and Thamban, 2018). The study revealed that inter-conversion of nitrogen and sulfur species between the gas and particulate phases and their interaction with alkaline species influences the acidity of the aerosols and surface snow. Air measurements carried out Ny-Ålesund, Svalbard, suggested that nitrate-rich aerosols are formed when PAN (peroxy acetyl nitrate) disassociates to form NO_2 and HNO_3 which further hydrolyzes to formpNO_3^- (particulate nitrate). The bicarbonates/carbonates of Mg^{2+} played an important role in neutralization processes of surface snow while the role of NH3was dominant in aerosol neutralization processes. Chloride depletion in the snow was significant as compared to the aerosols, indicating two important processes, scavenging of coarse sea salt by the snow and gaseous adsorption of SO_2 on the snow surface.

Way Forward for Future Research

Critical overview of field as well as satellite based observations support glacier-climate inter-linkage from millennium to inter-annual scale. The accentuated rate of glacier recession over the large of the Indian Himalaya observed during seventies and eighties of the past century favoured global warning to be a major forcing factor controlling the glacier-climate linkages (Raina, 2009; Gaddam *et al*.2016; Brun, 2015; Bhambri *et al*., 2011; Kulkarni *et al*., 2011). However, the present evidences that rate of recession has slowed significantly in the immediate past decade or two is inconsistent with continuing rise in global temperature (Ajai, 2018). Monitoring of snout and climate sensitive AAA index over the past 50 years have shown that while the glaciers in Central and NE Himalaya are continuously retreating, the glaciers in Western Himalaya are marked by advancement or are utmost stationary (Hewitt, 2005; Ganjoo *et al*., 2014). This Karakoram anomaly had begun to raise question whether glaciers in the western Himalaya defy the global warming (Yadav *et al*., 2004). It is also now well recognised that glaciers in the Central Himalaya are nourished by southwest monsoon whereas glaciers in the western Himalaya are fed by mid-latitude westerly (Archer, 2001; Treydte *et al*., 2006). Depending upon the primary source of precipitation and their strong seasonal character permit to view the Himalayan glaciers in two-types: (i) summer accumulation-cum-summer ablation and (ii) winter accumulation-cum-summer ablation. In such scenario, complex spatial and temporal changes manifested by the glaciers in different climatic zones of the Himalaya can qualitatively be attributed to the combined influence of temperature-precipitation inflicted perturbations (Azam *et al*., 2014; Thayyen *et al*., 2010. Lack of in-situ measurements of wet precipitation or AWS in Higher Himalaya have, so-far, inhibited numerical quantification of the influence of temperature/precipitation on the health and dynamics of the glaciers. Vertical distribution of accumulation/ablation areas with respect to snow line, modulation of albedo by debris cover, geometry of valley restricting limited exposure to the Sun, radiation from the wall of the valley etc. are identified as additional physical parameters influencing the dynamics of glaciers within the same basin or located in the intra-basins regions (Dobhal *et al*., 2013, Patel *et al*., 2016; Sharma *et al*., 2016). Here again the earlier field experiments were not specifically designed to test the role of additional physical forcing parameters, their numerical and physical validation has remained unexplored. Standard Operational Practice (S.O.P) to be adopted in future research programs should focus on: Establishment of flagship monitoring stations equipped with the Automatic Weather Stations for basin level mountain meteorology, optically sensed water discharge measurements for melt water contribution to hydrology of the region, particle size analyser and automatic sediment samplers for estimate of sediment transfer, steam drill to implant stakes for mass balance studies would be the key facilities. It should also deploy techniques of ground penetrating radar (GPR) and Natural EM Frequency sounder for mapping the bed rock profile, internal structure and thickness of glaciated column, whereas GPS and Total Station and SAR mapping will be helpful in characterizing movement and deep deformation associated with glacier dynamics. Estimate on the thickness of glaciated column would be a value addition to the AAA index as it would provide much better assessment of mass balance from the satellite data. The validation by comparison with field data would facilitate estimation of mass balance studies of glaciers on regional scale. The S.O.P being adopted by the NCAOR in Arctic and Antarctica can be role model for implementation in the Himalaya. The merit of the S.O.P for its duplication in the Himalaya is apparent from results emerging under the project 'HIMANSH', undertaken by the NCAOR. Reconstruction of past climate from Ice cores obtained from strategically located sites would be critical to answer whether the current retreating trends observed in the Himalayan glaciers is a direct consequence of global warming or is a part of long term Quaternary cyclic oscillations. In the holistic glaciological research in the Himalaya, it will be important to induct two new areas, perhaps for the first time: (i) the role of thermal flow from bed rocks to investigate and understand the role of sub-glacial heat element in glacier dynamics; (ii) deformation and stress fluctuation due to glacial loading/unloading assume even greater significance as resulting additional stresses can derive the already tectonically stressed fault to trigger seismicity. Further institutionalization of glaciology research will boost multidisciplinary studies for climate-glacier inter-linkages, melt water prediction towards sustained management of water resources for hydro-power generation, livelihood and agriculture development.

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Review Article

Gravity and Geodetic Studies in India: Historical Observations and Advances During the Past Decade

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Gravimetry and Geodesy deal with the mass distribution and transport in the dynamic Earth system and determination of Earth's shape and size. Since the 18th century, Indian scientists have been extensively contributing to the progress of Gravity and Geodetic studies. This article discusses the historical geodetic developments and summarizes the efforts that involve measurements and modelling of gravity and geodetic data in India over the past decade, using conventional land surveys to satellite observations. Historical obsevations, such as the Great Trigonometrical Survey during 1790-1850 for defining geodetic reference frame and gravity and geodetic observations in the Himalayan region (1830-1843) for hypothesising the concept of Isostasy, are phenomenal contributions made from studies in India. Recent studies are largely focused on understanding of subsurface mass distributions and mass variability due to different geophysical phenomenon, refining of geodectic datum, continental deformation and resource exploration.

Keywords: India; Gravity; Geodesy; Geoid; Datum

Introduction

The gravity and geodetic research worldwide has evolved as a scientific interface to facilitate the integration of satellite-based observations with the terrestrial measurements thereby making all earth observations interoperable.Both gravimetric and geodetic (using land, marine, borehole, airborne and satellite-based) studies have made tremendous progress during the past few decade and provided valuable insights with regard to the behaviour of spatio-temporal dynamics of the Earth (Tiwari, 2010). There has been an increased focus on precisely defining the local and regional geoid models worldwide due to their significance in the areas of applied geophysics and geodetic studies. Apart from the use of geoid in the engineering applications of surveying (geodesy), the detailed knowledge of geoid undulations at different wavelengths areused to infer the subsurface mass distributionsin the Earth (Li and Götze, 2001).

There are numerous studies on the interpretation of geoid in terms of mass anomalies at depth, tectonic forces, isostatic state of the oceanic lithosphere, Earth's rotation, total water storage and ocean circulation (e.g., Bowin, 2000). The gravitational potential decreases with distance from the surface of the Earth at a slower rate than the gravity, the geoidal variations tend to reflect deeper mass anomalies compared to the gravity anomalies (Hackney, 2004). The geoid anomalies thus provide information in terms of the subsurface mass distribution and dynamics of the Earth (Bowin, 2000; Vanicek and Christou, 1993; Featherstone, 1997).

The Indian geoscientific community, particularly during the post-independence era, has made significant scientific progress and achievements in tandem with the developments that took place worldwide in gravity and geodetic studies. These studies have led to several improvements in the Indian geodetic datum that was established in 19th century by the Survey of India (SOI), preparation of gravity anomaly maps using dense terrestrial gravity measurementsand the integration of satellite-based gravity data with ground-based observations for various applications by different organizations. This paper is intended to provide a brief

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overview of the historical development of the gravity and geodetic measurements in India with special emphasis on the recent studies/research work carried out by the Indian researchers in the allied areas of gravity and geodesy for various applications.

Brief History of Gravity Surveys in India

Gravity surveys in India were initiated in 1865 by J.P. Basevi and W.J. Heaviside, British Captains, using two brass pendulums provided on loan to Government of India by Royal Society of England for establishing about 30 gravity stations from Kanyakumari to Ladakh during 1865 to 1873 (Walker *et al*., 1901). Subsequently, Sterneck's half-second pendulums (1902 to 1925) and Cambridge pendulums (1926 to 1939) were used to establish 564 pendulum stations by the SoI in the different parts of the country. The pendulum measurements were suspended on account of the World War II from 1939 to 1947. The First gravimeter used in India was Frost gravimeter in 1947. Afterward, different organizations have procured gravimeters for the geophysical exploration, educational and training purposes. The systematic surveys were started during 1950s by the dedicated geodesists and geophysicists and continued over the years to map the subcontinent of India covering the northern mountains, the peninsular plateau, Indo-Gangetic plains, dense forests, deserts and coastal regions. Data of about 3000 gravity stations including 564 pendulum stations recorded during 1902-1955, have been published by Gulatee (1956).

Precise determination of the height of the Mount Everest is one of the most celebrated achievements in the history of Indian gravity and geodesy. The National refence gravity station, tied with Potsdam gravity basewas established at SOI, Dehradun and a North-South calibration line was set up (Manghnani and Woollard, 1963). Hari Narain *et al*. (1964) examined the status of gravity work in the country and found that a considerable amount of available gravity data were mostly referred to the old pendulum stations of SOI, which had irreconcilable discrepancies. Further, the entire gravity data in the country was brought on to a common datum tied appropriately to the World Gravity Net andused for the geodetic and crustral studies in India. NGRI initiated a National Gravity Programme of preparation of regional gravity studies of India in 1964 which led to the publication of a series of gravity maps of India in 1975.

Gravity base network was established and the gravity values were published in different parts viz Part-I:-150 gravity bases in South India (Qureshy and Brahmam, 1969); Part-II:- 93 gravity bases in Northern and Western India (Qureshy and Warsi, 1972); Part-III:- 50 gravity bases in North India (Qureshy and Warsi, 1973);Part-IV:- 125 gravity bases in North Eastern India (Qureshy *et al*., 1973) and Part-V:- 16 gravity bases in Central India (Subba Rao *et al*., 1982).During these investigations, several of the SOI stations were reoccupied for standardization anda few new first order and secondary gravity bases were also established by various organisations(Murthy *et al*. 1976; Verma *et al*. 1979; Singh *et al*., 1986 and Radhakrishna *et al*., 1998). Regional gravity surveys carried out by GSI over the Deccan traps during 1964-1970 delineated two major lineaments, one along the west coast and other along the 21st parallel degree north of the Earth's equatorial plane (Kailasam *et al* ., 1972). A detailed gravity survey covering 1900 gravity measurements in the Singhbhum region was carried out, which revealed Bouguer anomalies ranging from +10 mGal in the eastern part to about -60 mGal over the Singhbum granite batholith (Verma *et al*., 1984). Further, a large numberof gravity measurements are carried out under the National Gravity Programme by SOI. GSI launched National Geophysical Mapping (NGPM) programme during the 2002-2003 with an objective to generate gravity and magnetic responses in potential areas of mineral exploration.

Gravity Map Series of India

In the year 1975, the voluminous gravity data at National Geophysical Research Institute (NGRI), Survey of India (SOI), Oil and Natural Gas Commission (ONGC) and the Hawaii Institute of Geophysics (HIG) were compiled and the first ever Gravity Map series of India (1975), with 10 m Gal contour interval was published on 1:5 million scale. These maps were based on 30000 gravity stations located along the major roads at intervals of 6-8 km, where benchmarks or spot heights were readily available.In case of geodetic data gaps, two altimeters were simultaneously operated to obtain elevations of the gravity stations. Taking into account all the factors that contribute to errors in the Bouguer anomaly values, the anomalies could be accurate within ± 1.5 mGal. In case of the Himalayan region, however, such accuracy could not be obtained for stations for which the elevations were acquired using altimeters. This set of maps - Bouguer Gravity, Free-Air and Isostatic anomaly maps, led to formulate new exploration activities in India besides someimportant basic research such as refining the ideas of isostasy. The relationship between gravity anomalies and elevation was empirically derived and used to predict the thickness of the crust. These maps are further upgraded as Gravity Map of India (2006; Fig. 1(A)), a collaborative effort of several organisations; NGRI, Geological Survey of India (GSI), Oil and Natural Gas Commission (ONGC), Oil India Limited (OIL) and Survey of India (SOI). Data from 51,356 gravity stations at 3 arc interval are included with the implementation of detailed terrain corrections to the gravity stations, new theoretical gravity formula based on the Geodetic Reference System 1980 (GRS80) and the International Gravity Standardisation Net 1971 (IGSN71) datum. These revised maps are prodigious assset to the geosceince researchers and explorers. A brief description of the gravity anomaly map in relation to the geological features is given below.

Bouguer Gravity Anomaly Map

A mjor feature of this map is the predominance of negative Bouguer anomalies over the subcontinent reaching to value of -380 mGal over the Himalaya. A few pockets of positive Bouguer anomalies are observedon the west coast and reaching to a maximum value of +60 mGal near Bombay. The anomalies exhibit alignments/trends parallel to the major structural trends of the subcontinent such as the NNW-SSE Dharwarian trend of South India, NE-SW Eastern Ghat trend parallel to the east coast of South India, NE-SW Aravalli trend of North-Western India, ENE-WSW Satpura trend of Central India and the Himalayan trend. Besides these regional trends, there are several gravity 'highs' and 'lows' reflecting local geological features. The sediments of the Vindhyan and Gondwana basins, sedimentary tracts of the east coast, intrusive granites of Peninsular India are all characterised by gravity 'lows.' Gravity 'highs' are observed over the Eastern Ghats, south-western Cuddapah basin, the Satpura and Aravalli ranges. In contrast, there are also areas where the Bouguer anomalies do not readily correlate with surface geology. Prominent among themare the 'lows' over the Deccan Traps of Western India, eastern Cuddapah basin, Peninsular gneisses of south India and Bastar region. The area west of Aravalli, which is mostly covered by alluvium, is a zone of mixed highs and lows. Synclinal structures filled with sedimentary or metasedimentary formations, volcanics, basic and ultrabasic intrusions, granitic intrusions of batholithic, differentiation of granites are inferred as gravity high in the Singhbhum group, Dhanjori and Simlipal basins in East India. The gravity high revealed in the North Eastern India, Shillong Plateauindicates the presence of relatively higher density underlying rocks. Strong negative anomalies as in Assam Valley, eastern Himalaya and Arakan-Yoma indicate areas characterized by mass deficiency due to a thickening of sediments and root formation or both. Gravity anomalies over India are used to construct crustal and lithospehric density models (e.g. Tiwari *et al.*, 2013).

Brief History of Geodetic Studies in India

Indian Horizontal Datum

The Indian Horizontal Datum adopted the Everest ellipsoid as the local geodetic datum in 1830. It is non-geocentric and the oldest among all the principal ellipsoids. The source of Everest ellipsoid set at Kalianpur with the initial point position of $24^0\ 07'\ 11.26''$N and $77^0\ 39'\ 17.57''$E. The center of the Everest ellipsoid does not coincide with the center of the Earth however, it is locally the best fitting ellipsoid to the Indian subcontinent. SOI generated topographical maps on 1:50,000 and 1:25,000 with reference to Everest ellipsoid for expressing geographical coordinates of places in India more than 150 years back. SOI has revised the ellipsoids from time to time (i.e., International (Hayford), GRS80 and WGS84) leading to the revision of the parameters assumed for the ellipsoid. Advancement satellite geodesy in satellite tracking technology has provided geodesists with new measurements such as VLBI, SLR, DORIS and GNSS to define the best Earth-fitting ellipsoid and for relating existing coordinate systems to the Earth's center of mass. Accurate World Geodetic System (WGS84) ellipsoid was established using new gravity data, astro-geodetic measurements, satellite configuration and earth-fixed models (ECEF). WGS84 datum is a geocentric geodetic datum and globally consistent within + 1 meter, which does not change from place to place or from country to country.

Indian Vertical Datum

Vertical datum, which nearly coincides with mean sea level, provides the height information. In other words, the geoid is a visual representation of zero elevation which is considered to be reference height. This datum is derived based on tidal observations, astronomical, GNSS-levelling and gravimetric measurements. MSL is described as a tidal datum that is the arithmetic mean of hourly water elevations observed over a specific 19-year cycle (Aung *et al*., 2009). SOI has been using the astrogeodetic geoid for the Indian vertical datum observations with respect to Everest ellipsoid since 1840 and using the first-order levelling Bench Marks (BM) measured in the early nineteen century (Fig. 1(B)). Fore and back levelling and invar staves instruments were used for measurements. The first vertical datum for India was establieshed based onadjustment of leveling network, which had included data collected from 1858 to 1909 and referenced to MSL values of nine tide gauge stations and limited number of surface gravity observations.

Significant Contributions in Gravity and Geodetic Research During the Past Decade in India

Salient Outcome of the Geodetic Research

Everest datum, which was developed using a small volume of data, is not suitable for high precision geodetic and allied activities of the modern age. Utilizing open source global products for positioning, the datum transformation from Everest coordinate system to geocentric coordinate system (ITRF) was initiated in the 21st century (Singh, 2010). SOI has set up a Ground Control Point (GCP) Library, as a part of which 292 primary control points were established at a spacing of 250-300 km in the first phase. In the second phase,the network was strengthened with 2200 GCP Library pillars with an interval of about 30-40 km and in the third phase, further 65,000 GCP of 6-7 km spacing were added to provide necessary horizontal reference points. SOI completed the high precision levelling network with an adjustment of 45,775 km along the national and state highways, as a part of redefining Indian vertical datum project (Fig. 1(C)).

Nagarajan and Singh (2010) demonstrated the utilisation of GPS to provide planimetric coordinates of GCP's with 1 m control interval for initiating a comprehensive development plan for the Bangalore metropolitan area. GPS vertical datum has turned out to be a progressive tool in establishing a vertical network for engineering applications, though it has certain limitations. In the recent years, most of GTS benchmarks got destroyed due to urbanisation and industrial development. There are global gravity models that allow determining geoidal undulations; however, the global models are constrained by spatial resolutions. Determination of geoid undulations over southern Indian region is of specific importance because the largest geoid depression in the world is centered in the Indian Ocean encompassing South India (Marsh, 1979) and therefore a large spatial gradient of geoid undulation is observed in this region. Geoid height decreasing towards south reaching up to the minimum value of –106 m, located in the Indian Ocean, is generally known as Indian Ocean Geoidal Low (IOGL). The cause of this anomaly is attributed to the depression in the Core-Mantle boundary, relict of earlier subduction and so on. The wavelet analysis of the corresponding gravity low in the IOGL provides depth at ~1260 and ~693 km reported by Tiwari and Goyal (2010). Modeling of the large wavelength regional gravity anomaly corresponding to the IOGL provides a three-layer model at depths of 1300, 700 and 340 km (Mishra and Ravikumar, 2012) related to the spectral depths obtained from the geoid and regional gravity data with negative density contrasts. The relatively short wavelength sources of the spectrum of the geoid data at depths of 162 and 85 km suggest sources along the lithosphere-asthenosphere boundary (LAB) under the Indian continent and surrounding oceans, respectively. All the studies of this long wavelength geoidal low suggest a deep causative source, a density heterogeneities in the mantle. Upper to middle mantle low-density anomalies are mainly responsible for the formation of IOGL and are clearly explained by the presence of low-density anomalies in the ~300-900 km depth beneath the IOGL (Ghosh *et al*., 2017). Some of the recent studies attempted to compute an accurate geoid model without terrestrial gravity observations. Goyal *et al*. (2018) have shown that the EGM2008 model is the best GGM available for India with an accuracy of 28 cm, without model fitting. Similarly, GOCE GGM has demonstrated

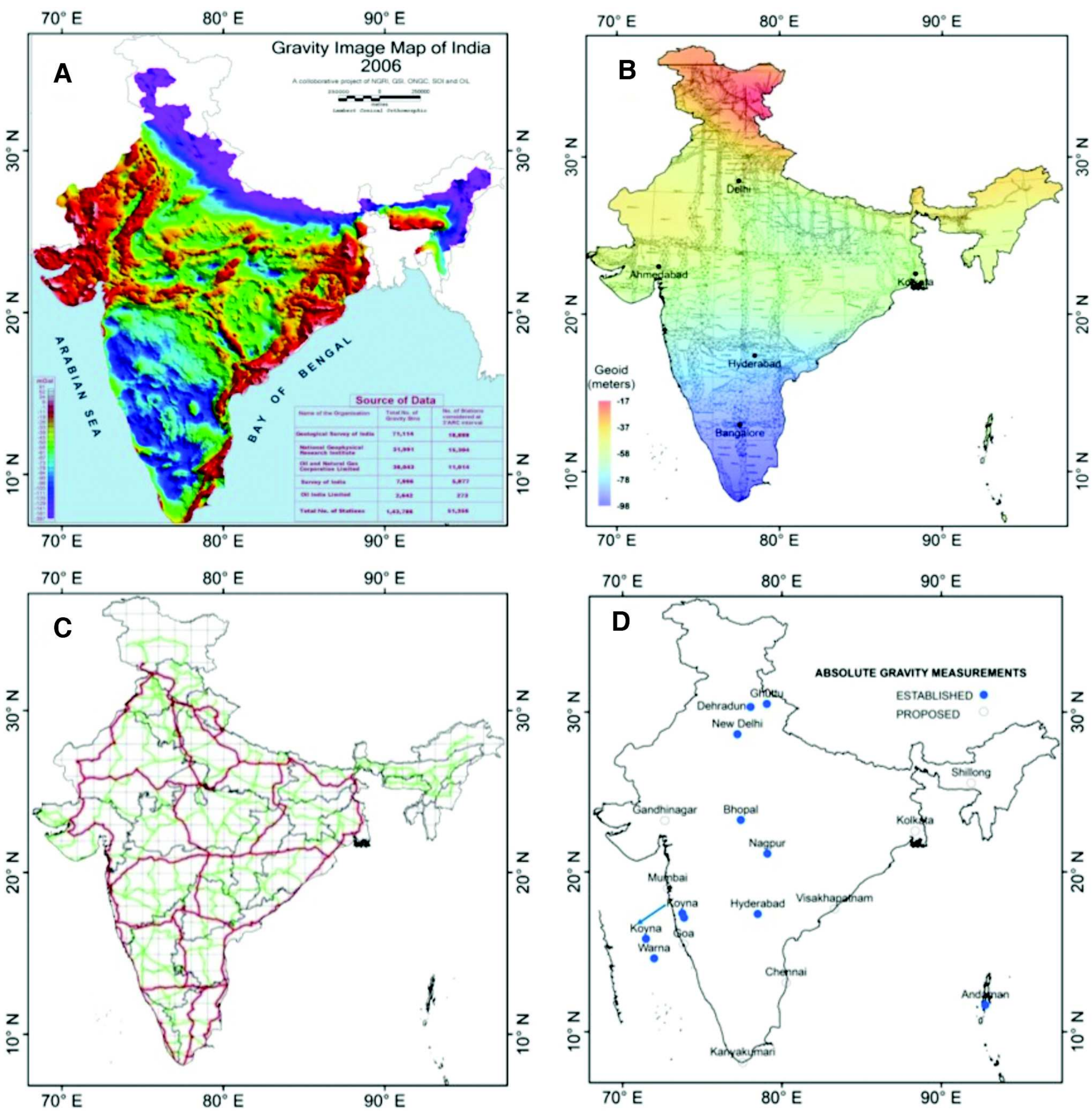

Fig. 1: (A) Bouguer gravity anomaly map of India :Gravity Map Series of India-2006; (B) Spatial distribution of GTS benchmarks in India (1905) (source: Wikipedia); (C) Status of high precision levelling (after Singh and Srivastava (2018)) and (D) Locations of established/proposed precise gravity reference stations in India using the absolute gravimeter

significantly better results with an accuracy of 19 cm for India after modelling with seven parameterisations. SOI developed the first version of Indian Geoid model called INDGEOID ver 1.0 in 250th year celebrations of Surveying and Mapping activities in India in 2017.

Local Geoid Determination

Orthometric height is the height of the surface above or below the geoid. Precise information of geoid undulation is vital for understanding the subsurface mass distribution of the Earth. The geoid surface is not an actual physical figure of the Earth, thus it cannot be directly measured. The current point-based geodetic height determined using GPS-levelling is not sufficient to generate the accurate geoid surfacefor any application. The determination of orthometric heights over a local area is obtained through the GPS-levelling observations or calculated from terrestrial gravity values. Few attempts were made for computation of gravimetric geoid and the results were compared with GPS-levelling measurements over the Indian subcontinent (Singh *et al*., 2007; Carrion *et al*., 2009; Srinivas *et al*., 2012; Singh and Srivastava, 2018). Ghosh and Mishra (2016) determined the geoid undulation for Dehradun using the astro-geodetic method in conjunction with GNSS observations. The accuracy of the computed geoid has been found to be better than global geoid models. Mishra and Ghosh (2017) computed accurate geometrical geoid model in Dehradun with the help of sufficiently dense and homogeneous control stations. The advantage of the geometrical approach of geoid modelling is its being non-dependence on gravity field or deflection of vertical. Utilization of existing gravimetric data may provide the precise geoid surface with the help of different geoid computational methods such as Remove Compute Restore (RCR) method, Stokes-Helmert method, Least squares modification of Stokes formula etc. SOI derived the optimised solutions of the local gravimetric geoid with Free Air gravity anomaly data for some region of the Indian subcontinent by implementing the RCR method. GPS-Levelling Points: 84 (Bangalore city: Singh *et al*., 2006), 50 (Delhi region: Singh *et al*., 2007) and 72 (Central India: Singh, 2007) were selected for performing a realistic assessment of geoid model and subsequently optimised the integral parameters of Stokes Formula. The RCR procedure has been applied to combine the GGM, high-frequency height data from a DEM and local terrestrial gravity anomaly data. The hybrid geoid model has shown a considerable improvement over gravimetric geoid, and standard deviation of post-fitting residuals is improved to approximately 5cm precision after the Least Square Collocation (LSC) technique.

Carrion *et al*. (2009) computed the geoid undulations over a part of southern Indian region with terrestrial gravity data using the RCR technique to calculate Stokes coefficients and compared with EGM2008 global geoid model with a difference of fewer than two meters. Similarly, Prajapati and Singh (2010) determined the residual geoid for some of the Indian plateaus (i.e., Saurashtra, Malwa, Satpura, Ajanta) by removing the effects of geopotential model, Free-air gravity anomalies and height data by applying the LSC technique. The geoidal undulations suggest that the primary source of geoidal high lies within the crust-upper mantle. Another attempt is made to compute and validate the geoid undulations (Fig. 2) concurrently using terrestrial gravity data and GPS-levelling observations and to compare them with geoid undulations obtained from global geopotential models over the southern part of India (Srinivas *et al*., 2012). An agreement between GPS-levelling data and global geopotential model was found on a regional scale. However, geoid from GPS-levelling over a small region is considerably adequate to the gravimetric geoid and suitable for the local applications.

Geoid undulations are also derived from LiDAR survey and GTS benchmarks over the Kosi and Mahanadi basins and compared with the GOCE derived geoid heights. A bias of 1.5 m with reference to the ground geoid is reported by Satishkumar *et al*. (2014). The hybrid geoid is a combination of the Geometric geoid and Gravimetric geoid. Tripathi and Tripathi, (2015), utilised the terrestrial gravity, elevation and positioned data of 190 GPS-Levelling data spread across Chhattisgarh region to calculate the hybrid geoid with an accuracy of 60 cm. Mishra and Ghosh (2016) also adopted the RCR method to determine gravimetric geoid for two different types of topographical regions (i.e., Hyderabad and Dehradun) and achieved ~ 20 cm accuracy in the highly elevated Himalayan region and ~ 10 cm in the gentle elevated Hyderabad region.Singh and Srivastava (2018) explained the development of Gravimetric geoid model for Western India using the RCR method and implemented the spherical Fast Fourier Transformation (FFT) with optimised Stokes's kernel to achieve an accuracy of 14 cm for gravimetric geoid and 7 cm for hybrid geoid model with the help of GNSS observations on first order benchmarks at 39 locations. SOI initiated a program "Redefinition of Indian Vertical Datum" by optimal utilisation of existing gravity GNSS and levelling data to develop a hybrid geoid model, to achieve an accuracy of better than 10 cm.

High Precision Gravity Measurements

The absolute gravity (AG) observations across India and at Maitri, Antarctica were first carried out by NGRI, to establish reference gravity stations with aprecision of 1 μGal using Micro-g LaCoste FG5 absolute gravimeter. A reference gravity base station was established with an accuracy of about 2-3 μGal with the help of Absolute Gravimeter (FG5 #219) at

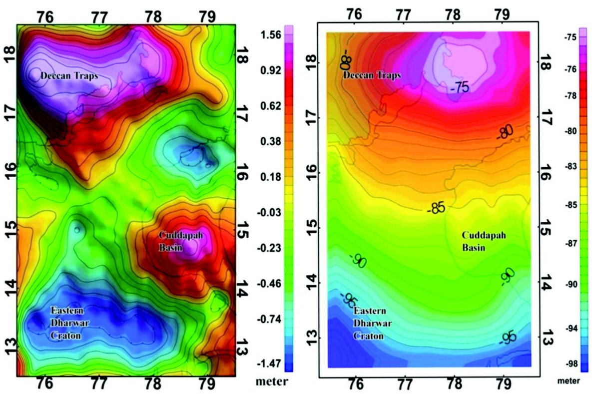

Fig. 2: Residual geoid and gravimetric geoid of a part of south India (after Srinivas *et al.*, 2012)

the NGRI Gravity Observatory, Hyderabad (Tiwari *et al.*, 2006b). New precise reference gravity base stations were established in different parts of India (New Delhi, Dehradun, Ghuttu, Bhopal, Nagpur, Koyna, Warna, Port Blair and Maitri, Antarctica (Tiwari *et al.*, 2006b)). The AG observations comprised of regular repeat measurements over a network of existing and proposed absolute gravity sites (Fig. 1(D)) throughout India to provide information about the mass redistribution, vertical deformation and metrological applications (Tiwari *et al.*, 2014a).

The Superconducting Gravimeters (SG) are in operation at two locations in India, Ghuttu by WIHG, Dehradun (Arora *et al.*, 2008) and Badargadh by ISR, Ahmadabad. The SGs continue to provide a high precision record of the time variation of gravity with an accuracy of nGal. SG observations at both the above locations are located by other geophysical observations with the primary objective of earthquake precursory studies. Chauhan *et al.* (2016) observed the annual variations in SG gravity data at the rate of 112 nms^{-2}/year with a variation of 16 m in water table level and vertical displacement of 2.2 mm/year. Repeat AG observations are being madeat the site of SG located in the Himalayan region for drift corrections and calibration of SG. Gravity variations using gPhone gravimeter are being continuously recorded at Warna, Maharashtra, a seismically active region of peninsular India for investigation of potential gravity changes related to seismic activities. Prasad *et al.* (2017) successfully demonstrated the temporal gravity changes recorded by using gPhone and GRACE satellite and interpret the observed changes in conjunction with seismological, geodetic (cGPS) observations and groundwater level measurements.

Satellite Gravimetry

Most of the Indian researchers engaged in the observation and modelling of the earth's gravity field are focusing on deciphering tectonic and geodynamic processes that have shaped the present day lithospheric structure. The studies are carried out over the diverse tectonic and geological setting of the Indian subcontinent through a large number of gravity data in peninsular India. Since ground and marine gravity measurements cannot adequately cover the Indian subcontinent and adjoining ocean, satellite measurements are often oused. High-resolution Gravity field determination from space can be obtained from various measurement methods, namely Satellite radar altimetry (Geosat, European Remote Sensing (ERS-1), CryoSat-2, Jason-1, Saral-Altika), Satellite-Satellite tracking (CHAMP and GRACE), Satellite Gravity Gradiometry (GOCE). Since summarising the results from all the studies goes beyond the scope of this review article, results from selected studies of satellite gravimetry are briefly mentioned.

Applications of Satellite-derived Gravity for Crustal Studies

Applications of satellite gravimetry in India are reported in several studies related to exploration of natural resources, lithospheric structure, hydrological changes and geodynamics studies. Bhattacharyya *et al.* (2009) generated a composite high-resolution free-air gravity anomaly map for the Arabian Sea from Seasat, Geosat GM, ERS-1/2 and Topex/Poseidon altimeters data. Satellite altimetry derived gravity combined with terestrial gravity data provide enhanced imaging of geological features of Indian penesula and adjoining ocean basins (Majumdar *et al.*, 2001; Mishra *et al.*, 2004 and 2012; Mishra and Tiwari, 2008; Mishra and Rajasekhar, 2005; Tiwari *et al.*, 2007 and 2013; Tiwari and Mishra, 2008; Chatterjee *et al.*, 2007; Mishra and Ravikumar, 2012; Ravikumar *et al.*, 2013a; Ravikumar *et al.*, 2013b; Kumar *et al.*, 2013; Kumar *et al.*, 2014; Rajesh and Majumdar, 2014; Singh *et al.*, 2015), Bay of Bengal (Radhakrishna *et al.*, 2000; Rajesh and Majumdar, 2003; Radhakrishna *et al.*, 2010; Nandi and Rao. 2015; Kar *et al.*, 2015; Rao *et al.*, 2015; Rao *et al.*, 2016; Dubey *et al.*, 2017), continental margins of India (Chand *et al.* 2001;

Subrahmanyam and Chand, 2006; Mishra, 2011; Sreejith *et al*., 2013; Murray, Laxmi, Chagos-Laccadive, 85°E and 90°E ridges (Tiwari *et al*., 2003; Bansal *et al*., 2005; Subrahmanyam *et al*., 2008; Rao and Radhakrishna., 2014; Rajesh *et al*., 2015; Nair *et al*., 2015; Majumdar and Chander, 2016), Western Continental Margin of India (RadhaKrishna *et al*., 2002; Arora *et al*., 2006; Mukhopadhyay *et al*., 2008; Rao *et al*., 2010; Arora *et al*., 2012; Majumdar and Bhattacharyya, 2014; Rao *et al*., 2018), Eastern Continental Margin of India (Singh and Diljith, 2009; Bhanja Bastia *et al*., 2010; Radhakrishna *et al*., 2012; Desa *et al*., 2018), Andaman arc (Grevemeyer and Tiwari, 2006; Radhakrishna *et al*., 2008); Himalayan region (Rajesh and Mishra, 2003; Tiwari *et al*., 2006a,2009a, 2010 and 2014b) Antarctica (Majumdar *et al*., 2018). A 3D lithospheric density model of the Andaman-Sumatra subduction zone is constructed from joint modelling of satellite-derived gravity and geoid data (Yadav and Tiwari, 2018). The geophysical mapping of Singhbhum-Orissa Craton and Jharia Coalfield are carried outusing the GOCE, EGM2008 and EIGEN6-C2 and compared with the in-situ gravity (Pal and Majumdar, 2015; Vaish and Pal, 2015; Pal *et al*., 2016).

A revised gravity anomaly map of the 85°E Ridge (Pal *et al*., 2016) and Bay of Bengal (Narayan *et al*., 2017) was generated utilizing the EIGEN6C4 global gravity model. Singh *et al*. (2015) analysed satellite gravity and geoid anomaly and topography data to determine the 3D lithospheric density structure of the Singhbhum Protocontinent. Kalra *et al*. (2014) interpreted the occurrence of sub-basalt sediments at the margin using the satellite gravity and encapsulated to provide a basis for assessing deepwater petroleum prospect of the entire western margin offshore. Rao and Radhakrishna (2016) carried out evolutiontests based on the statistical estimates, spectral analysis and image enhancement filters have been performed to assess the spatial resolution and quality of Earth Gravitational models (EGM2008, GOCE, DTU13 and SSV23.1) and crustal magnetic field model (EMAG2) over the Indian shield and its surrounding offshore regions.

Hydrogeodesy

Hydrogeodesy is referred to the application of geodetic techniques to the study and monitoring of the terrestrial waters. Dedicated gravity mission senses the spatiotemporal variations of the gravity field caused mainly by the hydrological mass changes in the Indian region and glaciological mass changes over the Himalayan region. Tiwari *et al*. (2009b) estimated a massive loss of groundwater in Northern Indian region at a rate of 54 ± 9 Km^3/yr from 2002 to 2008 utilizing the GRACE data with a combination of hydrological (Fig. 3). The hydrological signal derived from GRACE was also validated with in-situ measurements in India and demostrated the application in the monitoring of water storage (Tiwari *et al*., 2011 and 2014a; Bhanja *et al*., 2016, 2017a; Asoka *et al*., 2017). The GRACE dataset reveals a declining trend of groundwater in different parts of the Indian subcontinent (Tiwari *et al*., 2009b; Khan *et al*., 2013; Dasgupta *et al*., 2014; Banerjee and Kumar 2014; Chinnasamy *et al*., 2015; Verma *et al*., 2016; Gautam *et al*., 2017a; Banerjee and Kumar 2016; Singh *et al*., 2017; Mukherjee and Ramachandran, 2018). Lowering of groundwater storage are caused due to anthropogenic groundwater withdrawals to sustain rice and wheat cultivation in the Ganga basin (Panda and Wahr, 2016; Barik *et al*., 2017). The GWS depletions that constitute about 90% of the observed TWS loss are influenced by a marked rise in temperatures since 2008. Bhanja *et al*. (2017b) noted that the paradigm shift in Indian groundwater withdrawal and management policies for sustainable water utilization appear to have resulted in replenishing the aquifers in western and southern parts of India. GRACE data are also used for detecting significant extreme events, such as flash floods of Mumbai 2005 and Bihar 2008 (Dutt Vishwakarma *et al*., 2013); drought 2015 (Mishra *et al*., 2016; Sinha *et al*., 2017), heat waves (Panda *et al*., 2017). Soni and Syed (2015) estimated the influence of ENSO on ground water storage in major river basins of India.

Hydrological Loading

Indian subcontinent receives a considerable amount of mass in the form of rainfall during south-west (summer) monsoon season and partly during north-east (winter) monsoon period. The mass influence causes the hydrological loading on the crust surface depending on the geological provinces and its intensity. GPS and GRACE data sets can sense this hydrological loading behaviour that may lead to crustal deformation and tectonic movement. Tiwari *et al*. (2014a) analysed the influence of hydrologic loading on vertical

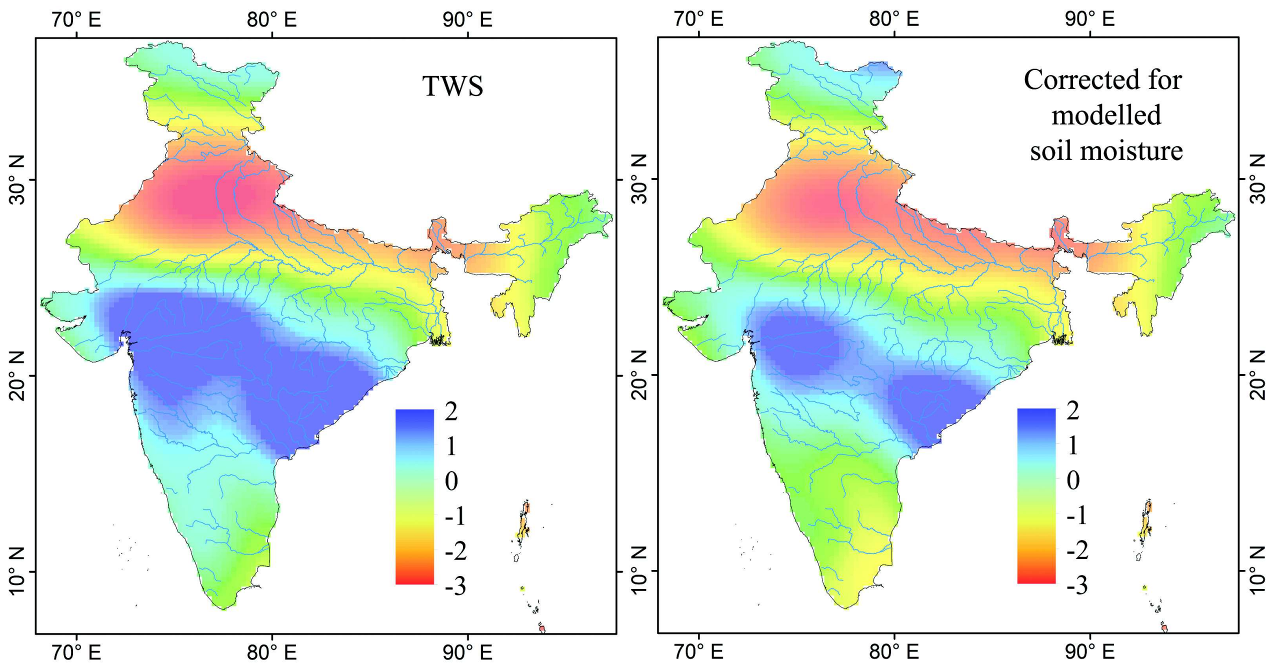

Fig. 3: Rate of change of Total Water Storage (TWS) in the Indian subcontinent (after Tiwari *et al.*, 2009b)

deformation over South India (1-2 cm) and compared with data derived from GRACE (Fig. 4). Khandelwal *et al*. (2014) correlated the GPS data with the water load storage in the Ganga plains, with the minimum in displacement coinciding with the maximum storage of water in Ganga plains immediately after the monsoon and vice versa. Such variations also appear to cause the annual variation in the low-magnitude earthquake frequency in the Himalayan region, being relatively more in the winter period. The anthropogenic groundwater unloading in the Indo-Gangetic plains influenced 2015 Mw 7.8 Gorkha, Nepal earthquake that occurred on the MHT beneath the Himalayan arc (Kundu *et al*., 2015). Seasonal variations in the Himalayan region are the most prominent in the vertical and north components of GPS time-series. Gahalaut *et al*. (2017) explained the combined effect of the local reservoir water load and the regional hydrological and atmospheric loading of Tehri reservoir in the Garhwal region of NW Himalaya from the GPS and Interferometric Synthetic Aperture Radar (InSAR) analysis. Kundu *et al*. (2017) demonstrated thatthe evaporation induced unloading in the Himalayan foothills and adjacent Indo-Gangetic plains during the post-monsoon period adds a significant component of horizontal compression to the interseismic contraction at the MHT, which is the primary driving mechanism for the seasonal modulation. The influence of seasonal loads is maximum in the vertical component which decreases in the north and then in the east component in the Garhwal-Kumaun Himalaya (Gautam *et al*., 2017b). Prasad *et al*. (2017) estimated the hydrological loads of Koyna warna region (KWR) from GPS and GRACE of regional water storage and reservoirs storage, which can lead to the perturbation of stress condition as well as pore pressure condition at the depth.

Airborne Gravity Gradiometry

Airborne gravity gradiometry (AGG) can provide a gravity map efficiently over a large, highly inaccessible undulating region in a short period with an accuracy of ~5-10 Eötvos over a wavelength of 400 meters. AGG data can be used for the mapping of subsurface structure with a good spatial resultion. Successfully, the first Airborne Gravity Gradiometer (AGG) survey in India has been carried out through Fugro Falcon Airborne System over the rugged terrain of the Western Ghats in the KWR of Maharashtra to infer subsurface structure as a prelude to the first deep scientific drilling in the region. Joint inversion of AGG

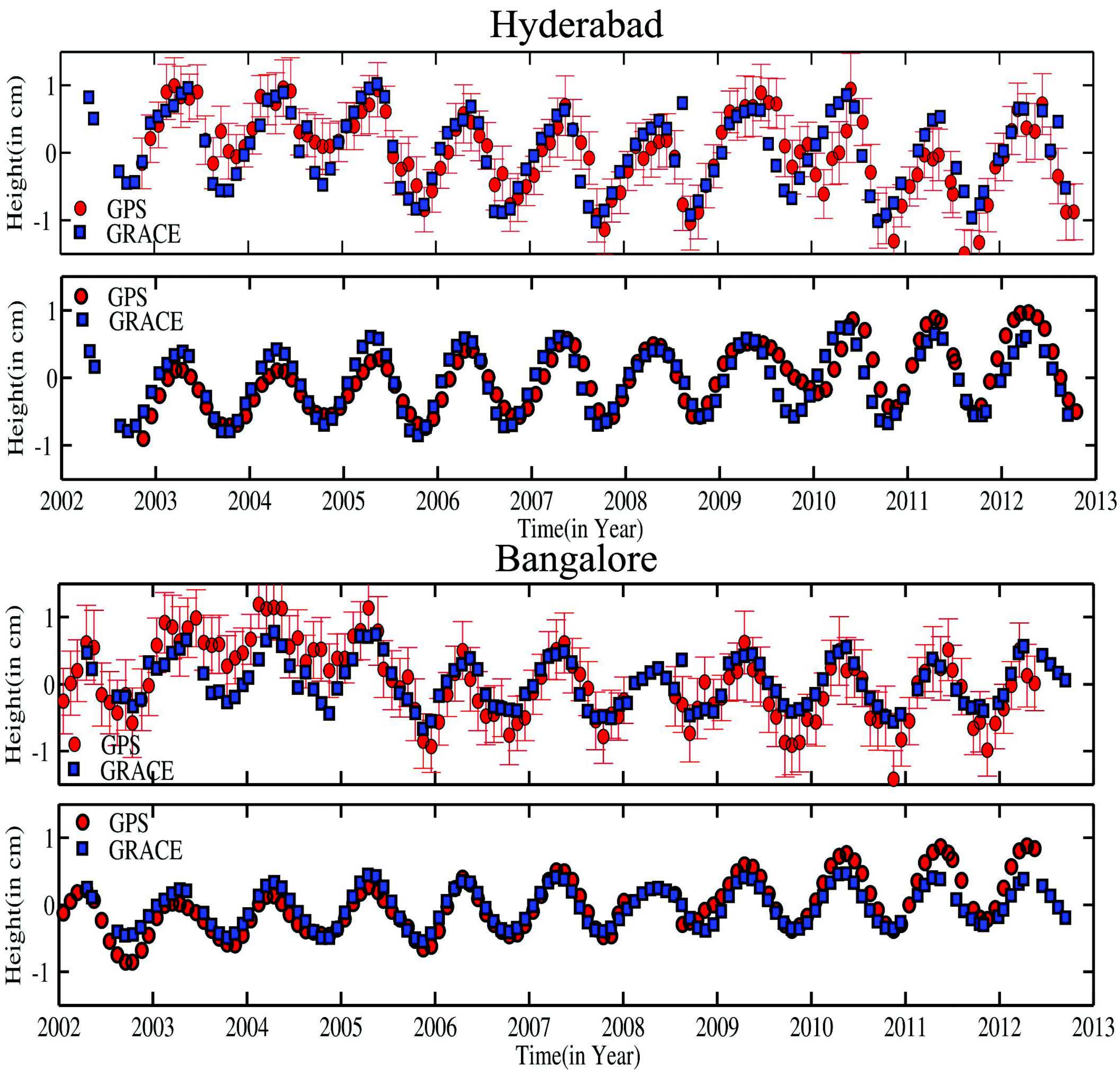

Fig. 4: Comparison of daily and seasonal variations of vertical velocity from GPS & vertical elastic deformation using GRACE data in major cities in Hyderabad and Bengaluru (after Tiwari *et al.*, 2014a)

datasets allowed to propose 3D structural setting beneath KWR and across the Western Ghats. In this Survey, AGGM data covering 5,012 line km were recorded along N-S flight paths at an average 120-m drape surface, cutting across the Koyna seismic zone. The subsurface model provides thickness of the Deccan basalts varying from 400 to 1,700 meters in the KWR (Gupta *et al.*, 2015). Deccan basalts are thicker on the eastern side of the topographic escarpment compared to the western side (Gupta *et al.*, 2017).

Studies for Exploration of Natural Resources

Several central and state government organizations, such as GSI, ONGC, OIL and other exploration companies have extensively acquired gravity data in different basins for regional prospecting. Some of the target areas are basins located in northwest India, Godavari basin, Rewa basin and frontier basins of northeast India. There have also been efforts to map the mineral resources (Mishra, 2011), exploration of hydrocarbons (Singh *et al.*, 2012) and sub-basalt sediments (Goyal and Tiwari, 2014). Gravity measurements are made for mineral exploration in different parts of the country by GSI and exploration companies. Several studies at specific localities are taken up for mineral prospecting purposes (http://www.portal.gsi.gov.in). One of the new initiatives was gravity survey for manganese exploration in the Nagpur and Bhandara districts of Maharashtra. Gravity survey carried out in Meghalaya revealed gravity high in the southern part over tertiary rocks corresponding to the high-density intrusive metavolcanics and also due to Khasi Greenstones including epidiorite. Gravity observations recorded for structural mapping and location of mineralized zones in the parts of Singhbhum brought out the disposition of the Copper belt.

Tectonic Geodesy

Tectonic geodesy refers to the application of modern geodetic measurements (InSAR, GPS) of crustal deformation due to numerous earth processes, like plate movement, earthquakes, volcanoes, isostatic adjustments and so on and modelling of measured deformation from GPS to understand processes responsible for them. Researchers from several national research institutes (e.g. CSIR-NGRI,CSIR-4PI, IIG, WIHG, SOI and ISR) and universities have established GPS stations for monitoring the crustal deformation over the Indian shield region and in the plate boundary regions like Himalaya and Andaman. Many campaign mode and about 100 semi-permanent/permanent GNSS/GPS measurements have been providing the up-to-date comprehension of crustal deformation continuously enriching our knowledge of dynamics of the different tectonic regions of the Indian plate (Gahalaut *et al*., 2008; Catherine *et al*., 2015; Mahesh *et al*., 2012a; Gahalaut *et al*., 2013; Jade *et al*, 2017). Analyses of GPS data from peninsular India indicate that there are no significant internal intraplate deformations; however, there are a few regions like a part of Godavari Rift basin which shows crustal deformation (Mahesh *et al*., 2012b). Continuous GPS data from Andaman region have allowed constraining the recurrence time of large earthquakes (Gahalaut *et al*., 2006; Jade *et al*., 2005; Catherine *et al*., 2014). Several new findings reported from GPS observations from NE Himalaya and Karakoram have important implications for the seismic hazard of the region (Jade *et al*., 2007; Mukul *et al*., 2010; Gahalaut and Kundu, 2012). 25 years of GPS data (campaign mode and continuous) from central and western Himalaya offer a new finding of total arc normal shortening, slip and an estimate of locked fault widthof ~ 110 km (Kundu *et al*., 2014).

Tidal Observations

The responsibility of carrying out systematic tidal observations and monitoring of tidal stationswas entrusted to SOI in 1877 and since then data is beingcollected continuously at tidal observatories located along East and West Coasts and also Andaman & Nicobar and Lakshadweep Islands. Sea-Level data from about 24 Tidal observatories, collected during the last 10 decades, is utilized mainly to determine Mean Sea-Level to serve as the Vertical Control Datum for heights for the country, tidal predictions for navigational purposes and for estimation of long time sea level changes. Tide tables are printed a year in advance and made available to National/International users to facilitate their navigational activities. Tiwari *et al*., (2004) analysed the Indian ocean sea level changes and ascribed the changes in terms of warming and cooling of the ocean. The mean sea level (1993-1999) estimated from T/P altimetry (Tiwari *et al*., 2005), which compares well with tide gauge records, seems to be a part of decadal variations of sea level in the Indian ocean.Catherine *et al*. (2014) analyzed the sea level variations from satellite altimetry data and tide gauge from Andaman Islands for tectonic studies. During the past decade, state-of-the-art digital tide-gauges at ~ 30 locations along the Indian coast have been established and connected to the dedicated VSAT network for real-time tidal data transmission to the centrally located hub at National Tidal Data Centre, G&RB, SOI. This near real-time tidal data is also shared with the National Early Tsunami Warning Centre, INCOIS, Hyderabad for the issuance of a tsunami warning in the event of any eventuality. Extensive analysis of tidal data is carried out for extreme events like Tsunami, storm surge, cyclone, etc.

