Institutional Report

CSIR-National Geophysical Research Institute

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Introduction

CSIR-National Geophysical Research Institute, Hyderabad (NGRI), is a research institution in geosciences under the aegis of the Council of Scientific and Industrial Research (CSIR), Ministry of Science and Technology, Govt. of India. Scientific pursuits of this institute encompass many important disciplines of basic and applied earth sciences research such as geophysics, geology, geochemistry, geochronology and geodesy. Continuing with its mandate for basic and applied research in geosciences, CSIR-NGRI made a significant progress over the last five years.

Ever growing population and ensuing demands have a direct impact on the Earth resources. Any

major changes in weather and climate, earthquake and other natural hazards have become areas of increasing concern affecting the availability of food, water and safety of the built habitats. CSIR-NGRI has the responsibility to develop new R&D capabilities for observing and understanding the Earth, and translate these new capabilities into national needs by creating decision support mechanisms for policy makers and help the societal well being.

CSIR-NGRI was established in 1961, as a center of excellence to pursue multidisciplinary earth sciences research programs that are in tune with the mission of CSIR and frontier global challenges. The present R&D activities have seven major themes: Hydrocarbon exploration, Mineral and Engineering

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Geophysics, Groundwater, Seismology, Geodynamics, Theoretical Geophysics, and Geochemistry and Geochronology. For the convenience, these activities are conglomerated into three broad themes: (i) Groundwater Exploration and Management, (ii) Exploration of Minerals and Hydrocarbons, and (iii) Basic Research: Studies on the Lithosphere, Earth's Interior and Past Climates. Common objective of all these studies is to improve our ability to image deep and shallow regions of the Earth to understand its structure, composition and rheology, both spatially and temporally.

Since 2010, over 900 research papers have been published in SCI journals by the CSIR-NGRI researchers. This report highlights some of the substantive contributions of the institute and lists some significant publications.

Contributions and Achievements

Groundwater Exploration and Management

To address a wide range of hydro-geological issues of societal importance, CSIR-NGRI has taken up various aspects of groundwater research on its exploration, assessment and management. High-resolution heliborne geophysical surveys to map regional-scale aquifer system in three-dimension and integrating these results with the geological and hydro-geological data have been useful to reliably characterize groundwater aquifers for effective management of groundwater resources. State-of-the-art heliborne transient electromagnetic (HeliTEM) investigations for aquifer mapping were successfully carried out for the first time in India in varying geological terrains of hard rocks, desert, alluvial plains and coastal regions of India (Fig. 1). Using SkyTEM system, this pilot study was carried out in collaboration with the Central Groundwater Board (Ministry of Water Resources, River Development and Ganga Rejuvenation, New Delhi) and Aarhus University, Denmark. The results, in general, helped in mapping the aquifers in three-dimensions for reconstructing the concealed subsurface spatial disposition of structures controlling the groundwater dynamics. The salient hydrogeological features of the six geologically distinct sites emerging from the pilot HeliTEM experiment are:

- A clear delineation of clayey and sandy beds

and their spatial distribution defining the multi-layered aquifer typical of the Gangetic Plains.

- Delineation of low resistivity zones in the quartzite below the overexploited aquifers indicating the possibility of new aquifers in a Precambrian sedimentary setting.
- Presence of comparatively freshwater zones underneath the saline water aquifers in the thick and dry sands in a desert.
- Clear demarcation of different lava flows, mapping the structural controls as well as highly porous zones at the contact between Deccan basalts and the underlying Gondwana strata.
- A complete and continuous mapping of weathered portions in the hard-rock (granite) terrain providing information on the recharge zones.
- The setting of multi-layered aquifer and different zones of salt-water intrusion in the coastal sedimentary formations.