Planetary Gravity Studies

Satellite-Satellite tracking technique can provide recovery of gravitational ûeld with high-resolution data of the Moon with the help of Gravity Recovery and Interior Laboratory (GRAIL) mission. Detailed analyses were carried out by Satyakumar *et al*. (2018)

and GRGM900C gravity anomaliesare derived from GRAIL mission and topography over the Lunar far side covering the major impact basins to understand subsurface structure. The observed nature of gravity anomalies and crustal thickness are attributed to the buried impact crater under this region. The structure and evolution of the near and far side of the Moon have been studied using integrated analysis of Free-air, Bouguer gravity anomalies of the Moon along with morphological and structural information derived from various remote sensing datasets. Gravity anomalies of Venus are also computed using gravity model (MGNP180U) derived from Magellan mission. Inversion of Bouguer gravity anomalies resulted in computation ofcrustal thickness map of Venus.

New Initiatives

Considering the global development in the field of Geodesy, its importance in strengthening the National Mapping and Geodetic organizations and requirement of human resources in this field, a "National Programme on Geodesy" has been launched by the Department of Science & Technology, Government of India, with the following objectives:

1. To build up the capacity in different aspects of Geodesy in Indian institutions.
2. To strengthen the Human Resource Development in Geodesy in the country.
3. To address the need of National Mapping and Geodetic organizations.

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Review Article

Research Highlights of the Indian Contributions to Geomagnetism and Aeronomy in the 21st Century

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Study of the Earth's magnetism is one of the oldest disciplines of geosciences whose history dates back to several centuries. The field has played a vital role in fostering formal international cooperation as back in time as more than two centuries. India has been a part of this endeavor and started geomagnetic observations almost at the same time as anywhere else in the world. IAGA, the International Association of Geomagnetism and Aeronomy, one of the eight Associations of the IUGG, is dedicated to the promotion of international research cooperation in the field of Geomagnetism and Aeronomy covering very diverse disciplines, from the magnetism of the Sun and other planetary bodies, solar winds, magnetosphere and upper Atmosphere, to the Earth's internal structure and processes. A significant amount of research work in these fields has been carried out by Indian researchers in the 21st Century, a majority of which has been reported in various Indian National Reports to the IUGG. This article provides a glimpse of some of these studies carried out by Indian researchers in the last one decade in field of Geomagnetism and Aeronomy. It is not an exhaustive review of all the work done during this period but a window to the topics covered within the framework of IAGA.

Keywords: Geomagnetism; Aeronomy; IAGA; IUGG

Introduction

Study of the earth's magnetism is one of the oldest disciplines of geosciences whose history goes back to several centuries. According to the historical records the Chinese had discovered the existence of magnetism more than two millennium B.C. but the first detailed description of a magnetic compass in China dates back to 1088 A.D. (*c.f.* Lanza and Meloni, 2006). The first description of the use of a magnetic needle in European literature comes from 1190. Over the centuries, there were several developments to explore the magnetic properties of matter, the concepts of magnetic polarity, declination and inclination, and especially the use of magnetic needle for maritime navigation. However, the first comprehensive description of the geomagnetic field in modern world, *De Magnete*, was published by William Gilbert in 1600. The 19th century witnessed a quantum jump in the field of geomagnetism when Carl Friedrich Gauss published the theory of geomagnetism (1832-1840) and for the first time gave a procedure for the measurement of magnetic field intensity. Another major impetus in the study of geomagnetism came in 1919 when Larmor linked the origin of the earth's magnetic field to a self-sustaining dynamo mechanism operating within the earth. The field of geomagnetism has grown significantly in the past one century both on observational front using a network of ground observatories, airborne and satellite measurements, and theory development through large-scale simulations of the internal and the external fields.

The field of geomagnetism has played a vital role in developing formal international cooperation as back in time as more than two centuries. Alexander von Humboldt organized widespread simultaneous magnetic observations in the first decade of the nineteenth century. Later, Carl Friedrich Gauss along with Wilhelm Eduard Weber and Alexander von Humboldt founded the Magnetic Union, which fostered the institution of magnetic observatories during 1836-1841 resulting in simultaneous observations at more than 50 observatories distributed

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over five continents (Ismail-Zadeh, 2016). These were some major efforts on international cooperation that, along with development in other sub-disciplines of geosciences, led to the creation of the International Research Council, the predecessor of the International Council for Science (ICSU) in 1918 and the International Union of Geodesy and Geophysics (IUGG) in 1919. IAGA, the International Association of Geomagnetism and Aeronomy, is one of the eight Associations of the IUGG. It is one of the major Associations of the IUGG that deals with the understanding and knowledge from studies of the magnetic and electrical properties of the (i) Earth's core, mantle and crust, (ii) the middle and upper atmosphere, (iii) the ionosphere and the magnetosphere, and (iv) the Sun, the solar wind, the planets and interplanetary bodies through its six Divisions and several Working Groups.

Geomagnetic observations in India started almost at the same time as anywhere else in the world and have a history of more than two centuries. The first magnetic observatory was established at Madras (now Chennai) in 1792 where regular observations started from 1822 and continued till 1881. Another observatory was established at Shimla under the plan of the Göttingen Magnetic Union where magnetic observations were recorded at hourly intervals during 1841-1845 (Rastogi, 1986). The observatory at Trivandrum was constructed in 1837 but the actual observations started in 1841 and continued till 1870 with a brief hiatus between 1860 and 1863 (Basavaiah, 2012). Realizing the importance of this place as close to the magnetic equator, another observatory was setup at Augustia Malley about 22 km ENE of Trivandrum (Rastogi, 1986). Although the earliest observations were made at Madras, the beginning of the era of Indian geomagnetism is attributed to the establishment of the Colaba observatory at Bombay (now Mumbai) where magnetic measurements started in 1841 (Rastogi 1986; Basavaiah 2012). In 1904, another observatory was started at Alibag about 35 km SSE of Bombay. These two observatories together provide the longest series of magnetic data anywhere in the world (Rastogi, 1986).

In India, many Institutes pursue research activities related to the IAGA domain of Geomagnetism and Aeronomy. Among these, Indian Institute of Geomagnetism (IIG), Navi Mumbai, is the nodal Institute for operating geomagnetic observatory network, acquiring data in the form of annual data bulletins as well as maintaining repository of the digital data generated by the National Geomagnetic Observatory Network. Sister Institutions, e.g. CSIR-National Geophysical Research Institute (CSIR-NGRI), Hyderabad, Indian Institute of Astrophysics (IIA), Bengaluru, and Survey of India (SoI), Dehradun, co-ordinate and supplement the operation of geomagnetic observatories. In addition to the geomagnetic observatories, IIG along with its regional centers at Tirunavelli and Allahabad, and Space Physics Laboratory (SPL), Thiruvananthapuram, CSIR-National Physical Laboratory (CSIR-NPL) New Delhi, Guwahati University, Guwahati operate a network of Digital Ionosonde, Partial Reflection Radar, Meter Wind Radar, and Optical Radars across the country (Arora and Veenadhari, 2015). Physical Research Laboratory (PRL) operates a solar observatory at Udaipur. In Solid Earth Geophysics, many institutes, IITs and universities work in the field of electromagnetic geophysics, paleomagnetism, and earthquake precursory studies.

Since the inception of geomagnetism studies in India with the installation of geomagnetic observatory, enormous research work has been carried out in India covering different aspects, from space weather to the earth's interior. A lucid description of the Indian contribution to Geomagnetism and Aeronomy has been presented by Rastogi (1986). Bhardwaj *et al.* (2016) have reviewed the status of space weather research in India. The present paper is aimed at briefly listing the major contributions from India in the 21st century in the realm of IAGA. However, it is not an exhaustive review of all the Indian contribution to Geomagnetism and Aeronomy during this period.

Contributions in the 21st Century

A significant amount of research work in the field of Geomagnetism and Aeronomy has been carried out by Indian researchers in the 21st Century, a majority of which has been reported in various Indian National Reports to the IUGG (Lakhina, 2003; Bhattacharyya, 2007, 2011; Arora and Veenadhari, 2015). Here, a brief account of the major studies during the past one decade is covered. The article is sub-divided into Sections following IAGA classification of Divisions.

Internal Magnetic Fields

Theory of Planetary Magnetic Fields

Studies related to the 3-D dynamo simulations of planetary magnetic fields have been initiated in India. In one study, the effect of thermo-compositional convection on generation of planetary magnetic field through a dynamo mechanism was studied. For terrestrial planets having growing solid inner core, such as the Earth, the release of light density elements at the inner core boundary contributes to convection through compositional buoyancy force. The difference in the thermal and compositional diffusivities may lead to interesting double-diffusive effects. Manglik *et al.* (2010) studied this process of double-diffusive convection by solving two separate transport equations with different diffusivities in a double diffusive dynamo model for the planet Mercury. They have found significant changes in the resulting magnetic field in double-diffusive models. Breuer *et al.* (2010) studied the influence of thermal and compositional driving sources on double diffusive convection for a large Ekman number of 10^{-3} and moderate Rayleigh numbers. Sahoo and Sreenivasan (2017) studied the onset of convection in a rotating spherical shell subject to laterally varying heat flux at the outer boundary at low Ekman number where the natural length scale of convection is significantly smaller than the length scale imposed by the boundary heat flux pattern. Contrary to earlier studies at a higher Ekman number, they found a substantial reduction in the onset Rayleigh number (R_{ac}) with increasing lateral variation. The decrease in R_{ac} is shown to be closely correlated to the equatorial heat flux surplus in the steady, basic state solution. The results also showed a notable analogy between the role of a laterally varying boundary heat flux and the role of a laterally varying magnetic field in confining small-scale convection. Simultaneously, an experimental facility has been set up at Indian Institute of Science, Bengaluru to study dynamo process and experiments have been carried out to investigate the convection in a rapidly rotating tangent cylinder (TC), for Ekman numbers down to $E = 3.36 \times 10^{-6}$ (Aujogue *et al*., 2017).

Paleomagnetism

Flow-by-flow paleomagnetic measurements of 37 lava flows in the 900 m-thick, isolated lava pile around Mandla in the eastern Deccan Volcanic Province (DVP) reveals multiple magnetic polarity events: implying C29n–C28r–C28n magnetostratigraphy. The Virtual Geomagnetic Pole (VGP) position determined for these lavas, when compared with the Deccan Super Pole, indicates concordance with the main Deccan volcanic province, thus assigning a shorter period of eruption close to the Cretaceous–Palaeogene boundary (K/PB) for the eastern and western Deccan Traps (Pathak *et al*., 2016). The Damodar valley within the Chhotanagpur Gneissic terrain at the northern-most margin of the Singhbhum craton, eastern India, is perhaps the only geological domain in the entire Indian shield which hosts the early Cretaceous Rajmahal as well as the late Cretaceous Deccan igneous activities. Intrusives from the Damodar valley distinguished two generations of the activities belonging to the Deccan Traps (~65 Ma) and to the Rajamahal Traps (110-115 Ma) magmatism (Srivastava *et al*., 2014).

A refined paleomagnetic pole for the Upper Vindhyan sequence inferred that the Seychelles microcontinent formed the western margin of the Rodinia Supercontinent at 750-755 Ma. Neoproterozoic igneous rocks of Malani (NW India), Bhopal Inlier, the Seychelles and northern Madagascar probably constituted an Andean type arc, formed on the western margin of East Gondwanaland, above an east dipping subduction zone (Venkateshwarlu and Mallikarjuna Rao, 2013). Similarity of refined palaeomagnetic poles for the Eastern Dharwar craton kimberlites with the Eastern Dharwar and the Bundelkhand cratons support (i) a Mesoproterozoic closure age for the ‘Purana’ sedimentary basins and (ii) accretion of the northern and southern Indian blocks prior to 1.1 Ga contrary to several earlier tectonic models which consider them to be distinct blocks at that time (Dash *et al*., 2013; Venkateshwaulu and Chalapathi Rao, 2013; Radhakrishna *et al*., 2013).

Precambrian paleomagnetic records from dyke swarms provide a unique source of information regarding the Archean geomagnetic field and more specifically the average field strength produced by the early dynamo. A study was carried on 16 paleomagnetic sites from the Dharwar giant dyke swarm in southern India which was emplaced between 2.365 and 2.368 Ga. Two sites retained a pristine magnetization that yielded suitable directions and paleointensity estimates. The results indicate a mean field intensity of 9.2±7 μT yielding a VDM value of 1.3+1 x 10^{22} Am^2. Integration of these estimates within the present paleointensity database emphasizes the existence of a rather long period with pronounced low intensity during a few hundreds of millions years (~2.3-1.8 Ga) (Valet *et al*., 2014).

Rock- and Environmental Magnetism

A state-of-the-art Environmental Geomagnetism Laboratory was setup at IIG in 2004 to study the geomagnetic field beyond the instrumented and archaeological timeframe and paleo-climate changes through multi-proxies utilizing lake, river and marine sedimentary cores. Basavaiah and Khadkikar (2004) defined a new parameter, S-ratio (backfield IRM/ SIRM), and showed that this parameter is more sensitive to climatic changes as compared to the magnetic susceptibility. Using this parameter, a composite climatic map for the entire Indian sub-continent was prepared, which suggested prevalence of prolonged dry spells ~3,500-years back along the eastern (~Iskapalli) and western (~Nal Sarovar) coasts of India.

Environmental magnetism studies were performed on a sediment core from Schirmacher Oasis in East Antarctica. It is found that the glacial periods characterized by high of coarse SSD titanomagnetite were recorded during 40.78, 36.08, 34.51, 29.03 and, 28.02-21.45 cal. ka B.P. Relatively warm periods are documented during 38.44-39.22 cal. ka B.P., 33.73-29.81 cal. ka B.P. and 28.52 cal. ka B.P. The LGM has documented the highest concentration of magnetic minerals, indicating widespread glaciation in the Schirmacher Oasis. The Holocene period is characterized by alternating phases of relatively warm (12.55-9.88 cal. ka B.P. and 4.21-~2 cal. ka B.P.) and cold (9.21-4.21 cal. ka B.P. and from ~2 cal. ka B.P. onwards) events (Warrier *et al*., 2014). A review of the application of magnetic stratigraphy to the Quaternary sedimentary records from India is presented by Sangode (2014).

In the past decade considerable studies have been carried out on fabric analysis of deformed rocks using Anisotropy of Magnetic Susceptibility (AMS). One of the most important applications of this technique has been in the vorticity analysis and deciphering of superposed deformation in rocks that are devoid of visible foliations and lineations (Mamtani and Arora, 2005; Mamtani and Sengupta, 2010; Mamtani, 2014). Integration of AMS data with field, microstructural and SEM-Electron Backscatter Diffraction (EBSD) data have helped in understanding structural control on fluid flow/vein emplacement and gold mineralization as well as in kinematic studies of quartzites, quartz veins and granitoids (Mondal and Mamtani, 2013; Lahiri and Mamtani, 2016; Renjith *et al*., 2016; Bhatt *et al*., 2016; Goswami *et al*., 2018).

The application of mineral magnetic techniques as pollution proxy for road deposited sediments has also been explored by using various statistical approaches. Road deposited sediments are a complex mix of particulates and contaminants accumulated on pavements and road surfaces.They are derived from extensive range of urban and industrial sources and are an important pathway for urban pollution (Kanu *et al*., 2017).

Aeronomic Phenomena

Equatorial Plasma Bubble

A phenomenon unique to the low latitude ionosphere is that of the equatorial plasma bubble (EPB). This is so because presence of a horizontal geomagnetic field at the dip equator makes the plasma on the bottom-side of the equatorial ionospheric F region unstable to the growth of the Rayleigh-Taylor (R-T) instability in the post-sunset hours, giving rise to the EPB. Growth of EPBs involves the interchange of entire magnetic flux tubes. Hence they are aligned with the geomagnetic field lines so that irregularities at different altitudes over the dip equator map down along the geomagnetic field lines to ionospheric F region peaks at different latitudes, and thus may extend up to 15-20º in latitude on either side of the dip equator for several hours after sunset. Importance of EPBs stems from the fact that the intermediate scale length (~100m-few km) irregularities in them scatter VHF and higher frequency trans-ionospheric radio waves, producing fluctuations or scintillations in their amplitude and phase, and thus have the potential to degrade the performance of satellite-based communication and navigation systems such as GNSS (Global Navigation Satellite Systems). Given the day-to-day variability of the ionosphere due to forcing from the atmosphere below and magnetosphere above it, there is a great deal of interest globally in prediction of the occurrence, strength, and other characteristics of EPBs, which are an important component of space weather in the low latitude ionosphere.

A large amount of work has been carried out in India as well as abroad, to study the effect of geomagnetic storms on the occurrence of EPBs and scintillation producing irregularities, because it is known that the equatorial ionospheric zonal electric field gets altered due to geomagnetic activity. One of the drawbacks of these studies was that the age of the EPB, detected using radar, ionosonde, and scintillation observations, was not known. After the initial stage of their development, EPBs tend to drift eastward with the ambient plasma throughout the night. Hence, they could have been generated several hours earlier at a location to the west of the observer and then drifted overhead. Using scintillation observations and modeling Bhattacharyya *et al*. (2001) showed that in the initial stage of EPB development, the perturbation electric field associated with the R-T instability gave rise to fluctuations in the drift speed of the irregularities, which could be used to differentiate between nascent and fossilized EPBs. This enabled the proper identification of EPBs which were actually caused by geomagnetic activity (Bhattacharyya *et a*l., 2002; Kakad *et al*., 2007).

The EPB is a night-time phenomenon, because during daytime geomagnetic field-aligned currents associated with EPBs can flow through a highly conducting E region to stop the growth of the instability. Just after sunset, the E-region electrical conductivity decreases but does not become zero. A transmission line analogy for the development of EPBs, formulated to provide an explanation for satellite observations of magnetic field fluctuations associated with EPBs (Bhattacharyya and Burke, 2000), was extended into the non-linear regime to estimate the time taken by post-sunset E-region conductivity to discharge an EPB and hence its role in preventing chaotic evolution of EPBs to produce small-scale structure (Bhattacharyya, 2004).

Nearly all the remote sensing studies of EPB irregularities using radar, ionosonde, or scintillation observations, have tried to identify the basic conditions for the growth of the R-T instability by focusing on the various ambient parameters that appear in expressions for the linear growth rate of the R-T instability. However, for prediction of scintillations and development of structure in EPBs in the non-linear phase of their evolution is of critical importance. Towards this end, simultaneous observations of EPB irregularities using radar, and scintillation data on VHF (251 MHz), and GPS L-band radio signals were used as EPB irregularities of different scale sizes contribute to each of these observations (Sripathi *et al*., 2008). The GPS data were obtained under GAGAN (GPS Aided Geo-Augmented Navigation) project of ISRO and Airport Authority of India.

Spatial scales in the ground scintillation pattern of intensity variations produced by scattering of the incident radio waves by the EPB irregularities are converted into temporal scales in the scintillation data recorded by a ground receiver due to movement of the ground scintillation pattern across the receiver as the irregularities drift across the signal path. However, spatial scales in the ground pattern are directly related to the spatial spectrum of the irregularities only when the scattering is weak. Therefore, spectral studies of scintillation data may be used to directly study a power-law type of spatial spectrum of intermediate-scale EPB irregularities only when the scintillations are weak (Kakad*et al*., , 2012). Since most of the scintillation data does not fall into the weak category, a method was developed to estimate the dominant spatial scale (coherence scale) in the ground scintillation pattern using scintillation data of all strengths, which automatically adjusted for the irregularity drift variation (Bhattacharyya *et al*., 2003). This paved the way to study the temporal evolution of the irregularity spectrum near the equatorial F region peak, which is important for predicting scintillations recorded in the equatorial region (Bhattacharyya *et al*., 2014). Further, it was shown that the less dense top side of the equatorial F region was more structured than the equatorial F region peak, leading to much stronger scintillations on GNSS signals recorded around 15º away from the dip equator (Bhattacharyya *et al*., 2017). This technique has also been used to study the structuring of EPBs produced by a magnetic storm (Kakad *et al*., 2016, 2017).

Space Weather and Geomagnetic Storms

A case of the westward disturbance dynamo (DD) electric field, influencing the daytime equatorial and low-latitude ionosphere, during a geomagnetic storm that occurred on 28-29 June 2013 (minimum

Dst ~-130 nT) was studied. The GPS total electron content (TEC) observations from a network of stations in the Indian equatorial, low and middle latitude regions along with the radio beacon TEC, ionosonde, and magnetic field observations were used to study the storm time behavior of the ionosphere. The results reveal that there was hardly any change in the TEC over Shimla, Delhi and Trivandrum from the quiet-day mean behavior on 28 June 2013. The TEC over Bhopal (anomaly crest region) showed only a marginal increase (close to the standard deviation) in the afternoon hours. However, on 29 June 2013, the TEC over the stations Shimla, Delhi and Bhopal remained substantially low from morning till evening. This negative ionospheric storm effect seen over the low and middle latitudes is basically due to the presence of a westward Disturbance Dynamo Electric Field (DDEF) (Thampi *et al*., 2016).

The 2D (lat. x long.) TEC maps have been generated by using the ionospheric correction data transmitted by the Indian Satellite Based Augmentation System (SBAS)-GAGAN. The advantage of this unique technique is the fact that by using a single SBAS-enabled receiver, the information over the entire region served by SBAS can be obtained irrespective of the location of the receiver. These 2D maps have been employed, for the first time, to investigate the effect of the most talked about space weather event of the current solar cycle, i.e., the St. Patrick's Day geomagnetic storm that triggered on 17 March 2015, on the equatorial and low-latitude region of the Indian longitudes. These 2D TEC maps for 16 March (Quiet day) and 17 March 2015 (Storm day), having a large latitudinal (5°S-45°N) and longitudinal (55°-110°E) coverage, show the complete reversal in the longitudinal structure/pattern of EIA during the recovery phase of the storm as compared to the quiet day. It was observed that even a separation of few degrees in longitude (~15°) could experience significantly different forcing (Yadav *et al*., 2016).

The impact of the geomagnetic storm event of 18-21 February 2014 (Dst ~130nT) on latitudinal changes in the disturbance electric fields and composition was studied. The GPS TEC data from the Indian Antarctic station, Bharati, the northern mid-latitude station Hanle, northern low-latitude station lying in the vicinity of the anomaly crest, Ahmedabad, and the geomagnetic equatorial station, Trivandrum, were used for this purpose. The impact of the storm on the southern hemisphere high-latitude station was a drastic reduction in the TEC (negative ionospheric storm) The large decrease in TEC observed over Bharati could primarily be due to the composition changes related to the upwelling of the air rich in molecular species from the lower altitudes. The enhanced plasma densities seen over the mid-latitude location, Hanle on 19 February were a consequence of this. On 19 February, there was an enhancement in TEC over Trivandrum, equatorial station and Ahmedabad, a low latitude station with a time delay (Shreedevi *et al*., 2016).

The first direct observational evidence for the possible role of meteoric activity in the generation of the equatorial Counter Electrojets (CEJ), an enigmatic daytime electrodynamical process over the geomagnetic quatorial upper atmosphere was presented using the data from Proton Precession Magnetometer and Meteor Wind Radar over a geomagnetic dip equatorial station, Trivandrum. The results revealed that the occurrence of the afternoon CEJ events during a month is directly proportional to the average monthly meteor counts over this location. The study proposed that the presence of meteoric ions reduces the strength of the upward polarization field thus paving way for easy reversal of field (Vineeth *et al*., 2016).

In the equatorial electrojet (EEJ) region, significant long wavelength (longitudinal range greater than 45°) day-to-day variations in the CEJ have been extensively reported but their short-wavelength (~1000 km) variability is not well studied. In a recent study, Chandrasekhar *et al*. (2017) used geomagnetic data from two ground observatories, one at the southern tip of the Indian mainland (VEN) and the other from the Andaman - Nikobar islands (CBY), about 15° apart to study the short-wavelength variations, if any. They demonstrated occurrence of local variability in the CEJ and suggested that the ionospheric electrodynamics and associated atmospheric-ionospheric effects could vary considerably between the sites separated at 15° longitude both during quiet and disturbed periods. Archana *et al*. (2018) extended the work to three equatorial and low-latitude pairedstations/sites at 5°, 15° and 20° longitudinal separation in the Indian sector; (i) Minicoy and Alibag, (ii) Vencode and Hyderabad, and (iii) Campbell Bay and Nabagram and have shown that EEJ amplitudes increase from west to east whereas CEJ amplitudes increase from east to west.

The unique chain of Indian and Russian geomagnetic observatories, confined to a narrow longitude belt, was used to establish the solar quiet-day (Sq) ionospheric current system. Conspicuous disappearance of Sq vortex during winter symbolized failure of ionosphere dynamo (Campbell *et al*., 1993). In recent years, this network in conjunction with partial reflection radar and measurement of mesospheric winds has shown dominance of inter-hemispheric currents and it has been used for proposing generating mechanism of counter electrojet within the tidal framework as well as strong auroral-equatorial electrojet coupling (Doumouya *et al*., 2003; Arora and Bhardwaj 2003; Vichare and Rajaram 2011; Vichare *et al*., 2012).

Other Studies

Extensive studies using multi-platform instruments have been carried out to study the impact of the solar eclipse of 10 January 2010 on middle and upper atmosphere over the Indian geomagnetic equatorial belt. The significant results of the study are (i) a large drop in the ambient electric field, by up to 65%, during the eclipse bringing to the fore the long lasting paradox of conductivity enhancement during eclipse, (ii) reduction in the Total Electron Content not just at the magnetic equator but, more markedly, in the Equatorial Ionization Anomaly (EIA) zone, a further 10º to the north, and (iii) reversal in the zonal winds to eastward direction in the entire altitude range above 100 km (Choudhary *et al*., 2011; Anil Kumar *et al*., 2013).

A comprehensive analysis of nocturnal thermospheric meridional wind pattern encompassing two solar cycles was carried out using the night time F-layer base height information from ionosondes located at two equatorial stations and Sriharikota. Significant difference is seen in winds between High Solar Activity (HSA) and Low Solar Activity (LSA) epochs, with less equator-ward winds during pre-midnight hours for HSA years. Mean wind response to Solar Flux Unit (SFU) is established quantitatively for all seasons for pre-midnight hours (Madhav Haridas *et al*., 2016).

A high-altitude balloon experiment (BEENS, Balloon Experiment on the Electrodynamics of Near Space) was successfully conducted on a 110,000 cu. m balloon platform from the TIFR's National Balloon Facility at Hyderabad on 14 December 2013 to probe stratospheric electric fields from low latitudes. The instrument packagefor the experiment comprised of four deployable booms for measurements of horizontal electric fields and one inclined boom for vertical electric field measurements, all equipped with conductingspheres at the tip. Float duration of about 4 hours at a ceiling altitude of 35 km could be achieved during this launch. A noticeable feature of the observations has been the detection of horizontal electric fields of ~5mVm^{-1}at thestratospheric altitudes of ~35 km (Gurubaran *et al*., 2017).

Magnetospheric Phenomena, Solar Wind and Interplanetary Field

Bhardwaj *et al*. (2016) present a detailed review of the work done at various institutions/universities in India in the last four decades which led to significant progress in the understanding the terrestrial magnetosphere-ionosphere-thermosphere domains as a coupled system and its response to the solar and interplanetary variability caused by varying space weather. The review also describes the ground observatories as well as space missions being pursued by Indian researchers.

Geomagnetic Observatories, Surveys and Analyses

Observatory Network

Indian Institute of Geomagnetism (IIG), Navi Mumbai, is the nodal Institute for operating geomagnetic observatory network (Fig. 1), acquiring data in the form of annual data bulletins as well as maintaining repository of the digital data generated by the National Geomagnetic Observatory Network. It maintains a network of 12 observatories, two of which are in the NE India (Shillong and Silchar) and one in the Andamans (Port Blair). The Alibag and Jaipur observatories maintained by IIG are a part of the International Real time Magnetic Observatory Network (INTERMAGNET). The Alibag observatory together with its predecessor Colaba Observatory, established in 1841, provide more than 175 years of geomagnetic time series data. The Institute also maintains a World Data Center for

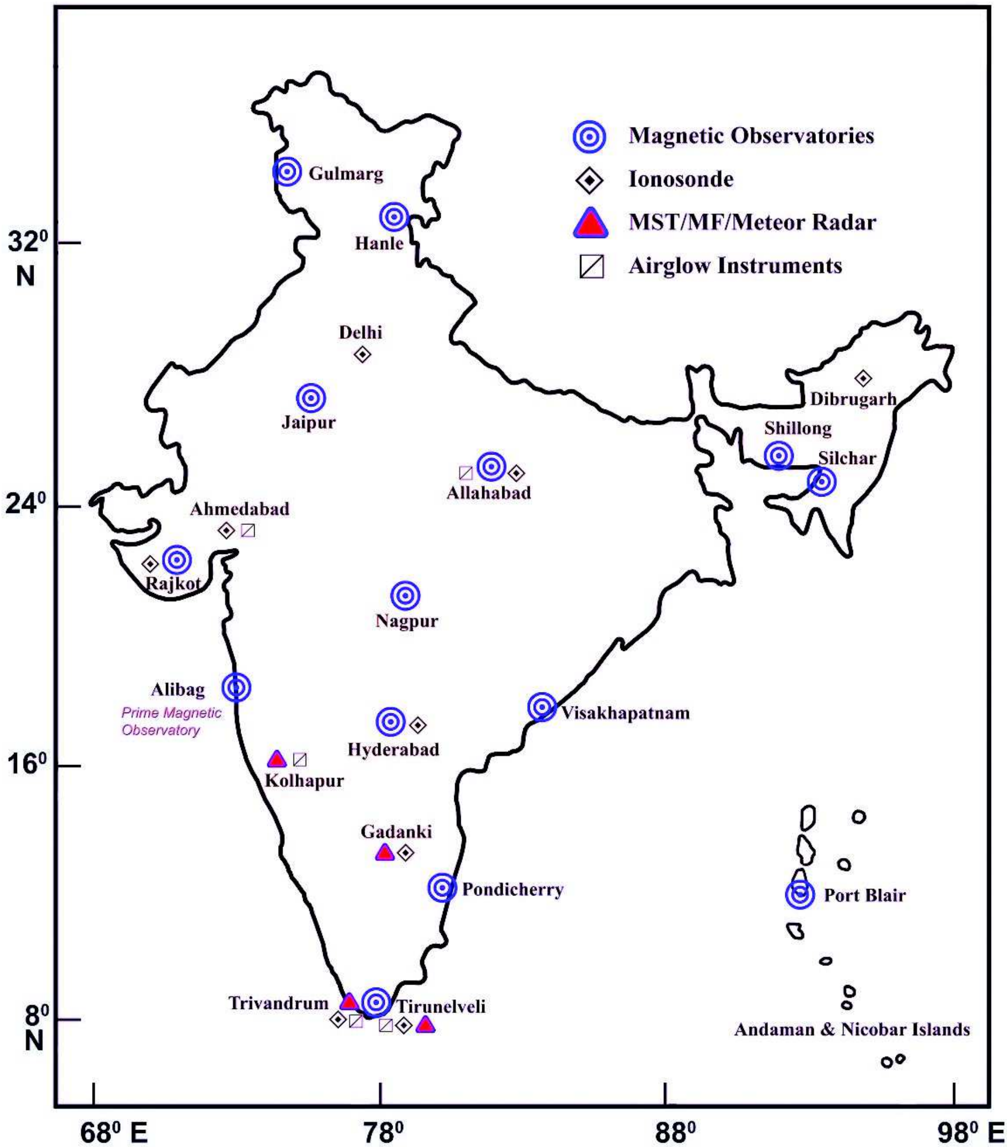

Fig. 1: Geomagnetic and Aeronomy observational network in India (after Arora and Veenadhari (2015))

Geomagnetism, WDC-Mumbai. In addition to these observatories, there are some more that are maintained by CSIR-National Geophysical Research Institute (CSIR-NGRI), Indian Institute of Astrophysics (IIA), and Survey of India (SoI).

The geomagnetic observatory of CSIR-NGRI at Hyderabad (HYB) was established in 1964 and has an uninterrupted baseline over the last 54 years. With renewed efforts and under collaboration with Adolf-Schmidt Observatory of GeoForschungs Zentrum (GFZ), Potsdam at Niemegk, HYB became an INTERMAGNET observatory in 2009 and the beginning of a new era for this observatory started in 2010 with complete digital data acquisition and processing to produce minute mean data. The raw data are transmitted with a few hours latency while the definitive data are submitted every year. Since 2016, storms and other events are reported to the Ebre Observatory, Spain and reporting of quasi-definitive data was started in 2012.

Geo-electric and pulsation observatories were established in Choutuppal in 1967 and Ettaiyapuram in 1970. Subsequently, Ettaiyapuram was closed down in 2002 and recording in Choutuppal was suspended in 1993. In 2012, work was initiated to re-establish the Choutuppal Observatory, which was completed in early 2014 with a complete digital acquisition and near real time transmission system. The efforts are ongoing to make it into an Observatory reporting one second data of INTERMAGNET standards. This kind of data will open up new avenues of research of the subtler signatures of the geomagnetic field.

During 2011 and over the next few years a network of Equatorial variometer sites has been setup in the Andaman-Nicobar and Lakshadweep Islands as well as at Kanyakumari, yielding minute data of vector variations. This data acquisition has been continued till present and has been the source of some important findings and publications on the variability of the Equatorial ionosphere. 2010-11 also saw the establishment of a new Observatory in Gan, Maldives, under a tripartite cooperation among Eidgenössische Technische Hochschule (ETH), Zürich, Maldives Meteorological Service (MMS), Maldives and CSIR-NGRI, India. GAN is now an INTERMAGNET observatory.

In October 2014, an IAGA Observatory Workshop with 93 observers from 33 different countries was organized at CSIR-NGRI, Hyderabad. This was followed by the two-day long INTERMAGNET meeting. An ICSU project MAGNIO was awarded during 2014-15, which was intended to encourage regional cooperation among the northern Indian Ocean countries to share magnetic field data and work collaboratively on developing regional models. A start has been made in this direction and plans of a larger project to take it forward are in the offing.

Under an ongoing Indo-Russia collaboration, efforts are on to implement sophisticated processing techniques to handle such volumes and quality of data, leading to near real time reporting of major and minor events. Since the basic idea of one second data is to establish compatibility with the data derived from satellites, aspects of research involving ground and satellite (SWARM) data have also been started, providing interesting insights into the role of the equatorial atmosphere in modulating signatures of pulsations.

Multi-parametric Geophysical Observatories and Earthquake Precursory Studies

Multi-parametric Geophysical Observatories (MPGOs) are being operated by Wadia Institute of Himalayan Geology (WIHG) in the Himalaya, Institute of Seismological Research (ISR) in the Kachchh intraplate seismic zone, and Indian Institute of Geomagnetism (IIG) in the Andamans.

MPGO in the NW Himalaya

WIHG established India's first MPGO at Ghuttu, Uttarakhand, immediate south of the Main Central Thrust (MCT), a major tectonic boundary in the Himalaya, to study earthquake precursor signals in the Himalaya in an integrated manned (Arora *et al.*, 2012). It is located in a narrow belt of high seismicity where the colliding Indian - Asian plates are locked and it is expected that strains are accumulating for future great earthquakes. The observatory became operational in April 2007 and is equipped with a superconducting gravimeter, Overhauser and fluxgate magnetometers, ULF band search coil magnetometer, GPS, radon and water-level recorders. Supplemented by a dense network of broadband seismometers, the MPGO is designed to record precursory signals resulting from stress-induced changes in density, magnetization, resistivity, seismic wave velocity, fracture propagation, crustal deformation, electromagnetic and radon gas emission as well as fluctuations in hydrological parameters.

The data from the MPGO are analyzed to identify potential earthquake precursor signals. A sudden drop in the geomagnetic field intensity, lasting from several days before to a week after the earthquake, was observed for the Kharsali earthquake of 22 July 2007 (M_L 4.9) (Arora *et al.*, 2012). Similarly, the variability in the fractal dimension was studied for the data of 2010 and correlated with the earthquakes of Me >3.5 within a zone of radius 150 km from the MPGO. It was found that the fractal dimension increased during the first half of the year when there was seismic activity whereas it had a steady behavior during the second half when there were no earthquakes. Similar study was carried out for the 20 June 2011 earthquake (Rawat, 2014).

MPGOs in the Kachchh Region

The Kachchh rift in Gujarat is one of the most seismically active intraplate regions in the world and lies in seismic zone V (BIS, 2002). Two large earthquakes, namely the 1819 Allahbund (Mw 7.9) and the 2001 Bhuj (Mw 7.7), occurred in this region. In order to pursue the science of medium- and short-term precursors for earthquakes, ISR established three MPGOs, in March 2009, at Vamka, Badargadh and Desalpar, in the vicinity of the Wagad Fault area, Kachchh. These sites are east and northeast of the aftershock zone of 2001 Bhuj earthquake. A total of 11 types of precursory parameters are continuously monitored with Broadband Seismograph, Strong Motion Accelerograph, GPS, Magnetometers, Ground water leveler, Superconducting Gravimeter and Radon detectors. The Magnetometer setup comprises the Digital Fluxgate, Overhauser, D/I and ULF Magnetometers. ISR reports magnetic observations during magnetic storms, magnetic pulsations and local earthquakes. A number of studies have been carried out by ISR utilizing the data from these MPGOs, some of these are listed below.

Earthquake Precursors

Short-term earthquake prediction is considered to be one of the most important areas of research. The electromagnetic precursors are in the forefront among all precursors and tremendous progress has been achieved in the field of seismo-electromagnetics during the last two decades. ISR made an attempt to study the pre-seismic ULF emissions in the frequency band 0.001-0.5 Hz recorded by Digital Fluxgate Magnetometers and ULF Magnetometers at Desalpar, Badargadh and Vamka for 18 local earthquakes (M>3.7) during 2011-2017 including one earthquake of M5.0 on 20th June 2012. The magnetic data of mid-nights (i.e., 18-21 UT) were considered to reduce the manmade and atmospheric perturbations and analyzed with reference to local seismicity, geomagnetic storms and lightning events. In order to discriminate seismo-electromagnetic signatures from global geomagnetic effects, polarization analysis and principal component analysis were applied to the magnetic data. Moreover, fractal dimension analysis was also applied to understand the dynamics of earthquake processes.The results showed that the maximum variability in polarization ratio appeared during some of the local earthquakes, particularly prior to the moderate earthquake on 20th June 2012 (M 5.0). It is also observed that there is a marginal increase in the observed fractal dimensions few days before this earthquake. Similarly, the geomagnetic variations during eighteen small magnitude earthquakes (3.8-4.5) during 2011-17 reveal small anomalies before six earthquakes (30/03/2013, M4.4; 29th July 2013, M 4.5; 29th Sept 2014, M 3.8; 05/09/2015, M4.2; 07/12/2016, M 4.2; 23/08/2017, M 4.1). However, for small magnitude earthquakes, the pre-seismic signatures are observed in a few cases but are not seen in many cases and no uniform pattern is discernible.

Magnetic Storms

Magnetic data of three severe magnetic storms (18Mar2015; 23June2015 and 07Mar2016) were analyzed during the storm periods to investigate the characteristic of the local magnetic field components dH, dD and dZ during the events. All three phases, i.e., initial, main and recovery are clearly visible in the H-Comp during these three storms. The most intense magnetic storm was observed on 21June 2015 with a Dst value of –205 and K_P value of 9. During this storm, the sudden commencement (SC) in the form of sharp increase of the H-component occurred during the initial phase at 16:45 UT. Subsequently, the main phase occurred when the H-component decreased for long time duration. Finally, the recovery phase lasted for 8 days after the storm, until 29 June 2015. The solar wind Pressure, Density and IMF Bz are found to be more influencing parameters during the storm since they have a coherence >0.6. The correlation of solar wind velocity with total magnetic field is found to be 0.79 during the June 2015 storm.

Schumann Resonances

Schumann resonances (SchR) are the electromagnetic eigen-modes in the almost concentric spherical cavity formed by the Earth's surface and the lower ionosphere layers (at an altitude of approx. 50-60 km). These are obtained from ULF/ELF magnetic field emissions recorded by a set of 3-component search coil magnetometers (LEMI-30). The corresponding eigen-frequencies lie in the ELF range (the first one about 7.8 Hz, then approx. 14, 20, 26 Hz and higher). Spectrograms of the Induction Coil Magnetometer data and their diurnal behavior for winter, summer seasons are studied. The clear appearance of first three bands of Schumann resonance has been observed over the two magnetically disturbed days. The effect of summer high solar glint is clearly seen on 07th Mar 2016. During the afternoon period, the resonance band has depleted with the high temperature. The same phenomenon has not been observed during the winter magnetic storm regime (1st February 2016).

MPGO in the Andamans

A new MPGO has been setup at Shoal Bay-8 in South Andaman by IIG. It started functioning from March, 2015.The MPGO hosts a variety of sophisticated instruments to monitor both long and short term excursions in the Earth's magnetic field at varied frequencies using Overhauser, Induction coil and Fluxgate magnetometers. It also houses Very Broad Band Seismometer, Ground Accelerometer and GPS to record both vertical and horizontal components of the seismic disturbances. In addition, various meteorological parameters are also being recorded.

Electromagnetic Induction in the Earth and Planetary Bodies

Electromagnetic (EM) induction techniques, e.g. magnetotellurics, have been extensively used by Indian researchers to delineate the crustal and lithospheric structureof various segments of the Indian peninsular shield as well as the plate boundary regions. Similarly, there is an increasing use of Transient EM techniques to map the near-surface region for mineral and groundwater, and geotechnical investigations. Some of the results are briefly mentioned below.

Crustal Studies

In the past 15 years, several MT profiles were covered across different segments of the Himalaya. These have provided new information about the crustal structure of the Himalayan collision belt. Long-period magnetotelluric MT data were collectedat 15 stations on a 250 km long profile in the northwest Indian Himalaya (Leh segment) to study the structure of this continent-continentcollision zone. The results revealed the presence of a broad low resistivity zone in the mid-crust beneath the ITSZ and Ladakh which was attributed to the presence of a few percent partial melt. The northern end of the profile showed a decrease in the deep resistivity of the lithosphere, similar to observations further east on the Tibetan Plateau (Arora *et al*., 2007).

Another profile was covered from Roorkee to Gangotri in the Uttarakhand Himalaya where MT data were acquired at 37 sites. The obtained 2D geoelectrical structure of the crust brings out, among many other features, a prominent low resistivity (<10 Ohm.m) feature in the MCT zone extending to the depth of 30 km indicating the presence of a ramp structure. Hypocenters of many earthquakes are concentrated along the boundary of this low resistivity zone and relatively high resistivity blocks around it. The model supports flat-ramp-flat geometry of the Main Himalayan Thrust (Miglani *et al*., 2014). A third, 250 km long, MT profile in the NW Himalaya was covered between Bijnaur in the Indo-Gangetic Plains and Mallari at the Southern Tibet Detachment (STD) zone. Geoelectrical resistivity cross-section derived from MT/LMT and vertical magnetic transfer function reveals a prominent low-angle north-east dipping intra-crustal high conducting layer with change in depth from the Lesser Himalaya to the Higher Himalaya. This transition is interpreted as a Ramp in the Main Himalayan Thrust (MHT) that also coincides with the concentration of seismicity (Rawat *et al*., 2014).

In the Sikkim Himalaya where, as against the thrust dominated earthquakes, strike slip becomes the dominating earthquake mechanism, MT study along a 200-km-long profile suggested that the Main Himalayan Thrust forms the base of several resistive blocks within the wedge and that a ramp structure is present south of the Main Central Thrust Zone (MCTZ). Another significant result is that the crust and mantle lithosphere beneath the MCTZ and the Higher Himalayan Crystallines (HHC) seem to be compositionally/geologically different from the lithosphere south of the MCTZ. A steep crustal-scale fault with the Moho offset of 14 km is inferred to be separating these two blocks. The deep crustal seismicity could be related to this fault whereas shallow seismicity can be linked to the deformation within the wedge (Pavan Kumar *et al*., 2014).

In the central Ganga Basin, MT study was carried out along a 285 km long profile between Hamirpur and Rupadia (Nepal border) across the basin to understand its basement structure and sediment thickness. The thickness of sediments gradually increases to about 500-600 m at Kanpur, and to about 1.2 km at Lucknow, and the basement depth increases to more than 2.5 km within a profile distance of 20 km, perhaps due to the presence of Lucknow fault. The sedimentary sequence at the northern end of the profile around Bahraich is more than 9 km thick. Integration of the resistivity model with published seismic velocity structure and borehole lithology revealed that the top 4 km succession is constituted of highly conductive Oligocene and younger rocks of the Matera Formation and the Siwaliks, and recent sediments. Whereas, the underlying >5 km section is composed of sedimentary rocks of the Bahraich Group overlying the Archean basement (Manglik *et al*., 2015).

Synthesis of continuing MT surveys in the Deccan Volcanic Province (DVP) indicates that the thickness of the traps in DVP decreases from about 1.8 km in the west to a few hundred meters (approx. 400 m) towards the east. The traps also exhibit considerable variation in resistivity, with higher resistivities (approx. 150-200 ohm-m) in the western half and lower resistivities (approx. 50-100 ohm-m) in the eastern half of DVP. Two significant fissure/fracture zones have been detected in DVP, which might have acted as conduits for the outpouring of Deccan lavas in addition to the primary structures along the west coast and the Narmada-Son lineament (NSL) zones.

A 3D modeling of large-scale broad-band MT data covering the western segment of Narmada-Son lineament zone in Central India brought out several major crustal conductors with different geometries at different depth levels in the crustal column. The conductive features, correlating with gravity high anomalies and high seismic velocity zones were interpreted as mafic-ultramafic bodies derived from mantle and inferred to be resulted from the intrusive component of the Large Igneous Province (LIP) of the Deccan volcanic episode triggered by the passage of the Indian continent over the Reunion hot spot during the Late Cretaceous (Patro and Sarma, 2016).

Several deep EM imaging studies were carried out in the Indian shield region to elucidate the tectonics and geological history of the various critical geological segments. The evolutionary history and ambiguity in the suture location between the southern and northern blocks of the Indian peninsular shield were studied using magnetotelluric data acquired across the eastern segment of the Central Indian Tectonic Zone (CITZ). The study revealed deep crustal and upper mantle conductive anomalies associated to Tan Shear and suggested a suture status to the Tan Shear. Similar lithosphere scale imaging across western Dharwar craton and Coorg blocks in south India revealed the suture between the two blocks and indicated the individuality of the two Archean terrains. Broadband magnetotelluric investigations were carried out in the NE part of Cuddapah basin to image the conductivity structure of the Palnad sub basin and Nallamalai fold belt. The study suggested E-W compression along the eastern margin during the Neoarchaean-Neoproterozoic (~2700 Ma – 970 Ma) tectonic convergence between India and east Antarctica (Naganjaneyulu and Santosh, 2012; Abdul Azeez *et al*., 2015, 2017).

The lithospheric electrical resistivity structure of the Cambay basin was studied using broadband and long-period magnetotelluric data along an east-west profile of ~200 km long profile. The two-dimensional modeling showed a highly conductive (~1000 S) thick Quaternary and Tertiary sediments within the Cambay rift zone. The Cambay rift zone is clearly delineated with a steeply dipping fault on the western margin, whereas the eastern margin of the rift zone gently dips along the NE-SW axis, representing a half-graben structure. A highly resistive body identified outside the rift zone is interpreted as an igneous granitic intrusive complex. Moderately conductive (30-100 Ohm.m) zones indicate underplating and the presence of partial melt due to plume-lithosphere interactions (Danda *et al*., 2017).

Utilizing the satellite magnetic data from CHAMP satellite mission, IIG in collaboration with NASA has generated a proxy-heat flow map of India which can provide relative information about the regional temperature distribution at depth and the concentration of subsurface geothermal energy (Rajaram *et al*., 2013).

Mapping of Seismogenic Zones

Ground Electrical and EM studies were carried out in the Koyna-Warna seismic zone to map the basalt cover and the electrical nature of the underlying granitic basement. These studies ruled out the presence of any sub-trappean sediments in this region and a well-defined crustal block structure, characterized by high resistive blocks interspersed with moderately conductive features, was identified. Also, conductive anomalies correlating with the known seismogenic structural features (e.g., the Konya Fault Zone, the west coast fault, the Donachiwada fault) filled with fluids, were mapped. It is inferred that, because of the NE to NS oriented compressive stress regime in the Indian shield due to the Himalayan collision tectonics, some of these structural features may become the locales of stress accumulation which may get released due to fluid filling of these zones under the influence of nearby reservoirs, resulting in triggering of seismicity (Patro *et al*., 2017).

For the region of 2001 Bhuj earthquake (Mw 7.6), Pavan Kumar *et al*. (2017) delineated the crustal geoelectric structure by MT and attributed the seismicity in this intraplate region to the fluid transfer from a reservoir at the Moho depth to the seismogenic zone through the South Wagad Fault and the north Wagad Fault that act as feeder channels for the fluid migration. In another MT study from the same region, Mohan *et al*. (2018) inferred the signatures of the Kachchh Mainland Fault (KMF) and the Katrol Hill Fault (KHF) in the geoelectric section. They also estimated the maximum sedimentary thickness of 2.3 km in this region.

The occurrence of lower crustal seismicity in the Central Indian Tectonic Zone (CITZ) of the Indian sub-continent was investigated using MT data and constraints from other geophysical studies. MT derived crustal resistivity models across the CITZ showed the presence of small volume (<1 vol. %) of aqueous fluids for the most part of lower crust and indicated brittle/semi-brittle lower crustal rheology in conjunction with xenoliths and other geophysical data. Additionally, MT results imaged localized deep crustal zones with higher fluid content (2.2-6.5 vol. %) that leads to high pore pressure conditions. It is inferred that the fluid-rich pockets in the mid-lower crust seems to catalyze earthquake generation either as the source of local stress (fluid pressure), which together with the regional stress produce critical seismogenic stress conditions, or reduce the shear strength of the rocks to favor tectonic stress concentration at the low resistive (weak) zones, which is being transferred to seismogenic faults to cause earthquake (Abdul Azeez, 2016).

Interpretation of high resolution aeromagnetic data helped to delineate the horst and graben structures, several hitherto unknown dykes, faults, etc. over the seismically active Kutch Rift basin. Banni basin depicted aureole-like magnetic anomalies which may possibly relate to hydrocarbon induced micro seepages.

Near-surface Imaging

MT, AMT and Transient EM (TEM) techniques have been used to image the shallow subsurface structure for hydrocarbon, mineral and groundwater resources. An attempt was made to evaluate the efficacy of MT in the detection of sub-trappean sediments in basaltic trap covered areas of India using independent MT modeling as well as taking constraints from borehole and seismic data. Two different geological scenarios were considered, one trap covered area like the Saurashtra peninsula and the other where the trap itself is overlain by conductive sedimentary column represented by the Cambay basin. It was seen from inversion of synthetic as well as real data that in the first case MT alone produces highly dependable subsurface models, while in the second case a constrained inversion of MT data using inputs from seismic/borehole results for overlying Tertiary sediment thickness, provides a more realistic sub-basalt subsurface model than that retrievable from any one of the individual methodologies (Patro *et al*., 2015). Earlier, Manglik *et al*. (2009) developed an algorithm or joint inversion of MT, Direct Resistivity, and seismic reflection and refraction data and tested the efficacy of the technique for delineation of thin sedimentary layer sandwiched between the traps and the resistive basement.

AMT survey was carried out in the Bakreswar hot spring area of the eastern India to locate the geothermal source in the vicinity of the hot spring. The results show that the north-south fault close to Bakreswar is a shallow feature, not deeper than 300 m, and thus cannot act as a heat source. The subsurface formation below the fault zone is highly resistive up to a great depth, indicating the absence of a heat source and geothermal reservoir in the vicinity of the Bakreswar hot spring.

In recent years, high-resolution heliborne TEM along with magnetics has been extensively used in India for uranium exploration and groundwater exploration programs. In uranium exploration, CSIR-NGRI and Atomic Minerals Directorate for Exploration and Research (AMD) have used these techniques in association with radiometric parameter to cover different blocks in Jharkhand, Chhattisgarh, Andhra Pradesh, Rajasthan, Karnataka and Maharashtra states of India. Most of these studies are classified in nature but a few results have been published, e.g. by Sridhar *et al*. (2018) for the Kaladgi basin, Peninsular India where heliborne magnetic, electromagnetic and radiometric data were used to identify horst and graben structures and intra-basinal fault systems. CSIR-NGRI also took up heliborne surveys for groundwater exploration in six pilot areas of the country representing different hydro-geological conditions (Ahmed, 2014).

In another application of electrical and EM techniques, Manglik *et al*. (2009, 2011) employed MT and electrical resistivity tomography (ERT) to investigate the detailed deep and shallow electrical conductivity structure, respectively, of several potential High Voltage Direct Current (HVDC) sites in India. HVDC power transmission systems require setting up of specially designed ground electrodes at terminal ends of the transmission line to close the circuit with an earth return path. The design parameters of these electrodes need the information about the electrical conductivity structure within a radius and depth of several km of the site in order to ensure that the injected current penetrates deep enough into the earth.

Concluding Remarks

IAGA is one of the largest Associations of the IUGG that covers very diverse disciplines, from the magnetism of the Sun and other planetary bodies, solar winds, magnetosphere and upper Atmosphere, to the Earth's internal structure and processes. The techniques to observe the magnetic environments of the planetary bodies in general and the Earth in particular in space and time have also grown manifold and utilize ground based and multi-platform (airborne, shipborne, satellites, balloons, etc.) sensors. The applications are also wide ranging, from the basic understanding of the magnetic field at present and in the past, to radio communication, geo-resource exploration, geo-environment, etc. An attempt is made here to provide a glimpse of the work done by Indian researchers in the last one decade in the field of Geomagnetism and Aeronomy. It is not an exhaustive review of all the work done during this period but a window to the topics covered within the framework of IAGA. The opportunities for future research in this field are enormous, e.g., Indian space missions for planetary exploration, launching of national geoscience missions for systematic probing of the Indian lithosphere at multi-scales, up-scaling of observatory network for detection of seismo-electromagnetic signals as precursors to earthquakes, development and application of magnetic and electromagnetic techniques for geo-resource exploration in complex geological settings and monitoring of the environment, etc.

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Review Article

Hydrological Studies in India During Last Decade: A Review

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In the recent past, with the availability of enormous datasets and advanced computational skills, hydrological science is trending towards integration of multidimensional studies for the comprehension of complete hydrological cycle. Numerous studies have been carried out in varied hydrological, climatic and geological settings of India during the last decade. These studies cover groundwater exploration and management; surface water-groundwater interactions; geogenic and anthropogenic contaminations; water balances;predictive modelling and others. This article provides a glimpse of these studies.Some reports and studies might not have been described here due to their unavailability in the public domain and due to space limitation.

Keywords: Hydrological; Multidimensional Studies; Computational Skills; Anthropogenic Contaminations

Introduction

India has a great hydrological and climatic diversity; from alluvial plains to hard rock aquifers and Thar Desert, Rajasthan having rainfall less than 250 mm/yr to Mawsynram, Meghalaya recording 11,872 mm/yr. These diversities, along with uneven demand of water, are posing a challenge for management of water resources in India. India is bestowed with a large amount of annual rainfall and total average annual river flow is 1953 km^3 while the annual utilizable surface water is estimated to be around 690 km^3 (Kumar *et al.*, 2005). The total annual replenishable groundwater resources and the net annual groundwater availability as on March 2011 of the country have been assessed to be 433 km^3 and 398 km^3 respectively while the annual groundwater draft for all uses is 245 km^3 (CGWB, 2014-2015). Aquifers in India are broadly categorised as consolidated and unconsolidated formations (Fig. 1). The water resources of India and other related information are summarized in Table 1. Almost 83% of the water resources are being used in the agriculture sector and the rest are utilized for domestic, industrial and other activities (Table 2). The distribution of groundwater in the country is highly diverse and the availability of safe drinking water from many aquifers is restricted due to geogenic contaminants. Considerable decline of well yields and the depletion of groundwater levels are the major concerns. The situation is further worsened due to the water contamination, and extreme conditions of climate variability including floods and droughts. Extreme climatic events pose more challenges to groundwater management plans. The various geo-spatial datasets related to hydrology (including topography, Land Use Land Cover (LULC), soil etc) are available through open sources like Bhuvan (http://bhuvan.nrsc.gov.in) and India-Water Resources Information System (India-WRIS, http://www.india-wris.nrsc.gov.in/) which are routinely used for governance, administrative purpose as well as research in hydrological sciences.

Surface Water Resources

Surface water hydrology includes water availability analysis, flow duration curve analysis and environmental flow requirement, flood estimation and routing, structural and non-structural measures of flood management, snow and glacier melt monitoring and modeling, sedimentation studies for flood control etc.

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Fig. 1: Map showing the hydrogeological map of India with different formations. (Source: https://india-wris.nrsc.gov.in/)

Almost 61.5% of utilizable water available within country belongs to the surface water resources.

Glaciers and snow cover play a pivotal role in controlling the headwater river run-off variability of monsoon influenced areas (Thayyen *et al*., 2007). A positive regional mass balance as well as reduction of river runoff for the period 1999 to 2008is reported from the Hindu-Kush-Karakoram-Himalaya glaciers and it is suggested that the contribution of Karakoram glaciers to sea-level rise is-0.01 mm/yr (Gardelle *et al*., 2012). A consistent and prolonged negative mass balance in Western Himalaya from 1997 to 2014 is ascribed to the increased supraglacial debris cover (Pratibha *et al*., 2018). It is proposed that this approach of finding debris cover can be adopted to study the effect of climate change with respect to mass balance and increase in the number of supraglacial and moraine dammed lakes on much larger spatial scale in different regions of Himalaya.Glacier-mass balance approach was adopted to infer the high-altitude precipitation in the upper Indus Basin and it was shown that the amount of precipitation required to sustain the observed mass balance of large glacier systems is far beyond that at valley stations or estimated by gridded precipitation products (Immerzeel *et al*., 2015). The findings from this study had an important bearing on climate change impact studies, planning and design of hydropower plants and irrigation reservoirs. Haritashya *et al*. 2010 made a detailed study of the temporal variations in particle size, texture, mineralogy, origin and evacuation pattern of the sediments based on studies on the proglacial meltwater stream of Gangotri glacier for the period 2000-2006. A study related to climatic processes and their genesis is carried out in middle Satluj Valley, western Himalaya (Sharma *et al*., 2017). Pottakkal *et al*. (2014) attempted dye tracer experiments to characterize the subglacial pathways that transport the meltwaters from glaciers through the lower ablation zone of the Gangotri glacier.The studies mentioned that the actual snowmelt contribution remains speculative under both present and future climatic conditions (Siderius *et al*., 2013).

A regression model for runoff forecasting is developed using available hydro-meteorological data within a glacial valley (Srivastava *et al*., 2014). Twenty-five flood events are correlated with sediments which were generated and transported from higher Himalayan crystalline and the trans-Himalaya regions. These events were supposed to be generated by landslide lake outburst floods during precipitation.The coupling between the moisture bearing monsoon circulation and southward penetrating mid-latitude westerly troughs were implied for extreme precipitation events and such outburst floods.

Most of the Indian river basins are climate sensitive and the study of their sediments provides a better understanding of continental-scale fluvial system, variations in weathering and erosional processes over the whole subcontinent. The river Ganga, originating from Himalaya, is the most dynamic among world's major rivers. The sediments of the Ganga river were analyzed for its textural properties (characterized by fine to very fine sand at Himalaya orgenic belt; medium to find sand at northern Indian craton and very fine sand to clay at alluvial plain region), grainsize characteristics (nearly 80% of bedload sediment to be transported as graded suspension) and transportation dynamics (extremely

Table 1: Water resources of India (Source: Central Water Commission)

S.No.	Description	Value
1	Geographical area & location	328.7 M ha Latitude 8^0 4' & 37^0 6' North Longitude 68^0 7' & 97^0 25' East
2	Population as of 2011	1210.19 Million
3	Rainfall variation	~ 100 mm in Western most regions to ~11000 mm in Eastern most regions
4	Major river basins (catchment area > 20,000 Sq km)	12 Nos. Having a catchment area 253 M ha
5	Medium river basins (catchment area between 2000 and 20,000 Sq km)	46 Nos. Having catchment area 25 M ha
6	Average annual rainfall (2010)	3989 BCM
7	Mean annual natural run-off	1869 BCM
8	Estimated utilisable surface water potential	690 BCM
9	Total replenishable groundwater	431 BCM
10	Groundwater resources available for irrigation	369 BCM
11	Groundwater potential available for domestic, industrial and other purposes	~71 BCM
12	Maximum irrigation potential	140 M ha
13	Irrigation potential from surface water	76 M ha
14	Irrigation potential from groundwater	64 M ha
15	Storage available due to completed major & medium projects (including live capacity less than 10 M. cum)	253 BCM
16	Total cultivable land	182.2 M ha
17	Gross sown area	192.2 M ha
18	Net sown area	140.0 M ha
19	Gross irrigated area	86.4 M ha
20	Net irrigated area	63.3 M ha
21	Ultimate hydropower potential (as per reassessment)	84044 MW at 60% L.F.
22	Potential developed by 31st March, 2014 (installed capacity)	40531.41 MW

Table 2: Water use in India

Sectors	Consumption of water
Agriculture	83%
Domestic	7%
Industry	2%
Energy 1%	
Other 7%	

high rate of water discharge, huge sediment load during monsoons and high discharge variability) by Singh *et al*. (2007).

The effective discharge for suspended sediment transport in the alluvial reaches of Ganga River in the Western Ganga Plains was computed using analytical and an alternative magnitude-frequency approach. It was concluded that the effective discharges at different places have recurrence interval of 1-2 years and are channel maintaining (Roy *et al*., 2014). It was proposed that the changes in the effective discharge (monsoonal fluctuations) influenced the long-term landscape development and valley filling episodes in the Ganga river plain.Hydrology and sediment dynamics were linked to landscape diversity in the Ganga dispersal system (Roy *et al*., 2017).

Mahi River basin in western India, was quantified for contemporary and paleo-discharges and the changes in the hydrologic regime through mid-late Holocene. In this river basin the discharge estimates were based on the channel dimensions and established empirical relations for mid-late Holocene, historic and the present ones. It was inferred that the precipitation is showing a decreasing trend since the mid-late Holocene (Sridhar, 2007). Important hydrological features of the flood region were investigated to treat entire Damodar river system from source to mouth. The climatological data along with stream flow records were analysed. The study revealed the significant changes in the hydrological behavior of the region were characterized by an increase in temperature levels and reduction in rainfall and river flows (Roy and Majumdar, 2007).

A few other characteristics of surface water resources were made available by other workers. The implications of forest use and reforestation on surface and sub-surface hydrology were explained by Bonell *et al*., 2010. The importance of soil water retention capacity to maintain the base flow levels and the effect of deforestation was conveyed by Qazi *et al*., 2017. An integrated approach using remote sensing data, borehole data, field data, isotopic and water level data was adopted to identify major paleochannels and studied their hydraulic connectivity with adjacent alluvial plains, rate and source of natural recharge and the groundwater flow direction (Samadder *et al*., 2011).

Groundwater Resources and Aquifer Mapping

The conventional electrical method (Vertical Electrical Soundings) continues to be the most reliable method for correlating the geoelectrical parameters with lithology to delineate groundwater potential zones. Such studies are carried out in the Tamil Nadu (Ballukaray, 2001) and other parts of the country. A number of researchers have successfully carried out groundwater exploration and modeling to assist in sustainable long-term management of groundwater resources (Mondal and Singh, 2004; Saxena *et al*., 2005; Mondal *et al*., 2011). Use of Electrical Resistivity Tomography (ERT) resolved various challenging problems faced by the Geoscientists working with geohydrological and geotechnical methods (Andrade, 2011). Among the other geophysical methods, Mise-le-masse technique to locate the extension of fractures in hard rocks (Kumar *et al*., 2003), use of gravity methods in crystalline aquifers (Murty *et al*., 2002), seismic methods for delineation of aquifers (Sundararajan *et al*., 2004) and integrated studies using hydrogeology (Singh *et al*., 2003, Dutta *et al*., 2006, Barker *et al*., 2003, Sharma *et al*., 2005, Rai B, *et al*., 2005, Hodlur *et al*., 2006, Dar *et al*., 2017) are successfully employed for groundwater studies. Over the decade, a systematic approach towards mapping of aquifer and groundwater management techniques led to initiation and accomplishment of an ambitious programme of pilot aquifer mapping over the six representative terrains of the country (Ahmed, 2014). An area of approximately 3,264 km^2 covering Deccan Traps of Maharashtra, desert areas of Rajasthan, Gangetic plains of Bihar, coastal region of Tamil Nadu, contaminated aquifer system of Bihar and hard rock aquifers of Karnataka and Rajasthan were explored. The dual-moment Aero-Electromagnetic methods were effective in delineating the 3D aquifer configurations marking a new chapter in the hydrological science in India. The Heliborne Transient Electromagnetic surveys were used to delineate the aquifer geometry and identify the conductivity patterns in a few chosen areas of hard and soft rock aquifers in the pilot aquifer mapping. These results were used to validate and model the hydrogeology of an area in Rajasthan (Chatterjee *et al*., 2018).

Remote sensing techniques were applied to assess groundwater favorable zones for development and exploration in and around Guntur area in Andhra Pradesh. It was observed that the deeply weathered pediplain (PPD), moderately weathered pediplain (PPM) and shallow weathered pediplain (PPS) are good, moderate to good and poor to moderate groundwater prospect landform whereas residual hill (RH) was considered as a poor groundwater prospective zone (Subbarao *et al*., 2001). Further satellite imageries were used to explore the groundwater potential zones and identifying sites for rainwater harvesting sites in Aravalli-Pegmatite Precambrian terrain of Delhi (Mukherjee, 2008). Groundwater flows were delineated by observing the impact of water table variations and depth-dependent fracture connectivity (Guiheneuf *et al*., 2014). A plan of artificial recharge to groundwater in 22 States/UT of India has been efficaciously implemented by the Ministry of Water Resources (Annual Report, CGWB, 2016, www.cgwb.gov.in).

Prediction and Modelling

Monsoon rainfall is a major source of water in India. Indian Meteorological Department (IMD) is the nodal government agency, which issues seasonal prediction (LRF) based on a statistical forecast system with 8 predictors, which have a strong physical linkage with Indian summer monsoon. Statistical models have their own limitations due to their dependence on interrelationship of predictors (Rajeevan *et al*., 2008) and therefore, ensemble mean forecast (with an assumption of prediction between 7-45 days) is often adopted Forecast model is improved using bias correction for precipitation and air temperature (Shah *et al*., 2017). Pattanaik and Kumar (2010) showed that even though the major features of monsoon are predicted successfully in all forecasts between March and May, the significant correlation of ISMR with observations are noticed for forecasts initiated in April only. Ramu *et al*. (2016) attributed the skill of ISMR to the better teleconnections of El Nino related SST and ISMR in these models and in a recent publication, Ramu *et al*., (2017) came out with a dynamic prediction system for seasonal summer monsoon rainfall over five homogenous regions of India by showing a higher anomaly correlation coefficient (ACC-0.45). A case study on the semi-arid Musi sub-basin (11,000 Km^2) of Krishna Basin was performed using three dimensional MODFLOW model (Massuel *et al*., 2013) and two water allocation scenarios were assessed and compared. Simulations involving all sources and sinks showed that there is 13% less groundwater available for exploitation as compared to the one modelled on the groundwater availability linked to quantifield fluxes. By integrating complex interactions between components of the water budget in space and time, the groundwater model was able to provide a more comprehensive conceptual assessment of the groundwater-resource sustainability. In turn, this has major implications for the existing water allocation modelling framework used to guide decision makers and water-resources managers worldwide.

Ghosh and Majumdar, (2008) presented a methodology of statistical downscaling based on sparse Bayesian learning and Relevance Vector Machine (RVM) and generated a model at river basin scale for monsoon cycle using General Circulation Model (GCM) simulated climatic variables. To address the problem of handling the dynamic, non-linear and noisy data to understand the physical processes in watershed, Nayak and Sudheer, (2008) came up with a Fuzzy model for reservoir inflow forecasting in the Narmada basin. In addition, Singh *et al*. (2008) proposed a new conceptual sediment graph models based on coupling of popular and extensively used methods like Nash model based instantaneous unit sediment graph (IUSG), soil conservation service curve number (SCS-CN) method, and Power tawwhich vary in their complexities. Correspondingly, Dhar and Mazumdar, (2009) came up with a hydrological model of the Kangsabati river, West Bengal, with reference to climate change scenario. Parameters (evapotranspiration, transmission losses, potential evapotranspiration and lateral flow) were evaluated and predicted for years 2041-2050 towards sustainable development of the river basin which show an increasing trend over the time period. Singh *et al*. (2010) deliberated on the impacts of climate change on discharge of River Irrawaddy in the Loktak Lake watershed, which included a wetland in Northeast India. This was achieved by running pattern-scaled GCM output through distributed hydrological models (developed using MIKE-SHE) of each sub-catchment.

In addition to conventional statistical methods, the kernel-based machine learning approaches gained popularity including Artificial Neural Networks (ANNs). Gupta *et al*. (2011) used the Global Circulation Model (HadCM3) projected data to quantify the impact of climate change on runoff of the lower part of Ganga Basin and upper parts of Mahanadi Basin. Their results predicted a decline in the future climatic runoff in most of the river basins of India as compared to normal climatic runoff further indicating that the agriculture in the eastern India may be more affected due to shortage of surface water availability. Similarly, Islam *et al*. (2012) assessed the impacts of climate change on streamflow of the Brahmani River basin using Precipitation Runoff Modeling System (PRMS) run under the platform of Modular Modeling System (MMS). In contrast to this, Goyal *et al*. (2012) worked on downscaling of the output of GCM to obtain simultaneous projection of mean monthly maximum and minimum temperatures (T-max and T-min) along with monthly precipitation and pan evaporation to lake-basin scale in climatically sensitive semiarid region of India. They used the nonparametric methodofK-Nearest Neighbor (K-NN) approach to select the nearest neighbors for projections. Model predictions associated with different climate change and abstraction scenarios in the Upper Bhima Basin indicated that the continuation of current rates of abstraction would lead to significant groundwater overdraft, with groundwater levels predicted to fall by -6m in the next 3 decades (Surinaidu *et al*., 2013); Physically-Based Distributed (PBD) hydrological model, the Distributed Runoff and Erosion Assessment Model (DREAM) predicted sediment flow rates and sediment yields in Pathri Rao watershed in Garhwal Himalayas (Ramsankaran, 2013). The hydrological impacts of climate change in Central Indian River basin were studied by Raje *et al*. (2014) using Variable Infiltration Capacity (VIC) MHM (macroscale hydrologic model). This studyshowed an increasing trend for summer monsoon surface runoff, evapotranspiration and soil moisture in most of the central Indian river basins. On the other hand, a decrease in runoff and soil moisture are projected for a number of regions in southern India, with important differences arising from GCM and scenario variability using VIC model over Ashti catchment (Godavari Basin) to evaluate the impacts of LULC changes and rainfall trends on the hydrological variables (Hengade *et al*., 2016). The hydrologic impacts of climate change in Tunga-Bhadra river basin, India were assessed using HEC-HMS and SDSM models, by comparing present and future stream flow and evapotranspiration estimates (Meenu *et al*., 2013); Modelling hydrology, groundwater recharge and non-point nitrate loadings were carried out in the Himalayan Upper Yamuna basin by integrating hydrological SWAT model with the MODular finite difference groundwater FLOW model (MODFLOW) and Modular 3-Dimensional Multi-Species Transport model (MT3DMS) (Narula and Gosain, 2013). It also includes studies on rainfall (Menon *et al*., 2013; Salvi and Ghosh, 2013etc.), water availability and streamflow (Gosain *et al*., 2011; Singh and Kumar, 2015), soil erosion (Mondal *et al*., 2014), water quality (Rehana and Mujumdar, 2012), irrigation demands (Rehana and Mujumdar, 2013), and groundwater availability and recharge (Panwar and Chakrapani, 2013).Also, the advances in computational techniques for the enhanced hydrological modelling in the Indian context were reviewed and discussed by Mondal *et al*., 2016.

Numerical Weather Prediction model output was used to verify the spatio-temporal monsoon rainfall variability across theIndian region. It was observed that the prediction of dry spell rainfall was more uncertain than that of the wet spell. The percentage area of India under wet conditions (rainfall amount over each grid is more than its daily mean monsoon rainfall) and rainwater over the wetarea is overestimated by about 59% and 32%, respectively, in all models (Ranade *et al*., 2014).

The reliability of hydrological models for prediction in ungauged basins (PUB) was improved. The potential of multi-basin modelling for comparative hydrology using PUB grouped 6000 sub-basins on the basis of similar flow signatures. This gave more insights into the spatial patterns of flow generating process at larger scale (Pechlivanidis and Arheimer, 2015). This hydrological setup was named as India-HYPE (Hydrological Predictions for the Environment).

Tiwari *et al*. (2018) examined the mid-21st century climate projections over western Himalaya from Coupled Model Intercomparison Project Phase 5 (CMIP5) global climate models under Representative Concentration Pathways (RCP) scenarios (RCP4.5 and RCP8.5). It was proclaimed that the western Himalaya and Satluj River Basin will be warmer by mid-century. Considering the reported models with different assumptions, Chawla and Mujumdar (2018) provided a generalized framework for hydrologists to examine stationarity assumption of models before considering them for future streamflow projections and thereby isolate the contribution of various sources to the uncertainty.

Changing Scenarios with Climate Variability

Climate Dynamics

Impact of the climate change on the water resources of Indian river system using the HadRM2 daily weather data to determine the spatio-temporal water availability in the river systems was quantified (Gosain *et al*., 2010). In this study, SWAT was used to prepare the distributed hydrological model. Simulations over 12 river basins were made, using the data for over 40 years (20 years for Present and 20 years for Green House Gas or future climate scenario), which revealed that two out of 12 river basins are predicted to be the worst affected (one with respect to floods and other with respect to the droughts). Similar impact study for Bhavanisagar Reservoir of Tamil Nadu was attempted by Wilk and Hughes, (2002). They simulated the impact of land-use and climate change on water resource availability for Bhavanisagar Reservoir of Tamil Nadu and concluded that the land-use and climatic changes that are likely to occur (apart from extreme events) will have a negligible impact on the yield of the Bhavanisagar Reservoir.

In regional and global modelling studies for climate change assessments, Sen Roy*et al*. (2007) supported the use of irrigation and agricultural impacts along with land use change and aerosol feedbacks. In their work, they analysed the monthly climatological surface data sets at the regional level over India and showed that agriculture and irrigation can substantially reduce the air temperature over different regions during the growing season. The macro scale study over the tropical site in Gujarat also indicated that the absorbing aerosols delay the growth and promote the early collapse of atmospheric boundary layer (Pandithurai *et al*., 2008).

The climate change impact on hydrology and water resources was assessed by Majumdar (2008) along with the variability in sustainable water resources planning and management. Further, the role of clouds in affecting the sub-season/intra-seasonal variability of sea surface temperature (SST) and atmospheric convection in the equatorial and South-Eastern Tropical Indian Ocean (SETIO) during monsoon break transitions were analysed by Samala and Krishnan (2008).

The first basin-wide assessment of the potential impact of climate change on the hydrology and production of the Ganges system was presented by Jeuland *et al*. (2013) as a part of the world Bank's Ganges Strategic Basin Assessment Program. Based on the series of modelling efforts (including downscaling of climate projections, water balance calculation, hydrological simulation, economic optimization), the General Circulation Models (GCC) were found to be highly variable. This leads to considerable differences in predictions of means flows in the Ganges and its tributaries.

It was submitted that the unsteady nature of the onset phase of the monsoon and the dependency of its migration on regional hydrological processes makes northwestern India, in particular, susceptible to variability and changes (Bollasina *et al*., 2013). This study used atmospheric general circulation model in a realistic configuration to conduct ''perpetual'' experiments aimed at providing new insights into the role of land–atmosphere processes in modulating the annual cycle of precipitation over India.

The variations in rainfall indices found to be driven by large scale climate variability in a study of extreme rainfall indices over 57 urban areas of India during the period (1901-2010) gave a future projection of climate for next 50 years upto 2060 (Ali *et al*., 2014). It was shown that the urban areas with major increase in rainfall maxima under the projected future climate is far larger than the number of areas that experience significant changes in the climate during the 20th century. These results indicated a strong need for urban storm water infrastructure planning and management arising out of climate dynamics. The decrease in the intensities of Indian Winter Monsoon (IWM) and its response to external forcing over the last 250 years were suggested (Munz *et al*., 2017) as a part of climate variability.

Contamination of Hydrological Resources

The groundwater pollution studies routinely carried out by Central Pollution Control Board (CPCB) reported high level of arsenic, fluoride and other industrial hazardous wastes during the last decade. The national compilation of all the relevant information on major geogenic contaminants in and their remediation for major parameters like arsenic fluoride, salinity, iron and manganese, uranium, radon, strontium, selenium and chromium are compiled and reported with special emphasis on Nitrate (CGWB, Annual report, 2014). Geogenic contamination studies in the principal aquifers of local areas of Yavamal Maharastra. The defloridation units were installed at the community level and improvement in the health was indicated (Gwala *et al*., 2014).

Arsenic contamination produced from shallow depths in the parts of Damodar fan-delta and west of Bhagirathi river in West Bengal and Bengal basin were reported by many workers. The deep domestic pumping only slightly perturbs the deep groundwater flow system while the substantial shallow pumping for irrigation forms a hydraulic barrier that protects deeper resources from shallow arsenic sources. Michael *et al*.,(2008), evaluated the sustainability of deep groundwater as an arsenic-safe resource in the Bengal basin. Coyte *et al*. (2018) demonstrated the enhancement of Uranium mobilization from geogenic cause to anthropogenic cause. They further stressed the need to revise the current water quality monitoring program in India, measures of evaluation of human health risks in high uranium prevalent areas, improvement of remediation technologies and proper implementation of preventive management practices to solve the problem.

The understanding of hydrochemical parameters and activity of natural radionuclides (H-3) was used to determine the relative age of groundwater in the river basins of Karnataka (Ravi Kumar *et al*., 2011). On this basis, the agricultural water management (AWM) strategy was adapted with an aim to increase the agricultural production through the enhancement of available water resources while maintaining ecosystem services (Garg *et al*., 2013). In addition, improvement in the ability to develop Environmental flows assessment (EFA) through difference case studies from rivers across the country resulted in developing sustainable management of the water system (Jain and Kumar, 2014). The major focus for the development of EFA was to create an open database for hydrological, ecological and socioeconomic data, developing hydrology-ecology relationships, evaluation of ecosystem services, and addressing pollution due to anthropogenic activities. The studies on the chromium dumpsites indicated that the leaching of carcinogenic hexavalent chromium from COPR dumpsites leading to groundwater contamination is a major risk to environment (Matern *et al*., 2017). Renganayaki *et al*. (2013) developed a concept of inverting the water quality as an effectof recharge to address the geogenic and anthropogenic contaminations.

Participation in international projects supported integrated treatment process for agro-food industry effluents and the municipal wastewater (Annual Report, NEERI, 2012). The concept of "zero emission" and "zero discharge" was also started providing Environmental Impact Assessment (EIA) certifications to different industries which is a landmark achievement.

Origin and Source of Floods in India (Palaeo-flood-Hydrology)

Annual flooding of monsoon-fed rivers are caused due to high spatio-temporal variability of rainfall. Paleoflood hydrology, which studies the recent and historic records of large floods is an upcoming field of hydrology. The potential of palaeoflood hydrological studies in the Indian context was highlighted by summarising the results for eight Indian rivers over the last two decades and it concluded that such studies in different hydro-geomorphic regions of India are vital for flood-risk assessment of gauged as well as ungauged rivers (Kale 2008). The study proposed that the potential for palaeoflood analysis was high in Deccan rivers, dominated by favourable lithologies (granite, gneisses, sandstones and quartzites) along with stable boundary conditions. Contrary to this, the potential for palaeoflood studies was low in alluvial rivers particularly in Ganga-Brahmaputra Plains and Gujarat Plains. The study revealed that the potential for reconstructing past or recent natural dam-failure during floods was high in Himalayan rivers. It was clearly pointed out that the real data on extreme climatic events produced by palaeoflood records may help in modelling and predicting the future climate changes. Baker (2008) included new techniques for accurate geochronology of flood sediments to solve the coupled hydraulic calculations.

The fluctuations of the monsoon over the Indian sub-continent, paleo-hydrological changes of two playas, Phulera and Pokharan, in Thar desert were studied by Roy *et al*. (2009) using stratigraphical, mineralogical, geochemical and optical dating methods. They concluded that the sediment successions in shallow profiles from these two playas contain three and four stratigraphic units along with characteristic geochemical properties. Sridhar (2009) showed an evidence of correlation between the extreme hydrological events in Mahi, Narmada and Tapi river basins and attributed them to the regional monsoon domain. He stressed that the palaeoflood records are of great significance in revealing the magnitude and frequency of large floods.

Challenges Along the Coast (Coastal Hydrology)

The Indian coast line hosts 77 major cities with different challenges such as lack of drainage system, overdraft of groundwater, sea water ingression and variations in agricultural practices while the deltaic plains have their own challenges.

A number of studies were carried out to address the problems arising out of irregular withdrawal leading to saltwater intrusion. A simulation model based on groundwater quality in the Godavari delta developed by Ghosh (2002) indicates a considerable increase in seawater intrusion. Upstream development and inter-annual variations in rainfall of Indian river basins is likely to cause both episodic (periodic) and chronic (constant) shortages in water supplies downstream. Rapid development of surface and groundwater throughout thebasin in India resulted in historically low inflows to the main canals. The situation in these deltas is much worse as widespread seawater intrusion is transforming the fresh groundwater to brackish/saline water (Saxena *et al*., 2004) even in the channel islands like Pesarlanka (Mondal *et al*., 2010).

A flow and transport simulation model, on the basis of finite element method, was established to evaluate the effectiveness of planned strategies for pumping, in order to locally control the intrusion (Datta *et al*., 2009). Submarine groundwater discharge (SGD) with special reference to its prevalence as a source of freshwater and nutrients to coastal ecosystems is prominent in coastal research. Very recent study carried out by National Centre for Earth Science Studies (NCESS, annual report 2016) on geomorphological mapping and submarine groundwater discharge reported the lithology variations, water table fluctuations and hydrochemical heterogeneity along the coastal aquifers of Kozhikode in a scientific manner. Kanagaraj *et al*., (2018) investigated the influence of seawater intrusion in the coastal aquifers of Kalpakkam, Kancheepuram district of Tamil Nadu by using integrated geophysics, geochemical and stable isotopes techniques and recommended various precautions to be adopted. Central water Commission (CWC) recently examined the salination issues of surface to coast with solution specific study (CWC salinity report 2017).

Use of Isotope for Subsurface Studies (Isotope and Tracer Hydrology)

The source of wetland groundwater, surface water-groundwater interaction and mixing of groundwater at different depths of aquifer was understood (Sikdar and Sahu, 2009) using isotopic signatures associated with hydrogeology of East Calcutta Wetlands, a peri-urban inland wetland ecosystem. They utilized hydrogeology and isotope composition of groundwater to understand the present hydrological processes prevalent in the wetland, source of wetland groundwater, surface water-groundwater interaction and mixing of groundwater of various depth zones in the aquifer. Their study concluded that the shallow groundwater has high tritium content due to local recharge whereas the deep groundwater has low tritium due to recharge at distant area. At some places, high tritium in deep aquifer was attributed to mixing of groundwater from both shallow and deep aquifers. Isotopic signatures and geochemical behaviour of groundwater in an arsenic-enriched part of the Ganga Plain helped in characterizing the recharge processes in both the shallow and deeper aquifers (Saha *et al*., 2011). In the reservoir triggered seismicity area of Koyna-Warna region, a model was conceptualized based on the hydrochemical and isotopic characteristics of different well waters for aquifer breaching and mixing of deep aquifer water with shallow aquifer water due to earthquakes (Reddy *et al*., 2011).

The stable isotope delta O-18 was used to identify stream and spring origins of a mountainous catchment in a case study from Liddar watershed, Western Himalaya, India (Jeelani *et al*., 2010). The spatial and temporal distribution of delta O-18 and delta D measurements in precipitation and stream waters were used to distinguish various sources and components of stream flow and to estimate their residence times in snow dominated mountainous catchments of Kashmir Himalaya (Jeelani *et al*., 2013). Air-mass trajectory analysis to find out the moisture contribution of rains over the Kolkata city indicated that these moisture traces originate from Arabian Sea and travel over dry continental region over the Bay of Bengal before arriving Kolkata (Dar *et al*., 2017). The same isotope (delta D and delta O-18) along with strontium was used in Indus River water to understand the regional hydrology, water sources, and catchment processes (evaporation, transpiration, recycling and mixing) by Sharma *et al*. (2017). Isotopic studies in Indus civilization of northwest Rajasthan provided an evidence for the climate change in this region associated with both expansion and contraction of Indus urbanism along the desert (Dixit *et al*., 2018).

Department of Science and Technology, GOI and Physical Research Laboratory (PRL) funded a programme on Isotopes led by Deshpande and Gupta (2007) under the title "National Program on Isotope

Fingerprinting of Waters of India (IWIN) – a New Initiative". The major objectives of the program included generation of isotope data for addressing important hydrological questions related to origin of water sources and the processes of redistribution by evapo-transpiration, stream flow generation, groundwater recharge and discharge – from watershed to continental scale; and providing quantitative estimates of residence time of the water and vapour in each hydrological reservoir and the fluxes across them in a temporally and spatially distributed manner.

Applications of Big Dataset from Satellite Observations

Information from big datasets is well presented by applying remote sensing methods and thematic maps. With the latest data acquisition systems, it is now possible to obtain many conclusive results for recharge structure sites, water balance studies, agro-hydrology balance studies, forecasting or predictive studies, basin assessment studies, etc. National Remote Sensing Corporation (NRSC) has been playing a vital role in mapping the resources through satellite images to be used for agriculture planning, atmosphere and climate, water resources and many more. Their major focus is on irrigation infrastructure monitoring and performance assessment, water bodies monitoring, basin level water resources assessment, flood forecasting and inundation modelling studies, reservoir capacity loss assessment, preparation of nationwide Ground Water Prospect (GWP) maps at 1:50,000 scales etc. Their output is beneficial in providing baseline information studies for decision support for effective planning, monitoring and management of water resources so as to prepare frameworks for water resource models. The delineation of water bodies using SAT-1/SAT-2 A WiFS/LISS-III data is useful for mathematical assessment of the data characteristics along the glaciers as well as moraine-dammed lakes. NRSC works closely with CWC in providing exclusive datasets for proper planning. Their involvement in Accelerated Irrigation Benefit Programme (AIBP) helped CWC in proper management of canals as well as irrigation network.

On the basis of the confluence dynamics of the Ganga-Ramganga Valley, detailed analysis of the channel morphology, hydrology and sediment transport characteristics of the different rivers was studied through mapping of channel configuration using multi-date remote sensing images and topographic sheets for 90 years (1911-2000) by Roy and Sinha (2007). Sinha *et al*. (2008) integrated the hydrological analysis with GIS based floor risk map in Kosi river basin and reported very high discharge variability and high sediment flux from an uplifting hinterland. Sreedevi *et al*. (2013) showed the efficacy of SRTM DEM and GIS based approach in evaluating drainage morphometric parameters over the conventional methods. Meraj *et al*. (2015) used Linear Imaging Self-Scanner satellite data and Advanced Spaceborne Thermal Emission and Reflection Radiometer digital elevation model in a GIS environment for assessing the surface hydrological behavior of Lidder and Rembiara watersheds of the Jhelum basin which helped in formulating better flood mitigation strategies in this data scarce part of the Himalayan region. Garg *et al*. (2017) investigated the capabilities of variable infiltration capacity hydrological model to hydrologically simulate the Pennar basin under LULC scenarios. Chaudhuri *et al*., (2017) showed that the remote sensing based estimates of impervious surface area in urban hydrology are very important indicators for the assessment of water resource depletion. They also developed a correlation between land-use change and their potential impact on urban hydrology. Sentinel-1 and Sentinel-2 data were used to estimate the seasonal impact of groundwater use in the granitic watershed in South India (Ferrant *et al*., 2017). Gupta and Singh (2016) discussed the methodology to retrieve the hydro-meterological parameters estimated from satellite based instruments (including Altimeters, Radar, Optical and microwave radiometers) and their variability in case of extreme conditions of drought and flood over India.

CWC came out with a study for "Reassessment of water availability of River Basins in India using Space inputs" for assessing the average annual water resources in the country (2017). The study was approved by Ministry of Water Resources, River Development and Ganga Rejuvenation (MoWR, RD & GR), Government of India. NRSC developed a tool that integrates all input images like basin boundary, LULC, soil, rainfall, temperature, command area and reservoir mask and generates the outputs in the form of image layers and test files. Various abstractions were estimated for 20 basins/sub-basins of India for a 30 year period from 1985-2015. Water resource availability at the basin scale was assessed by model outputs from computed groundwater fluxes using the data from CGWB. This study by CWC laid emphasis on basin scale wealth quantification through transformation from present basin terminal gauge site discharge, aggregation to meteorological data based water budgeting exercise through hydrological modelling approach.

Gravity Recovery and Climate Experiment (GRACE) allow the possibility of measuring the spatio-and-temporal variations in total terrestrial water storage giving precise estimates of water storage over different time scales. The study by Tiwari *et al*., (2009) stressing the depletion of North Indian aquifers alerted the water managers to take precautionary measures. As per the study, the areas showing decrease in groundwater storage fall in the Ganga River Basin, which is densely populated and also a major contributor of agricultural products. Since then, these aquifers are investigated by various research communities for further estimates (Chen *et al*., 2014, Long *et al*., 2016). Very recently, the spatial and seasonal variations of the surface water budget are examined (Singh *et al*., 2017) by using GRACE measured gravity anomalies on earth to estimate Total Water Storage (TWS) content over the NW region of India.

Critical Zone Studies

Various processes in the critical zone affect each other directly or indirectly. Integrating these subsurface process is always a challenge due to temporal and spatial variability. Climate change may increase aquifer uses and rates of depletion, thus increasing complexity and challenges of aquifer management. Key climate impacts on aquifers are changes in recharge and discharge zones and volumes, contamination and saline infiltration. Critical zone comprises of the unsaturated zone, all above the water table to the tip of the trees. Unsaturated zone is the most important zone for deciphering the pathways of rainfall recharge as well as the infiltration of contaminants to the aquifer system. This process pertains directly to the climate system as the moisture to the atmosphere is highly dependent on the complexity of a few meters of the sub-surface and is equally important parameter for the long term sustainable monitoring of the aquifers. Kumar *et al*. (2009), Anoop *et al*. (2017) and Pal *et al*. (2017) used the satellite data to retrieve the soil moisture qualities and their variabilities. CSIR-NGRI designed a different experiment to relate the soil moisture (from neutron probe) and resistivity variations in vadose zone through time lapse geophysical datasets and proved the efficacy of fourth dimension (time) parameter for locating the point of recharge as an input to the model (Arora *et al*., 2016). Geophysical methods gained importance towards studying the small scale variability of critical zone. However, the relationship between soil moisture and electrical resistivity could not be standardized. Parate *et al*., (2011) argued that electrical resistivity measurements can be used to measure soil moisture content for red soils only. Recently, the information on root zone properties are sought by inversion of crop models (Sreelash *et al*., 2017) by characterizing soil water reservoir and impact of land use and environmental changes on hydrology of agricultural catchments.

Among 24 Critical Zone Observatories around the globe, there is only one observatory on the Kabini River Basin, Karnataka, in India. Considering the huge land area of the country and varied geological and climatic conditions, it is proposed to consider creation of more observatories within country.

Diversified Studies for Management Plans at Watershed and Basin Scale

Estimation of Water Availability and Budgeting at Different Scales

The growing demand for groundwater availability and the rapid depletion of resources have opened up a forum to discuss on the extent and spatial distribution of groundwater depletion and the connectivity of aquifer system and its dynamics in terms of geological time span. The water balance of entire India has been studied on daily, monthly and annual time scales (Aggarwal *et al*., 2013) and it revealed that the VIC model results take into account a large number of parameters influencing the process. Sinha (2015) strongly proposed to design a strategy to understand the geology and geometry of the aquifer system defined by the buried channels in order to get the precise estimation under stress conditions through a 3-Dimensional representation of the paleochannels. Li, Lu *et al*. (2017) established an understanding of the present water budget in Himalayan Basins and proposed a two-way coupled implementation of the Weather Research and Forecasting (WRF) Model. The WRF-Hydro hydrological modeling extension package (WRF/WRF-Hydro) was employed in its offline configuration over a 10 year simulation period for a mountainous river basin in north India to capture precipitation and resulting stream flow hydrograph which shows a good correspondence with observation at monthly timescales. They concluded that WRF-Hydro modelling system has the potential for predicting potential changes in the atmospheric-hydrology cycle of ungauged or poorly gauged basins.

Rural, Peri-Urban and Urban Management

A significant change in Land-Use and Land-Cover is observed through high resolution satellite data. Roy *et al*. (2015) have generated LULC maps at decadal intervals for 1985, 1995 and 2005 following the International Geosphere Biosphere Program (IGBP) to meet the global standards of interpretation. Various organizations like The Energy Research Institute (TERI), IISc Banglore, SaciWaters, etc have extensively worked at local level along with respective municipal corporations to reduce the usage of freshwater and use of contaminated water after treatment. NGO's have also worked towards the awareness on lake encroachment in order to save them from urbanization. The International Water Management Institute (IWMI) along with IITM undertook a part of international collaborative project to demonstrate the usage of local waste water treatment plants and change in cropping pattern over almost a decade (Jampani *et al*., 2015).

The lack of technical capacity for the informal construction of small dams in rural India was highlighted by Oblinger *et al*. (2010). They quantified the seepage loss and thereby came across a strategy to deal with water scarcity. The impact of urbanization on the hydrology of Ganga Basin was studied with quantified observations (Misra, 2011) which revealed the change on water habitats, exports, high concentration of pollution into the rivers, wetlands and reservoirs, destabilize the ecological processes and influence the ecological stability of ecosystems.

It was observed that use of gauge calibrated satellite observations significantly improve the rainfall estimation over the metro cities, in an area with a few rain gauge observations (Mishra 2013). Looking towards another metro city of Kolkata, the impacts of pumping on water sources was reported for planning the future water supply and understanding the threat of contamination (Sahu *et al*., 2013).

Spatial and temporal trends of mean and extreme rainfall and temperature values for 33 urban centers of Rajasthan helped local stakeholders and water managers to understand the risks related to climate change (Pingale *et al*., 2014). The rainfall indices over 57 major urban areas were derived for complete century (1901-2010) and future projections were given for next 5 decades from 2010-2060 (Ali *et al*., 2014).

An experiment was conducted to develop an eco-hydrological model for agricultural practices in rural catchment area, to assess the scope of data collecting strategy in data-scarce region (Jackisch *et al*., 2014). As a case study of Bangalore city, 26 CMIP5 (Coupled Model Intercomparison Project Version 5) GCMs (General Circulation Model) along with four Representative Concentration Pathway (RCP) scenarios were considered for studying the effects of climate change and to obtain projected IDF relationships. This study helped in quantifying the uncertainties arising from parameters of the distribution fitted to data and the multiple GCM models using Bayesian approach. Markov Chain Monte Carlo (MCMC) method using Metropolis Hastings algorithm is used to obtain posterior distribution of parameters (Rupa *et al*., 2015). Recently, the high concentration of Black Carbon reported over the high-altitude Himalayan Kashmir Region has posed serious implications for the regional climate, hydrology and cryosphere (Bhat *et al*., 2017)

Socio-Hydrology

An emerging theme related to the applications and use of hydrological results in the development of the society is Socio-Hydrology. It was also proposed as "Hydropsychology', where the discussions and transactions between humans and water-related activities should be included in water research (Sivakumar, 2011) and later it was called as "Duty of Water" (Wescoat Jr. *et al*., 2013). The need got materialized as the scale of interpretation of hydrological conditions, land use and available institutional structures influenced the watershed development (Syme *et al*., 2012) involving interactions between communities for result oriented data collection and dissemination of information. Now the theories of effective communication entertain the importance of hydrological information to users from socio-economic perspective. The challenging tasks of development in mountains could also be tackled by the interventions of stakeholders and interplay of local practices. As a result of socio-hydrological system adoption in Ladakh area, the irrigation and development characteristics took a positive turn in Upper Indus Basin (Nuesser *et al*., 2012).

Srinivasan, (2015) argued that there are some challenges in incorporating the feedbacks from people and proposed an alternative approach to use the counterfactual trajectories, which will allow policy insights to be gleaned without having to predict social futures. Again, Srinivasan *et al*. (2015) came out with a multiple-hypothesis approach in the data scarce region of shrinking Arkavathy River. According to them, the approach not only makes a meaningful contribution to the policy debates but also helps prioritizing and designing of future socio-hydrologic research in the watershed. Very recently, Pande and Sivapalan (2017) developed the economic model with various statistics from agriculture, values, norms, technology, economics, trade, environment in space and time, to explain the necessity of socio-hydrology for global water sustainability.

Department of Science and Technology, Government of India (www.dst.gov.in) pronounced the Technology Mission: WAR for Water which says "Winning, Augmentation and Renovation" in 2009. The main objectives of the mission was to find out inexpensive methods of converting saline water into fresh water; to find out methods of harnessing and managing the monsoon rain water; to manage the flood waters; to carry out extensive research on rain water harvesting techniques and for the proper treatment of waste water; and adoption of preventive and protective methods to preserve the wetlands and issues related to them. The agencies involved came up with viable solutions like installation of membrane based devices to provide safe drinking water; use of advanced aerobic, anaerobic process, membrane process and membrane bioreactor to recycle the domestic sewage water etc.; establishing desalination systems; and adopting various methods of recharge (pits, check dams, artificial dugwells etc) for utilising rainwater harvesting techniques.

Trans-Boundary Aquifers (TBA) and global networking

The study of trans-boundary aquifers on the Kosi River basin (Chen *et al*., 2013) described the characteristics of water hazards in the basin based on the existing literature and site investigations including hydrology and related aspects. The substantial groundwater depletion over the TBA including Indus River plains (over India and Pakistan) was proposed for the first time as the quantitative assessment of TBAs with an aquifer stress indicator for a period of 1960-2010 (Wada *et al*., 2013) using groundwater abstraction, groundwater recharge and groundwater contribution to environment flow.

The International Hydrological Programme (IHP) 7 contributed largely to elevate India on global platform through imparting water education for sustainable development, to revise the curriculum development along with Asian countries. IHP 7 collaborated with The Energy and Resource Institute (TERI) to provide wider education for sustainable development support to India and to improve cooperation with non-governmental institutions.

There was a call concerned with water technologies organised by the Directorate-General for Research and Innovation of the European Commission (DG RTD) and the Department of Science and Technology (DST) of India. As an outcome of this call, four EU and four Indian projects were selected for funding namely ECO-INDIA (Energy-Efficient, community based water and wastewater treatment systems for deployment in India), NAWATECH (Natural Water systems and Treatment Technologies), SARASWATI (Supporting consolidation, replication and up-scaling of sustainable waste water treatment and reuse technologies for India) and SWINGS (Safeguarding water resources in India with green and sustainable technologies). This joint collaboration led to the evolving technologies for sustainable water/ wastewater treatment, reuse and recycling with an unprecedented scope for replication and joint business development. Indo-EU project "SaphPani" (www.saphpani.eu) funded by EU for collaborative research including 20 partners from India, Sri Lanka, Europe and Australia. The project aimed towards the improvement of natural water treatment systems including River Bank Filtration (RBF), Managed Aquifer Recharge (MAR) and wetlands in India. The project worked on the case studies in various parts of India, particularly water stressed urban and peri-urban areas.

The India-France SARAL/AltiKa mission is the first Ka-band altimetric mission dedicated primarily to oceanography. The mission objectives were firstly the observation of the oceanic mesoscales but also global and regional sea level monitoring, including the coastal zone, data assimilation, and operational oceanography. SARAL/AltiKa also proved to be a great opportunity for inland water applications, for observing ice sheet or icebergs, as well as for geodetic investigations. The mission ended its nominal phase after three years in orbit and began a new phase (drifting orbit) in July 2016 (Verron *et al*., 2018).

Data sharing is an important aspect of hydrological science studies, be it modelling or prediction. The H^+ Network (http://hplus.ore.fr/en/) of hydrogeological research sites from India and Europe was established with an aim to maintain and coordinate a network of experimental sites to exchange the data towards a better understanding of water cycle and of the aquifer system. It also maintains a research partnership between basic research and professional experience. CSIR-NGRI's Experimental Hydrogeological Park at Chotuppal, Telangana, is one of the research sites in the network. Apart from these, there are many opportunities from DST, India towards collaboration in water science with different countries on the globe.

This review for the period 2001-2018 is showcasing the enormous efforts by Indian researchers in varied fields of surface water and ground water studies. More emphasis is laid to solve the issues related to the coastal hydrology and handling of big datasets acquired by the satellites. This period also witnesses the growth of upcoming areas like palaeoflood hydrology, socio-hydrology, and global networking. The management plans at the watershed as well as basin scale are incorporated in global projects towards sustainable development.

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Review Article

The Indian Monsoon: Past, Present and Future

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The Indian region receives 80% of its annual rainfall during summer. The spatial and temporal variation of the Indian summer monsoon has wide scale implication on the socioeconomic aspect of the people living in the Indian subcontinent. The study of monsoon has always been in focus starting from the British period. The understanding of the monsoon processes has improved with time as a result of availability of better observation, computational facility, better models and improved parameterization physics. In this paper, we try to review earlier works dedicated to the understanding of various monsoonal processes and predictions. The major synoptic monsoon studies such as on the low-level jet, tropical easterly jet, mid tropospheric cyclones, onset vortex etc. are analyzed. Afterwards, the major works done during 21[st] century is discussed with special focus on the interannual and intraseasonal variability, teleconnection and on recent role of dust on the monsoon. The various forecasting methods of monsoon and the information dissemination is extensively debated along with the future prospects in this field.