Arsenic contamination of aquifers is a crucial issue that need to be addressed for providing clean water in the affected areas. Towards this, CSIR-NGRI has examined management of groundwater resources in arsenic contaminated Middle Ganga Plains (MGP) where earlier studies mostly dealt with geochemical aspects of the contamination and design of various filters for removal of arsenic. The sludge from the filter enters again into the subsurface and contaminates the groundwater regime in the surroundings. Detailed studies by CSIR-NGRI in the MGP have shown that subsurface lithology, specially the clay barrier play an important role in controlling the arsenic contamination in groundwater. The results provided an insight into the process of arsenic contamination and elucidated the aquifer set up that helps separating the polluted aquifer(s) in a multi-aquifer system existing in the MGP (Fig. 1), India and aids in safeguarding the zones free from contamination.

Studies on the groundwater flow, hydro chemical and isotopic contents form an important component of research at CSIR-NGRI on water quality. Some of salient results are:

- The sustainability of fresh water in the coastal aquifers have immense socio-economic

importance as over-exploitation of these aquifers may lead to seawater ingress as per the GHYBEN-HERZBERG formula. However, our research results based on water level, hydrochemistry and stable isotopes (^{18}O & ^2H) in such coastal aquifers of Prakasam (Ongole) district in Andhra Pradesh state show no trace of seawater ingress even after the groundwater levels reached down to 5 m below the mean sea level. This has been attributed to the local geological conditions governing the recharge of the aquifer.

- A societal concern was raised through public litigation that the alkalinity and salinity of the Lonar Lake water is being diluted with increased lake water level as a result of external inputs (like seepage of water) into the lake from nearby surface reservoirs which are being used for agriculture purpose. CSIR-NGRI work has shown that water level and hydrochemistry of Lonar Crater Lake water are controlled by local rainfall and evaporation and that there is no other external water input to the lake.
- Chronic kidney disease (CKD) has been prevalent in a few coastal regions of Uddanam, Srikakulam district, and Chimakurthy Mandal (~30 to 40 km away from the coast) in the Prakasham (Ongole) district of Andhra Pradesh, India. Hydrochemical investigation carried out in these areas ruled out the possibility of drinking water being a cause for CKD as believed by the locals and medical experts.
- Fluoride affected water is a big social issue in parts of the Nalgonda District of Telangana (India). Detailed investigations by CSIR-NGRI, in the Wailapally granitic watershed of this district have shown that it is characterized by high-F groundwater (up to 7.6 mg/L), due to abundant F sources, in the form of hornblende, biotite, apatite, fluorite and F-rich calcretes. A closed hydrological basin and dry climate provide favorable conditions for the release of F to groundwater. It is hypothesised that the rather uniform concentrations of F in different morphological units with different hydrochemistry is due to removal of F from the groundwater by co-precipitation with, and/or adsorption to, calcrete formation. Thus, we have enhanced the understanding of the sources and

mechanism for high fluoride in groundwaters and further infer that hydrochemical processes and geochemical controls on fluoride concentration in groundwater of granitic and alluvial regions are different.

For groundwater exploration and development of management strategies for quality improvement, safe drinking water supply and aquifer sustainability, CSIR-NGRI made significant contributions in the field of aquifer recharge using geochemical, tracer and rainwater harvesting techniques to quantify aquifer parameters. Some of the salient results are listed below:

- To model the pollutant migration in terms of soil physical & hydraulic properties; sub-surface hydrogeological conditions; surface and groundwater hydrochemistry; delineation of plausible palaeostream channel pathway of pollutant migration etc., geophysical and hydrogeological investigations were carried in active tailings pond and closed tailings pond of the Jaduguda and Turamdih mining areas of Jharkhand state. The resistivity tomography was used to map the tailings thickness and disposition clearly in one of the closed tailings pond. The effluent nature of the stream carrying the polluted groundwater was identified and remedial measures for arresting the migration of pollutants through groundwater were evolved. Using the soil-moisture tension, a new way of estimating the permeability of soils at different depths without disturbing the conditions was evolved and compared with the lab permeability measurements under disturbed conditions. In-situ Kd (adsorption coefficient) of Uranium and its nuclides with respect to soil conditions was designed and tested.
- With an objective of determining the site's safety and environmental impact, hydrological data (both saturated and unsaturated zone) were generated at Madras Atomic Power Station (MAPS) and Tarapur Atomic Power Station (TAPS) areas. Geophysical investigations at both sites helped to understand subsurface lithological variations and mapping the subsurface geometry. Based on lithology and geophysical results, two aquifers were delineated in the MAPS area. The top sandy aquifer is followed