Keywords: Monsoon; Century; Summer; Post-independence

History of Monsoon Research in India

Monsoon is characterized by the seasonal reversal of wind, which is generally associated with precipitation. This arises due to the differential heating between land and Sea. The word 'Monsoon' has been derived from the Arabic word 'Mausam' (means season). The Indian Summer Monsoon (ISM) contributes around 75-80% of total annual rainfall over India (Maharana and Dimri, 2014 and 2016). Hence, its spatiotemporal distribution influences the socio-economic conditions of more than a billion lives in the subcontinent through affecting the agricultural productivity or food security. This attracts many researchers from centuries to understand the mechanisms and processes associated ISM. Few pioneer researchers of ISM during British periods were H F Blanford, John Eliot, W L Dallas, G T Walker, S K Banerjee, S C Roy, V V Sohni, K R Ramanathan, S Basu and many more (Tyagi *et al*., 2012). G T Walker and Field promoted the upper air observation through pilot balloon, meteosondes and kites. The availability of upper air data helpe to study the monsoon structure (wind, temperature and moisture); which led to better a understanding of ISM processes. Eliot emphasized collecting data over Sea, which laid the foundation of very first monsoon mission during 1897. Post-independence, Indian meteorology got an impetus with the increase in the observational station network, satellite, ocean observations and field experiments such as International Indian Ocean Experiment (IIOE), Indo-Soviet Monsoon Experiment (ISME), Monsoon-77 and Monsoon experiment of 1979 (MONEX-79). The introduction of numerical weather prediction techniques further increased the understanding of various associated processes and its prediction capabilities.

Monsoon Studies in the Last Century

The major features associated with ISM are the seasonal reversal of wind, formation of low-level jet (LLJ) and upper level topical easterly jet (TEJ; Raman *et al*., 2009). These features are directly associated with the strength and variability of ISM. The cross equatorial flow during summer arises due to the two successive warming over land (Tibetan high and

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northwest India; Yanai *et al*., 1992). These winds accelerate along the African coast and become LLJ or Find later jet, which moves towards the intertropical convergence zone over northern India (Findlater, 1969-1970).This LLJ brings in the moisture towards Indian landmass and directly modulates the rainfall over India. Findlater (1970) suggested the splitting of LLJ at Arabian Sea into two branches: one branch approaches Indian subcontinent while other moves towards southeast crossing Srilanka. Krishnamurthy *et al*. (1976) explained the splitting of the Somali jet in terms of baroclinic instability. However, the LLJ does not split over the Arabian Sea rather it changes its position over India (passing through Indian land mass or flow over Srilanka) which causes active and break monsoon spells over India, Fig. 1 (Joseph and Sijikumar, 2004.©American Meteorological Society. Used with permission). The convective heating primarily drives this positioning of LLJ. Koteswaram (1958) discovered the upper level easterly jet, which is associated with an upper level anticyclone, a result of upper level divergence of the winds as a consequence of the ascent of low level converging monsoon flow over the Indian region. ISM is associated with few major synoptic systems, which are responsible for heavy rainfall during monsoon such as the monsoon trough (MT), monsoon lows, depressions, mid-tropospheric cyclones (MTCs) etc. The zonal motion of MT is maintained by Coriolis term and horizontal pressure gradient force (Keshavmurthy and Awade, 1970). The MTCs are characterized by warm (cold) anomaly above (below) the cyclone (Krishnamurthy and Hawkins, 1970). These mainly dominate around 700hPa to 500hPa and modulated by the latent heat release (Carr, 1977). Monsoon depressions generally originate over the Bay of Bengal and cause rainfall by its westward movement through Odisha and West Bengal (Rajeevan *et al*., 2001) with a periodicity of 3-10 days. The westward movement is due to the formation of vorticity along the western sector (Rajamani and Sikdar, 1989).

The onset time of ISM is very important as it directly influences the agricultural yield. Several criteria for onset of monsoon has been defined based on the rainfall estimation (Ananthakrishnan and Sonam, 1988), organized deep convection (Soman and Krishnakumar, 1993), through isopleths (Ramage, 1971) and formation of onset vortex over the Arabian

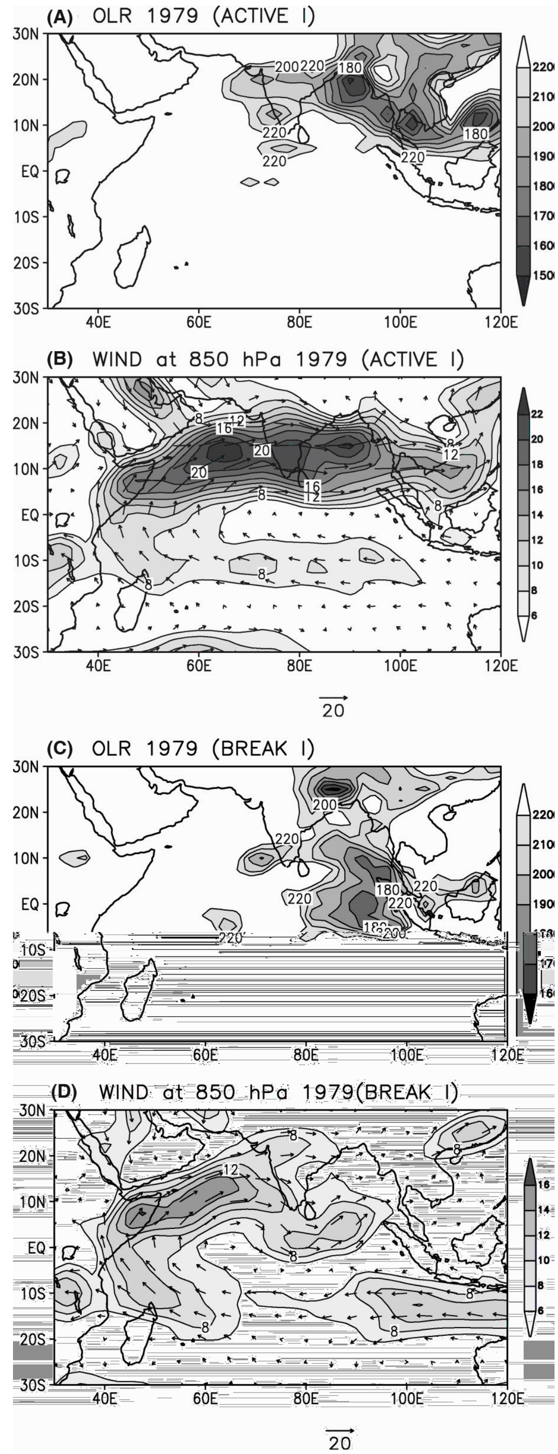

Fig. 1: Average (a) OLR and (b) 850-hPa zonal wind averaged for the first active monsoon spell of 1979 (23 Jun-2 Jul). Isolines of OLR at 220 and less at intervals of 10 W/m2 and of zonal wind at 6 and more at intervals of 2 m/s. Avg of (c) OLR and (d) 850-hPa zonal wind averaged for the first break monsoon spell of 1979 (17-23 Jul). Isolines of OLR at 220 and less at intervals of 10 W/m2 and of zonal wind at 6 and more at intervals of 2 m/s (Joseph and Sijikumar, 2004. ©American Meteorological Society. Used with permission)

Sea (Krishnamurthy *et al*., 1981). The drought years are associated with weaker near tropical zonal westerly winds, stronger mid-latitude westerlies and a shift in the Tibetan high and divergence eastward as compared to a normal year. The heavy rainfall years are associated with strong upper level divergence of wind over the region of active convection (Murakami, 1976). The activity of MT and its oscillation from central India to foothills give rise to active and break spells of ISM (Keshavmurthy *et al*., 1980). Pant (1983) suggested a rapid fall of temperature over Tibetan plateau that leads to a break spell of monsoon. Whereas, the revival starts with the gradual rise of temperature and strengthening of the Hadley cell.

Sikka and Gadgil (1980) found a two maximum cloud zones (MCZ) from the analysis of satellite pictures over the longitude range of 70-90^{o}E, Fig. 2 (Sikka and Gadgil, 1980. ©American Meteorological Society. Used with permission)). The first one over the monsoon zone just north of 15^{o}N (continental) and the second one around 0-10^{o}N (oceanic). The break condition arises just prior to the disappearance of MCZ over monsoon zone. The secondary MCZ becomes active during this period, moves northward to re-establish the MCZ over monsoon zone and hence revives the rainfall. The primary MCZ appears in around 74% of the total days over monsoon zone during peak monsoon days. It implies that the continental MCZ is active for most of the period, while the oceanic MCZ becomes active for a brief period and leads to a break period. The monsoon intraseasonal Oscillations (MISOs) have a broad time scale of 10-90days. Within this broad band, two major monsoon intraseasonal oscillation are identified as the westward propagating 10-20 days oscillation (Krishnamurthy and Bhalme, 1976; Krishnamurthy and Ardunay, 1980) and northward propagating 30-60days oscillation (Sikka and Gadgil, 1980; Dakshinamurthy and Keshavamurthy, 1976). Joseph *et al.* (1994) identified an active (suppressed) convective belt operating over south of Arabian Sea to South China Sea (equatorial west northern Pacific Ocean). This convection has systematic temporal evolution with a periodicity of 30-50 days. The warm sea surface temperature (SST) anomaly over equatorial central Pacific delays the shift of convection towards Indian Ocean and hence delays the onset of monsoon. The northward propagating cloud movement from equatorial Indian

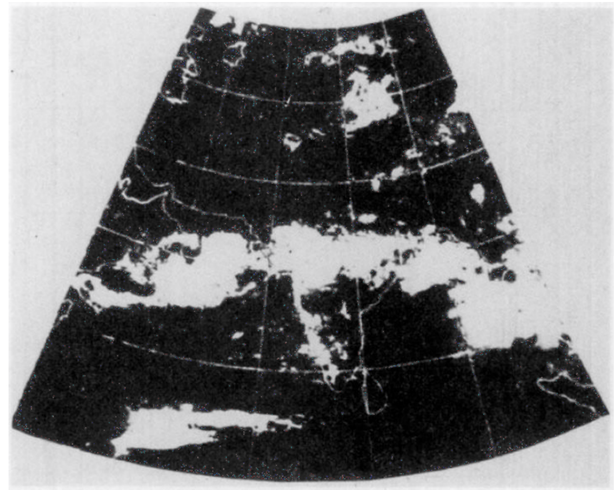

Fig. 2: Monsoon cloud zones on 8july 1973 (Sikka and Gadgil, 1980. ©American Meteorological Society. Used with permission)

Ocean towards foothills of the Himalayas with a periodicity of 30-40 days over India during summer time is linked to the active and break cycle of the ISM (Sikka and Gadgil, 1980; Krishnamurthy and Subrahmanyam, 1982). Goswami and Shukla (1984) illustrated the Hadley circulation oscillates in two major dominant range of periodicity of 10-15 days and 30-40 days. These oscillations are result of interactions between moist convective and dynamic processes similar to the oscillation observed over tropical Indian Ocean (Madden and Julian, 1971; Sikka and Gadgil, 1980). ENSO is a coupled atmosphere-ocean phenomenon, in the tropical ocean influencing the ISM in interannual and interdecadal scale. The warmpool (warm phase of ENSO) over the equatorial Pacific early in the years leads to decrease in the monsoonal rain leading to drought over India (Rammuson and Carpenter, 1982). Sikka (1980) found that good monsoon years are associated with higher cyclogenesis, which keeps the monsoon trough near its normal position and cyclonic vorticity causes heavy rainfall over India.

In the last century, various modeling techniques were also used to understand the ISM processes. The MT, which is baroclinically unstable at lower level, provides the triggering mechanism for the formation of monsoon depression (Shukla, 1978; Mishra and Salvekar, 1980), while conditional instability of second kind (CISK) is responsible for growth of monsoon depression (Charney, 1973). Pearce and Mohanty (1984) illustrated that the monsoon onset is associated with the strong cross equatorial flow and maintained by the release of latent heat. The moisture builds up over Arabian Sea can be considered as the first indicator of onset of monsoon (Mohanty *et al*., 1984), while a rapid increase of the kinetic energy of non-divergent flow just before the onset is also observed (Krishmamurthy and Ramanathan, 1982). Annamalai *et al*. (1999) proposed a dynamical monsoon index (DMI), which describes the interannual variability of rainfall, is skewed towards the negative side (break spells). The interannual and intra seasonal variability are connected to the north-south movement of tropical convergence zone (Fennessy and Shukla, 1994). Webster and Yang (1992) talked about the predictability barrier of complex monsoon-ENSO relation and their selective interaction. The ENSO phenomenon should be considered while formulating a climate model for long-range forecast (Torrence and Webster, 1999).

Monsoon Study During the 21st Century

With the advancement of modern technology (computational facility, dense high quality observational network, quality of observation and improved numerical modeling approaches), the monsoon studies have taken a larger step forward in 21st Century. In this section, studies related to ISM will be discussed with special focus on the onset, different component of ISM, interannual and intraseasonal variability, role of teleconnections (atmosphere-ocean coupling), role of dust along with the improvement in prediction and forecasting techniques.

Variability and Predictability

Mooley and Shukla (1989) studied the origin, growth, propagation and dissipation of the low-pressure systems (LPSs) along with their contribution towards the monsoonal rainfall whose lifespan ranges from 1-2 weeks. The LPSs cause wide spread rainfall as compared to cyclonic storms during ISM. They generally originated over Bay of Bengal and travel northwestward causing rainfall along its way (Jadhav and Munot, 2007). The number of LPS per month during monsoon ranges from 3-6 with August having the maximum number of LPSs. The rainfall over Odisha during monsoon is associated with the number of LPS days (Mohapatra and Mohanty, 2008). Mesoscale convective systems (MCSs) have produced very heavy rainfall (~100cm/day) over Mumbai during 27 July 2007 causing devastated flood (Jenamani *et al*., 2006). The numerical simulation of Mumbai flood event shows that the initial part of this rainfall event was contributed by cloudburst whereas the later phase is due to the continuous rainfall associated with thunderstorms due to the activity of mesoscale clouds (Vaidya and Kulkarni, 2007). The moisture flux and convergence along with the vorticity lead the initial mature stage (Bohra *et al*., 2006). The modeling study of Mumbai flooding and Odisha super cyclone (1999) illustrated that the prediction is very sensitive to the dynamics, physics and horizontal resolution embedded in numerical models (Sikka and Rao, 2008). They also emphasized the importance of the data assimilation for better prediction of weather extremes. The heavy rainfall events over west coast of India are associated with the MTCs, which intensify the lower monsoon level circulation with cyclonic shear. This extreme precipitation spell sometimes leads to disastrous consequences and hence the early prediction of these would be a great benefit for the society. The model simulations with nudging and assimilated data are able to represent the location, time of heavy rainfall and movement of rain band associated with MTCs (Routroy *et al*., 2005; Bhaskar Rao and Prasad, 2005). Rao and Sivakumar (1999) identified that the monsoon vortex originates from a mini warm pool (core temperature >30°C) during the pre-monsoon season over southeastern Arabian Sea. However, the growth and sustenance of warm pool greatly dependent upon the fluxes, low-level winds and salinity stratification (Kumar *et al*., 2009).

Various methods and indices are proposed to compute the monsoon onset over Kerala (MOK). Fasullo and Webster (2003) derived the onset and withdrawal dates of monsoon by analysing the variability of hydrological cycle. They computed an onset index, which represents the variability in monsoon, analyses the effect of monsoon teleconnection and takes care of the false onset signals. Few more onset indices have been computed using the rainfall, circulation and pressure gradient between west Asia and west equatorial Indian Ocean (Pai and Nair, 2009; Joseph *et al*., 2006; Chakraborty and Agrawal, 2017). The build-up of the moisture over Arabian Sea and strength of the Hadley cell are also the indicators of monsoon onset (Simon *et al*., 1994, 2006; Joseph *et al*., 2003). Goswami and Xavier (2005) constructed dates for MOK as well as that for withdrawal of monsoon based on the north-south gradient of the tropospheric temperature gradient, giving an objective definition of the length of the rainy season (LRS). Webster and Yang (1992) calculated an index of Indian monsoon (WYI index), based on the vertical zonal wind shear, which is a good indicator of planetary scale variation of ISM. However, regional aspect of ISM is not well represented as it is poorly correlated with the all India monsoon rainfall Index (Parthsarathy *et al*., 1992). Further, Goswami *et al*. (1999) proposed another index of ISM, a Monsoon-Hadley circulation Index (MH index) which is able to represent the interannual variability of rainfall over India better. The index is meridional wind shear anomaly (between 850hPa and 200hPa) of the seasonal average over the extended Indian monsoon region (this includes rain over neighbouring land and sea). The MH index is found to be superior as compared to WYI; because it is not only well correlated with the south equatorial Indian ocean SST but also with the all India rainfall index (which represents the rainfall variability over India).

Recently, many scientists tried to study the interannual variability of ISM using observation data and different Regional and Global Climate Models (GCMs and RCMs; Ratna *et al*., 2011; Seth *et al*., 2007; Bhate *et al*., 2012). The interannual variation of rainfall (drought and flood year) is directly related to intraseasonal variability or number of active and break spells (Krishnamurthy and Shukla, 2001; Gadgil and Joseph, 2003). The draught (flood) years have greater negative (positive) rainfall anomaly over India. Maharana and Dimri (2014) studied the interannual variation of rainfall over India and its homogenous sub-regions using a RCM. They reported that the model is showing good skills in simulating the normal and draught years as compared to the excess rainfall years.

The modulation of LLJ around its mean position results in the active and break spells (Joseph and Sijikumar, 2004). The speed and width of TEJ is relatively higher during active spell as compared to the break spells (Roja Raman *et al*., 2009). The concurrent drying of upper troposphere and weakening of low-level convergence leads to break spell. The satellite observation supported the upper tropospheric drying (relative humidity decrease by 30%) over tropical convergence zone during just 3 days before the break spell (Rao *et al*., 2004; De and Mukhopadhyay, 2002). A composite analysis shows that the active and break cycles and associated convection are related to the fluctuation of tropical convergence zone over India (Goswami and Ajayamohan, 2001; Sikkaand Gadgil, 1980). However, the seasonal mean rainfall is determined by the frequency of the intraseasonal oscillation. The monsoon breaks are characterized by enhanced (suppressed) convective activity over equatorial Indian Ocean (Southeast Asia) (Krishnan *et al*., 2000). Break spell approaches with the arrival of high-pressure Rossby wave over northwest India. The most striking observation during break spell is the decoupling of the slow eastward moving non-convective anomaly from the faster northward moving anomalies, Fig. 3 (Krishnan *et al*., 2000.©American Meteorological Society. Used with permission). A peculiar quadrapole structure of OLR is observed during the break period over Asia west of Pacific region. The negative anomalies over east Pacific during break spell reflect that the convection over India is linked at interannual (ENSO) as well as intraseasonal scale. The primary drivers for the monsoon variability are the slowly varying boundary conditions (SST, surface temperature, snow etc.) of the preceding winter and pre-monsoon (Kripalani *et al*., 2004). Maharana and Dimri (2016) identify a region (monsoon core region: MCR) where the monsoon trough oscillates during the monsoon period. The rainfall over this MCR is evaluated to compute the active and break spells and are compared with the earlier studies (Table 1a-b). The 3-4 days spell makes 80% of the total active spells while 10% of the break spells last longer than 10days (Rajeevan *et al*., 2010). This study confirms the presence of heat-trough type circulation over MCR during break period.

This 10-20days and 30-60 days oscillation dominates the intraseasonal oscillation of the tropical region. The onset of monsoon is triggered by a poleward propagating monsoon intraseasonal oscillation of 30-60days. The similar temporal characteristics of 30-60 days oscillation and MJO are found. It is also observed that the eastward propagating clouds along the equator is related to northward propagating convection. Further quantification shows that 78% of the northward propagation is related to MJO (Lawrence and Webster, 2001). Jiang *et al*. (2004) proposed that

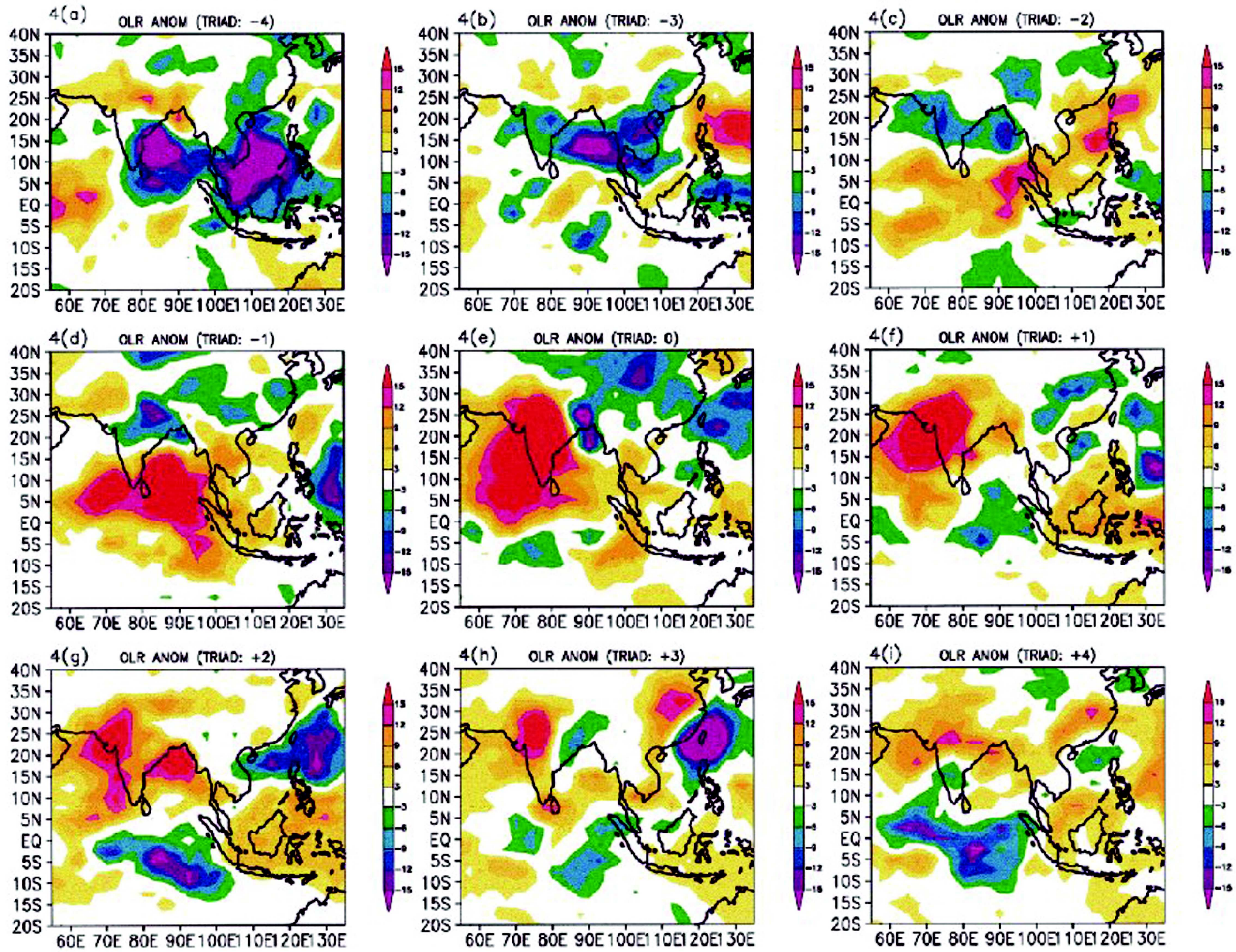

Fig. 3: Sequence of composite OLR anomalies showing the evolution of monsoon break (Triads) (Krishnan *et al*., 2000. ©American Meteorological Society. Used with permission)

"moisture feedback convection mechanism" and "vertical wind shear mechanism" are driving the poleward propagation of cloud bands. Krishnamurthy and Ardanou (1980) reported a 10-20days westward moving oscillation during monsoon, which plays a major part in defining the active and break period of ISM, as a convectively coupled westward moving Rossby wave (Chatterjee and Gowami, 2004). Goswami *et al*. (2006a) reviewed the contribution of slow processes such as the air-sea interaction (ENSO) in generating the interannual variation of mean annual cycle. They concluded that the limitation in the predictability of the Asian Monsoon is due to the larger contribution of internal IAV as compare to predictable external IAV. The tropical climate is considered to be very less sensitive to the Initial condition, whereas the Indian monsoon region is found to be a great exception (Krishnamurthy and Shukla, 2000), and hence very difficult to simulate through a model. The monsoon ISOs are very difficult to predict because of their quasi-periodic nature, which is beyond the current skill of prediction of medium range forecast. However, the potential predictability of break period is much higher as compared to active period (Goswami and Xavier, 2003).

Goswami and Xavier (2005) suggested the length of rainy season (LRS) is determined by the meridional tropospheric temperature gradient. The ENSO shortens (expands) the LRS and hence affecting the rainfall distribution over India. The warm pools of the Indian and western Pacific Ocean modulate the ISM. The years with moderate to cool pools over equatorial Pacific producing heavy rainfall, while the warm pool not necessarily producing draught over India in the recent past. Hence, the Monsoon-

ENSO relation is found to be weakening during these decades (Krishna Kumar *et al*., 2006). This answer to the declining relation of Monsoon-ENSO is provided through the discovery of a coupled atmosphere-ocean phenomena called the Indian Ocean Dipole (IOD; Saji *et al*., 1999). IOD is characterized by two phases: positive phase (eastern equatorial Indian Ocean is cooler compared to equatorial west Arabian Sea) and negative phase (the opposite warming). During positive (negative) phase, the convection over eastern zone is suppressed (increased). The negative phase increases the convection over equatorial region and influence the Hadley Cell in such a way that the convection over Indian region suppressed and leads to lesser rainfall or weakening of ISM. The atmospheric part of IOD is termed as EQINOO (Gadgil *et al*., 2007), which describes the sea level pressure modulating the wind and organized convection along the equatorial Indian Ocean. Analyzing the teleconnections, Gadgil *et al*. (2004) found that if the ENSO and EQINOO are in phase than they suppress the convection over India leading to a drought year. The effect of IOD explains why few recent El-Niño years didn't lead to draught over India (Ashok *et al*., 2001; Sreejith *et al*., 2015; Behera and Yamagata, 2003).

The multi decadal variability of ISM is poorly understood due to lack of good quality and long-term observations (Goswami, 2006). The analyses of long-term proxy data (from tree ring and oxygen isotope method) reported a multi-decadal oscillation of Asian monsoon in the range of 50-80 years (Goswami *et al*., 2016), which is an integral part of global multi-decadal mode of 50-80 years such as Atlantic multi-decadal Oscillation (AMO), El-Niño Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO). They also speculate the origin of this variability arises due to the interaction of ocean-atmosphere-land. The teleconnection link between the ISM and north Atlantic in interannual and decadal scale has been reported (Srivastava *et al*., 2002; Rajeevan, 2002). The positive AMO is responsible for longer monsoon period over India by enhancing the meridional tropospheric temperature gradient (Malik *et al*., 2017; Goswami *et al*., 2006). However, this positive correlation between AMO and ISM is only observed after 1750 (Sankar *et al*., 2016). Because of the natural multi-decadal variability, the ISM rainfall is showing a declining trend (Goswami *et al*., 2016) from late 1940s. The mean rainfall and rainfall extremes are expected to increase under the increasing CO_2 concentration in the atmosphere or under a warmer climate. As the present scenario, the declining rainfall trend of ISM shows that multi-decadal variability has a stronger signal as compared to the increasing CO_2 forcings. Therefore, it is interesting to know that the rainfall is going to decrease under the influence of natural variability while the rainfall extremes are going to increase under warming climate.

Observation (National Observation Network and its Improvement)

This section deals with the role of various organizations in strengthening of the national observational network. The observation data are used for the study of atmospheric processes, preparation of the initial condition for the modelling experiments and the validations of the models.

Role of IMD: Surface Observation : India Meteorological Department (IMD), an agency under the Ministry of Earth Sciences (MoES), Govt. of India (GoI), is mainly responsible for collection of meteorological data from the weather stations, weather forecasting and issue of early warnings. IMD is obtaining meteorological data form 675 Automatic Weather Stations (AWS) and 969 Automatic Rain Gauge (ARG) Stations, which has been increased to 1289 recently. The upper air observation network consists of 62 pilot balloon upper air observatories and 39 radiosondes across the country. Currently, IMD is maintaining 353 Cyclone Warning Dissemination Systems (CWDS) along the vulnerable coastal areas. IMD also utilizes RADAR system to track the cyclones and extreme weather events. These information are quite helpful for forecasting purposes, navigation industries, etc. The updated Doppler RADAR has replaced the conventional RADAR of the early part of the century. Currently, IMD is using 21 RADARs across India and about 9 more RADARs are to be installed across the hilly region of the country. However, due to some reasons the expansion these RADARs could not happened. The data collected by IMD is available on the Global Transmission System (GTS) for forecasting purposes.

Role of INCOIS: Ocean Observation : Indian National Centre for Ocean Information Services (INCOIS) is the main agency involved in the collection of ocean observations, disseminating warning and advice to various stakeholders such as the scientific community, common people, Government and industries.

INCOIS is mainly responsible for maintaining ARGO data centers. It has contributed 401 ARGO floats to the global ARGO float network across Indian Ocean, out of which 136 are still in active state. The ARGO floats measures the temperature and salinity profile of upper ocean along with pressure, dissolve oxygen, nitrate and pH. National Institute of Ocean Technology (NIOT) has deployed 20 moored buoys to measure oceanographic and surface meteorological variables along with the thermal structure of the upper ocean. The number will soon be increased to 40. Several sub-surface moorings, anchored at the bottom, are deployed for long-term current measurements. The drifting buoys are primarily used for the measurement of SST. The tsunami buoys are modified surface buoy, which is connected to the Bottom Pressure Recorder (BPR) through acoustic modems. The research moored array for African-Asian-Australian monsoon analysis and prediction (RAMA) are designed to study the role of Indian Ocean on ISM. It is a part of the Indian Ocean observing system program and consists an array of basin scale moored buoy. The array consists of 38 surface and 8 sub-surface moorings for the measurement of current in upper 300-400m through acoustic Doppler current profiler along with the SST anomalies. These collect the high-resolution oceanic and meteorological information for climate research and forecasting (Mcphaden *et al*., 2009). This is designed to study the ocean-atmosphere interaction, mixed layer dynamics and intraseasonal oscillation in seasonal to decadal time scale. The main objectives of this project is to understand and forecast of major monsoon systems around the Indian Ocean and other part of the world, which are linked through teleconnections.

Satellite Observation : The space programme of India is led by Indian Space Research Organization (ISRO), which launched many satellites for the observation of earth resources along with the scientific studies of the earth systems. These satellite data are utilised for remote sensing and meteorology. Another advantage of utilising satellite data is its higher spatial coverage, data availability over difficult terrain at a higher temporal resolution. India launches INSAT-3D, an exclusive meteorological satellite, for earth as well as ocean monitoring. This provides the vertical profile of temperature (up to 70km), humidity (up to 15km), fog, SST, atmospheric motion vectors, outgoing long wave radiation, total precipitable water etc. in the atmosphere along with the integrated ozone from surface to top of the atmosphere by utilising Very High Resolution Radiometer (VHRR). These satellite information are validated with the ground observations. The satellite helps to collect the atmospheric observation at a very high spatial as well as temporal frequency and hence very useful to prepare the initial condition for better weather forecast. Presently, satellites contribute around 90% of the data for assimilation purposes. At present, KALPANA-1 and INSAT-3A satellites are also supporting the meteorological imaging and data collections. INSAT-3A also provides the normalised difference vegetative index (NDVI) and aerosol optical depth. Initially, the Ocean based observations were measured by Oceansat-1, which is replaced by Oceansat-2 on September 2009. The Oceansat-2 satellite provides the information of SST, sea surface elevation, wind vector, coastal weather which some specific oceanic features such as sustainable fishery management, identification of algal bloom and study the ocean productivity. This satellite provides the data at 1 km horizontal resolution. However, many more atmospheric observations could be measured using the satellite.

Monsoon Forecasting and Prediction With Modeling Approach

As discussed in the earlier section, the interannual and intraseasonal variability of monsoon rain has a significant effect on the socioeconomic status and life of Indian population (Maharana and Dimri, 2016; Goswami and Ajayamohan, 2001; Webster *et al*., 1998) by influencing the change in agricultural productivity. Therefore, the prediction of monsoon rainfall in short range, long range and extended range is very important for the country. The monsoon prediction and modeling got a huge thrust at the beginning of the century with the improvement in the availability of long term observed data, higher resolution climate models with improved parameterization schemes, computing facilities and better data assimilation facilities. This makes the Indian modeling and prediction capabilities comparable

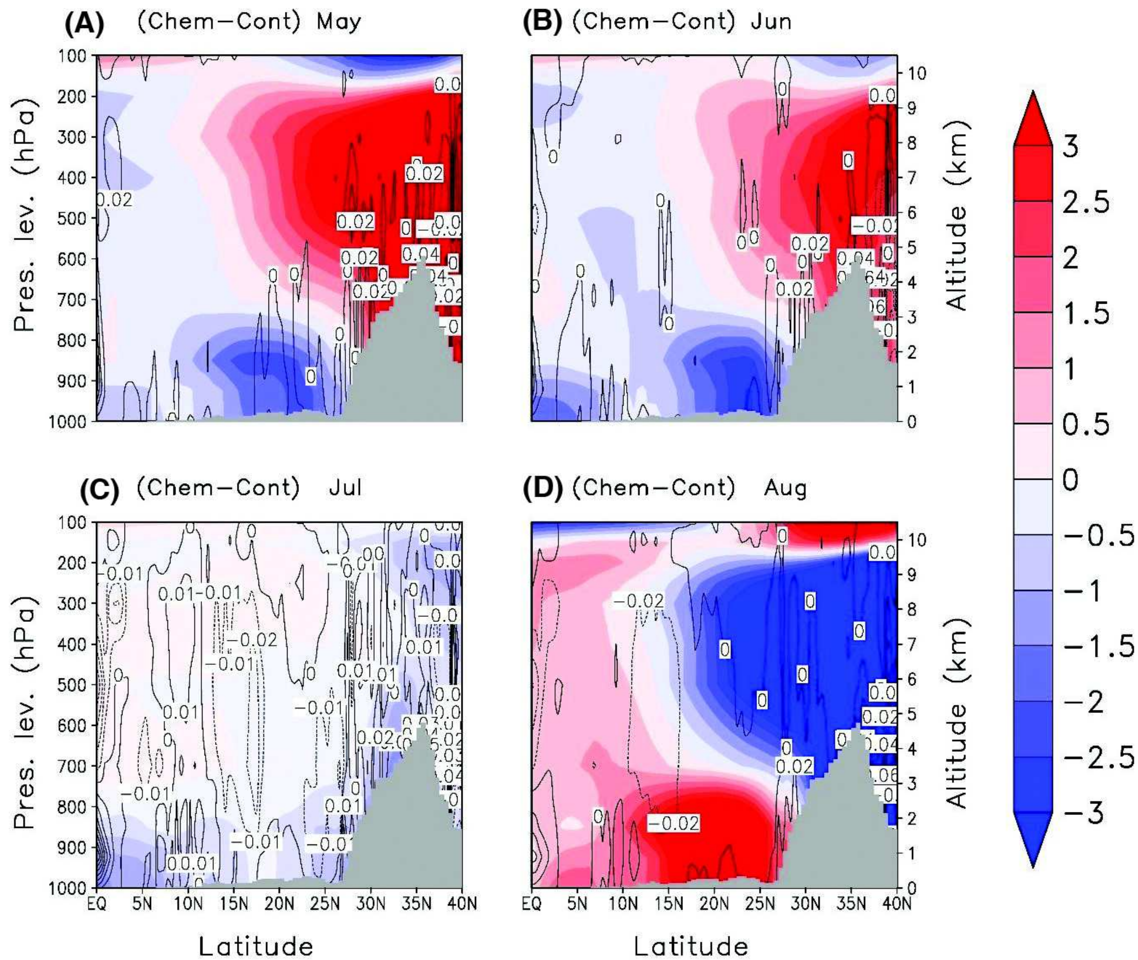

Fig. 4: Pressure-latitude section of difference (Chemistry-Control) of simulated temperature (degC; shaded) and omega (hPa/s; contour) averaged over 70E-90E during (a) May, (b) June, (c) July and (d) August (topography is shown in grey shade). The primary Y-axis represents the pressure levels (hPa) and secondary Y-axis represents altitude (kms)

to with of other developed countries. This current status in modeling and prediction is achieved through proper capacity building in modeling and planned upgradation of the high performance computing systems by MoES through Indian Institute of Tropical Meteorology (IITM). The National Monsoon Mission (NMM) started by MoES with an aim to develop a state of the art dynamical prediction system for monsoon rainfall at different time scale (http://www.tropmet.res.in/monsoon/files/about_us.php). The main objectives of NMM is to predict the rainfall variability well advance in order to minimize the loss in agriculture yield through the improvement of model skill for short range, long range and extended range forecast. IITM involves in the improvement of seasonal and intraseasonal forecast, while National Centre for Medium Range Weather Forecasting (NCMRWF) is engaged in the improvement of the medium range forecast up to two weeks. IMD makes these usages of these inputs for operational purposes. A huge amount of funding of around 290cr has gone to improve these forecasts during last 5 years from 2012 to 2017 (http://www.moes.gov.in/programmes/monsoon-mission-india).

Initially, a coupled model "Climate Forecast System" is adopted for the forecasting purpose by MoES and has been constantly improved by IITM researchers. Currently for operational purpose, IMD is running a state-of-the-art global model for deterministic weather prediction at a horizontal resolution of 12km resolution (http://nwp.imd.gov.in/index.php). Recently, India has ordered two state-of-the-art global prediction systems (EPS) for making 10days probabilistic forecast with a horizontal resolution of 12km. At every forecast cycle, the system produces an ensemble of forecasts with slightly varying initial conditions. From where it was a decade ago, this is a significant advancement in capability of the Indian forecasting system.

Earlier the extended range forecast was made using statistical model (Jones *et al*., 2004), empirical model (Goswami and Xavier, 2003; Dwivedi *et al*., 2006) and dynamical model (Webster and Hoyos, 2005). Recently, the improvement in extended range forecast (7-30days) helps to bridge the gap between medium range forecast and seasonal forecast. These forecasts help to predict the intraseasonal variability or the active and break spells of ISM, which will be beneficial for the agriculture and water resource management sector. The potential predictability of the intraseasonal oscillation is around 25 days (Goswami and Xavier, 2003 and Waliser *et al*., 2003a). The atmosphere-ocean interaction plays a major role in defining the intraseasonal variations of ISM (Fu *et al*., 2003). Therefore, for prediction of intraseasonal oscillations a ocean-atmosphere coupled climate model is required. An ensemble of coupled model climate forecast system version-2 (CFSv2, Saha *et al*., 2014) at different horizontal resolutions is used operationally by IMD for this purpose, such as CFSv2 and bias corrected CFSv2 at T382 (38km) along with CFSv2 and bias corrected CFSv2 at T126 (100km) (http://nwp.imd.gov.in/erf_outlook.php). The model verification and prediction are made over four-rainfall homogenous region over India such as northeast India, central India, northwest India and south peninsular India.

The long range forecasting (LRF) of ISM is very old in the Indian context starting from the few pioneer of this study (Walker, 1910). The LRF in India is based on the statistical regression method (Rajeevan *et al*., 2007); however, this method has been updated with time by rejection (addition) of less (more) significant old (new) parameters (Tyagi *et al*., 2012). The climate prediction models are evolved from NWPs, where the representation of earth system complexity and atmosphere-ocean coupling is given priority. In the early stages of development, most models failed to provide the seasonal forecast because of ill representation of seasonal surface processes and internal variability leading to less forecast skill (Kang *et al*., 2004; Krishnamurthy *et al*., 2006, Kumara *et al*., 2007). The prediction skill of coupled model found to be much higher as compared to the standalone GCMs (Preethi *et al*., 2010) and the skill further improves with the consideration of model ensemble (Rajeevan *et al*., 2012). The predictability may further improve by applying bias correction methods at each grid point and super-ensemble technology for better LRF of rainfall. Therefore, there is a lot development yet to be done for the improvement of dynamic seasonal monsoon prediction. A coupled climate model CFSv2 at T382 (38km) is currently used for operational seasonal forecasting of monsoon or longrange prediction of monsoon.

Apart from these improvements in the monsoon forecast, a major step forward in the field of meteorology is the development of first Indian Earth System Model (IITM ESM, Swapna *et al*., 2015). As the commitment to improve the CFSv2 under the NMM, the seasonal forecast model was upgraded to an Earth System Model for long-term climate analysis. The IITM ESMv1 is created by replacing the ocean model, component of CFSv2 MOM4p0 by MOM4p1. The objective behind the development of IITM ESM is to study the detection and projection of climate change over south Asian monsoon region. This model is further upgraded to IITM ESMv2 by introducing time varying aerosol forcings and land-use and land cover changes (Swapna *et al*., 2018). This updated version shows much more improvement in the climatology of large-scale features and better representation of teleconnections with climate drivers leading to better representation of variability of ISM. It is a matter of pride for the Indian scientific community as IITM ESMv2 becomes the first model from India to contributes to the sixth assessment report (AS6) of the Intergovernmental Panel for Climate Change (IPCC).

The prediction of shorter scale intraseasonal variability is more useful for the society than the seasonal rainfall forecast (Webster and Hoyos, 2005). They emphasized on the careful selection of predictors to improve the forecast. A modelling study using mesoscale modeling version 5 (MM5) shows that the mean rainfall and its intraseasonal variability during ISM is very sensitive to the choice of cumulus parameterization scheme (Ratnam and Krishnakumar, 2005). Waliser *et al.* (2003a,b) found a positive relationship of model simulated intraseasonal variability and intra-ensemble variability of monsoon rain. The interannual and intraseasonal variation of ISM is linked to the synoptic convective systems, which is related to SST through a complex relationship (Gadgil, 2000; Sen Gupta and Ravichandran, 2001). Thus, it is recommended to use of satellite and observed data over sea is essential to understand the monsoon-ocean coupling. The ocean around the Indian subcontinent are interacting with the atmosphere from diurnal to interannual scale, which ultimately affects the ISMR. Therefore, these variabilities due to the air-sea interaction need to be understood properly using various observations and modelling studies, which will help for better prediction of the monsoon in future.

The interannual variability of ISMR have a greater impact on the agriculture (Gadgil *et al*., 1999). The longrange forecast of ISM before one season and extended range forecast of dry and wet spell before 2-3 week is very important in this regard (Webster *et al*., 1998; Sperber *et al*., 2000). The major reason for prediction failure is due to the partial representation of land-sea interaction and systematic bias associated with model output (Sperber *et al*., 2000). Goswami and Shukla (1991) tried to quantify the predictability limit of a coupled atmosphere-ocean model over tropics with an ensemble approach. The rapid growth in prediction error in forecast is due to the tight coupling of ocean and atmosphere, where the ocean model is not able to represent the correct SST anomalies. They illustrated that the atmospheric component is mainly responsible for a part of one-month prediction error, which grows with time and hence suggested the improvement of the atmospheric component for increasing prediction skill.

Monsoon Chemistry Interaction and Future Projections

The atmospheric dust modulates the local energy budget, which ultimately effects a large-scale phenomenon like ISM. Many researches try to understand the effect of dust on ISM either by analyzing observation data or modeling approach (Lau *et al*., 2006; Ramanathan *et al*., 2005; Chung and Ramanathan, 2006; Meehl 2008). There are two different school of thoughts on how the aerosols influences the ISM. Ramanathan *et al.* (2005) showed that the accumulation of aerosol cools the central Indian region; hence decrease the temperature gradient between sea resulting in to less rainfall. However, Lau *at el*. (2006) shows that the absorbing aerosol along the Himalayas increasing the tropospheric temperature (elevated heat pump; Fig. 4), which attract the monsoon wind much earlier than the normal monsoon period and cause rainfall at the foothills of Himalayas. The month wise analysis shows that the dust aerosol redistributes the ISMR over India (Maharana *et al*., 2018; submitted to MetAPP).

Many researchers have studied the possible behavior of ISM under future warming scenario using modeling approach. The increasing CO_2 would intensify the ISMR due to gradual rise of temperature, which escalate the evaporation form sea (Meehl and Arblaster, 2003; Kumar *et al*., 2006). May (2011) reported similar finding were under 2^{o}C warming with respect to pre-industrial time along with a decreasing circulation. The projected increase of rainfall over northeast India is around 30% during 2071-2100 (Syed *et al*., 2014). A climate change study using multiple GCMs and RCMs showed that both forcing and physical parameterization schemes play important roles while simulating future precipitation (Niu *et al*., 2015). However, the RCMs simulate early onset of monsoon during 2041-2060. Recently, Chevuturi *et al.* (2018) found an increase in the summer monsoon intensity under 1.5^{o}C and 2^{o}C warming scenario with respect to preindustrial time. In addition to these, there are few more studies dedicated to monsoon behavior under the warming climate (Menon *et al*., 2013a-b).

Tropical Cyclone Prediction

India took a big step forward in the tropical cyclone prediction and monitoring during last two decades. The recent increase in the observational network of surface (AWS and ARG) and upper air observation covering the coastline and islands of India are very useful in this regard, in addition, the satellite observations is very useful to monitor the development and movement of tropical cyclones. The earlier cyclone detection RADARs have been replaced by Doppler Weather Radars (DWRs) along the coastline of India (Mohapatra *et al*., 2014). They are very efficient in detecting the location of cyclone and provide the accurate estimate of the wind speed, rain of the numerical weather prediction in India is helping for accurate predictions of origin, path, landfall and dissemination of the tropical cyclones. Currently, IMD is using global ensemble forecasting system (GEFS) from NCEP, NOAA, US and Unified Model (UM) and Unified Model Ensemble Forecast System (UMEFS) at 12km horizontal resolution for 12 days forecast. IMD also runs Hurricane Weather Research and Forecast (HWRF) model at 12km, 6km and 2km to predict the track and intensity of the cyclone. In addition, IMD also uses the forecast products from other agencies like ECMWF, GFS (NCEP), UKMO (UK) and JMA (Japan) (http://www.pib.nic.in/Pressreleaseshare.aspx?PRID=1539003). The academic community of the country has contributed significantly towards the study of cyclone and its prediction (e.g. Mohanty *et al*., 2012a,b; Mohanty *et al*., 2013). The assimilation of good quality observational data including the data from RADARs in to the numerical models increase their prediction skills in terms of track prediction and intensity (Pattnayak *et al*., 2014, Srivastava *et al*., 2014; Osuri *et al*., 2015). Mohanty *et al*., (2014) illustrates data assimilation could provide better forecast (WRF-ARW) up to 72hours with reasonable errors. Further, the assimilation of satellite-derived wind significantly improves the position of cyclone by 34%. Hence, the error in prediction of cyclone is attributed to the error in the initial conditions (Raju *et al*., 2012).

Social Implication and Future Work

The early prediction of the monsoon will help the farmers to plan their crop and maximizing their yield and profit. IMD and National Center for Medium Range Weather Forecast (NCMRWF) are responsible providing the forecasts. IMD deals with collection of meteorological data, weather forecasting and issue of early warning system (www.imd.gov.in). There are several specialized divisions of IMD, which deals with agricultural meteorology, civil aviation, climatology, hydrometeorology, meteorological telecommunication, satellite meteorology and seismology. The major objective of NCMRWF, which is also under Ministry of Earth Sciences is to develop numerical weather prediction system with increased reliability and accuracy over India (http://www.ncmrwf.gov.in). It includes development of both global and regional weather forecast model in medium range (3-10 days). The medium range forecast based agro-meteorological is crucial for food security of India. These forecasts are disseminated to the agricultural community through agro-meteorological advisory services (AAS). There are 127 agro-climatic zones in India and each have one AAS (Rathore and Maini, 2008). The agricultural meteorology division of IMD was set up in 1932 to provide service to the farming community with the aim to minimize the agricultural loss due to the impact of adverse weather on crops and to make use of crop-weather relationship to boost agricultural production (http://www.imd.gov.in/pages/services_agrimet.php). This division deals with the Gramin-krishi-mausam-seva and dissemination of agromet advisory. The district level Agrometeorological advisory services (DAAS) started in 2008 by IMD in order to provide weather forecast and agricultural advice at district level across the country. It is a mechanism to disseminate the weather information to the farmers with an aim to increase the quality and quantity of the agricultural production. The major information support under AAS includes (Singh and Singh, 2011).

(a) The collection of weather, climate, pest disease and soil data for on-farm strategic and decisions.

(b) District level weather forecast for 5 days.

(c) Translation of climate and weather information into farm advisories (also 5-day forecast) to maximize the benefits from the forecasted weather information and reduce its harmful effects. A broad spectrum of advisory based on the analysis of forecast includes weather sensitive farm operations such as sowing, application of fertilizer based on wind condition and intensity of rain, pest and disease control, quantum and timing of irrigation and timing of harvesting.

(d) Crop modeling to adopt agricultural production system in the changing climate

(e) Timely dissemination of agromet advisory to the farmers.

(f) Effective training, education and extension of all aspect of agricultural meteorology.

With the improvement of skill of weather forecasts in recent times (as mentioned earlier), the usefulness of the agro-met advisories also has increased significantly bringing considerable economic benefit to the stakeholders.

The above discussion shows the importance of ISM on the Indian context in terms of water resource management, agriculture, flood management, food security etc. Therefore, the early and accurate prediction in terms of time and space would be a great benefit for the society as a whole. In addition, the accurate prediction of high impact weather event can save lives as well as property. While our understanding of processes driving the mean and variability of ISM as well as models for prediction of ISM weather and climate have made tremendous strides over the past couple decades, there are still major gaps in our understanding and model skill still remains below limit of potential predictability. Therefore, there is still a lot of scope in this field of study, such as

1. The collection of better quality observational data including satellite information and the expansion meteorological station to remote places
2. The improvement of the model dynamics and various physical parameterization schemes
3. The use of four dimensional data assimilation for better forecast
4. Improvement of coupled model for better representation of air-sea interaction in forecast
5. Use of ensemble model for forecasting
6. Careful use of the observation and model output and efficient dissemination of prediction to the target community.
7. Narrowing down the uncertainty in the model, so that the information can be used directly for policy making

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Review Article

Physical Sciences of the Ocean: A report to IAPSO/IUGG

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A brief sketch of the advances in the oceanographic research in India that deals with physical, chemical and biological processes in the ocean during the period 2000-2018 are highlighted in this report. It is found that there have been significant progress in the research activities in this field with more than 2300 research papers published during the past 18 years. About 4827 Indian researchers were involved in authoring/co-authoring these papers and many publications were co-authored with foreign researchers spread across 44 countries. Notable achievements in the field of ocean sciences in the recent past are (a) a revolutionary understanding on the coupled processes over the tropical ocean and atmosphere, (b) enhanced capability in the numerical ocean modeling and data assimilation, (c) advancements in remote sensing techniques, algorithms and applications, (d) progress in our knowledge on coastal processes, and (e) marine bio-geochemistry.

Keywords: Ocean; IAPSO/IUGC; Physical, Chemical and Biological Sciences; Publications

Introduction

There has been significant advancement in research and development activities in the field of Physical Sciences of the Oceans in India in the 21st century. Since January 2000 to February 2018, 2345 research papers were published in this field. About 4827 Indian researchers were involved in authoring/co-authoring these papers in collaboration with 44 foreign countries. The steady growth in the number of papers published in different areas of physical sciences of oceans can be seen in Fig. 1 which depicts the number of papers published each year. The number of publications steadily rose from about 30 in 2000 to more than hundred in 2006-2007 and then increased rapidly to 240 papers per year in 2015. The same number continued in the later years also. Research areas within the broad category of physical sciences of the oceans, in which significant research have been carried out in India can be further classified as follows (number of publications in each category are given in brackets).

1. Air sea interaction (95)
2. Bio-geochemistry (104)
3. Climate change (85)
4. Coastal studies (94)
5. Estuaries and nearshore waters (260)
6. Marine ecosystem (38)
7. Ocean acoustics (15)
8. Ocean circulation (227)
9. Ocean modeling and data assimilation (205)
10. Ocean optics (75)
11. Physical processes (97)
12. Potential fishing zones (44)
13. Remote sensing (205)
14. Sediment transport (68)
15. Tides, Storm-surges and Sea-level (261)
16. Tsunami (142)
17. Waves (308)

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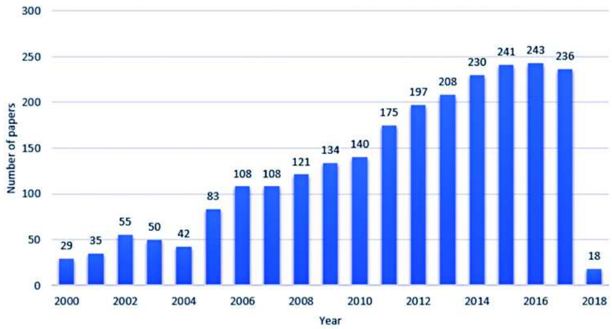

Fig. 1: Year-wise number of publications in the field of Oceanography for the period 2000 to present

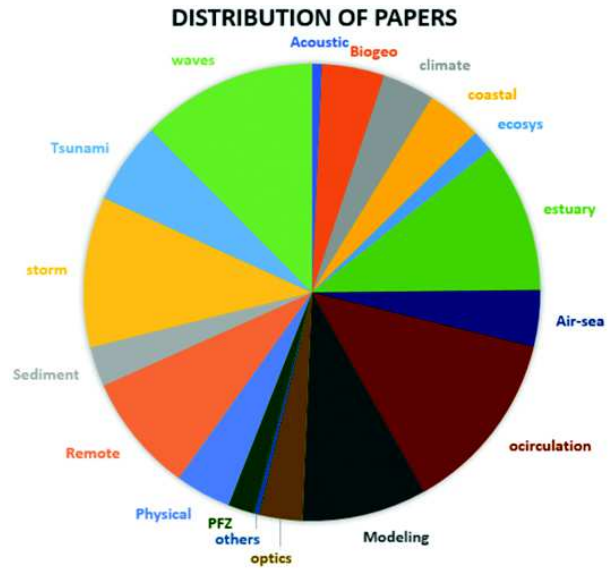

Fig. 2: Distribution of research papers published after 2000 in different sub-categories in the broad field of Oceanography

Topic wise distribution of publication is shown in Fig. 2. It is interesting to note that maximum number of papers were published in the field of tides, storm surge and sea-level changes (261) and this is closely followed by research in estuaries and nearshore waters (260) and ocean modeling and data assimilation (205). Ocean remote sensing (205), Tsunami (142) and ocean biogeochemistry (104) are the other areas which witnessed significant amount of research in the branches of physical sciences of the oceans.

Discussion

A large number of papers were published on the physical processes in the Indian Ocean, which mainly described the large-scale oceanic circulation including that in the coastal waters of India, equatorial Indian Ocean and Southern Indian Ocean. These studies reported the basic mechanisms involved in the observed variability in physical parameters in the Indian Ocean. The deployment of Acoustic Doppler Current Profilers (ADCPs) in the shelf and slope regions in the coastal waters around the country has been providing continuous high-frequency data of coastal currents for the past 10 years and that has enhanced our insights in the variability of coastal circulation. Similarly, the data from Ocean Data Buoys deployed in the deep and shallow waters in the Indian Ocean also helped in improving the understanding of Indian Ocean variability and air-sea interaction processes. Research publications based on the data from observational campaigns in the Indian Ocean, the Arabian Sea Monsoon Experiment (ARMEX), Continental Tropical Convergence Zone (CTCZ), Bay of Bengal Boundary Layer Experiment (BoBBLE), Ocean Mixing and Monsoon (OMM), International Indian Ocean Expedition-II (IIOE-II), etc., have also contributed significantly to the increased number of publications in this category.

Numerical Ocean Modeling has been one of the key research areas among the Indian researchers. 217 papers were published in this area. Access to high performance computational facilities, availability of ocean observations and exposure to state-of-art numerical ocean models have contributed significantly to this achievement. Supported by the ocean modeling activities, Indian National Centre for Ocean Information Services (INCOIS) has setup India's first Operational Ocean Forecast System (INDian Ocean Forecast System, INDOFOS) in 2010, which comprises a suit of numerical ocean models and that has now evolved into one of the leading ocean forecast system in the world. INCOIS is now providing real-time ocean analysis for the global oceans and short-term ocean forecasts for the Indian Ocean. Very high-resolution coastal forecasts are also being provided now by INCOIS for the waters around India. Publications in the field of ocean modeling describe the results of the studies on how the ocean models could be improved by incorporating various physical processes and by using improved atmospheric forcings. Ocean models were also used to study the specific oceanographic features and the processes responsible for the genesis of the ocean features. Ocean data assimilation has also been a focus of research in the last two decades. Fifty seven papers were published on data assimilation, including the studies that described the methodologies of data assimilation and how the data assimilation improved the ocean analysis and forecasts. One of the significant studies in this field described how the ocean analysis in the pre-Argo era are contaminated due to the assimilation of data from the bounded observational network like Tropical Atmosphere Ocean (TAO) moorings in the Pacific.

Publications on air-sea interactions, including those focused on the response of oceans on tropical cyclones and monsoon have also contributed significantly to the growth of research publications in the recent years. Many papers in the field of air-sea interaction also discussed the influence of oceans on tropical cyclones and Indian and South Asian monsoon. The increase in the number of publications on air-sea interaction processes in the Indian Ocean could be largely attributed to the discovery of Indian Ocean Dipole (IOD) in late 1990's and Equatorial Indian Ocean Oscillation (EQUINOO) in early 2000's. These discoveries have revived the research interests in the field of tropical coupled air-sea interaction processes and their influence on the Indian summer monsoon. Several papers were published on the potential impacts of Indian Ocean Dipole, EQUINOO, El Nino and Southern Oscillation (ENSO) on Indian monsoon. Several other studies focused on the processes involved in the initiation and evolution of IOD. Some of the papers revisited the relationship between sea surface temperature and convection.

Studies on Marine Bio-geochemistry also have shown considerable growth in the past two decades. 109 papers were published during this period on Bio-geochemistry which dealt with geochemical and biological processes mostly focusing on studies of Carbon, Nitrogen and Oxygen elements. Several papers were also published focusing the sources, sinks and internal cycles of the trace elements as they have important applications in chronology, paleo-oceanography and ocean mixing. Substantial number of studies on zooplanktons and phytoplanktons described their spatial and temporal distributions. The role of mesoscale dynamics in regulating the phytoplankton biomass by modulating the nutrient input to the surface layer and the mixed layer depth were the focus of some of the publications in this area. Several papers were published on the marine ecosystems. Some publications brought out the need for the conservation of Mangroves and Seagrass Ecosystems. Group level classification of zooplankton and phytoplankton, study of plankton taxonomy, their behavior and adoption to the anthropogenic effects were also studied. Around forty publications came from Indian authors on marine ecosystem during this period. Some of them dealt on how to improve the Potential Fishing Zones (PFZ) identified based on the satellite remote sensed sea surface temperature and Chlorophyll concentrations in the sea water. The additional information on ocean circulation and marine ecosystem parameters are shown to improve the identification of PFZ.

Considerable number of research papers were published on climate change by Indian authors since 2000. They included Indian Ocean warming, sea level changes, changes in primary productivity related to global change, sea surface salinity and hydrographic changes owing to climate change. Some papers reported the Climate Change and Sea-Level Rise and impact on agriculture. Studies using ocean observations and global coupled ocean–atmosphere model simulations have shown that besides the direct contributions from greenhouse warming, the long-term warming trend of the western Indian Ocean during summer depends on the asymmetry in El Niño-Southern Oscillation (ENSO) teleconnection, and the positive SST skewness associated with ENSO during the recent decades.

There are several publications on the changes taking place on the shoreline of India. Most of them focused on mapping and monitoring of coastline changes associated with the Indian Ocean tsunami and tropical cyclones. Few papers reported on coastal pollution and erosion and their implications. The papers on estuaries and nearshore waters of Indian coast described some of the physical and biogeochemical processes with the help of observations and models. Few publications dealt on the mangroves and sea grass. Some papers discussed on the influence of hydrological and anthropogenic factors controlling the abundance and variability of enteropathogens in the estuaries.

Ocean remote sensing is another major area of research during the past few years as remote sensing has established with wide ranging applications in the field of coastal engineering, estimation of sea surface temperature, chlorophyll content, suspended sediment concentration, algal blooms, wave characteristics, identification of Potential Fishing Zones (PFZ), etc. Many papers reported the use of remote sensing and GIS in the mapping and monitoring of coastal resources, detecting shoreline changes, studying coastal landforms etc. The advancement in technology and the availability of high resolution data has attracted many researchers in this field which is highlighted by the increased number of publications in the last decade. Several papers were also published on the algorithms used for the retrieval of various parameters using remote sensing data. Studies on bio-optics also witnessed remarkable growth in the recent years. Papers describing the superiority of regional algorithms for the retrieval of oceanographic parameters using remote sensing methods were also published. Some of the studies described the effective use of statistical and computer aided tools like Wavelet Analysis, Neural Network, etc. for the accurate retrieval of geophysical parameters.

The Indian Ocean Tsumani in 2004 has dragged the attention of many researchers in this field. Indian researchers published 35 papers based on 2004 tsunami. Several studies described how the Indian Ocean tsunami affected various islands in the Indian Ocean and the vulnerability of coasts and estuaries to such natural disasters. Few papers were published on the tsunami early warning system and few addressed the socio economic impacts and mitigation of tsunami. There have been several papers in the field of Paleo-tsunami as well. Overall 120 papers were published from India related to tsunami after 2000.

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Review Article

Recent Seismological Investigations in India

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Recent seismological researches in India can be broadly classified under a) seismogenesis and seismotectonics of Himalaya, Burmese-arc, Andaman-Nicobar subduction zone, the Stable Continental region, b) study of reservoir triggered seismicity, with specific emphasis on earthquakes in Koyna, c) earthquake precursory studies, d) study of tsunamigenic earthquakes and establishment of Indian Tsunami Early Warning System, e) studies on site response, microzonation, earthquake risk, vulnerability, disaster management and risk, and f) use and developments of new seismological methodologies to study the deeper structure of the Indian shield.

On account of the increase in population density and urbanization, the loss of human lives and properties by earthquakes are expected to continue to rise. To develop an earthquake resilient society, it is desirable to undertake seismic hazard microzonation, implementation of early warning system and carryout earthquake drills in critical areas. Further, emphasis have been given on the detail seismolgoical investigations on oceanic plate in the Indian ocean and slow slip earthquakes in the Himalaya.

The article reviews the history, accomplishments, status and challenging trends in seismological research and its applications. It further, shed light on the future directions and the growing needs for society.

Keywords: India; Seismotectonics; Himalaya; Andaman-Nicobar Subduction Zone; Tsunami

Introduction

Seismology was initially defined as the study of earthquakes and related physical phenomena. However, in recent times it does not restrict solely to the above definition due to its applications in diverse fields (e.g. reactor sitting, earthquake prediction and reduction of hazard, search for new fuel and minerals, understanding the deep interior of the earth, forensic etc). Nevertheless, basically, seismologists seek to understand where, when, how, and why earthquakes occur and how seismic waves propagate in the earth. These seismic waves may be generated either by natural way (e.g. earthquakes, volcanics) or by artificial manner (e.g. explosions). The nature of sources and propagation of waves thus generated are important aspects of seismological research. The scientific study of earthquakes evolved from mankind's desire to understand, and perhaps thereby to mitigate seismic hazards. However, many practical seismologists are not concerned with earthquakes per se but use the information derived from artificial seismic sources to image the interior of the earth for economic or scientific purposes. We find the mentions of earthquakes in historical records from the western (eastern Mediterranean) and the eastern (China and Japan) cultures, possibly due to the occurrence of major seismic events in these regions. The curiosity of west about the earthquakes greatly increased after the great Lisbon earthquake of 1755, although, the seismology became a full-fledged discipline in geophysics after mid-nineteenth century. The arrival of British mining engineer, John Milne and subsequently detection of first teleseismic waves by E. von Rebeur-Paschwitz in Hamburg in 1889, mutate the seismology from the study of earthquakes as a local phenomenon to a geophysical discipline on a global scale.

Prior to the instrumental seismology that started

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just before the twentieth century, T. Oldham, the first Director General, Geological Survey of India (GSI, Calcutta, now Kolkata), carried out earthquake geology studies of the 1819 Kachchh earthquake in Gujarat, western India and the 1869 Cachar earthquake in Assam, northeast India (Oldham and Oldham, 1882 and Oldham, 1928). He also first published a catalog of historical earthquake in India (1883). Subsequently, R D Oldham, illustrious son of T. Oldham, then Director General, GSI, made detailed geological and seismological studies of the 1897 great Shillong earthquake using the seismograms recorded by the seismographs outside India (Oldham, 1899). A magnitude Ms 8.6 was assigned to this earthquake, which is later modified to Mw 8.0 (Ambraseys and Douglas, 2004), with the displacement in main fault could be about 11m. Seiches were observed in many parts of the Indian and adjoining regions. However, India entered into the instrumental seismological era by establishing nation's first seismological observatory at Alipore in Calcutta (Kolkata) on December 1, 1898 under the auspices of the Indian Meteorological Department (IMD) equipped with Milne seismograph. This was the start of a culture of instrumental seismology in the Indian subcontinent; and subsequently five more seismological stations were established in Colaba (Bombay, now Mumbai), Kodaikonal, Shimla, Dehradun, and Nizamiah (Hyderabad). The number of observatories were increased to 8 by 1950, and then to 15 by 1960. The early versions of instruments were continuously upgraded to Omri Ewing then Benioff, Sprengnether and Wood-Anderson until the advent of the World Wide Standard Seismograph Network (WWSSN) in 1964, when five seismological stations were equipped with sensitive instruments. It was until 1964, the IMD was the only government agency installing and maintaining permanent seismological stations in the country. Since 1965, other agencies also started contributing to the national network. Among those are the Bhaba Atomic Research Centre (BARC, Mumbai), CSIR- National Geophysical Research Institute (CSIR-NGRI, Hyderabad), Geological Survey of India (GSI) - Kolkata, Regional Research Laboratory (RRL) (now Northeast Institute of Science & Technology, NEIST, Jorhat), Wadia Institute of Himalayan Geology (WIGH, Dehradun), Gujarat Engineering Research Institute (GERI, Gujarat), Central Water and Power Research Station (CWPRS, Pune), Institute of Seismological Research (ISR, Gujarat), Centre for Mathematical Modeling and Computer Simulation (CMMACS, Bengaluru), Indian Institute of Sciences (IISc, Bengaluru) and various universities (IIT-Kharagpur, IIT-Roorkee, IIT-Delhi, IIT-Mumbai, Osmania University, Jadavpur University, Indian School of Mines- Dhanbad, Banaras Hindu University, Manipur University, Kumaun University, Kurukshetra University, Guwahati University, Tezpur University to name a few).

A paradigm shift in the national network appeared by the establishment of a special seismological Array in Gouribidanur (Karnataka) by the BARC in 1965 in collaboration with UK. The primary aim of this array was to monitor underground nuclear explosions. Subsequently, the BARC also commissioned an indigenous-built analog telemetered seismic network in and around Bhatsa dam, Maharashtra for monitoring Reservoir Induced Seismicity. The network was in operation till 1990. Next to IMD, CSIR-NGRI has pioneered in national networking of seismological stations since 1970 with the installation of broadband instrument at CSIR-NGRI campus, Hyderabad with collaboration with GEOSCOPE.

Guha *et al*. (1968) noticed the seismic activities in the vicinity of Koyna dam just after its impoundment in 1962. In order to monitor these earthquakes a close network of 4 stations were installed in the vicinity of the Koyna dam (Gupta *et al*., 1969). After the 1967 Koyna earthquake Mw 6.3 which was identified as the reservoir triggered (Gupta *et al*., 1969), the CSRI-NGRI got involved into monitoring of seismicity by deploying a close spaced seismic network (cluster) around the Koyna region. Since 1980s several permanent and semi-permanent clusters came into operation in different parts of the country by several Institutes and Universities including CSIR-NGRI, NEIST, GSI, WIHG, GERI, IIT-Roorkee, Manipur University, Guwahati University, Kumaun University etc. The 1993 Killari earthquake of Mw 6.2 in Latur district, Maharashtra state, however, brought a radical change in networks and instrumentation in the country. All analog systems were gradually replaced by digital broadband systems. Today about 200 permanent broadband seismic stations are in operation by different Institutes in addition to several broadband clusters in the Himalaya, northeast India, Koyna, Gujarat and in

Andaman-Nicobar Island. The 2001 Bhuj earthquake Mw 7.7 in Gujarat state gave birth to the Institute of Seismological Research (ISR) in Gandhinagar, which runs a cluster of about 50 broadband and 50 strong-motion instruments in the state of Gujarat.

Seismic Monitoring – National Network

The seismological studies in India can broadly be divided into two domains e.g. understanding structures and earthquake mechanisms. The real impetus came with the national wide networking program under the umbrella of Nation Centre for Seismology (NCS). The National Center for Seismology (NCS) has been setup by bringing together all Seismology related activities of IMD (including those of EREC-Earthquake Risk Evaluation Centre) under one umbrella. It is maintaining 55 observatories spread over the entire country. It is also responsible for maintaining 16 stations with VSAT connectivity in Delhi and 20 VSAT based stations in Northeast India. Other major agencies such as CSIR-NGRI and universities also generate a large amount of data set in this en-devour. CSIR-NGRI is running 23 surface and 6 borehole broadband seismic stations in Koyna-Warna region to monitor the Reservoir Induced Seismicity (RIS) (Gupta *et al.*, 2017). These networks are now upgraded to digital telemetry system. In order to carry our seismological studies and monitoring of earthquakes, CSIR-NGRI is operating more than 170 broadband seismological stations as semi-permanent networks in different parts of the country, like in Sikkim Himalaya (e.g. Singh *et al*., 2010), Andaman-Nicobar Islands (e.g. Srijayanthi *et al*., 2012), Gujarat (e.g. Mandal *et al*., 2004), Andhra Pradesh (e.g. Rastogi *et al*., 1986) and most recently in Dharwar craton in southern India (e.g. Srinagesh *et al*., 2015) for multipurpose projects, like hydropower, nuclear plant, urbanization etc. In Singhbhum craton, CSIR-NGRI has operated 15 broadband seismological stations for crustal and lithopsheirc studies. Recently, it has launched an important network deploying 40 broadband, 30 strong-motion and 30 GPS in hitherto less studied region of Jammu and Kashmir Himalayas. Another multidisciplinary project was recently being initiated by CSIR-NGRI is in the northwest Himalaya of Garhwal region.

The CSIR-NGRI also runs some 80 educational seismographs under school laboratory program of the Ministry of Earth Sciences (MoES) in Maharashtra state. The NEIST (Jorhat) is operating 27 broadband seismometers equipped with VSAT in northeast India region, while the WIHG is operating permanent as well as semi-permanent networks using 46 broadband instruments in western Himalayas, viz., in Leh-Ladak, (Hazarika *et al*., 2014), Garhwal, Kangara-Chamba, Kumaoon and Kinnaur (e.g. Yadav *et al*., 2016) and in eastern Himalayas in Arunachal Pradesh (Hazarika, D, *et al*., 2012). The WIHG also focuses on real time monitoring with 15 VSAT connected broadband stations, earthquake precursor studies using a multi-parameter geophysical observatory (MPGO) in Ghuttu, Garhwal Himalaya and seismic-hazard microzonation for urban development. The GSI (Kolkata) is running 10 VSAT connected permanent broadband stations for the national network. The GSI is also involved in active fault mapping, aftershock investigation and seismic-hazard microzonation using 50 broadband instruments in different parts of the country (Kayal, 2008). Further, several Institutes and Universities as mentioned above are running several permanent broadband seismic stations for the national network in addition to different MoES research projects for special investigations (like Hydropower projects, microzonation studies etc.) using campaign mode or semi-permanent networks.

Earthquake Studies

Seismic Zoning Map of India

The Indian subcontinent has experienced several devastating earthquakes in the past. The major reason of seismic activity is due to the continuous motion of Indian plate towards NNE and collision with the Asian plate. In 1935, the GSI first published the seismic zoning map of India (GSI, 1939) and then upgraded (BIS-Bureau of Indian Standards, 1970, 2000). This was a very important step taken towards the hazard scenario of the country. An exercise carried out under *Global Seismic Hazard Assessment Program* (*GSHAP*) for seismic hazard map of India (Fig. 1) and adjoining regions (Bhatia *et al*., 1999). 86 potential seismic source zones have been classified based on the tectonic features and seismicity trends. Subsequently, it was inducted by the Department of Disaster Managements Authority (DDMA) with major modifications. Based on the intensity experienced, Indian plate has been divided into different Seismic

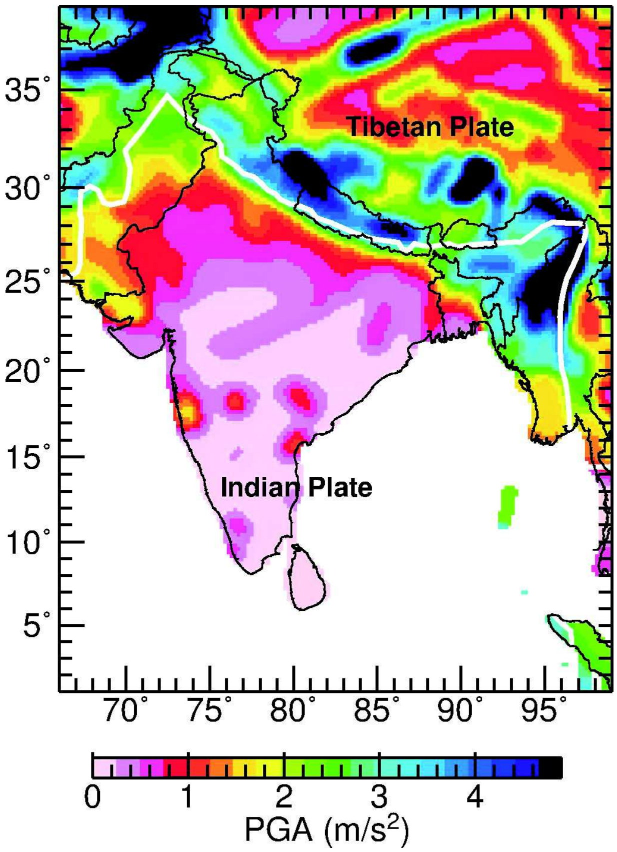

Fig. 1: Seismic Hazard Map of the India and its adjoining region. Peak ground acceleration (PGA) with a 10% chance of accedance in 50 years is depicted in m/s^2 (source: http://www.seismo.ethz.ch/static/GSHAP/index.html)

Zoning Map (BIS, 2004) viz. VI (M5), VII (M6), VIII (M7) and IX (Me"8). The corresponding peak ground acceleration assigned to zones II, III, IV and V are 0.1, 0.16, 0.24 and 0.36g respectively. The Himalayan -Andaman belt and Kutch regions have intensities of IV and V. Koyna and Latur are assigned zone IV, while Narmada belt and Indo-Gangetic plane are having zone III. Rest of the Indian shield is assigned zone II.

Seismic Hazard Assessment and Microzonation

The Himalaya, north-eastern Indian region, Andaman-Nicobar island belt, Bhuj and Koyna regions are known to have been prone to earthquakes (Mw 7.0-8.0). Southern peninsula shield including Koyna, Latur and Son-Narmada region have also hosted less frequent and lower magnitude (Mw<=6.5) seismic events. The spatial structural diversity in India possesses the irregular damage pattern which can be observed by any large earthquakes (Kayal, 2008; Nayak, 2011). While during 1980-1990 earthquake precursor studies were in forefront in global as well as in Indian scenario, in the beginning of the twenty-first century the importance of microzonation studies to mitigate seismic hazards/risks has been on forefront. The Department of Science and Technology (DST) took initiative for microzonation studies in all the major metro cities in the country. Subsequently, MoES have embarked on the national-wide seismic mitigation program constituting a National Steering Committee in 2008 to provide guidance for seismic microzonation studies in cities and urban regions. Extensive work has been done by the GSI, IMD, CSIR-NGRI, IITs and by many other institutes. A joint effort was first made under a DST program for the Jabalpur city area under Indo-Italian collaboration in late 1998 after the 1997 damaging Jabalpur earthquake of Mw 6.0 in Son-Narmada zone (Rao *et al*., 2011). Then a multidisciplinary joint project was formulated by the DST for microzonation of the Guwahati city area, the business hub of northeast Indian region, and a hazard microzonation atlas was prepared (Nath *et al*., 2008). Numerical computations have also been done to prepare the hazard map of Indian shield and adjoining regions (Parvez *et al*., 2017; 2003). On this basis, extensive work has been done to design earthquake resistance codes (e.g. Bansal, 2011). A comprehensive guideline for scientists and engineers for plans on hazard and disaster risk reduction have also been formulated (Gupta, 2010). Microzonations of many cities like Delhi, Bengaluru, Mumbai, Chandigarh, Dehradun, Gangtok, Agartala etc are done, and the job is continuing. Further, the CSIR-NGRI, ISR, IIT-R have done profound work on earthquake engineering, strong motion and seismic hazards. The Seismotectonic Atlas of India and adjoining region (GSI, 2000) has become a starting reference for seismic hazard microzonation studies.

Earthquake Source Characterization

Parameterizing the nature of earthquake sources enables an understanding of the physics of the source processes and seismic hazard. The key source parameters are seismic moment, stress drop, and corner frequency. Determination of these parameters is important for assessment of ground motion, aftershock patterns, and propagation of seismic waves. The initial work on source parameters of earthquakes associated with the Indian plate dates back to the early seventies, utilizing analog data. Tandon and Srivastava (1974) established a relation between the magnitudes of the after-shocks and the main-shocks based on the stress drop and average dislocation of a few earthquakes in India. Spectral analysis of body waves and source parameter estimation was performed by several workers earlier in a local scale in various parts of the Indian shield and Himalaya (Singh *et al*., 1979; Gupta and Singh, 1980; Gupta and Rambabu, 1993). With the advent of broadband digital seismology, the research in this field has brought much impact in terms of our understanding of the seismogenesis (Mandal and Rastogi, 1998; Mandal and Dutta, 2011; Hazarika, P and Kumar, 2012; Baruah *et al*., 2016) in the entire subcontinent.

Aftershock Studies

Sometimes large aftershocks pose a substantial hazard to populated areas by causing more damage than the main shock. Its forecast and study, especially in urban areas is important. The main purpose of the aftershock survey is to decipher precise location and depth so the size and orientation of the fault plane that ruptured in the earthquake can be estimated. Therefore, in order to study the aftershock sequences, it is critical to deploy sufficient number of simultaneously operating sensors continuing for a few weeks – even up to several months, depending on the aftershock sequence activity. Aftershocks are an important source of information for understanding the mechanism of earthquakes, faulting associated with the main shock and the long-term redistribution of stress in the aftershock zone. It may also furnish information about the physical properties of materials in the crust and upper mantle.

Several strong earthquakes (Mw>=6) have occurred in India and its adjoining regions in the past two decades viz. 1991 Uttarkashi (Mw 6.6), 1999 Chamoli (Mw 6.3) (Rastogi, 2000), 1993 Latur (Mw 6.3), 1997 Jabalpur (Mw 6.0) (e.g. Rao *et al*., 2002), 2001 Bhuj (Mw 7.7) (e.g. Kayal *et al*., 2002; Mandal *et al*., 2004), 2001 Andaman (Mw 6.5) (Kayal *et al*., 2004), 2004 tsunamigenic Andaman-Sumatra (Mw 9.3) (Mishra *et al*., 2007a,b; 2011), 2005 Kashmir (Mw 7.6) (Rao *et al*., 2006) etc. In order to understand the seismogenesis, rupture and stress distribution several organizations (e.g. GSI, CSIR-NGRI, IMD, WIHG) monitored the aftershock sequences of these earthquakes. In addition to these, several other events such as 2009 Bhutan (Mw 6.3), 2011 Sikkim (Mw 6.9), 2016 Manipur (Mw 6.7) are also studied in context of aftershocks by various workers (e.g. Kayal *et al*., 2010; Singh *et al*., 2017).

Reservoir Triggered Seismicity (RTS) – Koyna-Warna Region

Reservoir Triggered Seismicity (RTS) is an anthropogenic effect observed in the vicinity of the few reservoirs globally such as Hsingfengkinag (China), Kariba (Zambia-Zimbabwe), Kremasta (Greece). In India, the first observation of seismicity was noticed in the vicinity of Koyna dam just after its impoundment in 1962 (Guha *et al*., 1968). In order to monitor these earthquakes a close network of 4 stations were installed in the vicinity of the Koyna dam (Gupta *et al*., 1969). The phenomenon successfully explains the observation of intra plate seismicity which corresponds to the impoundment of the reservoir. Another reservoir, Warna was created in 1985 and that too contributed to the RTS in the region. The seismicity occurs with a small region of 20 km X 30 km. In order to monitor the seismic activity, initially CSIR-NGRI took initiative to deploy first few broadband seismic stations, however at present the number has been increased to 23 surface broadband and 6 borehole broadband seismic stations (Fig. 2). In the past few decades a number of new observations have been made regarding the source, processes and nature of seismicity in the region, such as the relation between the water level and occurrence of seismicity, difference between the normal earthquake and RTS (Gupta *et al*., 1972a,b; Gupta and Rastogi, 1974; Gupta, 1992; Rastogi *et al*., 1997; Talwani, 1997). The variation in stress pattern based on the source mechanism studies (Rao and Shashidhar, 2016), in situ pore pressure variations (Kumpel *et al*., 1991; 2017), co-seismic water level changes (Kalpana *et al*., 2010) etc. Recently, Kumar and Dixit (2017) presented a Vp and Vp/Vs tomographic images of the region using the seismicity data recorded at 4.5 Hz geophones. The results suggest that the intense seismic activities are clustered below the trap and localized in the space where there exist abrupt changes in Vp/Vs. The precise locations of the hypocentres have been made by Srinagesh and Sarma (2005) in the Koyna-Warna region. Using the waveform inversion a precise determination of focal depths have been attempted using local seismic waveforms (Shashidhar *et al*., 2011) identified the Donachiwada fault is the causative source for the 1967 Koyna earthquake (Mw6.3). However, another view on the sustained seismicity in this region is due to the influence of fault zone geometry and their interaction (Gahalaut *et al*., 2004).

A number of seismological studies have been carried out in this region to understand the source mechanism and structure, however, the triggering phenomenon of seismicity is poorly resolved. In this direction, to understand the role of fluid, pore pressure, loading and unloading of the reservoirs and source mechanism a major initiatives were taken by the MoES to drill deep boreholes in and around the region (Fig. 2). The main advantage of borehole observation is the increased sensitivity due to the rapid decrease in noise wave intensity with depth, since the interference consists mainly of surface waves. Scientific deep drilling in the region has revealed that the Deccan trap has 932.5m thick and underlain by the basement rock (Roy *et al*., 2013). The major science objectives and feasibility were discussed with the international community through ICDP workshops (Gupta and Nayak, 2011; Shashidhar *et al*., 2016). The deployment of borehole seismic sensors is first of its kind in India. The high signal to noise ratio waveforms have the potential not only to detect the sub M1.0 seismic events but also can provide structural information with unprecedented resolution. The preliminary studies show that the absolute errors in locations of earthquake based on the borehole data ranges from 800 to 300m (Shashidhar *et al*., 2016).

Nuclear Explosion Monitoring

Manmade explosion, such as nuclear explosion can cause ground shaking equivalent to an earthquake of Mw 4.5 or more. Detection of nuclear explosion and its location is an important task of the BARC. Detailed studies on the 1998 Pokhran explosions were studied by various researchers (Roy, *et al*., 1999; Douglas *et al*., 2001; Sikka *et al*., 1998; Gupta *et al*., 1999; Baruah *et al*., 2016). The monitoring of such explosions also has implications for deciphering the tectonics in the stable continental regions and more

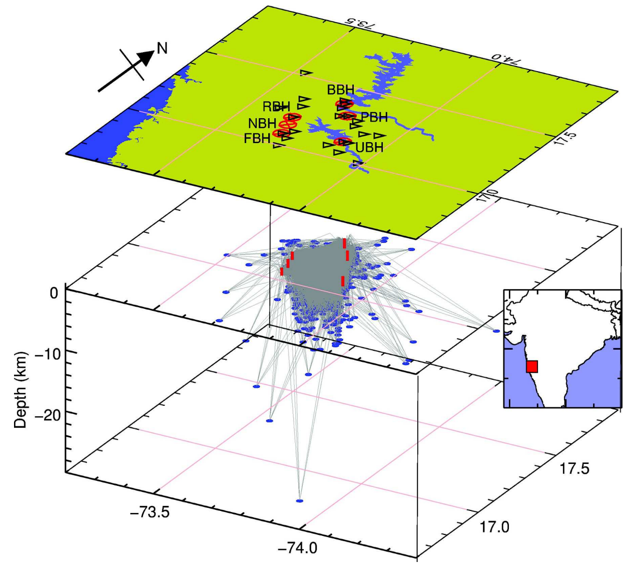

Fig. 2: 3D view of the seismic stations deployemnt plan of surface (open black traingle) and borehole sensors in the Koyna-Warna region. The hypocentres are shown in blue dots in the depth panel with ray paths (gray lines). The inset shows the location map the west coast of India

importantly for verifying the compliance with CTBT. For these explosions, yields have been estimated. Spectral content has also been analyzed (Gupta *et al*., 1999). Baruah *et al*. (2016) used Lg, Pn and Sn phases as discriminants for the explosion and natural earthquakes and further provides the yield which is consistent with that estimated by Sikka *et al.* (1998).

Monitoring Earthquakes in Ocean, Tsunami and Alert System

The Indian Tsunami Early Warning System (ITEWS) is established at the Indian National Centre for Ocean Information Sciences (INCOIS), Hyderabad under the MoES. The ITEWS encompasses at present a real-time seismic monitoring network of 57 broadband seismic stations, 14 Global Navigation Satellite System (GNSS), a network of real-time sea-level sensors with 7 Bottom Pressure Recorders (BPR) in the open ocean and 35 reporting tide gauge stations (Fig. 3) at different coastal locations and a 24 x 7 operational tsunami warning centre to provide timely advisories to vulnerable community. The ITEWS at NCS is a nodal agency that retrieves real time data through a dedicated Real Time Seismic Monitoring Network. The seismological stations are equipped with a SAT communication facility to transfer the data in real-time to the Operational Centre. With the current facility the reliability of identification and location are excellent. For a magnitude of 3.5 can be located within 5-10 minutes of time. The end information regarding the earthquakes and further guidelines are disseminated to all concerned state and central government departments through short message service (SMS), fax, and/or e-mail. IndiaQuake is an application developed to provide this information to citizens in real time. Since its inception in October 2007 to till date, the ITEWS has monitored more than 350 earthquakes of M > 6.5 out of which about 70 are in the Indian Ocean region. The ITEWS also acts as one of the Regional Tsunami Advisory Service Provider along with Australia and Indonesia for the Indian Ocean region.

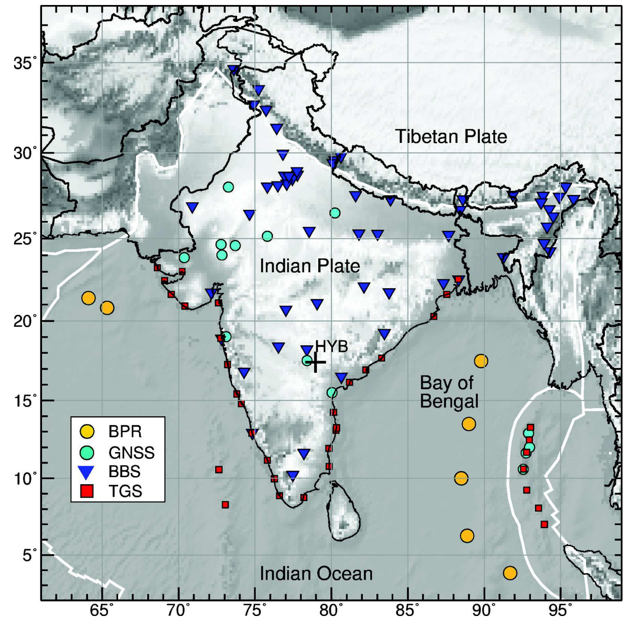

Fig. 3: The disposition of different sensors utilized by INCOIS at Hyderabad (HYB shown by a plus symbol). BPR- Bottom Pressure Recorder, GNSS-Global Navigation Satellite System, BBS-Broadband Seismic Stations and TG- Tide Gauge Stations (Venkatesan *et al.*, 2015; Kumar S., *et al.*, 2012; Kumar S. *et al.*, 2016; Nagarajan *et al.*, 2006; http://www.isgn.gov.in/ISGN/ ;http://www.incois.gov.in/portal/datainfo/ tidegauge.jsp; http://tsunami. incois.gov.in/ITEWS/ UpdateReporting Stations.do?st Type=BPR;http:// www.nio.org/index/option/com_nomenu/task/show/ tid/2/sid/18/id/11)

Forecast and Precursor Studies

Indian plate has frequently experienced small to large earthquakes in the Himalayan region, Andaman-Nicobar Islands and within the plate interiors. From time to time India has initiated a systematic multi-geophysical long term approach in seismic active regions (e.g. Gupta and Singh 1986) to understand the earthquakes processes and precursor phenomenon. That eventually may lead to the earthquake forecast. For long term assessment, active fault mapping programs have been initiated in the Himalayan and Kutch regions. Medium and Short-term precursory study and short term forecast is done by measuring several types of precursory phenomenon such as water level change, b-value, seismicity, helium, radon, GPS, magnetic field, gravity change etc. Based on *earthquake swarm hypothesis* (Evison, 1982), a medium-term forecast with space, time-period, magnitude and depth-range was successfully in northeast India region for the 1988 Manipur-Burma border earthquake Mw 7.3 (Gupta and Singh 1986). GSI conducted a detail geophysical surveys (gravity, magnetic, resistivity) and seismological (b-values, Vp/Vs, seismicity rate) precursors for the 1984 Cachar (Assam) earthquake Mw 6.0 and the 1988 Manipur-Burma border earthquake Mw 7.0. A remarkable study by Gupta (2007) in Koyna-Warna region leads to the feasibility of forecast through the rigorous monitoring the seismicity in the region. *Nucleation method* of short-term prediction has successfully been implemented for M~4.5 in the Konya region (Rastogi and Mandal, 1999; Gupta, 2007).

In this direction some of the significant agencies or institute engaged are CSIR-NGRI, ISR-Ghandhinagar, IIT-Roorkey, GSI and CSIR-NEIST. IIT-Roorkey has done profound work on earthquake engineering, strong motion and hazard at various important project sites. ISR has done extensive woks in active fault mapping in Kutch, Gujarat regions. New seismic experiments have been launched in this direction including seismic microzonation vulnerability assessment for major cities. GSI has carried out intensive studies in hilly regions of Sikkim, Tripura, Arunachal and Jammu by maintaining broadband seismographs. Ministry of Earth Sciences, Govt of India started a separated flagship program for earthquake prediction as National Project on Earthquake Prediction in Indian and adjoining regions.

Paleo-seismological Studies

Historic records and instrumental data are not adequate to understand the seismogenic active faults and recurrence time of large earthquakes. Recurrence time of large magnitude earthquakes is assumed to be ~500 yrs in the active plate convergence region and ~1000 yrs in a SCR (Stable Continental Region). Our instrumental data with fairly well located events are hardly 100 yrs old to make any statistical study or what so ever to assess recurrence time of large earthquakes. In such a scenario, paleo-seismology is one of the most commonly adopted techniques towards identification and cataloging the historic and pre-historic earthquakes.

In this direction humble efforts have been initiated by the Indian seismologists in some parts of the active regions, like that in the Shillong plateau, Latur, Bhuj, Himalayas. In Shillong region good paleo-seismic evidences like seismicity are found that give evidences of three large earthquakes with recurrence time of the order of 500 + 100 yrs (e.g. Rastogi *et al*., 1993; Sukhija *et al*., 1999). In the 2001 Bhuj earthquake source zone evidences are observed for two previous earthquakes, ~4000 and ~ 9000 years ago respectively (Rajendran *et al*., 2008). In the 1993 Latur earthquake zone the paleo-seismic investigation revealed a hidden fault that produced a similar strong event ~1000 yrs ago (Rajendran *et al*., 1996). In the Kangra earthquake zone in western Himalaya, Malik *et al*. (2010) reported recurrence time of large earthquake is ~1100 yrs. Several research projects are supported by the MoES for Paleo-seismological studies in the Himalaya, northeast India and Andaman Nicobar islands, and the work in progress.

Study of Earth Structure

Indian Lithospheric Study

The Indian shield is a mosaic of diverse terrains bearing the imprints of various tectonic episodes in geological history from Archaean to the late Proterozoic eon. Knowledge about the crustal structure of the Indian sub-continent initially comes from several active seismic studies (e.g. Kaila and Krishna, 1992). During eighties the passive seismic experiments changed the understanding of the Indian crust and mantle structures dramatically by adding a large number of data sets as well as developing new techniques. The passive seismological studies consist of (i) body wave studies of shallow earthquake (ii) surface wave studies. However, Gupta and Narain (1967) were the first to estimate crustal thickness in the Himalaya and Tibet Plateau region using surface wave dispersion. This result provided a better understanding of the Indian plate in terms of the collision dynamics with Tibetan and Eurasian plates. Their finding of an enormously thick crust (65 to 70 km) characterized by low shear wave velocities has been confirmed by recent investigations using sophisticated frequency time analysis technique, body wave and active seismics. Rayleigh wave attenuation studies suggest that the lowermost part of the crust beneath the Tibet Plateau is partially molten and uplift has been caused by horizontal compression. Another intriguing conclusion of their study was the shield-like upper mantle velocity structure exists below the Indo-Gangetic Plains IGP). Recently, CSIR-NGRI deploy 10 broadband seismic stations in IGP and investigated the thickness of sedimentay layer using converted wave technique (Srinivas *et al*., 2013).

With the advent of receiver-function technique utilizing the converted waves from a discontinuity proved to be a robust tool to map the crust and mantle structures. The compilation of all the results available for the crustal parameters as derived only by the converted wave techniuqe for the Indian shiled are depicted in Figure 4. It has been observed that the crustal thickness varies with the geological provinces in the India shield. The average crustal thickness (~35 km) of the Eastern Dharwar Craton (EDC) is less compared to that of the Western Dharwar Craton (WDC) (~45 km) (Ravi Kumar *et al*., 2001). But the western Dharwar Craton shows a complex geology and gradational transition from crust to down Moho (Sarkar *et al*., 2003). The velocity of the WDC (V_s ~3.73 km/s) is higher than that of the EDC (V_s ~3.71 km/s). Singh *et al* (2015; 2017) presented a comprehensive picture of the Indian and Himalayan crust by analysing data from a large number of stations thus filling the existing gaps in velocity models. The crust of the DVP is classified as more felsic-to-intermediate in nature (Ravi Kumar *et al*., 2001). The major features of the study are – the EDC has thinner and simple crust compared to that of the WDC, the crust in the Himalaya region has thicker than that of the continental shield region, rift zones, such as Narmada-Son lineaments, Godavari and Mahanadi have thicker crust compared to its surroundings. Evaluation of crustal and upper mantle structures of the eastern Indian shield has been made using seismological data recorded by the broadband station at the IIT-ISM, Dhanbad (Kayal *et al.*, 2011). However, the mechanisms through which the Achaean continental crust evolved are debatable. The end member models advocate horizontal accretion of island arcs or vertical accretion due to differentiation of magmatic material above hotspots. Also, there is no consensus on the processes that govern secular change in the character of the crust in Arching, as revealed by the seismological and petrological data. In order to address these key issues, Haldar *et al.* (2018) used converted wave data to extract the bulk crustal properties of the Indian cartons. They suggested that soon after its formation, the crust has been gradually altered, making it mafic-to-intermediate in bulk composition. Further, they proposed that the crust formation prevails at much higher temperatures predominantly through vertical accretion initially and then by slab melting – elucidating the secular evolution and alteration of the Archaean crust in India.

In order to understand the crust and lithosphere a number of theoretical works have also been done. Some of the notable contributions are the development of a method for iterative rotation of three-component of seismograms to isolate P-SV-SH wave-fields for computation of P- and S- receiver functions (Kumar *et al.*, 2005; 2006). Recently, a technique to estimate the shear-wave velocity contrast across an interface using the P-to-s transmitted wave amplitudes has been proposed that incorporate the effects of anisotropy and dip of the medium (Kumar *et al.*, 2014; Kumar, 2015). The extraction of green's function using auto and cross spectra to determined the reflection (Ravi Kumar and Bostock, 2006) response demonstrate the use of back scattered filed instead of forward response. The extraction of absolute P-wave velocity using converted wave data (Ravi Kumar and Bostock, 2008) is also an important forward step.

Indian Lithosphere

Amongst the various Gondwana fragments, the Indian plate assumes a unique place as it has been ravaged by three major plumes as soon as it separated ~180 My ago from the Super-continent Gondwanaland comprising Australia, Africa, Antarctica and south America. During this process, the Indian tectonic plate lost most of its lithospheric mass and became thin vis-a-vis its counterparts. Kumar *et al.* (2007) using state-of-the-art technique termed as S-to-p converted waves, first time imaged the Indian tectonic plate and suggested that the thickness of the Indian plate varies

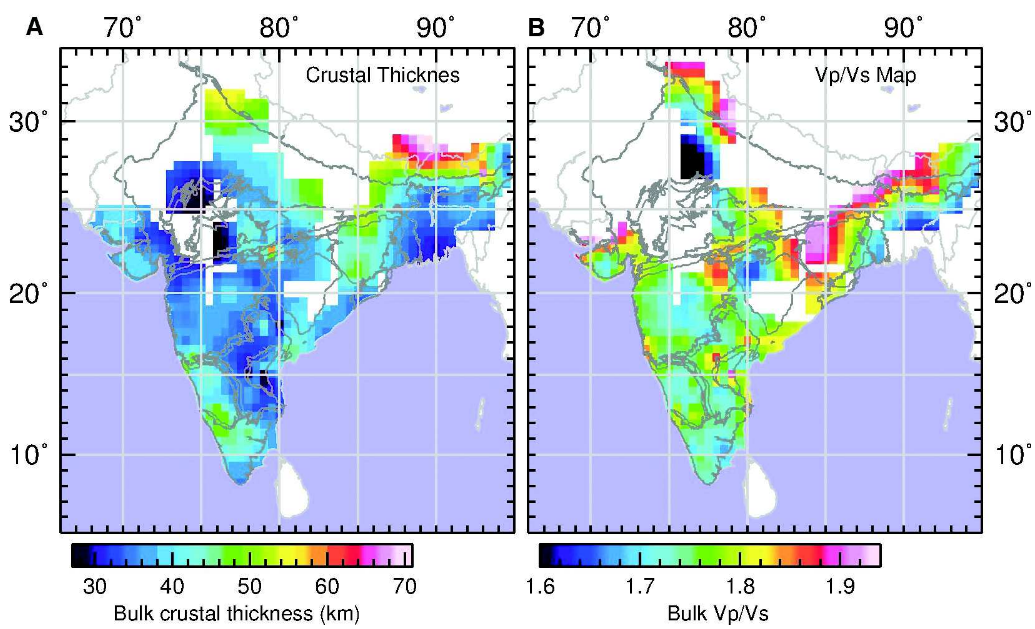

Fig. 4: Crustal parameters (a) bulk crustal thickness and b) bulk crustal Vp/Vs) for the Indian shield superimposed on the tectonic map. The images have been generated by compilation of all the data derived from refeiever fucntion analysis (modified after Haldar *et al.*, 2018)

between ~70 and ~140 km with an average thickness of ~100 km. They further, argued that the rapidly northward drifting (~18-20cm/yr) of the Indian plate could be due to its being thin (Fig. 5). The detail mapping of the thickness of the Indian plate has the potential to answer some of the fundamental questions regarding the post-collisional effect on the Indian plate. They observed the flexure nature of the Indian tectonic plate cased due to the hard collision with the Asian plate along the Himalayan arc (Kumar *et al*., 2013) as also observed by geodetic observations. The receiver function analysis has been further supplemented by the analysis of the vertical components of observed seismograms without using deconvolution (i.e. plain summation (Kumar *et al*., 2010)) consisting of back scattered reflected phases.

Such values are more or less consistent with the depths determined from surface wave dispersion studies (Suresh *et al*., 2008; Bhattacharya *et al*., 2009), where the thickness of Indian lithosphere has been reported to be ~80- ~155 km thick. The earlier tomographic image also shows that among the various depth extents of the cratons, India is only ~100km (Polet and Anderson, 1995). A Geoscope station located at Hyderabad (HYB) shows a similar depth value for the lithosphere below the Indian shield using

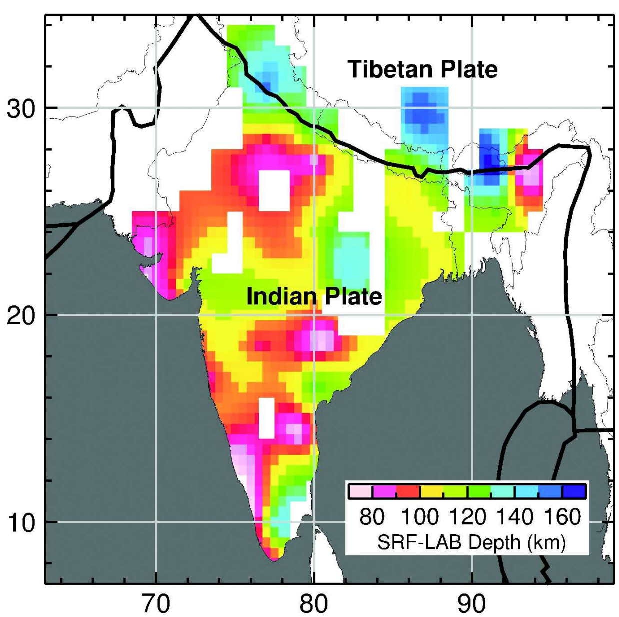

Fig. 5: Image of the LAB beneath India inferred by S-receiver function data. The image clearly reveals the undulating LAB topography probably related to the flexure of the Indian plate (modified after Kumar *et al*., 2013)

P-to-s conversions (Rychert & Shearer, 2009; Bodin *et al*., 2014). However, the tomographic images by Maurya *et al.* (2016) showed quite distinct lithospheric thickness for the entire Indian shield. However, their values in southern granulitic terrain, eastern Dharwar are in agreement with the other observations, but for other cratons there exist significant differences with their values lie between 160 and 200 km. The relative amplitudes of the LAB phases lie between ~2% and 5% with the shear contrast getting reduced for regions of thicker or bulged lithospheric regions.

The conversion from 410- and 660-km discontinuities have also been observed beneath large part of the Indian shield and interpreted in terms of phase transformation in the mantle from olivine to spinel and from spinel-structured gamma phase to perovskite-structured magnesiowüstite (e.g. Duffy and Anderson, 1989) respectively. These phases are in a state of equilibrium and governed by the temperature-pressure conditions at these depths. This is controlled by the Clapeyron slope. The sign of the Clapeyron slope described the nature of discontinuity i.e. positive and negative for the 410 and 660 km discontinuities respectively (e.g., Bina and Helffrich, 1994). Thus, the respective locations of these discontinuities can directly be interpreted in terms of the temperature in the upper mantle. For example, for temperatures in excess of <“200æ%C, the separation between these discontinuities can be reduced by <“20–30 km (Helffrich, 2000). Further, the conversion times of P-to-s from upper mantle discontinuities also depend on the average shear velocity in the upper mantle, i.e. any discrepancies in these timings with respect to the global average are related to the velocity perturbation in the upper-most mantle. Any delays in these phases might also indicate the lower average velocity in the upper mantle implying a thinner mantle lid and/or higher temperature of the oceanic lithosphere as compared to the continental mantle, corroborated by the Lithosphere-Asthenosphere Boundary at shallower depths. Mantle transition zone (MTZ) structure beneath the Indian shield region has been investigated using a large number of data. The delays observed in the conversions from the 410- km discontinuity below the Indian shield suggest low shear wave speeds in the lithospheric and sub-lithospheric mantles and that could be due to the higher temperatures (Ravi Kumar, *et al*., 2013) in the mantle, together with a thinner high velocity mantle-lid that contrasts with a thicker one found beneath most of the Archaean cratons.

The birefringence studies of the Indian lithosphere using core refracted shear waves have been attempted by few researchers. The anisotropy study using splitting is an important step forward to understand the continental scale mantle deformation pattern and signatures of rifts in the Indian plate. Based on the core refracted shear waves, it is suggested that there exist two layers of anisotropy beneath the Indian shield (Ravi Kumar and Singh, 2010; Saikia *et al*., 2010). A comprehensive analysis of core refracted shear waves (SKS, SKKS etc) data from the Indian stations reveal the anisotrpy in the D" possibly related to the presence of slab material in the outer core (Roy *et al*., 2014).

Evaluation of crustal and upper mantle structures of the eastern Indian shield has been made using seismological data recorded by the broadband stations (Kayal *et al*., 2011). The estimation of coda-Q variations in the Kuchchh Rift Basin (KRB) and eastern Indian shield have also been attempted to understand its seismotectonic implications (Mandal, 2007; Khan *et al*., 2011a).

Himalayan Region

This region is characterized by the convergence of the Indian plate against the Asian plate and bounded by the western and eastern syntaxes. In the recent past the region has experienced quite a few M~8 earthquakes and frequent small to moderate earthquakes. The relative northward drift of the Indian plate resulted in the onset of continental collision with Asian plate that produced extensive lithospheric deformation, producing one of the world's largest elevated regions, the Tibetan plateau and the great Himalayan Mountain ranges. The Plateau was created by the collision which began ~50My ago and possibly merging one or several terrains in between. To understand the fate of the colliding Indian and Asian tectonic plates below the high Tibetan Plateau, mapping of deeper seismic structures i.e. the crust-mantle boundary (Moho), the lithosphere-asthenosphere boundary (LAB), or the discontinuities at 410- and 660-km depths are of utmost importance.

In this direction CSIR-NGRI's contribution is of paramount important. WIHG, GSI and NEIST too contributed in our understanding of the Himalayan tectonics through the deployments of dense seismological networks in eastern and western Himalayan regions. In the eastern Himalaya, a semi-permanent CSRI-NGRI network of 11 broadband seismic stations revealed crustal geometry and presence of anisotropic layers below Sikkim Himalaya (Singh *et al*., 2010) that could be helpful in understanding of the genesis of seismicity in the region. They showed that the Indian plate is under thrusting beneath the Tibetan and there is a significant change in the slope of the Indian Moho where the occurrences of large earthquakes are observed. In the eastern syntaxis zone, receiver function and shear wave modelling revealed azimuthally varying crustal structure with a northeast dipping Moho Tidding Suture. Compared to an overall thickness of >70 km in the northwest and central Himalayas, the crust across the Tidding Suture is only about 55 km thick (Hazarika, D., *et al*., 2012). The data from the same experiment provide a detail attenuation characteristics of seismic waves in the region (Hazarika P., *et al*., 2013). Srinagesh *et al.* (2018) carefully analysed the 2017 Guptkashi earthquake of Mw 5.3 for source parameters and suggested that such analysis could be useful to characterize the ground motion during future events. Singh *et al.* (2017) studied the Gorkha earthquake sequence and designed the ground motion prediction equations which should be more reliable than the existing one.

In the western and central Himalaya, since the last decade, we have seen a number of ongoing international efforts to deploy large number of seismometers in the Himalayan-Tibetan region in order to decipher the deeper seismic structure with unprecedented details. In 1991, recording of earthquakes with broadband seismometers began on the Tibetan Plateau under Sino-American Tibetan Plateau broadband experiment till 1992 (Owens *et al*. 1993), in 1992 the Sino-French group began temporary passive source projects on the plateau with an experiment from the Lesser Himalaya in Nepal to the Qiangtang terrane (Hirn *et al*., 1995). This group continued with experiments in 1993 in the Qiangtang terrane to the Qaidam basin (Herquel *et al*., 1995). Data sets from Himalayan and Tibetan region from various international collaborations, a detail imaging of the Indian and Asian lithospheres has been presented along the arc of the Himalaya. Using both the converted waves viz., P-to-s and S-to-p, the subduction of the Indian plate is well established. However, the relationship between the Tibetan and Asian plate is more complicated. The main results of the various seismic field campaigns in Tibet can be summarized as follows:

In the western most part the Indian plate is observed beneath the Karakoram dipping from ~130 km to ~170 km towards north. The Asian plate is sub-ducted till ~270 km depth (Kumar *et al*., 2005). The Asian plate beneath Tien-Shan varies between 90 and 120 km and is 160 km beneath Tarim basin. The Indian plate progressively deepens from 120 km to ~200 km in the central Tibet. Further north, the Asian plate is seen at a shallower depth of ~150 km (Kumar *et al*., 2006; Zhao *et al*., 2010). This indicates that the north-western boundary of Tibet demarcates the lithosphere and supports deformation by strike-slip faulting. In the recent times, with the availability of seismological data from INDEPTH4, (Zhao *et al*., 2011) presented a unified seismic image till upper mantle using the data from INDEPTH2 & 3, PASCAL, LHASA, and IRIS stations. The result is interesting in a sense that they observed Tibetan and Asian plates separately. The Tibetan lithosphere is overriding the Asian lithosphere as India-Eurasia convergence is accommodated in the northern Tibet. This essentially signifies the presence of a micro plate below Tibet. The geometry of the Indian and Asian plate collision may also explain the difference in surface topography between west and east Tibet.

Burmese Arc

The Burmese arc lies on the eastern margin of the Indian plate and has been referred to as an active subduction zone. The geophysical and geological studies confirm that the Indian plate subducted eastwards (Verma *et al*., 1976; Mukhopadhyay, 1984; Gupta and Bhatia, 1986; Gupta *et al*., 1990) below the Burmese plate - an example for the continental-continental subduction system. The intriguing fact about it is that whether this subduction system is still active or not (Satyabala, 1998). The focal mechanisms of the seismic events in this region show an interesting scenario. The Burmese arc region is only one of its kind in the world, where there is an eastward subduction of the Indian plate, however, the direction of plate motion is nearly perpendicular to the down dip direction. Ni *et al.* (1989) and Rao & Kumar (1999) suggest that the Indian plate, along with the subducted plate in the east, shears slab past the Burmese plate in the NNE direction. The stress inversion of the focal mechanism data reveals an entirely interesting fact about the subducting slab. The upper part of the slab experiences horizontal tectonic forces, while, the lower part of the slab is controlled by the gravitational loading (Rao and Kalpana, 2005). It was further suggested that the Indian slab experienced resistance at 410 km discontinuity, that resulted in overturning of the slab (Fig. 6). Subsequently, the subduction terminated by slow sinking of the overturned slab leading to its detachment manifested as reverse faulting mechanism. However, based on the waveform modeling it has been argued that the deformation in Burmese arc is mostly accommodated by northward slivering of the eastward subducted Indian lithosphere (Singh A. P. *et al*., 2017). Significant work has been done with imaging of the detail lithospheric architecture of the subducting slab using stat-of-the-art tool, S-to-p receiver functions (Uma *et al*., 2011). This study presents first results of the collision geometry of the Indian and Asian plates in the eastern Himalayan region from Indian side of the Himalaya. The interesting observations of the lithospheric upwelling below the Shillong plateau suggest that the uplift of the plateau is confined to the lithospheric level. The subduction of the Indian plate beneath the Burmese plate has been mapped to a depth of ~200 km depth (Uma *et al*., 2011).

Andaman-Nicobar Islands

Seismological studies in the Indian Ocean intensified after the occurrence of a large earthquake on 26th Dec, 2004 of Mw9-9.3 in Indonesia that caused Tsunami in the Indian Ocean. Seismological studies in the Andaman-Nicobar islands started with an aftershock investigation deploying a four-station digital network in Andaman immediately after the 2002 Andaman sea earthquake Mw 6.5 (Kayal *et al*., 2004), that delineated northeast-dipping oblique subduction in north Andaman Sea basin. As a part of the earthquake monitoring 11 stations were installed in the islands of Andaman and Nicobar. The region has a complex tectonic setting and plays an important role in shaping the geodynamics of the oceanic plate. The mega event of 2004 provides a gross seismotectonics of the region (Dasgupta *et al*., 2007'

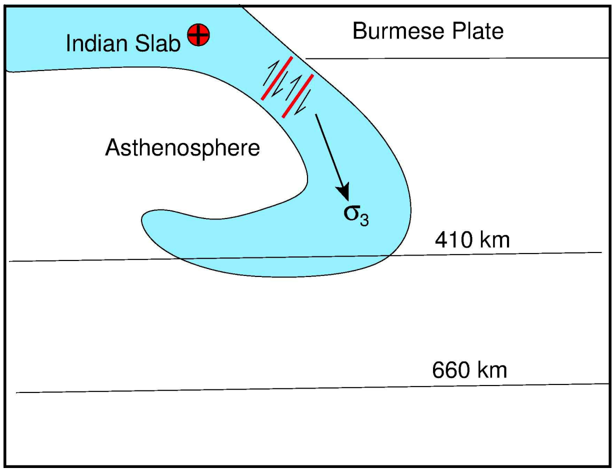

Fig. 6: Subduction model suggested by Rao and Kalpna (2005) based on stress inversion of focam mechanism data. The rapidly subducting Indian slab is slowed down encountering the resistance at 410-km upper mantle discontinuity and eventually overturns. Crossed Red circle indicates the strike-slip part of the slab and the deeper part exhibits the reverse faulting

Mishra *et al*., 2007a, and b). With the increase number of data, more research works based on attenuation of seismic waves in this region have been reported (Padhy *et al*., 2011; Singh *et al*., 2017). Based on the mechanism studies several zones have been demarcated for future possible sites for impending large earthquakes (Ghosh and Mishra, 2008). Further, the erratic trend of aftershocks revealed intricate pattern of seismogenesis that provided heterogeneity of the region (Mishra *et al*., 2007a, b; Ghosh and Mishra, 2008). Khan (2011b) studied the unbalance of the subducting slab based on the moment calculation. Quite a number of works have been conducted to understand the fault disposition, rifting mechanism and subduction tectonics based on the seismicity disposition (Mukhopadhyay *et al*., 2010; Rajendran *et al*., 2011). Crustal structure has been presented using the ambient noise and converted wave technique in this region by Gupta, S., *et al* (2016). However, a detail crustal and lithospheric structures have been imaged (Kumar *et al*., 2016), where the down-going of the Indian oceanic plate below the Andaman arc suffers deformation and lithospheric tearing possibly due to the dehydration of the slab (Mishra *et al*., 2011). Such an intriguing feature of slab tear has never been imaged using such high resolution.

In addition to the Andaman region, scientist from CSIR-NGRI also collaborated internationally and provided a model for asthenosphere based on the exclusive bore-hole broadband ocean bottom seismological (BBOBS) observatory data from Pacific and Philippine Sea Plates that explains successfully other geophysical observations. First time they have reported the nature of pure oceanic plates (Kawakatsu *et al*., 2009) and the detailed seismological evidence of the variation of thickness of oceanic plate with its age using high resolution data (Kumar and Kawakatsu, 2011).

Deciphering the seismic character of the young lithosphere near mid-oceanic ridges (MORs) is a challenging endeavour. Haldar *et al.* (2014) studied the hitherto elusive crust, lithospheric-asthenosphere boundary and upper mantle discontinuity near the mid-oceanic ridges using global seismological data. This was an interesting study that showed the nature of lithosphere near ridges first time and provided plausible geodynamic implications. In this study the seismic structure of the oceanic plate near the MORs is determined using the P-to-S conversions isolated from quality data recorded at five broadband seismological stations situated on ocean islands in their vicinity. Estimates of the crustal and lithospheric thickness values from waveform inversion of the P-receiver function stacks at individual stations reveal that the Moho depth varies between ~ 10 ± 1 km and ~ 20 ± 1 km with the depths of the LAB varying between ~40 ± 4 and ~ 65 ± 7 km. Evidence for an additional low-velocity layer is found below the expected LAB depths at stations on Ascension, São Jorge and Easter islands which probably relates to the presence of a hot spot corresponding to a magma chamber. Further, thinning of the upper mantle transition zone suggests a hotter mantle transition zone due to the possible presence of plumes in the mantle beneath the stations.

Public Outreach Programs

In the last decades there has been a substantial increase in engineering seismologists in India. Not only the prominent national institute practicing seismology but also a number of universities also started geophysical, a separate full-fledged discipline and embarked on the seismological projects. Institutes like NCS, MoES, NDMA, ISR and WIHG share their data through the websites to the public about the current seismic events with full information. CSIR-NGRI also shares the information to media at the time of major earthquakes and allays unnecessary fear of people by explaining the possibilities of damage potential. CSIR-NGRI provides awareness program by visiting remote parts of Indian and educating school children and local people. Under the school lab program CSIR-NGRI runs about 80 educational seismographs in the state Maharashtra. In addition, CSIR-NGRI also invites school children frequently and allows them to visit the laboratory with direct interaction with the scientists. This provides a broad perspective of the ever changing scenario in the field of seismology in the country.

Indian Antarctic Program

National Centre for Antarctic and Ocean Research (NCAOR) under MoES has been setup with the responsibilities for the country's research activities in the polar and Southern Ocean realms. CSIR-NGRI took the responsibility to install and maintain seismological station in the second base station Maitri in icy continent Antarctica. The data thus generated provide important clues to our understanding about the geodynamics, seismicity and structure of the continent. The data also serves an excellent supplement to that gathered by International effort. The analysis of the seismological waveforms suggest that the average crust in east Antarctica is about 40 km and also there is an effort to monitor the seismicity using the seismological stations (Malaimani *et al*., 2008). Recently, Gupta S. *et al.* (2017) used the seismological waveforms to compute the 1D crustal shear wave velocity profile below station Maitri. Another important finding came from the GPS study is the movement of the site with a velocity of 4.6 mm/yr northward (Ghavri *et al*., 2015).

Future Plans

Microzonation and Early Warning System

The seismological studies in India primarily focused on understanding the seismological processes, hazard mitigation and deep interior of the earth. These investigations identified active faults and earthquake risk zones fairly well. In recent times, it has been seen that frequent occurrence of seismic events in Himalaya, Andaman-Nicobar and plate interior posses serious threat to a large number of population especially the populated cities clustered in and around the thick sedimentary basin of Indo-Gangetic plain which lies in the vicinity of the Himalayan plate boundary. The threat due to the hazard is increasing due to the increase in population and also practice of making shoddy construction especially in the vulnerable regions. In this direction a major efforts have been already been made in India to carry out microzonation, however, it should be intensify in other cities those are situated in the Himalayan belt and Indo-Gangetic basins.

The second aspect is implementation of Earthquake Early Warning system near the most vulnerable areas of the country. In this direction a small step has been taken, however, an inexpensive prototype instrumentation should be developed and implemented. Further, GIS based intelligent earthquake hazard maps should also be a priority and that should be available in website just after the earthquake. MoES is providing shake maps soon after significant earthquakes. However, web-site should be accessible to anyone for all magnitudes. Such maps will be useful to the authorities involved in rescue and planning operation. This can be achieved through the monitoring of seismic activity all through the day using dense seismographs network. As soon as an earthquake occurs in and around the Indian plate, the seismic data should be quickly analyzed to estimate the hypocenter and magnitude. A number of tasks such as discrimination of earthquake, P-onset detection, hypocenter determination and so forth should be performed by fully automatic procedure.

Oceanic Plate

Indian plate is surrounded by oceans from three sides. We have not fully ventured into the ocean seismology as we did in continental region. The oceans are now the rich sources of conventional and non-conventional energy (hydrocarbon, gas hydrates etc.) and minerals. Geodynamically, oceanic plate is simple in nature as it originates from mid-oceanic ridge and destroyed along the trenches with shorter life span compared to the continental crust which survived billions of years. However, Indian oceanic plate particularly is complex, as it hosts a number of enigmatic features such as 90E ridge, oblique subduction along the Andaman trench, presence of Laccadive ridge, world's lowest geoid low, has a history of fast motion in cretaceous, ravaged by major plumes etc. Further, delineation the structure of the oceanic crust and uppermost mantle is essential for our understanding of the plate tectonics. Not much informations are available in this direction, mainly due to the paucity of the data from this region. However, few attempts have been made in deciphering the structure in Pacific and Atlantic regions by deploying passive ocean bottom seismometers.

The second aspect is to understand of the Andaman-Nicobar subduction system. We have two places Andaman and Makran, where major earthquakes have already been reported and ensuing tsunamis that caused loss of lives and damage to property in the coastal regions. Andaman is a complex region where we have a wide variation of crustal age (50-80Ma), variations in convergence rate along the arc. Some of the fundamental issues are still in debate such as slow ruptures speed, role of fluid in the subduction process, arc parallel volcanisms, different convergence rate along the arc etc. The lack of data leads to the poor understanding of the seismogenesis and geodynamic processes. In this regard, out attempt now should be towards the exploration of deep ocean by deploying more ocean bottom seismometers. Such attempts not only boost the already existing tsunami facility of India but also help to understand the geodynamic and resource aspects of the oceanic lithosphere.

Slow Slip Earthquakes

A slow slip events are episodic that releases energy over a period of hours to month, unlike the typical earthquakes. Most of the slow events are now understood to be accompanied by fluid flow and tremor related and can be detected in seismometers in the typical frequency range of 1 and 10 Hz, which is lower than that of the same sized normal earthquakes. Such tremor activities are reported in Japanese and Cascadia subduction zones. These tremors and slow slip are thought to represent the condition of the plate boundary and stress accumulation of the locked zone. It would be a challenging task to detect such type of phenomenon in Himalaya and Andaman-Nicobar trench.

Based on the historical earthquake data and inferred rupture extent of great earthquakes, it has been suggested that some segments of the detachment under the Himalayan arc have not experienced major and great earthquakes in the past 100 years or so and falls in the seismic gap. However, it is quite likely that the presence of creep in such segments may enable the seismic gap to ever be filled. In such cases the observations, monitoring and modeling of the slow slip events especially in the Himalayan region would be important to understand the seismogenesis and loading processes in these active regions.

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Review Article

Controlled Source Seismology in India in the 21st Century

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The controlled source seismology (CSS), where artificial sources are used and near-vertical reflections, refractions and wide-angle reflections are recorded, has been a powerful tool for delineating shallow/deep crustal structures and subsurface features. Significant results, brought out from the vintage and new CSS data in the 21st century, include geological/tectonic aspects of the Dharwar craton, Delhi-Aravalli fold belt, Central Indian Tectonic Zone, Southern Granulite Terrain, Proterozoic Cuddapah basin, Kangra fold-thrust belt, Hazara syntaxis in NW Himalaya, Chambal-valley Vindhya basin, Mahanadi delta and Bengal basins. These studies also provide useful inputs in understanding the genesis of 1997 Jabalpur and 2001 Bhuj earthquakes. Imaging sub-volcanic Mesozoic sediments, in which more than 50% of global oil is found, has been a challenge by routine geophysical methods. This problem has been alleviated by CSS experiments, and Mesozoic sediments below the Deccan volcanic rocks have been delineated in the Saurashtra peninsula, Kutch peninsula, Tapti-graben and Kerala-Konkan offshore regions, and Gondwana sediments below the Rajmahal Traps have been mapped in the Mahanadi and Bengal basin. Several approaches have been proposed for the detection, characterization and assessment of gas-hydrates from shallow seismic data. These have been applied to field data that has resulted into identifying gas-hydrates, a major future energy resource of India, in the Krishna-Godavari, Mahanadi and Andaman offshore regions. Gas-hydrates have been subsequently recovered by drilling & coring under Indian National Gas Hydrates Program. The prognosticated amount of methane stored as gas-hydrates within Indian Exclusive Economic Zone is so huge that only 10% production may suffice our vast energy requirement for the next 100 years.

Keywords: CSS Data; Crustal Structure; Geo-tectonics; Sub-volcanic Sediments; Gas-hydrates

Introduction

Near vertical deep-travelling multi-channel seismic (MCS) reflections, large-offset refractions and wide-angle reflections recorded in Controlled Source Seismology (CSS) are extensively used in deriving shallow and deep features of the earth. Shallow structures of sedimentary basins are useful for the exploration of hydrocarbons and understanding geological history, whereas crustal structures provide useful inputs for tectonic implications, deep insight on mineralized prospects and evolutionary processes of various regions. Since 1972, more than 6000 line-kilometers of CSS data (Fig. 1) have been acquired by CSIR-NGRI. Conspicuous structural and evolutionary signatures, which have been brought during the last three decades of the 20th century over several provinces of India, are available in review literatures (Kaila and Krishna, 1992; Kaila and Sain, 1997; Behera and Sain, 2006 and Sain, 2008). Several advancements have taken place in seismic data acquisition, processing and modeling during the last two decades. Application of new tools to the vintage data has led to the delineation of subsurface features that were not evident earlier.

Significant results derived from the vintage and new data that have been carried out in the 21st century are presented here. These cover geo-tectonic implications, imaging sub-volcanic sediments, delineation of sedimentary basins and exploration of gas-hydrates. Fig. 1 gives the locations of profiles discussed in this paper.

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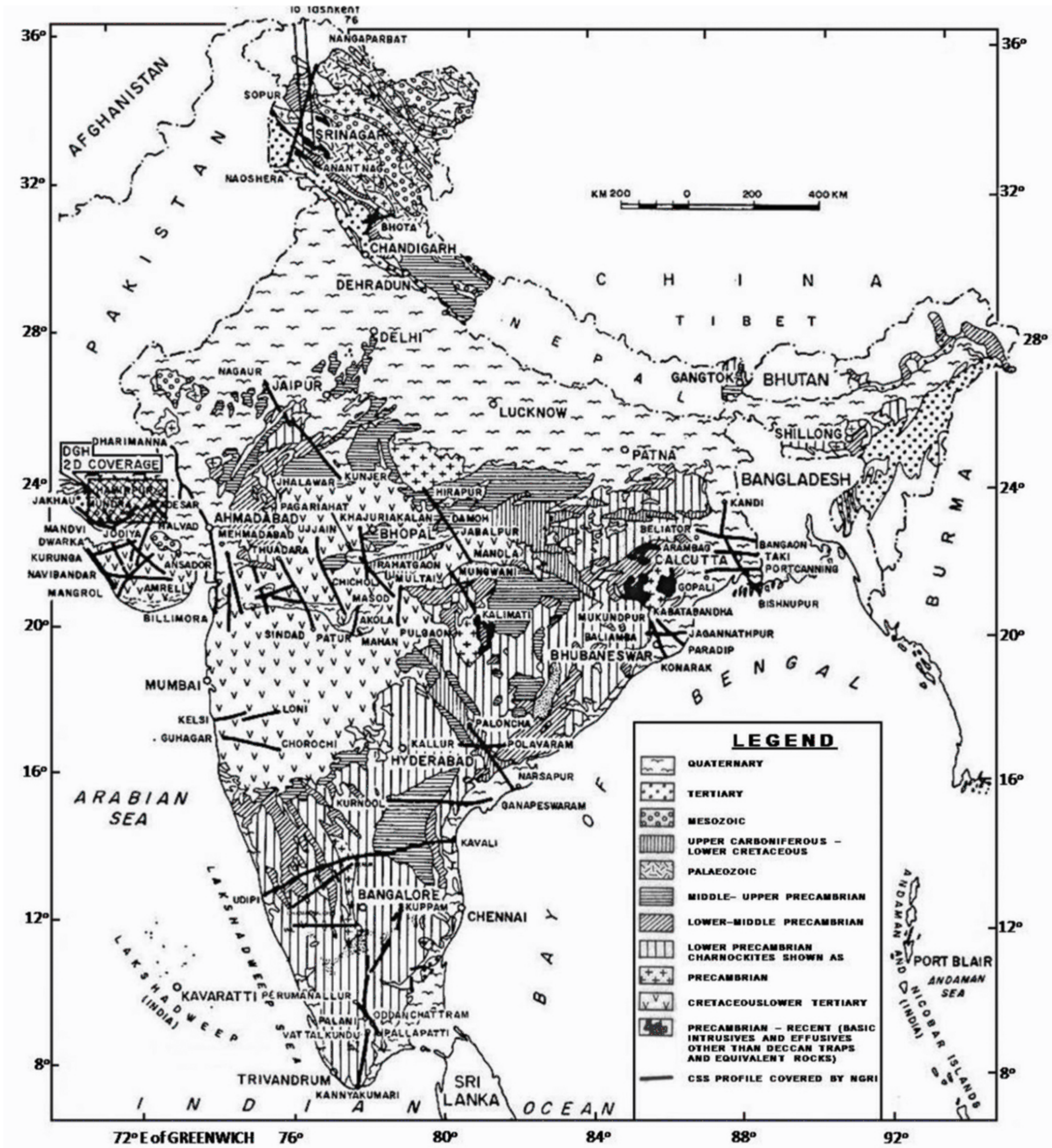

Fig. 1: Locations of CSS profiles (marked by solid lines) shown in different provinces superimposed on geological map of India

Crustal Structures and Geo-Tectonics

Dharwar Craton (DC) in Southern India

The tomographic 2-D velocity model (Fig. 2) in the upper crust with velocities varying between 5.7 to 6.4 km/s along the 200 km long NE-SW Perur-Chikmagalur profile in the DC (Rao *et al*., 2015) is consistent with the regional convergence and accretion of two crustal blocks: western Dharwar craton (WDC) and eastern Dharwar craton (EDC). The undulating high and low velocity contours representing the fold-thrust structure developed in compressional regime ceases at ~8 km depth, indicative of a probable detachment.

The steepness of the undulating layers is interpreted as near-vertical faults bounding various tectonic domains and geological units. Structural variations are indicated by pattern of velocity contours that also indicate the geological contacts on either side of the model. Recent analysis of deep seismic reflection data along the same line shows distinctly different reflectivity patterns in the Mesoarchean WDC and Neoarchean EDC (Mandal *et al*., 2017). The WDC consists of a simple structure with a major

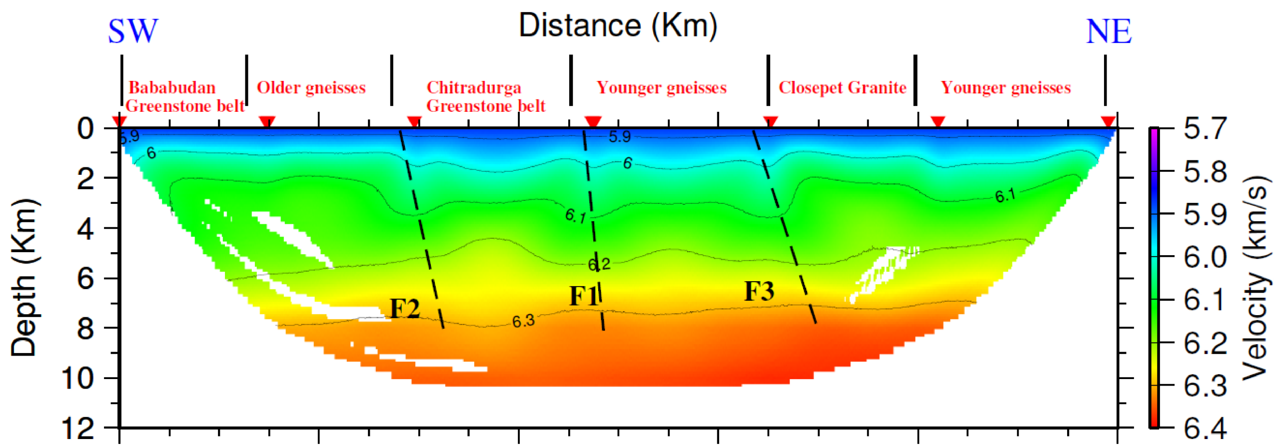

Fig. 2: Velocity model along Perur (NE) Chikmagalur (SW) line with 5:1 vertical exaggeration. Inverted triangles represent shot points. F_1, F_2 and F_3 are inferred faults that coincide with tectonic/geological contacts shown at the top (after Rao *et al*., 2015)

part of the crust from 6 to 28 km displaying a gently dipping reflection fabric and a sub-horizontal reflection fabric from 28 to 40 km except beneath the Chitradurga schist belt. On the other hand, the EDC displays a complex reflectivity pattern with deepening Moho, oppositely dipping reflection fabric and crustal-scale thrust fault. The west-dipping reflection fabric, extending from 34 to 43 km in EDC, may represent an upper-mantle subduction zone. The EDC is thrusted obliquely against the pre-existing proto-continent of WDC. Oppositely dipping reflection fabrics with a crustal root at convergence boundary suggest accretion of WDC and EDC during the Neoarchean orogeny. The collisional boundary coincides with the location of ~2.5 Ga Closepet granite. However, the disposition of almost near-vertical faults, as observed in shallow depths of tomographic model, are not so evident in deep crustal image.

Delhi-Aravalli-Fold Belt (DAFB) of Northwest India

The state-of-the-art common reflection surface (CRS) stack has been applied to the vintage deep seismic MCS data across the DAFB in NW India (Mandal *et al*., 2014). It has brought out Moho below the Marwar basin and Sandmata complex, prominent upper to mid-crustal reflectors and extension of crustal-scale Jahazpur thrust becoming listric at lower crust/Moho below the Sandmata complex (Fig. 3). The study indicates that the CRS stack is more appropriate than

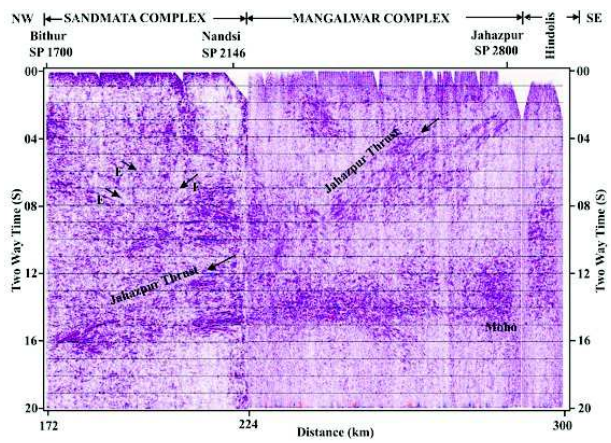

Fig. 3: Seismic section below the Sandmata and Mangalwar complexes. 'E' and 'F' mark the Jahazpur thrust and opposite dipping reflections (after Mandal *et al*., 2014)

conventional CMP stack (Rao *et al*., 2000; Satyavani *et al*., 2001, 2004; Tewari and Rao, 2003; Prasad and Rao, 2006) for imaging the complex region. Crustal thickness across the Proterozoic orogenic belt varies from 38 and 50 km. Paleo-signatures of the Proterozoic subduction and collision processes are still preserved in major portion of the crust as well as in several parts of the world.

Central Indian Tectonic Zone (CITZ)

The CRS stack to seismic reflection data in CITZ has revealed subsurface features (Mandal *et al*., 2013) that were either poorly resolved or entirely absent in earlier CMP section (Mall *et al*., 2008). The result has brought out Moho throughout the seismic line, existence of crustal blocks with distinct dipping reflection fabrics on northern and southern sides of central Indian suture (CIS), 8 km of Moho offset beneath the CIS, and high amplitude reflectivity that represents the CIS (Fig. 4). A deeply penetrating crustal-scale imbricated structure imaged up to 16.0 s TWT, to the south of CIS, suggests that the Bastar craton has subducted northwards. An oppositely dipping reflection fabric, Moho-offset, positive-negative gravity anomaly pair and the geological data indicate that the CIS represents a collision zone developed due to the interaction of the Bastar and Bundelkhand cratons with the evolution of Sausar orogeny at ~1000 Ma. This is contemporaneous with the Grenvelliean orogeny and Rodinia assembly. Another thrust fault extending from 4 to 14 s TWT observed to the north of CIS may represent the earlier pre-Sausar orogenic activity at 1.6-1.5 Ga.

Southern Granulite Terrain (SGT)

The coincident deep seismic reflection and wide-angle experiments along the Kuppam-Palani transect in SGT has delineated a four-layered crust (40-45 km) with 7-15 km thick mid crustal low-velocity (6.0 km/s) zone (Rao *et al*., 2006) and oppositely dipping reflection bands (Fig. 5), exhibiting southern dip for the northern segment and northern dip for the southern segment. This implies the collision tectonics between the Dharwar craton in the north and a crustal block in the south (a part of present day Eastern Ghats mobile belt) (Reddy *et al*., 2003; Rao *et al*., 2006). The high Vp (6.3-6.5 km/s), Vs (3.5-3.8 km/s), Vp/Vs (>1.75) and Poisson's ratio (0.25-0.29) up to 8 km depth in the tomographic image (Prasad *et al*., 2006) might be related to exhumation of mid to lower crustal rocks through the Mettur shear zone associated with the Pan-African tectonothermal activity during the Neoproterozoic (Kroner and Brown, 2005).

Further south along the Vattalkundu-Kalugumalai transect of SGT, another CSS profile (Prasad *et al*., 2007) shows noticeable changes in reflectivity pattern in structurally distinct crustal blocks. It is apparent from the north dipping reflectors near Vattalkundu that the Kodaikanal massif extends 5 km further south of Vattalkundu, where the dip direction changes southwards. The crustal reflectivity in central part (Sedapatti to Sarvathapuram) of the profile shows upliftment leading to crustal deformation of the Madurai Block. The dip is steeper on the southern flank than that on the northern side.

Mahanadi Delta

Modeling of wide-angle seismic and gravity data along three profiles in Mahanadi delta in eastern India have

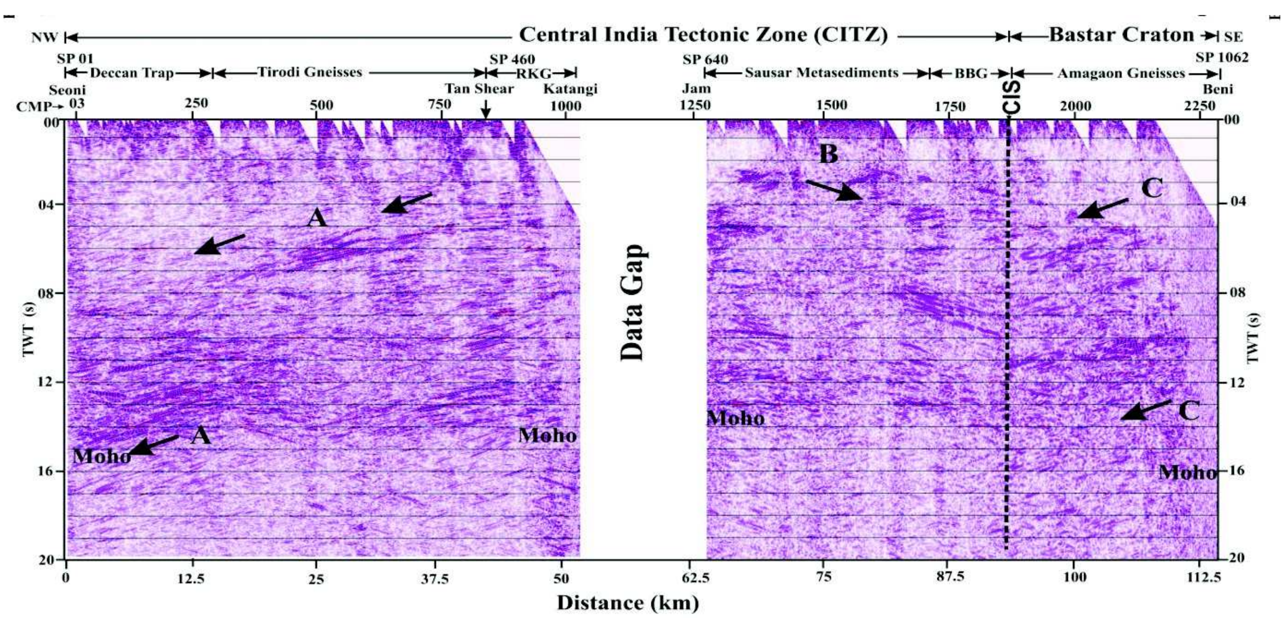

Fig. 4: Seismic section along Seoni-Beni line. End of seismic reflectivity represents the base of crust (Moho). A, B and C mark the dipping reflection bands (after Mandal *et al*., 2013)

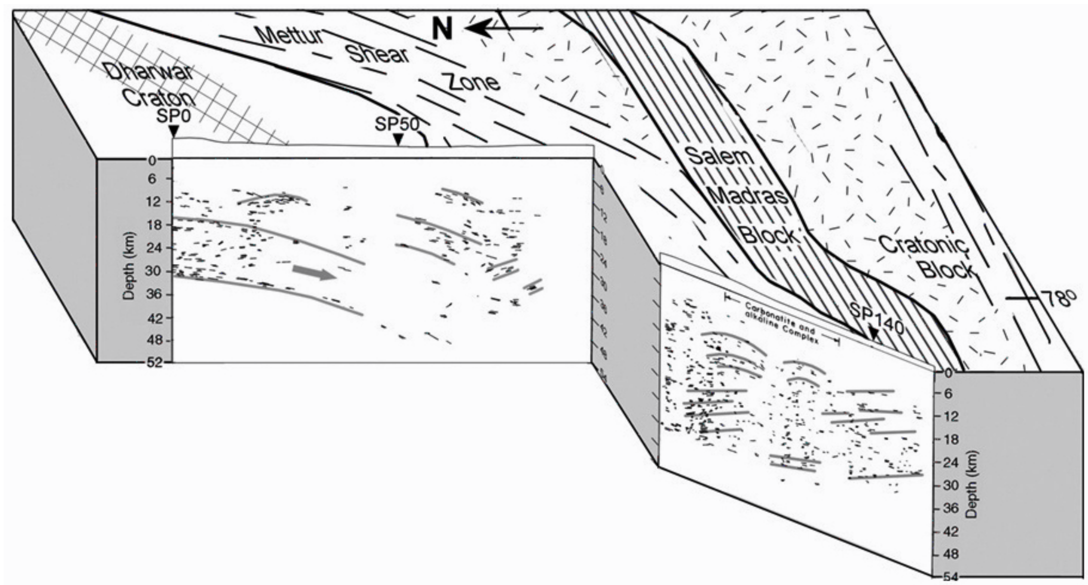

Fig. 5: 3-D representation of seismic reflection line drawings showing the collision zone with the Dharwar craton forced towards the south where it has subsequently collided with the southern crustal block. Also notice the evolution of a suture at the Mettur shear zone (after Rao *et al*., 2006)

delineated a five-layered 2-D crustal structure with velocities of 6.0, 6.5, 6.0, 7.0 and 7.5 km/s and densities of 2.7, 2.8, 2.65, 2.9 and 3.05 g/cc respectively (Behera *et al*., 2004). These results, along with high heat flux (Rao and Rao, 1983) and other geological/ geochronological information, indicate typical rift-related evolution of the delta. The crustal thinning (34-37 km), presence of mid-crustal low velocity/density zone and emplacement of ~10 km thick high velocity/ density material at base of the crust strongly suggests basaltic underplating probably associated with the Kerguelen hot spot activity. These activities are synchronous with the Rajmahal volcanism (~117 Ma) of northeast India and the Lambert graben of East Antarctica, and are linked to breakup of the Gondwanaland.

Complex Velocity Structure in central India Across Narmada Lineament

Re-analysis of wide-angle CSS data in central India along the Hirapur-Mandla profile shows Moho upwarp below the Narmada lineament, lateral and vertical structural heterogeneities and velocity inhomogeneities in the crust (Murty *et al*., 2008a). These have caused instability to the crustal blocks and could have been responsible for the reactivation of the Narmada south fault near Jabalpur. The features associated with the boundary fault near Jabalpur (Sain *et al*., 2000) might have acted as path for release of stress accumulated due to continuous northward movement of the Indian plate causing the 1997 Jabalpur earthquake.

Epicentral Region of the 2001 Bhuj Earthquake

The prestack depth migration of seismic refraction data, which were originally acquired for the delineation of basement configuration and overlying formations (Sarkar *et al*., 2007), reveal crustal-scale hidden faults beneath the 2001 Bhuj epicentral region and highly reflective 45 km thick crust compared to shallow (35 km) crust in the coastal region (Fig. 6). This observation contradicts the seismic activity in the Bhuj/ Kutch region due to thin rifted crust as was found along the East African rift (Mooney and Christensen, 1994). The crustal thickening could be due to the compressive regime of the past 55 my or may be attributed to magmatic intrusions during the Mesozoic rifting connected to the breakup of Gondwanaland.

Saurashtra Region

Remodeling of wide-angle seismic data along the 160-km long E-W Amreli-Navibandar profile in Saurashtra Peninsula has yielded a crustal model (Rao and Tewari, 2005) that is different from the earlier model (Kaila *et al*., 1980). The new model shows the upper

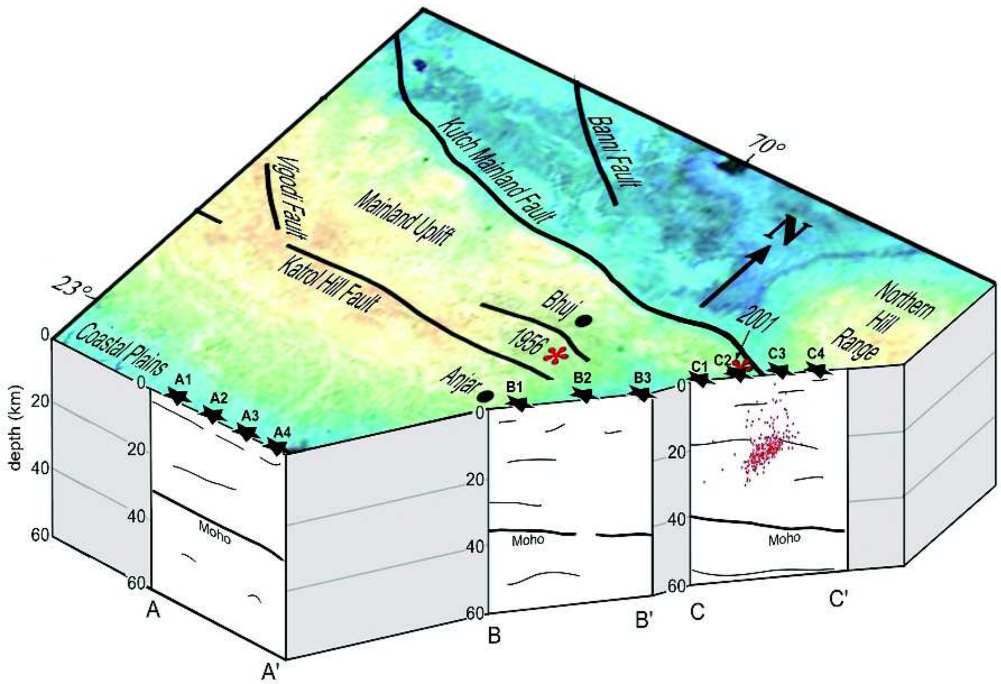

Fig. 6: Three seismic-reflection lines (A, B, C) with prominent subsurface reflectors shown in pie-slice diagram near the 2001 Bhuj epicentral region. Red dots are the aftershocks; location of the Kutch Mainland Fault is also shown (after Sarkar *et al*., 2007)

crust down to a depth of 16 km in the west and 13 km in the east and an underplating material (7.2 km/s) at the base of crust with Moho lying at ~36 km in western part and ~33 km in eastern part. This represents an uplifted crust, akin to Cambay basin, and exhibits an impression of India passing over the Reunion Plume during Late Cretaceous.

Eastern Ghats Belt-Cuddapah Basin Collisional Zone

Wide-angle seismic data along the Parnapalle-Kavali segment of Kavali-Udipi profile (Kaila *et al*., 1979), acquired for the first time in India, have revealed intracratonic Proterozoic Cuddapah basin with ~4 km thick sediments bounded by two major faults (Chandrakala *et al*., 2015). The fault, delineated up to the Moho on its eastern boundary, demarcates the Cuddapah basin from the Nellore Schist Belt. The crustal layers beneath the Nellore Schist Belt and the Ongole domain of Eastern Ghats Belt having distinct eastward dipping trend conform to an upthrusted feature. Besides this, the area lying east of Cuddapah Basin appears to be an accreted orogenic terrain, beneath which lower crust has upwarped substantially. The entire stretch of study area is underplated by unprecedently thick (~20 km) high velocity (7.0-7.4 km/s) magma layer above the Moho, indicating a strong crust-mantle thermal perturbation and massive sub-crustal erosion. Further, an expression of a deep seated mantle thermal anomaly has also been found below the Parnapalle region of the SW Cuddapah basin beneath which deeper crustal layers have been exhumed.

Imaging Proterozoic Chambal-valley Vindhyan Basin in NW India

The CRS stack of seismic reflection data along the 165 km long Chandli-Bundi-Kota-Kunjer profile in Chambal-valley, Vindhya basin shows a gently dipping structure of the Vindhyan basin with 7.5 km thick Proterozoic sediments and 1.5 km volcanic sequence over the granitic-basement (Mandal *et al*., 2018). The Great Boundary Thrust (GBT), a NW-dipping crustal-scale regional tectonic feature outcropping at Bundi and a new NW dipping reflection band from 9 to 30 km depth, named as the Chambal thrust (CT), are imaged beneath the Bundi-Kota segment (Fig. 7). Seismic images of compression on one-side and extension on other-side along with differences in the Moho characteristics, strong lateral discontinuity and

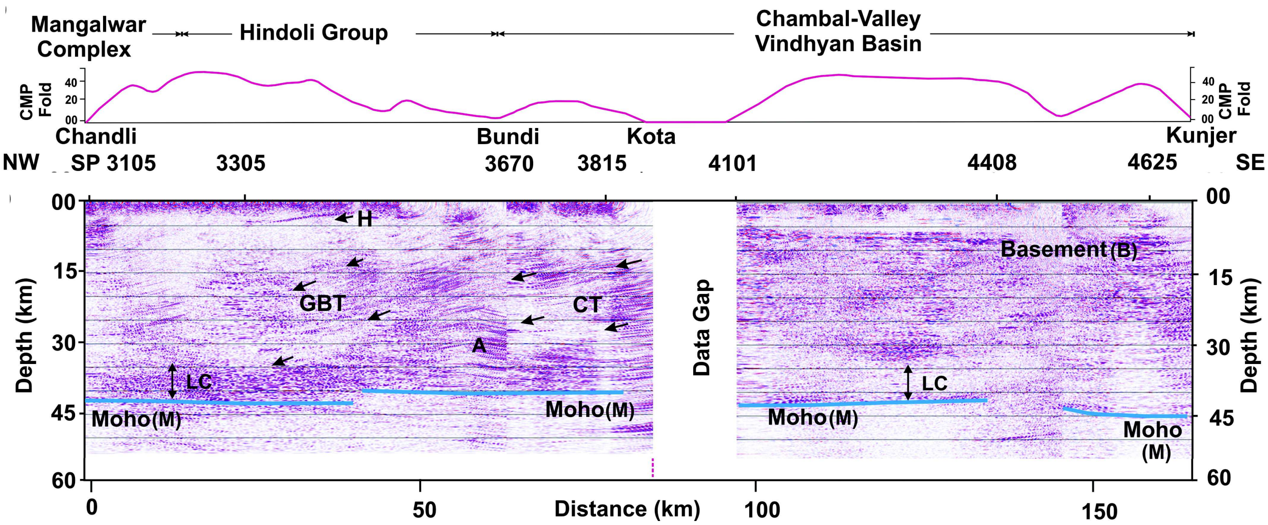

Fig. 7: Depth migrated CRS section along Chandli-Bundi-Kota-Kunjer profile. H represents basement for the Hindoli group; A is the SE-dipping lower crustal reflection band; M is Moho; B is Crystalline Basement; and LC is the Lower Crust (after Mandal *et al.*, 2018)

strike-slip features are observed. The Moho topography varying between 40 to 44 km with a 9-12 km thick mafic underplating at lower-crust suggests a post-collisional vertical tectonic. The difference in crustal structure to the west and east of Kota indicates a tectonic boundary that separates the compressional events in the west and extensional activity to the east.

Northwest Himalaya

Crustal Structure Across the Hazara Syntaxis

Re-analysis of seismic refraction, wide-angle reflection and gravity data along the 270 km long Lawrencepur-Astor profile (from the Indus plains, crossing over the Main Central Thrust (MCT), Hazara Syntaxis and Main Mantle Thrust (MMT) to the east of the Nanga Parbat) in northwest Himalaya infers the High Himalayan Crystallines (HHC) with a velocity of 5.4 km/s over the Indian basement (5.8-6.0 km/s). The crust consists of four layers with velocities of 5.8-6.0, 6.2, 6.4 and 6.8 km/s respectively with the Moho dipping from 55 to 61 km northward indicating the subduction of Indian plate beneath the Eurasian plate (Bhukta *et al*., 2006).

Structure Beneath the Sub-Himalayan Fold-thrust Belt, Kangra Recess

Most compressional orogens include recesses along their strike. In the Kangra recess, which is the largest recess within the active Himalayan orogen, the Sub-Himalayan sedimentary fold-thrust belt increases in width to 90 km in the Kangra basin and narrows to 10 km in the adjoining Nahan salient of the main Boundary Thrust (MBT) to the southeast.

The seismic reflection profiling places the Himalayan décollement at 6-8 km depth above a thin reflective Meso-Neo-Proterozoic Vindhyan strata (Lesser Himalayan Series-equivalent) (Prasad *et al*., 2011). The study shows that the Vindhyan sedimentary rocks are thinner in the Kangra recess than further southeast, supporting the hypothesis that the width of the Lesser Himalayan thrust belt and existence of the Kangra recess could be related to the pre-deformation basin thickness. This hypothesis obviates the need for control of the Kangra recess by a lateral ramp in the Main Himalayan Thrust, making it more likely that the Kangra segment could rupture as part of an earthquake far more than the devastating 1905 M = 7.8 Kangra earthquake. Below the Proterozoic sedimentary rocks, the study shows a west–southwest dipping reflective fabric spanning a 30 km-crustal thickness. This may correspond to a widespread "Ulleri-Wangtu" orogenic event at 1850 Ma affecting a pre-Tethyan Indian continental margin, thickening the basement by 20%. The deepest 10 km of 50 km-thick crust shows a more horizontal, arguably younger reflectivity, though the Moho is not clearly imaged.

Sub-Volcanic Sediments

As more than 50% global oil is found in Mesozoic sediments, oil industries show a lot of interest for exploration of Mesozoic sediments for possible oil resources. However, in India, a vast tract of such sediments (both onshore and offshore) are covered by volcanic rocks that have made routine geophysical methods including standard near-vertical seismic reflection technique incapable of probing them. Wide-angle seismic experiment has been successful in delineating large-scale velocity-structure of sub-volcanic sediments (Dixit *et al*., 2000; Mall *et al*., 2002; Sridhar *et al*., 2009; Sain *et al*., 2002a; Prasad *et al*., 2013; Murty *et al*., 2016) by traveltime tomography. The results show (i) ~1.6 km thick Mesozoic sediments masked by ~1.3 km thick Deccan volcanic rocks in Saurashtra peninsula that match with the litholog in Lodhika well; (ii) ~1.5 km Mesozoic sediments below ~0.45 km Deccan Traps in Kutch peninsula; and (iii) ~2.0 km thick Mesozoic sediments covered by ~2.0 km thick Deccan volcanics in Tapti graben.

The wide-angle seismic experiments have also delineated (i) ~1.5 km thick Gondwana sediments below ~200 m thin lid of Rajmahal Trap in Mahanadi delta (Sain *et al*., 2002b); and (ii) ~1.5 km thick Gondwana Sediments below ~1.0 km Rajmahal Traps in Bengal basin (Murty *et al*., 2008b). However, the velocity model as seen from the example section (Fig. 8) lacks in finer details in which oil industries look for structural traps or stratigraphic horizons for accumulation of hydrocarbons. The state-of-the-art full waveform inversion (FWI) can delineate not only accurate seismic velocity but also fine-scale structures by exploiting all components (traveltimes, amplitudes, frequencies, phases) of seismic data (Sain *et al*., 2004). The application of FWI has been demonstrated, for the first time in India, to industry-standard wide-angle ocean bottom seismic (OBS) data in Kerala-Konkan (KK) offshore. The data were procured from Oil & Natural Gas Corporation (ONGC) Ltd., Mumbai to pursue this cutting-edge research. The delineation of 105 m Limestone formation below 950 m volcanic rocks (Sain *et al*., 2018), which matches with the available log data, has boosted interest in improving structural images by advanced processing like the CRS stack or prestack depth migration (PSDM) or reverse time migration (RTM); increasing the study

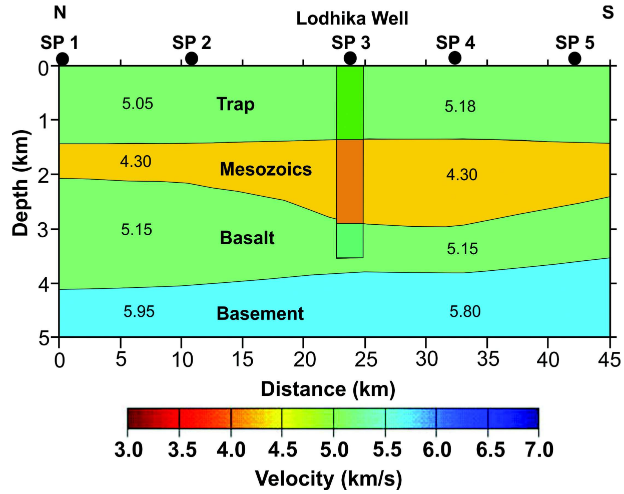

Fig. 8: Sub-volcanic Mesozoics along a N-S seismic line passing through the Lodhika well with litholog superimposed. Solid circles are shot points (after Sain *et al*., 2002a)

area in KK offshore; and extending similar works in other regions (Kutch, Saurashtra and Cauvery offshore) for exploration of hydrocarbons in sub-volcanic sediments. Industries have also developed interest for imaging Proterozoic Vindhyan sediments below the volcanic rocks and exploration of hydrocarbons in difficult terrains such as the thrust-fold belt regions in the sub-Himalaya.

Sedimentary Basins, Delta

Marwar, Mahanadi, Vindhyan and Cuddapah basins have been delineated from wide-angle seismic data. The basement configuration and overlying sedimentary formations of a few basins are described below.

Bengal Basin

Application of traveltime tomography to the first arrival seismic data along four profiles in West Bengal sedimentary basin has revealed a smooth structure of sedimentary formations including the Rajmahal Traps with velocities varying between 1.7 and 5.6 km/s overlying the basement, characterized by 5.8-6.0 km/s seismic velocity (Damodara *et al*., 2017). The sudden increase in basement depth from 8 to 16 km towards east within a short distance is identified as the Hinge zone (Fig. 9), where the stable Indian shield ends.

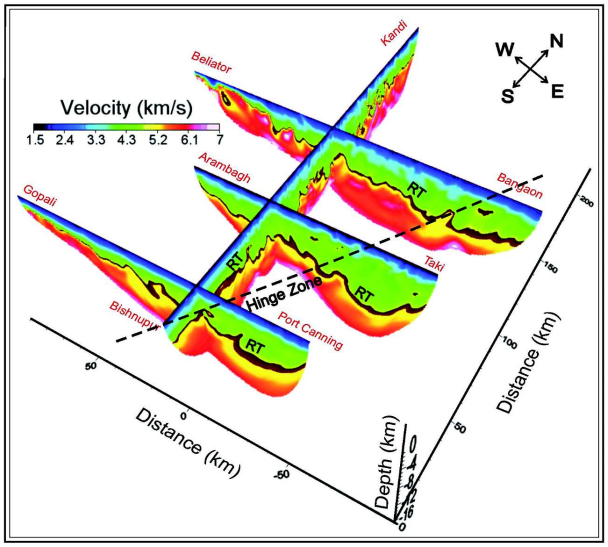

Fig. 9: Fence diagram, derived from tomographic velocity models along four seismic profiles (P_1, P_2, P_3, P_4), showing pseudo 3-D velocity structure in the West Bengal sedimentary basin (after Damodara *et al.*, 2017)

The subsurface Rajmahal traps delineated in the present study may be related to mantle plume activity, either the Kerguelen or the Crozet, which is responsible for the breakup of East Gondwana during the early Cretaceous. The Rajmahal traps at depth and the Hinge zone suggest the role of global tectonics on the architecture of the West Bengal basin.

Marwar Basin

Rao *et al.* (2007) have presented a new approach and applied to the single-ended first arrival seismic data, which were originally recorded for the investigation of deep crustal structure. The result shows a three-layered shallow model of the Neoproterozoic Marwar basin in northwestern Indian shield above the complicated basement (5.9 km/s), which was not recognized in earlier deep seismic reflection profiling (Tewari *et al.*, 1997). The first two-layers represent the Quaternary/Tertiary (2.2 km/s) and Marwar (4.2 km/s) sediments respectively, and the third layer is the Malani volcanics (4.9 km/s). The approach is quite successful for delineating refractor depths, steep dips and velocities, which are found to be qualitatively consistent with the near-vertical MCS section, and is thus the best suited to the long-streamer marine seismic reflection data.

Mahanadi Delta

The ray-based 2-D forward modeling of first arrival seismic data shows alternate graben and horst structures - the Konark depression (0-15 km), the Bhubaneswar ridge (15-50 km), the Cuttack depression (50-100 km) and the Chandikhol ridge (100-115 km) along the N-S Mukundpur-Konark profile (Behera *et al.*, 2002). The Konark depression is composed of three sedimentary layers with velocities of 1.75, 2.4 and 4.0 km/s and attains a maximum depth of 2.9 km at 9 km profile distance. To the north of the profile, a low velocity (4.0 km/s) layer with basinal shape, believed to be the Gondwana sediments, has been imaged using the 'skip' phenomenon of the first arrival data. This layer with a maximum thickness of 1.75 km near Cuttack is sandwiched between a thin (100-300 m) cover of high-velocity Rajmahal Trap (5.25 km/s) and underlying basement (6.0 km/s) rocks.

Vindhyan Basin

Remodeling of wide-angle seismic data along a 240-km-long Hirapur-Mandla CSS profile in central India (Sain *et al.*, 2000) has delineated shallow structure that depicts a horst feature in which high-velocity (6.5 km/s) lower crustal materials have risen up to a depth of less than 2 km below the Narmada lineament. North of this horst feature has received ~1.5 km thick Upper Vindhyan (4.5 km/s) and ~4.5 km thick Lower Vindhyan (5.3 km/s) sediments, which are verified by traveltime tomography (Zelt *et al.*, 2003). The tomographic model also provided the model bounds and lateral resolution that are required for assessing a model.

Cuddapah Basin

Cuddapah basin, one of the largest intra-cratonic Proterozoic basin, is situated in the eastern part of Dharwar craton and magmatically infested. Based on CSS and thermal driving force, it was perceived that the basin may contain as much as 10-12 km thick sediments (Mall *et al.*, 2008). However, the updated model (Chandrakala *et al.*, 2013) show a five layered upper crust associated with velocities of (i) 4.50 km/s, (ii) 5.20-5.30 km/s, (iii) 5.50-5.80 km/s, (iv) 5.85-6.00 km/s, and (v) 6.40 km/s respectively. The second and third layers correspond to the upper and lower Cuddapah sediments having only 4.0 km sediments in the deepest part of the basin below the Nallamalai fold belt. The study shows that the role of thermal driving force may be marginal, particularly in the deeper eastern Cuddapah, as isostatic subsidence due to sedimentary accumulation alone is enough to explain the depth of the basin.

Gas-Hydrates – Major Future Energy Resources

Gas-hydrates, ice-like crystalline form of methane (99.9%) and water, occur in shallow sediments along the outer continental margins and permafrost regions. These are envisaged as one of the best alternatives, as their energy content is more than two times that of total fossil fuels (oil, natural gas and coal). It is presumed that only 15% production from global reserve can meet world's energy requirement for about 200 years. The amount of methane prognosticated in the form of gas-hydrates along the Indian margin is more than 1500 times of country's present natural gas reserves, and only 10% recovery can meet India's overwhelming energy requirement for about 100 years (Sain and Gupta, 2008; Sain and Gupta, 2012). The production tests in Alaska of USA, McKenzie delta of Canada, Nankai Trough off Japan and South China Sea provide great hopes for energy security of many Asia-Pacific countries like India, Japan, South Korea and China. Hence, there lies a great interest for the delineation and quantification of gas-hydrates using various geo-scientific methods for evaluating the resource potential followed by technology development for viable commercial production. Globally, gas-hydrates have been identified by geophysical, geochemical and geological surveys, and recovered by drilling and coring.

Gas-hydrates are detected mainly with seismic experiment by identifying an anomalous reflector, known as the bottom simulating reflector or BSR, which lies at the base of gas hydrates stability zone. CSIR-NGRI has taken up this research, and established state-of-the-art Gas Hydrate Research Center at its own campus with world-class facilities that include inversion, processing, modeling & interpretation of seismic data for the detection and assessment of gas-hydrates along with laboratory studies to understand the formation and dissociation kinetics aiming for providing inputs to develop suitable production technology. The global status on exploration and exploitation of gas-hydrates and when will they be produced safely is available in a recent editorial (Sain, 2017). Salient features are described below:

- Prepared gas-hydrates stability thickness map (Fig.10) along the Indian margin (Sain *et al*., 2011), and illuminated the scenario within Indian exclusive economic zone (Sain and Gupta, 2012; Sain, 2012).
- Characterized gas-hydrates reservoirs using seismic attributes (Satyavani *et al*., 2008; Ojha and Sain, 2009; Sain *et al*., 2009; Sain and Singh, 2011; Satyavani and Sain, 2015; Kumar *et al*., 2018).
- Developed innovative methods for the quantification and assessment of gas-hydrates (Ghosh and Sain, 2008; Ojha *et al*., 2010; Ojha *et al*., 2016; Ghosh *et al*., 2010a; Ghosh *et al*., 2010b; Sain *et al*., 2010; Shankar *et al*., 2013; Shankar *et al*., 2014; Ojha and Sain, 2013; Wang *et al*., 2013; Wang *et al*., 2014; Jana *et al*., 2015; Jana *et al*., 2017; Satyavani *et al*., 2015; Satyavani *et al*., 2016).
- Identified prospective zones of gas-hydrates, using industry-standard seismic data, in Krishna-Godavari (KG), Mahanadi and Andaman offshore basins (Fig. 10) from where gas-hydrates were later recovered by drilling and coring of Indian National Gas Hydrates Program.
- Detected proxies of gas-hydrates in KK, Saurashtra, Kerala-Laccadive and Cauvery offshore basins (Fig. 10) also.
- Designed a specific experiment using state-of-the-art data acquisition system, and delineated new potential zones of gas-hydrates in KG and Mahanadi basins through acquisition, processing and modeling of MCS and OBS data (Sain *et al*., 2012).

Future Work With Social Implications

As requisite expertise in state-of-the-art seismic data acquisition, processing, inversion and modeling have been developed, future activities with regard to reprocessing and/or remodeling of vintage data using modern tools as well as acquisition processing and/or

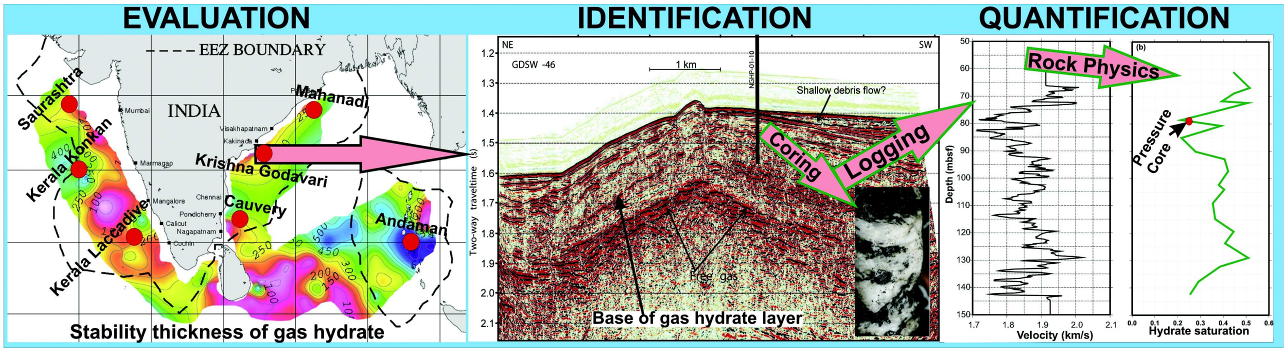

Fig. 10: (Left) Gas-hydrates stability thickness map within the Indian EEZ boundary showing the most prospective (Krishna-Godavari, Mahanadi and Andaman) and less-explored but potential zones (Kerala-Konkan, Saurashtra, Kerala-Laccadive and Cauvery) of gas-hydrates; (Middle) A representative seismic section showing BSR, marker for gas-hydrates, with recovered gas-hydrates samples at right-bottom corner; (Right) Sonic log and result of rock physics modeling for estimation of gas-hydrates

/modeling of new data are listed to derive improved image of the subsurface:

For the Five Year Scientific Program of CSIR, Delhi, during 2012-2017, acquisition of long-offset MCS and wide-angle OBS data was planned to shed light on seismogenesis of the Andaman subduction zone. Due to non-availability of ship, the data acquisition could not be achieved in time but have been in 2018. The data are to be advanced processed by CRS stack or PSDM and tomographic modelled to understand the geometries of both over-riding and undergoing plates, dip angles, extent of asperity zone, fault-systems that may help in understanding the seismo-tectonics of the region and undertaking similar studies in its counterpart Himalayan subduction zone. Besides these, the shallow sediments in the accretionary wedge may host gas-hydrates, and the data should be processed and inverted accordingly.

MCS and wide-angle seismic data have been recently acquired by CSIR-NGRI in the Kutch peninsula under the aegis of the Ministry of Earth Sciences (MoES), Delhi and Institute of Seismological Research, Gandhinagar, and the data will be processed/modelled by advanced tools for delineating crustal fabrics including the subsurface disposition of faults (both known and hidden) to shed light on seismotectonics of the Kutch.

After having successfully imaged the deep crusts in DC, DAFB, CITZ and Proterozoic Chambal-valley Vindhyan basin using CRS stacking, now it is planned for seismic tomography followed by CRS stack to available CSS data for imaging Achankovil Shear Zone in SGT with view to better understand the geotectonic of the region.

The conventional processing of CSS data in the sub-Himalayan fold-thrust belt acquired under the HIMPROBE Project of the Dept. of Sci. & Tech., Delhi in Kangra recess couldn't delineate the geometry of the decollement that detaches/separates deformed rocks above from undeformed or differently deformed rocks below. It is planned to utilize the available data for CRS stack or PSDM for improving the image of sub-Himalayan fold-thrust belt and delineation of decollement, which is the site for the large/major earthquakes. This study is very important for the investigation of the Himalayan seismogenic zone with respect to accumulation of strain and its release by major earthquakes that pose threat to population and properties of states adjoining to the Himalaya.

Wide-angle and multi-channel seismic data need to be acquired at suitable profile locations in the Himalaya using state-of-the-art wireless nodes to provide information on some fundamental issues related to subsurface disposition of decollement, nature of thrust geometry & splay faults, role of fluids in rupturing, effect of crustal thickness & rheology on locking, radiation patterns for future major events, observation of changes in physical properties as precursors for future events. All these may finally provide answer if the Himalayan seismogenic zones have the potential for great earthquakes.

As finding oil/natural gas at ease is almost over, industries look desperately for the exploration of hydrocarbons in difficult terrains such as the sub-volcanic areas or fold-thrust belt regions of the Himalaya or the deep-water regions or unconventional energy resources. After successful application of FWI to wide-angle seismic data in KK offshore, it is envisaged to image Proterozoic Vindhyan sediments covered by Deccan volcanics in central India through acquisition and advanced processing and inversion/ modeling of wide-angle seismic data as well as in the fold-thrust belt of sub-Himalaya in Himachal Pradesh near Jawalamukhi or in Assam-Arakan fold belt.

A lot of MCS data have been acquired for the investigation of gas-hydrates in the KG and Mahanadi offshore basins by CSIR-NGRI. The data can be subjected to FWI followed by PSDM or CRS stack for improving the image of shallow sediments to understand the genesis of gas-hydrates in respective areas. The data can be further utilized for estimating critical parameters such as the porosity, permeability, pore pressure and geo-technical properties that are required for the development of viable production technology.

MoES has acquired a large volume of MCS data along both margins of India under the Commission on Legal Continental Shelf (CLCS) program with a view to extend the Indian Exclusive Economic Zone (EEZ) that decides what portions of the seabed can be exclusively mined for natural resources. Both the margins of India have many petroliferous basins such as the Bengal, Mahanadi, KG and Cauvery basins in the eastern margin, and Kutch, Saurashtra and KK basins in the western margin. It is right time to reanalyze and remodel the available seismic data in deep-waters using modern tools that may lead to delineation of hydrocarbon bearing structures.

The Himalayan tectonics and regional climates are recorded into the sedimentary piles of the Indus Fan, Indo-Gangetic Plains and Bengal Fan, where high-quality large-offset MCS data are available with the industries (ONGC, Reliance Co.) It is the state-of-the-art seismic FWI in which CSIR-NGRI has recently demonstrated its capabilities for estimating accurate seismic velocities as well as delineating fine-scale structures of the subsurface. Hence, application of FWI followed by PSDM or CRS stack to large-offset MCS data in the Alluvial Plains or Bengal and/ or Indus Fans, and correlating the sections with available litho-stratigraphy may provide the sediment thickness map of different geological periods and lead to deriving sedimentation rate, spatial-temporal distribution of lithology. This, in turn, will shed light to understand the Himalayan geodynamics and paleo-climates.

During the last few years, a new tool based on amalgamation of several seismic attributes by artificial neural networks has been developed for advanced interpretation of seismic data (Singh *et al*., 2016; Kumar and Sain, 2018; Kumar *et al*., 2018a, b). The available seismic data may be subjected to cutting-edge interpretation.

Conclusions

The significant results obtained by the CSS experiments over the Indian subcontinent in the 21st century are the (i) delineation of fold-thrust structure and subsurface disposition of different geological boundaries in shallow part of Dharwar craton and noticeably different crustal reflectivity patters in Mesoarchean Western Dharwar (simple crust with gently dipping reflection fabric) and Neoarchean Eastern Dharwar (complex crust with dipping Moho, oppositely dipping reflection fabric and a thrust fault) cratons; (ii) imaging crustal-scale Jahazpur thrust that becomes listric at the lower crust / Moho below the Sandmata Complex in Delhi-Aravalli fold belt; (iii) imaging crustal blocks with distinct dipping reflection fabrics in the northern and southern sides of Central Indian Tectonic Zone, characterized by high amplitude reflectivity with 8 km Moho offset; (iv) mapping oppositely dipping reflectors in the Southern Granulite Terrain suggesting collision tectonics along with imaging of rapid exhumation of mid to lower crustal rocks through the shear zone as evidenced by high V_P and V_S; (v) imaging ~10 km thick underplating materials in Mahanadi delta and inferring hinge zone with steep increase in basement with mapping of subsurface Rajmahal volcanics in West Bengal sedimentary basin both indicative of Gondwana breakup; (vi) deriving heterogeneous crustal structure, Moho upwarp and deep faults in central India that has implications to the 1997 Jabalpur earthquake; (vii) imaging crustal-scale hidden faults and thickened crust beneath the 2001 Bhuj epicentral region; (viii) delineating Proterozoic Cuddapah basin with ~4.0 km thick sediments and unprecedented 20 km thick high velocity (7.0-7.4 km/s) underplating above the Moho; (ix) imaging crustal-structure beneath Kangra fold-thrust belt that places Himalayan decollement at 6-8 km depth above a thin but reflective Meso- to Neo-Proterozoic Vindhyan strata and delineating Moho dipping northward from 55 to 61 km across the Hazara syntaxis in the NW Himalaya associated with the subduction of Indian plate beneath the Eurasian plate; and (x) different crustal structures to the west and east of the Chambal-valley Vindhya basin indicating a tectonic boundary that has separated the compressional events to the west from the extensional activity to the east.

Oil industries show a lot of interest for the exploration of sub-volcanic Mesozoic sediments for commercial gain. The wide-angle shallow seismic experiments have revealed (i) ~1.6 km thick Mesozoic sediments below ~1.3 km thick Deccan volcanics in Saurashtra peninsula; (ii) ~1.5 km Mesozoic sediments hidden by ~0.45 km Deccan Traps in Kutch peninsula; (iii) ~2.0 km thick Mesozoic sediments covered by ~2.0 km thick Deccan Basalts in the Tapti graben; (iv) ~105 m Limestone formation below 950 m thick volcanic rock in KK offshore; (v) ~1.5 km thick Gondwana sediments masked by a ~200 m thin lid of Rajmahal Trap in Mahanadi delta; and (vi) ~1.5 km thick Gondwana Sediments below ~1.0 km Rajmahal Traps in West Bengal basin. The basement configuration and overlying sedimentary formations have also been delineated in the Vindhyan and Marwar basins from CSS data and their tectonic/geological implications have been provided.

Gas-hydrates are considered as a major future energy resource of India because of their abundant occurrences along the outer margins of India. The prognosticated amount of methane stored as gas-hydrates within Indian Exclusive Economic Zone is more than 1500 times of India's present natural gas reserve; only 1% production can meet our overwhelming energy requirement for about a decade. Several innovative approaches have been proposed for the delineation, characterization and assessment of gas-hydrates using seismic data. Prospective zones of gas-hydrates have been identified in KG, Mahanadi and Andaman regions from where gas-hydrates were later recovered by drilling & coring of Indian National Gas Hydrates Program. The test productions provide great hopes for a plausible exploitation of this gigantic energy reserves.

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Review Article

Koyna, India, An Ideal Site for Near Field Earthquake Observations#

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The Koyna earthquake of M 6.3 on December 10, 1967 is the largest artificial water reservoir triggered earthquake globally. It claimed ~ 200 human lives and devastated the Koyna township. Before the impoundment of the Shivajisagar Lake created by the Koyna Dam, there were no earthquakes reported from the region. Initially a few stations were operated in the region by the Central Water and Power Research Station (CWPRS). The seismic station network grew with time and currently the National Geophysical Research Institute (NGRI), Hyderabad is operating 23 broadband seismographs and 6 bore hole seismic stations. Another reservoir, Warna, was created in 1985, which provided a further impetus to Reservoir Triggered Seismicity (RTS). Every year following the Monsoon, water levels rise in the two reservoirs and there is an immediate increase in triggered earthquakes in the vicinity of Koyna-Warna reservoirs in the months of August-September. Peak RTS is observed in September and later during December. Another spurt in triggered earthquakes is observed during the draining of the reservoirs in the months of April-May. A comparative study of RTS earthquake sequences and the ones occurring in nearby regions made it possible to identify four common characteristics of RTS sequences that discriminate them from normal earthquake sequences. As the RTS events continue to occur at Koyna in a large number in a limited area of 20 km x 30 km, at shallow depths (mostly 2 to 9 km), the region being accessible for all possible observations and there being no other source of earthquakes within 100 km of Koyna Dam, it was suggested to be an ideal site for near field observations of earthquakes. This suggestion was discussed by the global community at an ICDP sponsored workshop held at Hyderabad and Koyna in 2011. There was a unanimous agreement about the suitability of the site for deep scientific drilling; however, a few additional observations/ experiments were suggested. These were carried out in the following three years and another ICDP workshop was held in 2014, which totally supported setting up a borehole laboratory for near field investigations at Koyna. Location of a Pilot Bore-hole was decided on the basis of seismic activity and other logistics. The 3 km deep Pilot Borehole was spudded on December 20, 2016 and completed on June 11, 2017.

Introduction

Artificial water reservoirs are created globally for flood control, irrigation and power generation. Reservoir Triggered Seismicity (RTS) is an anthropogenic effect observed in the vicinity of a few reservoirs. Carder (1945) provided the first scientifically accepted case of RTS at Lake Mead, Colorado, USA. In early 1960's RTS events exceeding M 6 were reported (Gupta *et al*., 1972 a&b) from Hsingfenking, China (1961); Kariba, in the vicinity of Zambia-Zimbabwe (1963); and Kremasta in Greece (1966). On December 10, 1967 an earthquake of M 6.3 occurred in the vicinity of the Shivaji Sagar Lake, created by Koyna Dam. Earthquakes began to occur in the vicinity of this lake soon after its impoundment in 1962 (Guha *et al*., 1970). The frequency of these tremors increased considerably from the middle of 1963 onwards. These tremors were often accompanied by sounds similar to blasting (Mane, 1967). There were no earthquakes reported from the region before the impoundment of the Shivaji Sagar Lake. Although there were no seismic stations in the

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*(The work reported here is carried out in collaboration with several colleagues at NGRI on Koyna earthquake related problems. These include Indra Mohan, B. K. Rastogi, Prantik Mandal, C. V. Ram Krishna Rao, Uma Maheshwar Rao, S. V. S. Sarma, R. K. Chadha, D. Srinagesh, D. V. Reddy, P. C. Rao, Sukanta Roy, Virendra Tiwari, H. V. S. Satyanarayana, Kusumita Arora, Prasanta K Patro, D. Shashidhar, M. Uma Anuradha and K. Mallika)

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immediate vicinity of the Koyna Dam, a seismic station operating at India Meteorological Department at Pune would have recorded any M ~ 3 earthquake from the Koyna region. To monitor these earthquakes a close network of 4 seismic stations was installed in the immediate vicinity of the Koyna Dam (Gupta *et al*., 1969). The hypocenters were found to cluster near the lake and were very shallow. Before the December 10, 1967 earthquake, 5 other earthquakes occurred during 1967 that were strong enough to be recorded by several Indian seismic stations, including the September 13, 1967 earthquake of M 5.5. In 1985 another reservoir Warna, some 20 km south of the Koyna reservoir was impounded (Fig. 1). This gave a further impetus to RTS in the region. It may however be noted that even before the impoundment of Warna reservoir, several RTS events of magnitude ~ 4 had been reported in the vicinity of Warna reservoir (Talwani, 1997). In this article the RTS associated with Koyna and Warna reservoirs is termed as Koyna RTS.

The December 10, 1967 earthquake claimed over 200 human lives and the Koyna Nagar Township was in shambles (Narain and Gupta, 1968). So far this is the largest RTS event globally. It is very unique with the Koyna region that seismic activity has continued since 1962, including over 20 earthquakes of M ~ 5, some 400 earthquakes of M ~ 4 and several thousand smaller earthquakes. All these earthquakes occur in a small region of 20 km x 30 km. The latest M ~ 4 earthquake occurred on June 3, 2017. Koyna region has been found to be a most suitable site for near field observations of earthquakes. Two International Continental Drilling Program (ICDP) workshops were held to discuss the suitability of the Koyna region for setting up a borehole laboratory. There was an over-whelming support for setting up such a facility.

In this communication, the relation between water levels in Koyna and Warna reservoirs and RTS; how RTS earthquake sequences differ from normal earthquake sequences in the concerned regions; how long RTS will continue at Koyna; is Koyna a suitable site for deep scientific drilling; brief mention of the two ICDP Workshops held in 2011 and 2014 to address RTS at Koyna and deep scientific drilling; location of the Pilot Borehole and completion of the 3 km deep Pilot Borehole are briefly presented.

Earthquakes in Koyna-Warna Region

Figure 1(A) gives the details of the location of Koyna and the Warna reservoirs near the west coast of India. All earthquakes of M ~ 5 since the beginning of RTS in the region including the M 6.3 earthquake of December 10, 1967 and smaller magnitude earthquakes for the period August 2005 to June 2017 are plotted. It may be noted that no M ~ 5 earthquake epicenter has repeated. The figure also depicts the location of 23 broad-band seismic stations as well as the 6 borehole seismic stations. It is noteworthy that most of the RTS is restricted in the vicinity of the reservoirs and limited to an area of 20 km x 30 km. Earthquakes are basically confined with in 50 km radius area and no earthquakes are reported from 50 to 100 km radius (the inset) from the Koyna Dam. Figure 1(B(i) and (ii)) are the depth sections of M ~ 5 earthquakes in N-S and E-W directions respectively. The alignment of these hypocenters on 73.7^{o}E longitude is noteworthy. Figure 1(B (iii) and (iv)) are similar plots for the period August 2005 through June 2017. Concentration of hypocenters along 73.7^{o}E longitude is noteworthy here also. This is consistent with the surface expression of the Donachiwada Fault (Fig. 7A), which has been recognized to have hosted the December 10, 1967 M 6.3 earthquake and most of the M ~ 5 earthquakes in Koyna region.

What is the Relationship Between the Water Levels in the Koyna and Warna Reservoirs and RTS?

There is a rapid loading of the reservoirs following the onset of monsoons during the months of June-July. The peak water levels are reached in August. Although the monsoons get over by September but inflow to the reservoirs continues and near peak water levels are maintained during August to October/ November. From December onwards water levels fall reaching a bottom during May end and June beginning every year (Fig. 2(A) and (B)). Figure 3 depicts the month wise distribution of number of M$\geq$ 4 earthquakes for the period 1967 to 2016. As ~ 200 M ~ 4 earthquakes have occurred in the region over the past 50 years, we take M ~ 4 temporal distributions as a major of the monthly RTS in the region. It may be noted that from a near minimum number of earthquakes in July, seismic activity increases in August. It reaches a peak in September, which is soon

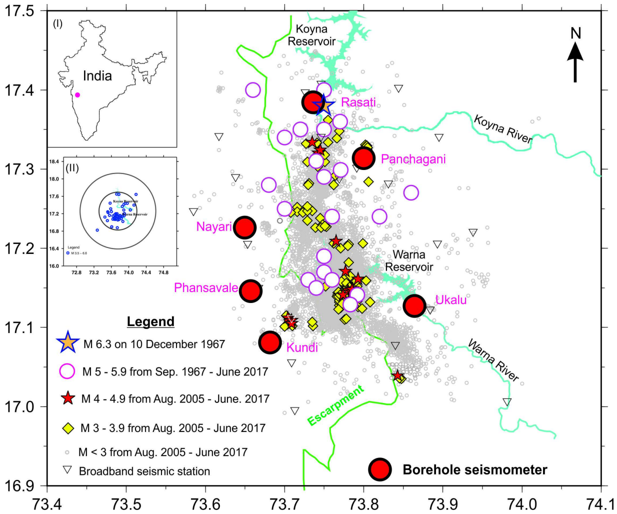

Fig. 1A: (Updated from Gupta *et al.* (2017). Koyna-Warna region near west coast of India. Location of the Koyna main earthquake of December 10, 1967; earthquakes of M ~ 5 during August 1967 through June 2017; smaller earthquakes from August 2005 through June 2017; surface and borehole seismic stations; green curve indicates the WGE (Western Ghat Escarpment). (I) Koyna location in India; (II) Distribution of M≥3.7 earthquakes for 1967-2015 (USGS) in the vicinity of Koyna and an outer circle of 100 km radius indicating that there is almost no seismic activity outside the Koyna region

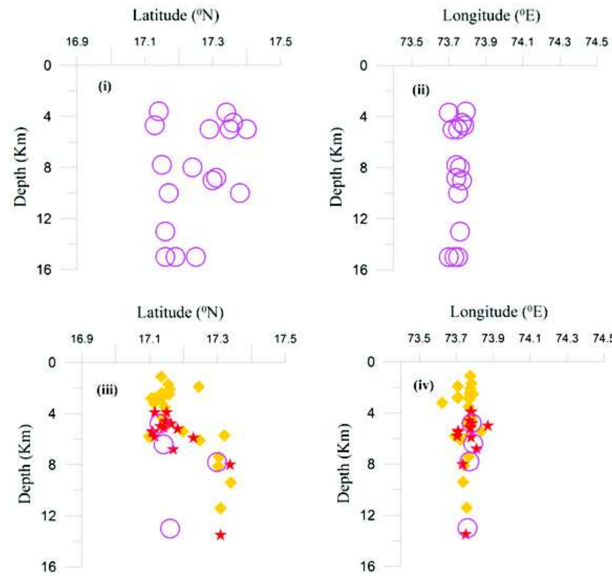

Fig. 1B: Depth section of M ~ 5 earthquakes (epicenters shown in (A) along latitudes (i) and longitudes (ii); and depth sections of M≥3.5 earthquakes along latitude (iii) and longitude (iv). Symbols same as in (Fig. 1A). The concentration of hypocenters along 73.75°E is noticeable that corresponds to Donachiwada Fault (Fig. 7)

after the peak water levels are reached in the two reservoirs. It may be noted that the first M ≥ 5 RTS event in the region occurred on September 13, 1967. Another peak is reached in December, which is not as prominent as the September peak. The largest M 6.3 earthquake in 1967 also occurred in December. There were several M ~ 5 aftershocks of the main December 10, 1967 earthquake that had a magnitude of M ~ 6.3. However, in later years only two M ~ 5 earthquakes occurred in the month of December. The frequency of M ≥ 4 earthquakes in January is quite low and later a peak is seen in March, which corresponds to a higher rate of emptying the reservoir. In a recent study (Shashidhar *et al*., 2016), a spurt in seismic activity in the month of March 2015 was observed, and it was pointed out that when unloading rate in the Koyna Reservoir increased from 0.053 to 0.170 m/day and in the Warna Reservoir from 0.065 to 0.106 m/day during the 3rd week of March 2015, there was a spurt in RTS.

In some earlier studies (Gupta *et al*., 1972 a & b; Gupta and Rastogi, 1974), it was observed that factors like rate of loading, highest water level reached and duration of retention of high water levels directly affected RTS at Koyna. In another study, it was found that a rate of loading of 13 m/week was a necessary but not a sufficient condition for M ≥ 5 earthquakes to occur in the Koyna region (Gupta 1983). It was also seen that whenever the previous water level maxima was exceeded at Koyna/Warna reservoirs and/or high water levels were retained for longer durations, M ~ 5 earthquakes occurred (Gupta *et al*., 2002).

How the RTS Earthquake Sequences Differ from Normal Earthquake Sequences?

By early 1970s, over a dozen cases of RTS were known. A major question had been to discriminate a RTS event from a normal event. Detailed studies of these RTS sequences lead to identification of four common characteristics which discriminate RTS sequences from the normal regional earthquake sequences occurring in close by regions, but not associated with the reservoirs (Gupta *et al*., 1972 a & b). These are: i) In the earthquake frequency-magnitude relation (log N=A-*b* M, where N is the number of earthquakes with magnitude ≥ M, and A

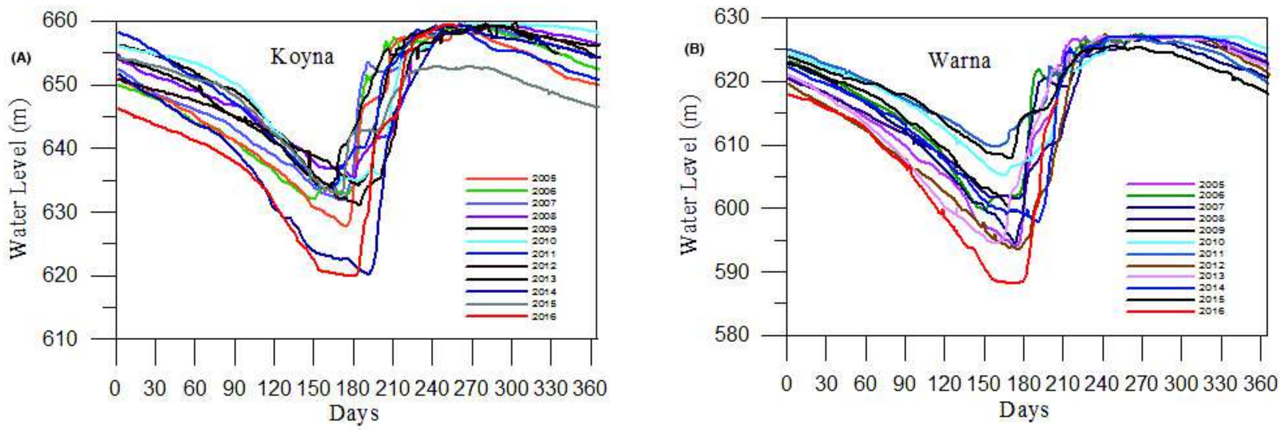

Fig. 2: Annual cycles of loading and unloading of the Koyna (A) and Warna (B) reservoirs for the period of 2005 through 2017 (updated from Gupta *et al.*, 2017). The reservoirs get loaded following the Monsoon (for details see the text)

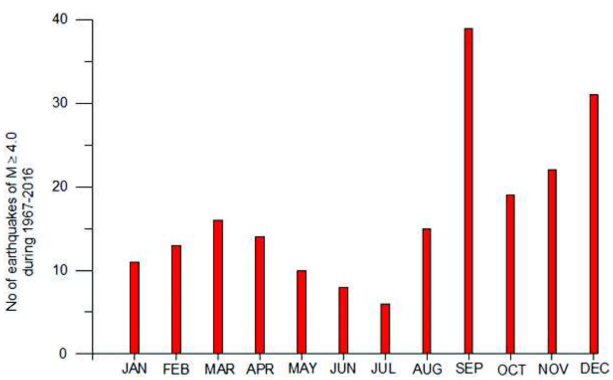

Fig. 3: Monthly number of M $\geq$ 4 earthquakes in the Koyna region for the period 1967 through 2016. There is a spurt in seismic activity soon after loading of the reservoirs (end of August-September). Another peak appears in December. The third peak is associated with fast draining of the reservoirs in March

and *b* are constants), the fore-shock and after-shock *b* values of the RTS sequences are higher than the regional and normal earthquake sequences *b* values. ii) The ratio of the magnitude of the largest aftershock to the main shock is high. iii) The decay of aftershocks in the RTS is slower. iv) The foreshock- aftershock pattern of RTS sequences belongs to Type II of Mogi's Model (Fig. 4), whereas the natural earthquake sequence pattern belongs to Type I. These characteristics are governed by the mechanical properties of the media, and their deviation from the normal implies that the filling of the reservoir has changed them by introducing heterogeneity in the media. This can be best illustrated from Fig. 4. In Fig. 4(II) "A" is a homogenous media rock volume. When the stress exceeds the strength of the rock, there would be a major earthquake releasing most of the strain, followed by peripheral adjustment aftershocks. In such a sequence, there would not be any foreshocks, the aftershock activity would be over in a short time, the ratio of the largest aftershock to the main event would be low, and the *b* value would be also low. This is typically the situation with the earthquake sequences in stable continental regions not associated with the reservoir loading. Due to filling of the water reservoir, the heterogeneity of the media increases (Fig. 4 (II)B), and the rock volume gets fragmented. As a consequence the accumulated strain is released through smaller rock volumes. In such a situation, the earthquakes would start occurring as and when the strength of an individual rock volume is exceeded. The main earthquake would correspond to the largest rock volume and there would be foreshocks and aftershocks, changing the pattern from Type I of Mogi's (1963) Model to Type II. These criteria are helpful in identifying whether an earthquake sequence occurring in the vicinity of a reservoir is triggered or normal. Safer sites for locating artificial water reservoirs are determined by doing *in-situ*-stress measurements and assessing how close to critical a site is stressed, and whether filling of the reservoir would trigger the earthquakes (Gupta, 1992). This model of RTS, developed in 1970's was based on the observations at about a dozen RTS sites. Now over 120 sites are globally known where RTS has been observed and these criteria are found to be applicable (Gupta, 2011). One of the recent examples is reported from Vietnam (Cao Dinh Trieu *et al*., 2014).

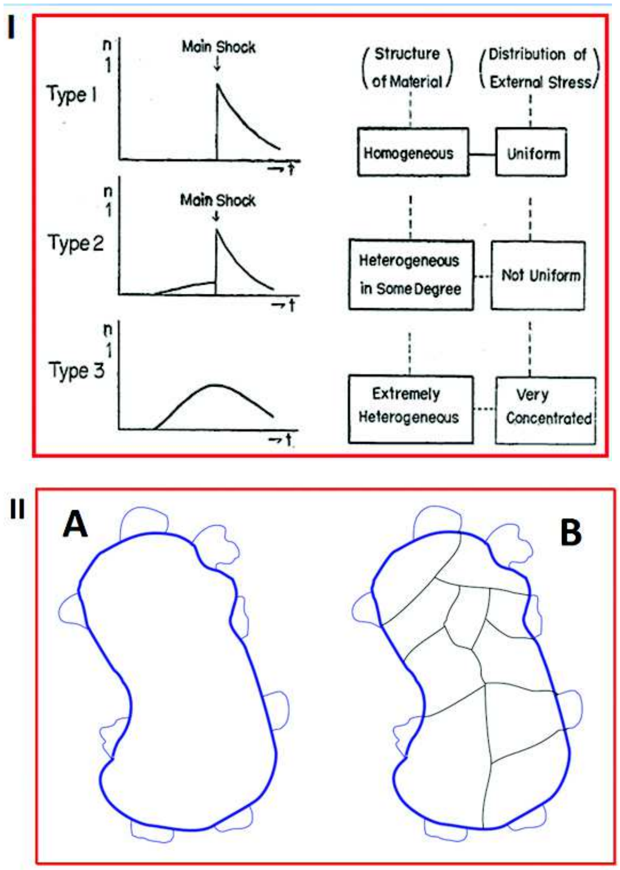

Fig. 4: (I) Depicts Mogi's (1963) classification of the earthquake sequences into three broad categories (Mogi, 1963 b). (II) Cartoon for (A) for homogenous rock mass, and (B) fragmented rock mass. For details see the text

It would be appropriate at this stage to point out that Stable Continental Regions (SCR) are very quite parts of the continent. It is estimated that the strain accumulation in such regions is of the order of (10^{-9}) to (10^{-10}) per year as compared to (10^{-7}) to (10^{-9}) for the intra-plate region and (10^{-5}) to (10^{-7}) at the plate boundaries (Johnston, 1993; Gupta and Johnston, 1998). RTS is mostly found to be occurring in SCRs. The occurrence of M 6.2 Latur earthquake on September 29, 1993 in the same Deccan Volcanic Province, some 300 km east of the Koyna earthquake of December 10, 1967 provided an excellent opportunity to compare the two earthquake sequences. The Latur earthquake occurred at 22h 25m UTC on 29^{th} Sept. 1993 (corresponding to 3h 55m IST on 30 Sept). The earthquake claimed some 11,000 human lives becoming the deadliest SCR earthquake till then (Gupta *et al*., 1997). It may be noted that DVP is basically a trust fault regime (Rajendran *et al*., 1992). The Latur earthquake focal mechanism is also trust fault dominated (Gupta *et al*., 1997). However, the earthquakes in the Koyna region are basically left-lateral strike-slip and/or normal fault dominated (Rao and Shashidhar, 2016). Rastogi (1994) compared the Latur earthquake sequence with the Koyna earthquake sequence and found that the Latur sequence had low 'b' values, low largest aftershock magnitude to the main shock magnitude ratio; in addition to not having foreshocks and the seismic activity getting over in a rather short time, contrary to the characteristics of Koyna earthquake sequences.

How Long RTS will Continue at Koyna?

At most of the RTS sites, triggered earthquakes start to occur soon after the impoundment of the reservoir and continue for different lengths of time varying from a few years to a decade or so. The Hsingfengkiang Reservoir, China was impounded in 1959 and soon after that triggered earthquakes started to occur. The largest triggered earthquake of M 6.1 occurred on March 19, 1962 (Chung-Kang *et al*., 1974). However, while in early sixties thousands of earthquakes occurred every month, their number dropped to a few by 1978 (Ishikawa and Oike, 1982; Gupta, 1992). Lake Kariba, Zambia-Zimbabwe border, was impounded in 1958. The levels kept increasing every year and a peak level was reached in 1963. This was followed by an immediate burst of triggered earthquakes, including the M 6.2 earthquake on April 23, 1963 (Pavlin and Langston, 1983). In the following years, a few M ~ 5 earthquakes occurred in the vicinity of the lake. However, the activity ceased in the following years (Gupta, 1992). Same is the case with the Lake Kremasta in Greece, which was impounded in 1965, with very rapid loading in January 1966 and the largest triggered earthquake of M 6.2 occurred on February 5, 1966. In the months to follow the earthquake frequency dropped considerably (Galanopoulos, 1967; Stein *et al*., 1982).

Unlike the above mentioned cases of RTS where M≥6 earthquakes had occurred and RTS stopped within a few years to a decade, triggered earthquakes have continued to occur at Koyna till now, that is some 55 years after the impoundment of the Shivaji Sagar Lake created by the Koyna Dam. The latest M ~ 4 earthquake occurred on June 3, 2017. The magnitude

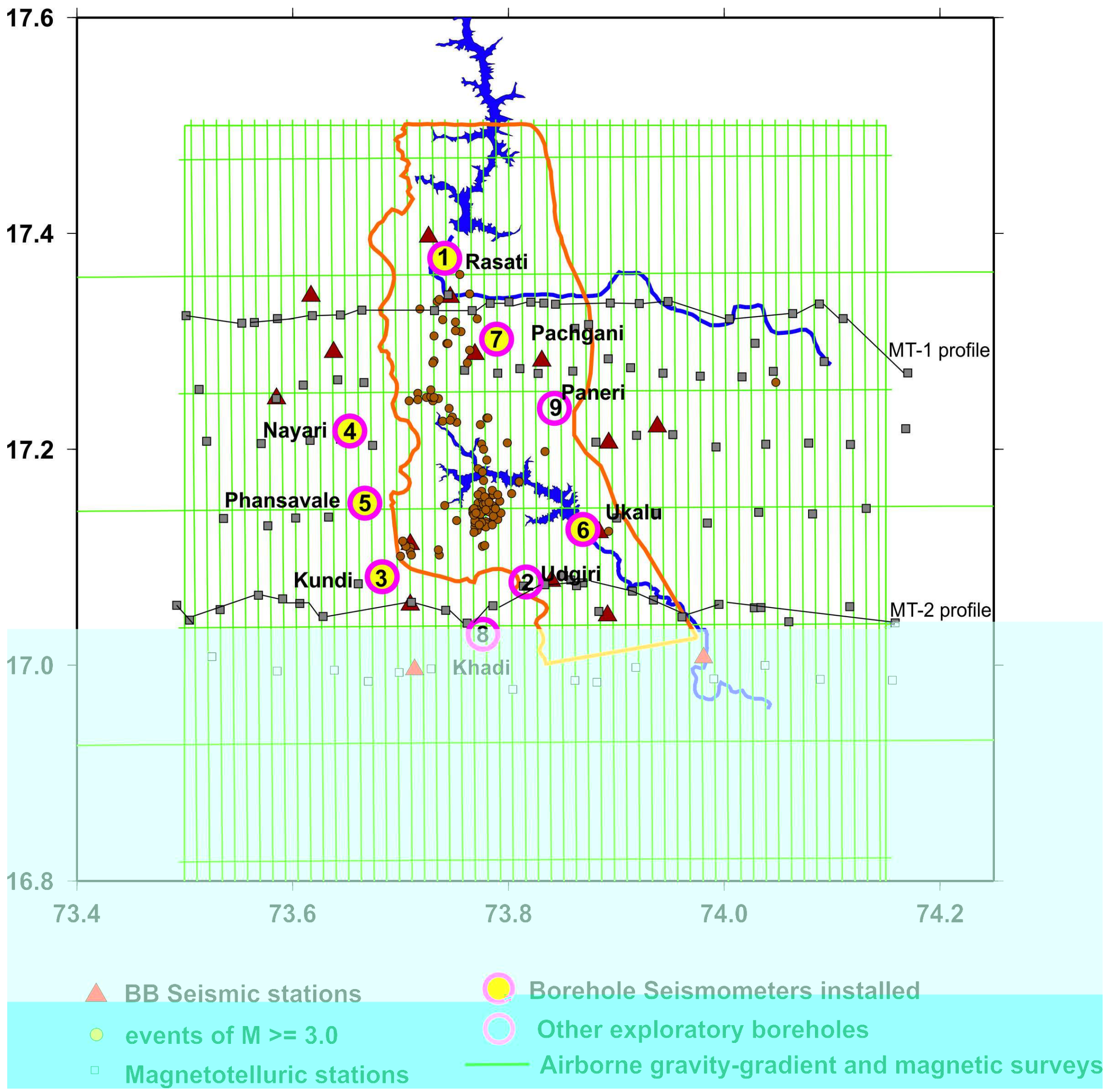

Fig. 5: **The study area indicating the installation or deployment plan of the various experiments undertaken in the preparatory phase of the deep drilling programme. Earthquakes of M $\geq$ 3.0 occurred during August 2005 to December 2013. MT-1 and MT-2 indicate the magnetotelluric profiles passing through Rasati in the north and Udgiri in the south, respectively. The area covered by LiDAR is enclosed by M $\geq$ 3.0 the brown line (Gupta *et al*., 2014)**

and frequency of the largest possible earthquakes in the stable continental region has been debated (for example Johnston 1994). It has been hypothesized that the maximum credible earthquake in the Koyna region is of M 6.8 and the region was stressed close to critical before the impoundment of the Koyna Dam (Gupta *et al*., 2002). As explained in the earlier section of this article, creation of the reservoir introduces heterogeneity in the media and earthquakes start to occur as and when the strength of an individual rock volume is exceeded. Considering that so far 22 M ~ 5, some 200 M ~ 4 and thousands smaller earthquakes have occurred in the region, the following is a simple calculation:

Energy Released in Koyna Region

The Max. Credible Earthquake (**M_{CE}**) considered for Koyna: **M = 6.8**

Empirical relation used: ***Log E = 1.5 M + 11.8***, (M = magnitude)

Using the above relation $E_{MCE} = 10^{22}$ ergs

Energy released so far:

➢ **Case 1**: Average magnitude of 22 M ~ 5, and 200

M ~ 4 events taken as 5.5 and 4.5:

$$E = 1 \times E_{M6.3} + 22 \times E_{M\,5.5} + 200 \times E_{M\,4.5}$$

$$= 10^{(21.25)} + 22\times10^{(20.05)} + 200\times10^{(18.55)} = 10^{21.94}$$

Percentage of $M_{CE} = 10^{21.94} / 10^{22} = 87\ \%$

➢ **Case 2**: Average magnitude of 22 M ~ 5, and 200 M ~ 4 events taken as 5.3 and 4.3:

$$E = 1 \times E_{M6.3} + 22 \times E_{M\,5.3} + 200 \times E_{M4.3}$$

$$= 10^{(21.25)} + 22\times10^{(19.75)} + 200\times10^{(18.25)} = 10^{21.51}$$

Percentage of $M_{CE} = 10^{21.51} / 10^{22} = 32\ \%$

Considering the average of the two extreme scenarios, about 60% energy of an M 6.8 earthquake has been released in the Koyna region. It is further noted that no M ~ 5 earthquake epicenter has repeated in the region (Fig. 1). This leads to a conclusion that RTS in Koyna region shall continue for another 2 to 3 decades.

Is Koyna a Suitable Site for Scientific Deep Drilling?

A number of studies have already established the association of Monsoon driven loading and unloading of the Koyna and Warna reservoirs with the RTS in the Koyna region. However, the triggering mechanism is poorly understood. We know precious little about the physical properties of the rocks and fluids in the fault zone and what role they play in sustaining triggered earthquakes for over 5 decades due to lack of near field observations. The earthquakes occur in a small area of 20 km x 30 km, are shallow (mostly between 2 and 9 km depth), the region is totally accessible, the RTS has continued for over 5 decades and there is no other earthquake source within 50 to 100 km of Koyna Dam. This makes Koyna physically and logistically a very suitable location for the near field observation of earthquakes. It was felt necessary to share this view with the international community and an International Continental Drilling Program (ICDP) workshop was held at Hyderabad and Koyna during March 21-26, 2011 (Gupta and Nayak, 2011). The objectives were: 1). To provide an international forum for sharing and exchange of lessons learned from investigations on RTS worldwide including Koyna, 2). To brain storm on the scientific motivation behind deep drilling in an active fault zone down to focal depths, at a classical RTS site in an intra-plate setting, 3). To prepare a complete drilling plan, 4). To plan the entire array of measurements/monitoring opportunities provided by deep drilling in consultation with national and international experts, 5). To develop a full proposal on scientific drilling at Koyna. The workshop was attended by 26 participants from abroad and 50 participants from India. They have had experience with San Andreas Fault Observatory at Depth (SAFOD); the Chelungpu Fault Drilling Project in Taiwan; the Nojima Fault Drilling in Japan; the Gulf of Corinth in Greece; and the Latur Fault in India. All the participants at the workshop agreed that Koyna is a world-class geological site and a natural earthquake laboratory to conduct a deep bore hole experiment to study earthquakes in near field. The Ministry of Earth Sciences (MoES) declared full support to the Koyna Project and ICDP offered to provide all technical support. Based on the presentations in the workshop and the experience of the participants, several suggestions for scientific work were made before initiating the deep drilling program. These included improving hypocenter location capabilities in the Koyna region; airborne gravity-gradient and magnetic surveys; seismic reflection studies; LiDAR; Magneto-telluric surveys; study hydraulic connectivity and based upon the results of the above surveys, plan the Deep Borehole Drilling Project.

During the period 2011-2014, the suggested investigations were undertaken through support of the MoES. These included:

1) Drilling 9 exploratory boreholes penetrating the basalt cover and getting 300- 500 m into the granitic basement for studying sub-surface geology and rock properties; 2) Airborne gravity gradiometry and magnetic surveys to delineate 3D subsurface structure in the Koyna region, specifically covering the RTS area; 3). Magnetotellurics to map subsurface electrical conductivity and estimate the thickness of Deccan Traps; 4) Airborne LiDAR surveys to get high resolution topographic information and prepare a bare earth model; 5) Heat-flow measurements and modeling of the subsurface temperatures; and 6). Instrumenting 6 bore holes with 3-component seismometers meters at depths of ~ 15,00 m to better estimate

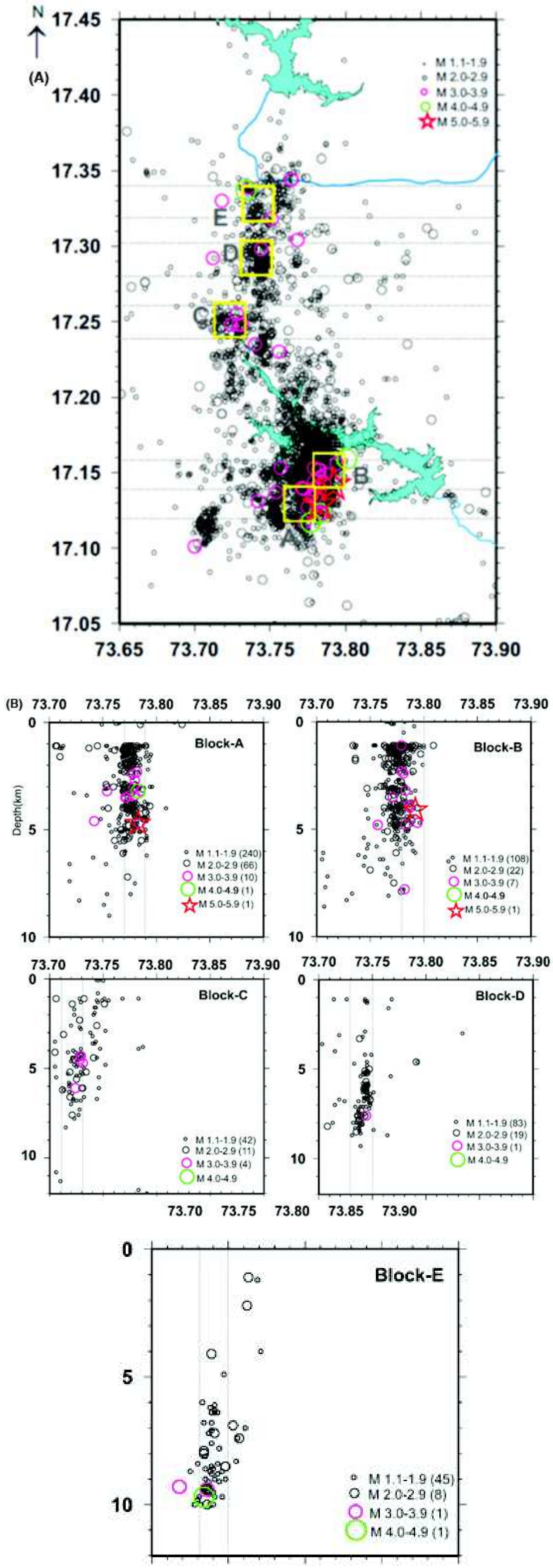

Fig. 6: (A) Seismicity of the Koyna-Warna region during 2009-2014. The five Blocks A, B, C, D and E are each 2 X 2 km^2 in area. Dotted lines indicate a swath of 2 km area at each Block. (B) Depth sections for 2 km swath for the 5 blocks. With in brackets are indicated the number of earthquakes that occurred in each of these blocks

earthquake parameters. Figure 5 adopted from Gupta et al (2017) shows the installation and deployment of various experiments. The major discoveries of this phase are as follows (Gupta *et al.*, 2014&2017):

a) There has been a long debate about the presence of Mesozoic sediments below the basalt cover. No such sediments were found.

b) It was discovered that the thickness of the basalt column is directly related with topography. Although, the topography in the area covered is almost ~1000 m, the basement is almost flat with variation of no more than 100 m, and lies about 300 m below the present mean sea level.

c) One of the requirements for setting up a borehole laboratory is not to have very high temperatures. The temperature was estimated to be ~ 150^{o}C at 6 km depth.

d) The basalt-basement contact was clearly identified through MT response. A direct correspondence was found in resistivity as inferred from MT surveys and the week zones in the region.

e) Hypocenters are associated with sharp density contrast and resistivity changes.

f) Geological/geophysical logging in 8 boreholes has revealed the alignment of prominent faults.

g) LiDAR surveys led to developing bare earth model of the region and identification and demarcation of the Donachiwada Fault which hosted the 1967 earthquake and most M ~ 5 earthquakes in the region.

h) Operation of borehole seismometers reduced the absolute errors in location of earthquakes from ~ 800 m to 300 m.

The above work was discussed in the 2nd ICDP workshop held at Koyna during 16 to 18 May 2014 at

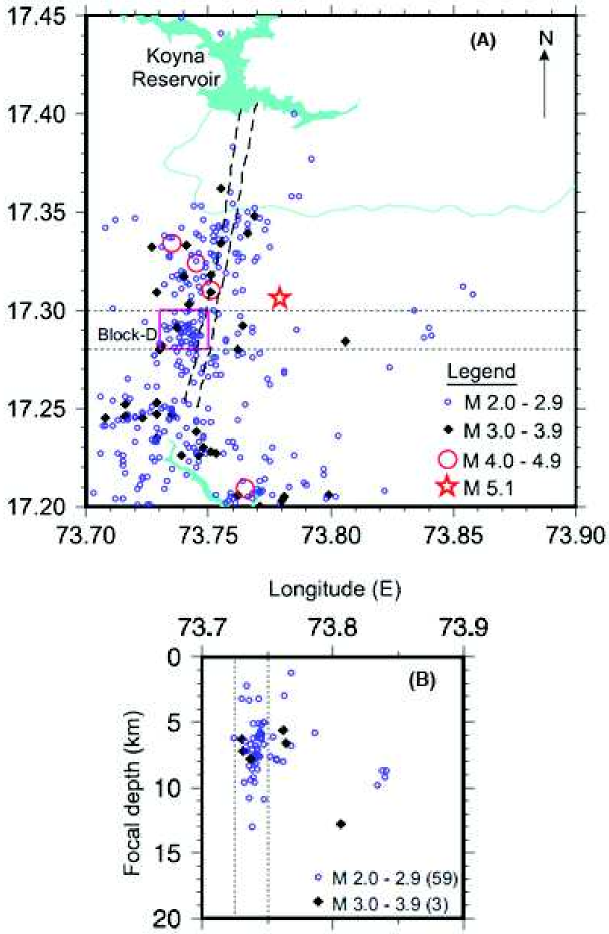

Fig. 7: (A) Earthquakes of magnitude $\geq$ 2.0 that occurred during August 2005-December 2015. Dotted lines indicate a swath of 2 km area of the Block-D. Dashed line indicates the Donachiwada fault zone. (B) Depth section for the 2 km wide swath in (a) above. Dotted lines indicate the area 2 x 2 km^2

(Gupta *et al.*, 2014). The workshop was attended by12 participants from abroad and 37 from India. The work carried out since the first workshop in 2011 was presented and discussed. A plan for Pilot Borehole(s) drilling was also presented. There were detailed discussions on various aspects of drilling, location and completion of the Pilot Borehole(s). Based on the hypocenter locations 5 possible sites for the location of the Pilot Borehole(s) were suggested. It was unanimously concluded that Koyna is one of the best sites anywhere in the world to investigate genesis of RTS from near field observations.

Location of the Pilot Borehole

Based on the hypocenters during 2009 to 2014 in the RTS in Koyna region, 5 blocks for possible location of the Pilot Borehole(s) were identified (Gupta *et al.*, 2017). It was kept in mind that that there should be enough repeating earthquakes with in a depth of 5 km of magnitude M 2, being the magnitude of the target earthquake. Two of these locations (A and B in Fig. 6) were south of Warna Reservoir and the remaining 3 north of Warna Reservoir (C, D, & E) just short of the Koyna Reservoir (Fig. 6). Considering several logistic constraints, particularly to be out of the demarcated forest cover, finally a location within site D was selected (Fig. 7). It may be noted in Fig. 7 that the Donachiwada Fault zone is in the immediate vicinity of this site. During the period August 2005 through December 2015, the site hosted 3 earthquakes of M 3.0 to 3.9 and 59 earthquakes of M 2.0 to 2.9.

The Pilot Borehole

The Pilot Borehole was spudded on December 20, 2016 and the drilling of 3000 m was completed on 11^{th} June 2017. Figure 8 provides the well configuration and a general lithology of the pilot borehole. The basement was reached at a depth of 1247 m. It may be noted that in a nearby borehole at Panchgani the basement was at a depth of 1252 m. Here also, no sediments were encountered at the bottom of the basalt column. It is interesting to note that several zones with immense fluid losses were encountered. Detailed geophysical logging has been carried out. With the help of ICDP, on-line-gas analyses (OLGA) facility had been set up. Cores were recovered from depths of 1679, 1892 and 2091 m depths. These are 9 m long and 4 inch diameter cores and there was almost 100% recovery. In-situ stress measurements have been carried out at depths of 1600 m and deeper. All the data acquired are being analyzed.

Concluding Remarks

RTS that got initiated in 1962 soon after the filling of the Shivaji Sagar Lake created by the Koyna Dam has continued till now. RTS is seen to be mostly occurring in Stable Continental Regions. For the Koyna region it is hypothesized that the region was critically stressed before the impoundment of the reservoir(s) and it could host an M 6.8 earthquake. However, heterogeneity introduced by the reservoir has fragmented the rock mass. So far about 60% energy of an M 6.8 earthquake has been released. Loading and unloading of Koyna and Warna reservoirs

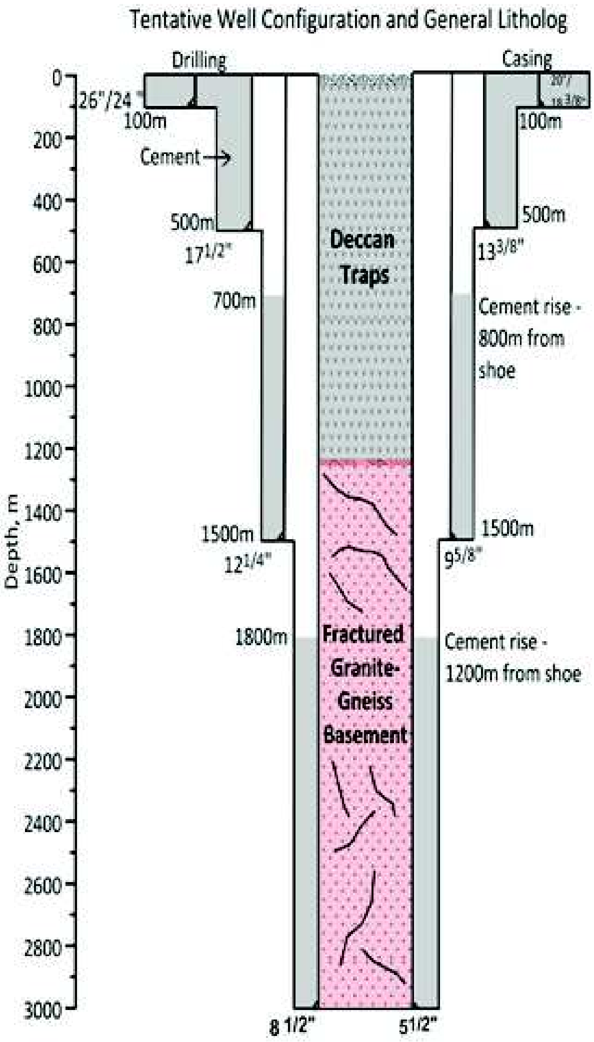

Fig. 8: Generalized configuration of the 3000m deep pilot borehole, giving the drilling and casing details. The borehole entered the basement at a depth of 1247 m after penetrating through the basalt column. Practically no sediments were encountered below the basalt column, which is lying directly on the pre-Cambrian granite-gneiss basement

influences RTS in the region. RTS is influenced by rate of loading, highest water levels reached and duration of retention of high water levels. Whether previous water maxima is exceeded or not is related to the occurrence of M ~ 5 earthquakes. Global study of RTS sequences has led to discovering their common characteristics that differentiate them from normal earthquake sequences occurring in the same region. Occurrence of an M 6.2 Latur earthquake on 29th September 1993 in same DVP some 300 km from Koyna gave an excellent opportunity to compare the two earthquake sequences and demonstrate the difference between the two. As earthquake epicenters are confined to an area of 20 km x 30 km, the focal depths being mostly between 2 and 9 km, the accessibility to Koyna region and the fact that there is no other seismic source within 100 km of Koyna Dam, make it a suitable site for near field studies of earthquakes. This was discussed in the first ICDP Workshop, where the site was found to be very appropriate for near field studies. However, a few suggestions for further work were made to be under taken before setting up deep bore hole drilling program. These were carried out during 2011 to 2014 with support from MoES. In the second ICDP workshop in 2014, the results of the work having been carried out as well as plan of the Pilot Borehole were presented. These were supported and during 2014 to 2017, the location of the Pilot Borehole was finalized and the 3 km deep Pilot Bore Hole was completed with all the necessary measurements having been carried out. The analysis of the measurements having been made in the Pilot Borehole is under progress.

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Several colleagues at the National Geophysical Research Institute (NGRI), Hyderabad made it possible to reach the present level of work in the Koyna region. Successive Directors of NGRI, namely Drs. V. P. Dimri; Y. J. Bhaskar Rao, Mrinal Sen and V. M. Tiwari supported the Koyna Program. Support of Ministry of Earth Sciences, particularly that of Dr. P. S. Goel and Dr. Shailesh Nayak is acknowledged for their understanding and support of the Koyna Program. The support from MoES continues with the current Secretary Dr. Madhavan Nair Rajeevan. Dr. Brijesh K. Bansal, Program Coordinator for Earth Science Program of MoES deserves a special mention because of his whole-hearted support all these years. Dr. Arun K. Gupta of MoES has been of much help. At the International Continental Drilling Program office, Prof. Rolf Emmermann, Dr. Uli Harms, Dr. Brian Horsfield and Carola Knebal have been very helpful in providing technical support as well as organizing the ICDP Workshops. Dr. M. Ravichandran and Dr. Rahul Mohan of NCAOR provided much needed support for running the Koyna Project.

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Review Article

Recent Advancement in Studies of Deccan Trap and Its Basement; Carbonatites and Kimberlites – An Indian Perspective in Last Five Years

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We made an attempt to provide a status report on volcanic rocks and mantle derived rocks with a special focus on studies related to Deccan flood basalt, carbonatites and kimberlites from India, during last five years. The important problems related to the Deccan volcanism include 1. Origin of Deccan Trap whether plume related or impact induced or triggered volcanism (2) the details of composition, the internal structure and age distribution and (3) the relation between the large igneous provinces and major mass extinction. Carbonatites are mantle derived rocks, which are helpful in modelling the Earth's interior. They vary in age from Archean to recent, and are found mostly on continents and thus provide valuable information about the evolution of the sub-continental mantle through time. This article also reviews most of the research contributions on Indian carbonatites of the last five years. Building on existing information on their modes of occurrences, field dispositions, chronology, petrology and geochemistry, we use the recent data to provide a comprehensive view on the origin and evolution of these carbonatites.

Keywords: Deccan Trap; Kimberlites; Mantle Rocks; Carbonatites; Mineral Physics; Phyllosilicates

Introduction

Geological Society of India (GSI) has brought out many interesting review books and memoirs related to the Deccan Volcanic Province (Suubarao, 1999), kimberlites and related mantle derived rocks (Fareeduddin and Mitchell, 2012). In recent years there has been a tremendous growth in the field and laboratory data related to Deccan Trap and mantle derived rocks from India. The aim of the present work is to review some important findings related to the Deccan Trap, carbonatites and kimberlites from India with a special focus on the work carried out during the last half a decade.

The ca.65Ma Deccan volcanic terrain, forming one of the prominent large Igneous Provinces (LIP) on the surface of the earth, has remained seismically active since historical times, including the famous Reservoir Triggered Seismicity in the Koyna region (1967 Koyna Earthquake) the 1993 Killari earthquake (Mw 6.3). Recently Gupta (2017) has edited a comprehensive collection of 25 original articles covering different geophysical aspects of Koyna Earthquake (Gupta 2017 and the references therein). In this article we provide a brief review of the work carried out in Deccan Volcanic Province near Killari region, which is equally important for the stable continental earth quake and geodynamic understanding. To study the seismotectonics of this earthquake-prone province in general and Killari earthquake region in particular, several boreholes were drilled in and around epicentral area. It included 617 m deep KLR-1 borehole, drilled 80 m south of surface scarp on the hanging wall near the Killari village (18°03'07"N, 76°33'20"E). It penetrated 338 m thick basalt flows, followed by 8 m of infratrappean sediments and a further 270 m of the Neoarchean crystalline basement.

Detailed geoscientific studies (including seismic, elastic and petrophysical studies) on the representative

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43 basement cores from various depths from the borehole indicated the Neoarchean crystalline basement to be made up of mainly amphibolite to granulite facies transitional, pervasively metasomatised, mid-crustal rocks with a few samples belonging to tonalite and granodiorite (Pandey *et al*., 2014, 2016a; Pandey 2016; Tripathi *et al*. 2012a, b; Tripathi 2015). The basalts are iron-rich compared to other basalts (average FeO_T: ~ 9 wt %) and characterised by an average density of 2.82 g/cm^3, with corresponding P- and S-wave velocities of 6.17 and 3.61 km/s respectively. Retrogressive alterations like saussuritization, biotitization, sericitization and iron enrichment have severely affected these rocks, including the reduction in measured velocities by as much as 15% (Pandey *et al*., 2016). Petrologically, they contain clinopyroxene, horneblend, calcic plagioclase biotite and minor orthopyroxene (Fig. 1), apart from accessories like ilmenite, magnetite, titanite, epidote etc. Geothermobarometric studies indicate that the basement below Killari was subjected to temperatures between 700 and 860ºC and pressure, 5-7 kb, (Tripathi *et al*., 2012) before their exhumation to the surface indicating that almost 15-20 km granitic upper crust has been eroded from this region even before the onset of Deccan volcanism, due to persistent geodynamic process of uplift and erosion. Besides, this amphibolite granulite facies basement has halogen-rich amphiboles and mantle derived carbonates with 2 wt % of CO_2 emanated from the mantle (Pandey *et al*., 2014). Carbon and oxygen isotopic studies on couple of extracted carbonate samples do confirm their mantle origin, suggesting large scale crust-mantle thermal fluid interaction beneath Killari seismic zone. Underlying mantle is still quite warm below areas covered by Deccan volcanics (Pandey *et al*., 2017). Rohilla *et al*. (2018) have made detailed analyses of shear wave velocity structure beneath Koyna region and found an unusually high upper crustal shear-wave velocity of about 4 km/s at 5 km depth that is comparable with that of the lower crust.

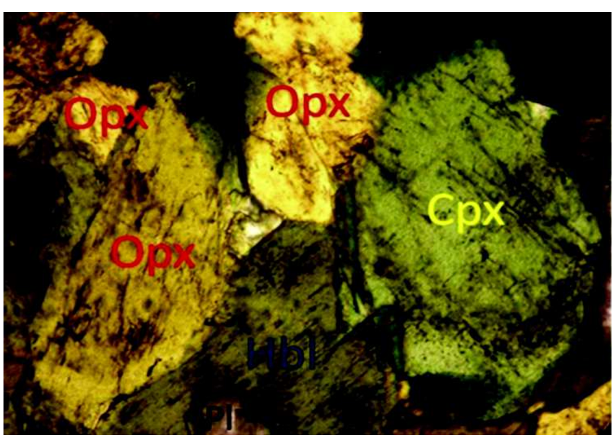

Fig. 1: Photomicrographs taken from thin section of the basement sample, KIL-12 from the KLR-1 borehole drilled in Killari. Hbl, Cpx, Opx and Plg refer to hornblende, clinopyroxene, orthopyroxene and plagioclase respectively

However, not much study has been carried out on the 338 m thick volcanic sequence which is comprised of eight flows, belonging to two prominent formations, Ambenali and Poladpur, representing the Wai Subgroup. The entire column is made up of fine to medium grained, rarely coarse-grained, and highly massive to vesicular basalts. Massive basalt core samples are heavy and greenish black to dark black in color with metallic lustre. In comparison, vesicular samples, which are usually found at the top of the flows, are greyish brown to dark brown in color. Petrological and geochemical examination of these samples indicates that the studied basalt rocks are relatively Fe and Mg-rich and silica deficient in composition and basically contain plagioclase, pyroxene phenocrysts, and microphenocrysts and occasionally, altered olivine as major constituents and magnetite and secondary silicates as accessory minerals. Quite a few samples are extremely glassy in nature (Fig. 2), while many of these contained abundant microlites and plagioclase laths. Some of the samples are filled with secondary minerals, and other forms of silicates, formed mainly by alteration of pyroxene and plagioclase grains.

The saturated massive basalt cores of the Deccan volcanic sequence have a mean density of 2.91 g/cm^3 and mean P- and S-wave velocities of 5.89 km/s and 3.43 km/s respectively. In comparison, vesicular basalts show a much lower density of 2.62 g/cm^3 as well as P- and S- wave velocities of 4.00 km/s and 2.37 km/s respectively. Based on this study, the Deccan volcanic sequence can be assigned a weighted mean density of 2.74 g/cm^3 and on an average, a quite low V_p and V_s of 5.00 km/s and 3.00 km/s, respectively. Lowering in velocities can be primarily attributed to the presence of glassy material, high iron contents, and large-scale inclusion of

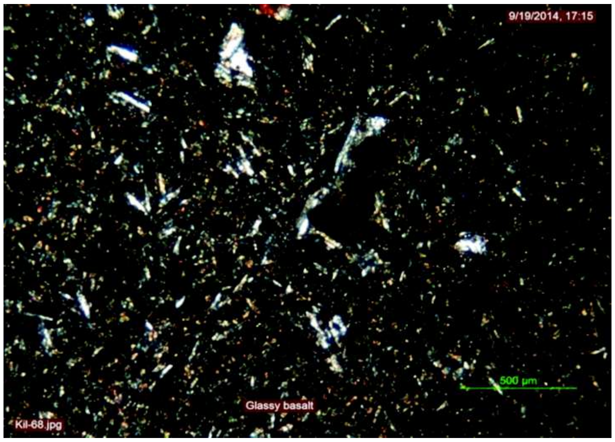

Fig. 2: Photomicrographs taken from the thin sections of Deccan basalt sample KIL-68 from the KLR-1 borehole drilled in Killari, showing glassy nature

secondary minerals. High order of attenuation is also reportedly noted in some of massive basalt cores, besides vesicular samples. It is argued that composition of the basalt itself could be a major contributing factor towards seismic attenuation. Recent studies over this region (Pandey *et al*., 2016) indicated that in comparison to Deccan volcanics, the subsurface thick Mesozoic sediments, can be seriously considered as a leading option for geologic CO_2 sequestration, while pervasively fractured, faulted and highly deformed, on-land exposed volcanics, should be given least priority.

Studies on Indian Carbonatites

Carbonate magma is unique because of its ability to enrich elemental carbon with respect to its silicate mantle source, where carbon is a trace element. Owing to its extremely low viscosity and short residence time in the crust carbonate magma passes through the crust without significant contamination. In addition, very high contents of most of the incompatible trace elements, many of which are used as elemental or isotopic tracers in mantle studies, tend to buffer any such contamination. Therefore, carbonatites preserve mantle signatures more efficiently than most other magmatic rocks and thus are the best known samples to study the secular evolution of mantle geochemistry and the long-term carbon cycle in Earth.

Carbonatites occur both in continental and oceanic settings but are found mostly in the former and hence, provide useful information about the less understood sub-continental mantle. Even though they are volumetrically minor, because of their widespread spatial and temporal distribution they provide valuable information about the secular evolution of the sub-continental mantle on the whole-Earth scale. The observation that many carbonatites are associated with Large Igneous Provinces (LIPs) or Continental Flood Basalt (CFB) provinces has led to the speculation that they too like the LIPs/CFBs could be genetically linked to the deep mantle plumes. The plume derivation hypothesis derives its support, albeit unconvincingly, from the observations that many carbonatites (1) occur within LIPs or CFBs (Ernst and Bell, 2010), (2) carbonatites generally possess isotopic ratios of Nd-Sr-Pb similar to that of the Oceanic Island Basalts (e.g., Nelson *et al*., 1988), (3) show lower (un-degassed) mantle noble gas isotopic signatures (Sasada *et al*., 1997; Tolstikhin *et al*., 2002), and (iv) have a HIMU (high $^{238}U/^{204}Pb$) component, which is usually found in plume derived melts (Bell and Tilton, 2002). However, a great majority of carbonatites show (1) overwhelming presence in continental crust, (2) geochemical and isotopic signatures akin to lithospheric mantle (Ashwal *et al*., 2016), (3) repeated magmatic activity in a given complex, separated by several millions of years (e.g., Woolley and Bailey, 2012), (4) derivation from mantle that is much cooler than plumes (Bailey and Woolley, 1995), and alkaline silicate rock association and their diversification which would require significant involvement of continental lower crust (Ray, 2009). All these point to the possibility that carbonatite magmas most likely are derived from sub-continental lithospheric mantle. Other important aspects of carbonatite magmatism those have not been fully understood include, nature and source of carbon (primordial vs. recycled), nature of origin of magma (primary melt vs. magmatic differentiation), and environmental effects of the release of large amounts of fluids associated with its eruption/ emplacement.

The carbonatite complex in India was first discovered by Sukheswala and Udas (1963). Ever since, more than 20 complexes have been identified (Krishnamurthy *et al*., 2000; Ray and Ramesh, 2006). In spite of years of research, questions on the origin of many of these complexes remain poorly understood. Most of the Indian carbonatites occur within major fracture zones (Krishnamurthy *et al*., 2000) and some are associated with Deccan and

Table 1: Summary of current chronological status of important carbonatite complexes of India

	Complex	Age (Ma±2s)	Dating Method	Reference	Remark
1)	Hogenakkal, Tamil Nadu	2406±32	Sm/Nd min-wr isochron (carbonatite + pyroxenite + minerals)	Kumar *et al*. (1998)	Weighted Mean of 3 age data
2)	Kambamettu (Kambam), Tamil Nadu	i. 2498±16 &2470±15 (magmatic) ii. 608±6 (crustal?) iii. 715±42	i. U/Pb zircon ii. U/Pb zircon iii. Th/Pb monazite	i. Renjith *et al*. (2016) ii. Renjith *et al*. (2016) iii. Catlos *et al*. (2008)	Four phases of magmatic activity? Age of monazite is deemed hydrothermal (Ranjith *et al*., 2016)
3)	Newania, Rajasthan	i. 1473±63(magmatic) ii. 904±2(thermal event)	i. Sm/Nd wr isochron ii. $^{40}Ar/^{39}Ar$ plateau (phlogopite)	Ray *et al*. (2013)	Earlier age estimates: 2.24 Ga to 959 Ma
4)	Sevattur, Tamil Nadu	i. 767±8 ii. 801±11 iii. 756±11	i. Rb/Sr wr isochron (syenite) ii. Pb/Pb isochron (carbonatite) iii. Rb/Sr isochron(syenite + pyroxenite)	i. Kumar *et al*. (1998) ii. Schleicher *et al*. (1997) iii.	Accepted age: 770 Ma (average of all reliable ages) Miyazaki *et al*. (2000)
5)	Sung Valley, Meghalaya	i. 107.2±0.8 ii. 106±11	i. $^{40}Ar/^{39}Ar$ plateaus (phlogopite from carbonatite + pyroxenite) ii. Rb/Sr isochron (wr-mineral from both carbonatite + pyroxenite)	i. Ray *et al*. (1999); Ray and Pande (2001) ii. Ray *et al*. (2000)	Accepted age: 107 Ma
6)	Jasra, Assam	105.2 ± 0.5	U/Pb of zircon/baddeleyite	Heaman *et al*. (2002)	
7)	Mundwara, Rajasthan	i. 102-110 ii. 80-84	$^{40}Ar/^{39}Ar$ plateaus	Pande *et al*. (2017)	Earlier age estimate: 68 Ma by Basu *et al*. (1993); Repeated alkaline magmatism
8)	Sarnu-Dandali, Rajasthan	i. 88.9-86.8 ii. 66.3±0.4	i. $^{40}Ar/^{39}Ar$ plateaus (alkaline silicates) ii. $^{40}Ar/^{39}Ar$ plateau: (melanephenite)	Sheth *et al*. (2017)	Same as Mundwara
9)	Chhota Udaipur alkaline-carbonatite sub-province, Gujarat	65.0	$^{40}Ar/^{39}Ar$ plateaus(alkaline silicate rocks; phlogopite from carbonatite)	Ray and Pande (1999); Ray *et al*. (2000); Ray *et al*. (2005)	Complexes/isolated bodies: Amba Dongar; Siriwasan; Tawa

Rajmahal-Sylhet CFBs (Fig. 1). All except Newania are carbonatite-alkaline silicate rock complexes. The ages of emplacement of the important carbonatite complexes are reviewed in Table 1.

Ages of Carbonatites Emplacements

Based on available geochronological information, Indian carbonatites can be broadly classified into two groups. The southern Indian complexes and Newania of Rajasthan are *Proterozoic* (2500-750 Ma; Table 1); the northeastern and northwestern complexes are *Cretaceous* (110-65 Ma; Table 1). New age data suggest that Newania carbonatite was emplaced at ~1473 Ma and was affected by a thermal event at ~904 Ma (Ray *et al*., 2013), and these results contradict the earlier suggestion from Pb-Pb ages that the complex had seen recurring carbonatite activities at 2270 Ma and 1550 Ma (Schleicher *et al*., 1997). However, the pre-Deccan alkaline-carbonatite complexes of Mundwara and Sarnu Dandali clearly had multiple activities during 110-66 Ma (Pande *et al*., 2017; Sheth *et al*., 2017), a finding that would likely to change our view on the LIP/CFB-carbonatite connection. Based on the U-Pb zircon data Kambamettu of Tamil Nadu becomes the oldest carbonatite-alkaline complex of India (~2.5 Ga; Renjith *et al*., 2016).

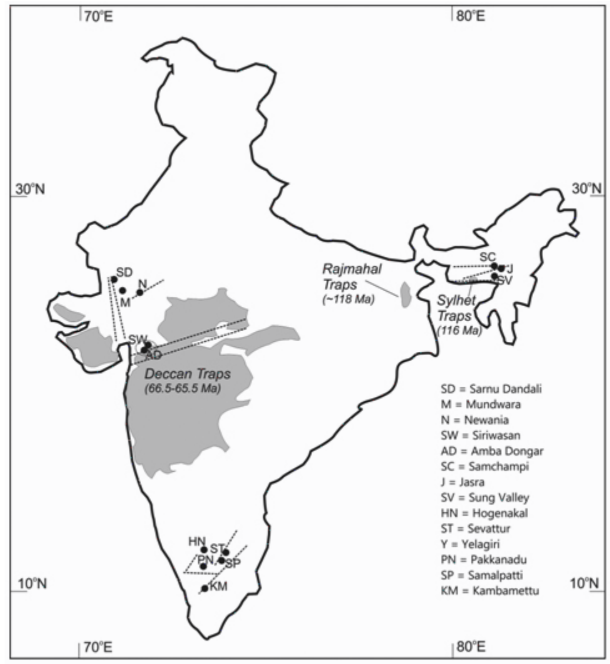

Fig. 3: Map of India (modified from Krishnamurthy *et al*., 2000), showing continental flood basalt provinces (grey shaded) and carbonatite complexes. Also shown are the major fracture zones/lineaments (dashed lines) in/along which the carbonatites occur. Ages of Deccan Traps, Rajmahal Traps and Sylhet Traps are from Renne *et al*. (2015), Bakshi (1995) and Ray *et al*. (2005), respectively

Geology, Geochemistry and Mantle Sources

Comprehensive reviews of general geology and geochemistry including isotopic compositions of Indian carbonatite-alkaline complexes can be found in Krishnamurthy *et al*. (2000) and Ray and Ramesh (2006). Here we shall present only the important geological and geochemical findings of the last five years, and their bearing on the origin and evolution of these complexes.

Proterozoic Carbonatites

All the southern Indian carbonatites, i.e., Hogenakal, Sevattur, Samalpatti, Jogipatti, Pakkandau, Kambamettu, and one north Indian complex, i.e., Newania, were emplaced at various times during the Proterozoic and most complexes show effects of one/multiple post-magmatic thermal histories (e.g., Renjith *et al*., 2016; Ray *et al*., 2013). All these complexes are located within the Southern Granulite Terrain (SGT) and are associated with major fracture zones (Fig. 3).

The most recent work on Kambamettu (Kambam) alkaline-carbonatite complex by Renjith *et al*. (2016) suggests that the complex had four distinct magmatic intrusions: i) quartz-monzonite (2.5 Ga) derived from a carbonated alkali-rich lower crustal source; ii) phlogopite-rich pyroxenite derived from carbonate metasomatized mantle; iii) mantle derived high Ba–Sr carbonatite (2.47 Ga); and iv) shoshonitic peralkaline syenite (0.61 Ga) derived from crustal source. We believe that the inference of crustal derivation for alkaline magmas is erroneous, what the younger ages and chemical compositions may actually mean is thermal resetting and/or metamorphism, and several such events, with the youngest being the 0.55 Ga Pan-African, are known to have affected the SGT. Pandit *et al*. (2016) carried out C-O-Sr-Nd isotopic study of the 2.4 Ga Hogenakal carbonatites and suggested their derivation from a heterogeneous mantle source (LREE depleted and enriched). Mineral Chemistry, stable carbon and oxygen isotopes of carbonatite from Salem- Attur shear zone indicated the mantle origin of the southern Indian carbonatites. (Kumar *et al*. 2001). Ackerman *et al*. (2017)'s work is the most recent addition to the research on Sevattur and Samalpatti carbonatites that provides a large amount of petrographic, geochemical (major-trace elements) and isotopic (C-O-Sr-Nd-Pb) data. This study confirms the findings from previous studies that there has been significant hydrothermal alteration in these complexes (e.g., Ray and Ramesh, 2006), however, failed to identify the nature of the mantle sources because of significant crustal contamination. The only north Indian Proterozoic carbonatite is Newania, which happens to be a pure dolomite carbonatite complex that has no alkaline silicate rocks. Using multiple geochemical (major-trace elements and isotopic techniques (C-O-Sr-Nd-Pb) Ray *et al*. (2013) established that the primary magma for the complex was a magnesio-carbonatite melt and that it was derived from a carbonate bearing mantle. This work also suggested that the source was a phlogopite bearing, metasomatized continental lithospheric mantle, which was located within the garnet stability zone.

Cretaceous Carbonatites

All northeastern and western Indian carbonatite complexes, except Newania, were emplaced within a short time in Cretaceous, during ~110 and 65 Ma (Table 1). Interestingly, these complexes are spatially and temporally associated with the Rajmahal-Bengal-Sylhet and Deccan CFBs, respectively (Fig. 3) and have been hypothesized to have been generated directly or indirectly by the Reunion and Kerguelen plumes, respectively (Basu *et al*., 1993; Ray *et al*., 1999; Ernst and Bell, 2010; Ghatak and Basu, 2013).

The northeastern Indian carbonatites (Swangkre, Sung Valley, Jasra, Barpunga and Samchampi) intrude into Archean basement rocks of the Proterozoic Shillong Group. They occur in a horst like feature called the Assam-Meghalaya Plateau that is bound by two major fractures (Fig. 3). The 107 million year old alkaline-carbonatite complex of the Sung Valley happens to be the best studied northeastern Indian carbonatite (Ray and Ramesh, 2006; Ray, 2009). Based on geochemistry (elemental and Sr-Nd-Pb isotopic) of carbonatites and associated alkaline silicate rocks Ghatak and Basu (2013) suggested that Sung Valley carbonatites were derived from a relatively primitive carbonated garnet peridotite source in the Kerguelen plume. The work also envisaged a similar model for Samchampi. N and Ar isotopic compositions of Sung Valley carbonatites suggest involvement of recycled (atmospheric/crustal) component in the origin of carbonatite magma in a heterogeneous sub-continental mantle (Basu and Murty, 2015). Studying petrogenesis of Samchampi complex with the help of geochemical and isotopic (Sr-Nd) tracers Saha *et al*. (2017) proposed that these carbonatites were derived from a metasomatized peridotitic source (LREE enriched) within the Kerguelen plume, similar to what was suggested earlier by Ghatak and Basu (2013). However, these studies failed to explain the highly radiogenic nature of Sr ($^{87}Sr/^{86}Sr(i) > 0.709$) and non-radiogenic nature of Nd ($_{Nd}(i) < -8$) in these rocks.

The western Indian Cretaceous carbonatites (Sarnu Dandali, Mundwara, Amba Dongar, Siriwasan, Panwad-Kawant) occur along two famous rift zones: the Barmer-Cambay and the Narmada-Son/Satpura (Fig. 3). Of these Amba Dongar, Siriwasan and many smaller plugs, dikes and extrusive bodies in Panwad-Kawant region of Chotta Udaipur district form a large alkaline-carbonatite subprovince within the Deccan LIP (Fig. 3; Gwalani *et al*., 1993; Ray *et al*., 2003). During the last five years only a couple of geochronological studies and one field based study have been done on Sarnu Dandali and Mundwara complexes (Tables 1 and 2). The works of Pande *et al*. (2017) and Sheth *et al*. (2017) suggest that there have been repeated alkaline magmatism in these two complexes after gaps of at least 20 and 40 Ma, respectively. These results clearly indicate that the initiation of magmatism in these complexes precedes the Deccan flood volcanism by a long time gap; therefore, the hypothesis of their origin from a Deccan-Reunion plume becomes untenable. Amba Dongar alkaline-carbonatite complex and its nearby smaller intrusive/extrusive bodies in Chotta Udaipur sub-province are by far the best studied carbonatites in India because of sustained efforts by Xavier College, Mumbai, Atomic Minerals Division, Gujarat Mineral Development Corporation and Physical Research Laboratory. Contributions by S.G. Viladkar and his group (e.g., Viladkar, 1996; Viladkar and Schidlowski, 2000; Simonetti *et al*., 1995) and J.S. Ray and his group (e.g., Ray, 1998; Ray and Pande, 1999; Ray and Ramesh, 1999; Ray and Ramesh, 2000; Ray *et* *al*., 2003; Ray and Ramesh 2006) have resolved most of the outstanding issues about the origin and evolution of Ambam Dongar and nearby complexes. The notable contributions for these complexes during the last five years have been by Basu and Murty (2015) and Chandra *et al*. (2017). The former presented N and Ar isotopic data from Amba Dongar carbonatites and suggested their derivation from a heterogeneous sub-continental mantle, a conclusion confirmed by a detailed geochemical study by Chandra *et al*. (2017). The latter study also substantiated the earlier claim made by Ray and Shukla (2004) and Ray (2009) that the carbonatites and alkaline silicate rocks of these complexes are derived from a single parental magma through liquid immiscibility and that lower crustal assimilation plays a critical role in their diversification.

Studies on Kimberlites and Lamproites

Significant advances have been made in the research frontiers of kimberlites and related rocks from the Indian context during past five years. Chalapathi Rao and his group at Banaras Hindu University have been very productive in studying mineralogical, petrological and chronological characterization of several kimberlite clusters of Mesoproterozoic (ca. 1100 Ma) and late Cretaceous (ca. 90 Ma). (Pandey *et al*. 2017; Dongre etal. 2017; 2016; Rao *et al*. 2016a; 2016b; 2017). From the paleomagnetic investigations on the 1.1 Ga Mesoproterozoic kimberlites from the Dharwar craton, southern India, Venkateshwarlu and Rao (2013) have shown that India, occupies a lower palaeolatitudinal position, was much separated from Australia and that East Gondwana very likely did not form an assembly until the terminal Neoproterozoic. A layered mantle stratigraphy has been documented in the sub-Bastar craton lithosphere from a comprehensive study of kimberlite- derived xenocrysts and xenoliths (Rao *et al*., 2013a). K-rich titanite, a characteristic mineral of orangeites, has been reported from ultrapotassic dykes of Jharia field, Damodar valley highlighting the transitional (lamprophyre-lampropite-orangeite) characters (Rao *et al*., 2013b). PGE determination from the Deccan-age orangeites of Bastar craton, central India, lacks Ir enrichment thereby excluding the Ir enrichment at K-Pg boundary from deep mantle sources (Rao *et al*., 2013b). A number of previously undated kimberlites from the Wajrakarur field from the Dharwar craton gave precise U-Pb 1.1 Ga ages highlighting a major tectonomagmatic event during that time (Rao *et al*., 2013d). Contrasting lithospheric source regions for the kimberlites and lamproites from the Dharwar craton and for orangeites from the Bastar craton have been documented from Re-Os isotope systematics (Rao *et al*., 2013c). Nickeliferous silicate (garnierite) has been reported from the tuff facies Tokapal kimberlite and its prospectivity for nickel has been highlighted; petrogenesis of the Tokapal kimberlite has also been constrained (Rao *et al*. 2013d). A SCLM origin for Mesoproterozoic Ramadugu lamproites has been deduced (Rao *et al*., 2014). Imprints of Kerguelen plume have been confirmed in the melt sources of the ultrapotassic intrusives from the Gondwana sedimentary basins (Rao *et al*., 2014). Petrogenetic model has been proposed for the macrocrystic as well as aphanitic intrusions in the diamondiferous pipe-2 kimberlite of Wajrakarur field (Dongre *et al*., 2014). Ti-garnet occurrence in kimberlite groundmass as a resultant of breakdown of spinel has been delineated from the Wajrakarur field (Dongre *et al*., 2016). Petrogenetic studies and age determination have been carried out for the lamproites at Sakri, Bastar craton (Rao *et al*., 2016a) and Garledinne, Cuddapah basin (Rao *et al* ., 2016b) and their geodynamic significance brought out. A Late Cretaceous diamondiferous kimberlite event (90 Ma) has been documented for the first time from the Timmasamudram kimberlites, Wajrakarur field, Dharwar craton of southern India (Rao *et al*. 2016c) and their genesis has been brought out (Dongre *et al*., 2017). A cognate origin for the clinopyroxene megacrysts from the Udiripikonda lamprophyre, Dharwar craton has been deduced (Pandey *et al*. 2017a). The role of subduction tectonics in the modification of the SCLM beneath the Dharwar craton has been brought out from the geochemistry of calc-alkaline lamprophyres towards the western margin of the Cuddapah basin (Pandey *et al*., 2017b and c). Modal metasomatism, from phlogopite+apatite assemblage, has been documented for the first time beneath the sub-Deccan lithosphere in an ultramafic mantle xenolith entrained in a Eocene lamprophyre from the Dongargaon area, NW India (Pandey *et al*., 2017d). Single crystal geothermobarometry on a chrome diopside megacryst entrained in a lamprophyre from the polychromous (100-68 Ma) Mundwara alkaline Complex, NW India, implies that pre-Deccan lithosphere was ~100 km depth. Phani *et al*. (2017)

have discovered a new kimberlite in Lattavaram Kimberlite Cluster (LKC) of Anantapur district, Andhra Pradesh, India. This new kimberlite pipe has been located in the riverbed of Balkamthota Vanka (name of the stream used by local farmers) at its confluence with Penna River, close to Pennahobilam. The kimberlite constitutes olivine macrocrysts, serpentinsed olivine pseudomorphs with xenocrystic ilmenite, phlogopite, perovskite, magnetite, Cr-diopside, garn*et al*ong with calcite veins. The kimberlite has been classified as hypabyssal macrocrystic calcite-phlogopite kimberlite (Phani *et al*., 2017).

Lamproitic dykes from Sidhi Gnessic Complex, Central India have been investigated by Satyanarayanan *et al*. (2018), showing that lamproite magma attained carbonatitic character, underwent metasomatism at deep crustal level. The geochemical studies shown that the discovered Central Indian lamproitic dykes indicate their parental magmas were originated from a subduction induced metasomatism process contain phlogopite and garnet.

Industrial Applications and Future Studies

Deccan volcanic rocks provide several secondary minerals like zeolites, hydrous silica, and sulfates that are useful in many Industrial applications. Recent discovery of jarosite in Kutch area (Bhattacharya *et al*., 2016) not only serves as a Martian analog material, but also applied for adsorption and redox reactions occur between arsenic-containing pyrite and arsenate in the form of shwertmannite. Shwertmannite is proven to be a powerful scavenger for trivalent arsenic. Ferrous saponite from the Killari region of the Deccan Trap has been used in not only as for the study of Mars analogs system, but also for the adsorption and reduction of carcinogenic water soluble hexavalent chromium. Systematic studies of mineral chemistry of Indian carbonatites are found to be most useful in the exploration and utilization of rare-earth minerals. Future discovery of new carbonatites will be of tremendous use in improving the rare earth minerals resources of our country.

Conclusion

In this paper we presented a status report on the work carried out on Deccan Volcanism, carbonatites, and kimberlites during the last five years. There has been some significant advancement in terms of geochronology of Mundwara, Sarnu Dandali, Newania and Kambamettu carbonatites. Most other studies are on geochemistry and they mostly reaffirm the conclusions made by earlier studies. One clear conclusion, however, emerges from these studies is that the primary magmas for the Indian carbonatites originated from the sub-continental lithospheric mantle.

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Contents

Preface

All information about the Earth's interior comes from field observations and measurements made within the top few kilometers of the surface, from laboratory experiments and from the powers of human deduction, relying on complex numerical modeling. Solid Earth Geophysics encompasses all these endeavors and aspires to define and quantify the internal structure and processes of the Earth in terms of the principles of physics, corresponding mathematical formulations and computational procedures. The role of Solid Earth Geophysics has gained prominence with increasing recognition of the fact that knowledge and understanding of Earth processes are central to the continued well being of the global community. Apart from persistent search for natural resources, this research line is linked to basic investigations regarding the mutual relationships between climate and tectonics and on the effects of global change in terms of a wide spectrum of natural hazards. Consequently, the pursuit of this science has seen spectacular progress all over the world in recent decades, both in fundamental and applied aspects, necessarily aided by advancements in allied fields of science and technology.

The ***Encyclopedia of Solid Earth Geophysics***, aims to serve as a comprehensive compendium of information on important topics of Solid Earth Geophysics and provide a systematic and up-to-date coverage of its important aspects including primary concepts as well as key topics of interest. It, however, does not claim to chronicle each and every niche area that in reality is a part of this multidisciplinary and multi-faceted science. Neither does it attempt to describe the basic physics of matter and energy systems, which comprise the underlying tenets of geophysical research. The first edition of this Encyclopedia, edited by Prof. James David, was published in 1989 by the Van Nostrand Reinhold publishing company. The extraordinary growth and diversification of this science over the last twenty years called for a complete revision. This is realized by identifying the necessary topics and bringing together over 200 articles covering established and new concepts of Geophysics across the sub-disciplines such as Gravity, Geodesy, Geoelectricity, Geomagnetism, Seismology, Seismics, Deep Earth Interior and Processes, Plate Tectonics, Geothermics, Computational Methods, etc. in a consistent format. Exceptional Exploration Geophysics and Geotechnical Engineering topics are included for the sake of completeness. Topics pertaining to near Earth environs, other than the classical Solid Earth', are not within the scope of this volume as it is felt that the growth of knowledge in these fields justify a dedicated volume to cover them.

Articles written by leading experts intend to provide a holistic treatment of Solid Earth Geophysics and guide researchers to more detailed sources of knowledge should they require them. As basic understanding and application of Solid Earth Geophysics is essential for professionals of many allied disciplines such as Civil Engineering; Environmental Sciences; Mining, Exploration and software industries; NGOs working on large scale social agenda; etc., it would be useful to them to have access to a ready and up to date source of knowledge on key topics of Solid Earth Geophysics. Hopefully, this Encyclopedia would prove to be an authoritative and current reference source with extraordinary width of scope, drawing its unique strength from the expert contributions of editors and authors across the globe.

I am grateful to Anny Cazenave, Kusumita Arora, Bob Engdahl, Seiya Uyeda, Rainer Kind, Ajay Manglik, Kalachand Sain and Sukanta Roy, members of the Editorial Board for their constant advice and guidance in developing the framework of this Encyclopedia and help with the editorial work. I am equally grateful to all the authors who readily agreed to contribute and honoured the guidelines and time schedule.

Petra Van Steenbergen, Sylvia Blago, Simone Giesler and D. Nishantini from Springer were very co-operative. It has been a pleasure working with Springer. Ms M. Uma Anuradha provided extraordinary assistance in the preparation of this volume. My wife Manju and daughters Nidhi & Benu supported me through the entire project.

Harsh K. Gupta

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