Fig. 1: Study area locations (as mentioned in the text of this report) for the groundwater research. AQ= Aquifer, BHR= Bihar, DRT=Desert, RAJ=Rajasthan, KAR=Karnataka, MAH=Maharashtra, TND=Tamilnadu, MGP=Middle Ganga Plains

by weathered–fractured aquifer. In the TAPS area weathered – fractured aquifer was delineated. The continuous water level data obtained from logger indicated significant recharge during high intensity rainfall events and outflow from MAPS area.

Groundwater usage in the Indo-Gangetic plains exceeds replenishment of aquifers, leading to substantial reduction in the mass. Such anthropogenic crustal unloading may promote long-term fault slip or may modulate seismic activity in the adjoining Himalayan region. Simulation of this unloading effect using Gravity Recovery and Climate Experiment data and hydrological models of such a process indicates that the thrust earthquakes on the Main Himalayan Thrust (MHT), including the recent 25 April 2015 Mw 7.8 Gorkha, Nepal earthquake, are probably influenced by the anthropogenic groundwater unloading process in the Gangetic plains.

Exploration of Minerals and Hydrocarbons

As a part of efforts for mineral and energy resource explorations, CSIR-NGRI successfully carried out

aerial fixed-wing and heliborne geophysical surveys for mineral and oil exploration for various Government and Private Organizations. To locate deep concealed conductive targets in varied geological terrains, the institute procured a VTEM (Versatile Time Domain Electromagnetic) system for its mineral exploration programme. This system was integrated with magnetic and radiometric sensors for heliborne high resolution multi-parametric geophysical surveys for uranium exploration for Atomic Minerals Directorate (AMD), Department of Atomic Energy, Government of India. Since 2010, the institute has acquired about 47,000 LKM transient electromagnetic, aeromagnetic, and radiometric data over North Singhbhum Shear Zone, Singhbhum Shear Zone, and parts of the Chhattisgarh basin. Integrated interpretation of the acquired multi-parametric geophysical data sets with the geological and borehole data helped to identify new target zones and, some as extension of already existing mines for further ground verification and drilling. Approximately 37,000 LKM data were acquired over parts of the Bhima and Kaldgi basins through outsourcing. Here also, some target zones

were identified for detailed work and drilling.

In collaboration with National Mineral Development Corporation Limited, multi-parametric and systematic exploration for kimberlite search was made in the vicinity of the Kalyandurg area within the Closepet Granite (CPG), Dharwar craton. This involved remote sensing and airborne geophysical surveys (100 and 200 m spacing; 60 m AGL), stream sediment sampling and electron probe analysis of heavy indicator minerals. These studies and subsequent drilling over the suspected anomalous zone led to the discovery of a kimberlite pipe.

In hydrocarbon exploration research work on imaging sub-basaltic sediments along the western offshore margin, quantification of gas-hydrates, and reservoir modeling for enhanced oil recovery were taken up. Significant contributions in this field are:

- Preparation of gas-hydrates stability thickness map along the Indian margin and illumination of gas-hydrates scenario within the Indian exclusive economic zone.
- Proposed new approaches for the delineation and characterization of gas-hydrates based on several seismic attributes and developed innovative methods for quantification and assessment of gas-hydrates.
- Identified prospective zones of gas-hydrates in Krishna-Godavari, Mahanadi and Andaman offshore regions using available industry standard seismic data, where gas-hydrates were later recovered by drilling and coring.
- Led a cruise by designing a specific experiment

using state-of-the-art data acquisition system and delineated new potential zones of gas-hydrates in the Krishna-Godavari and Mahanadi basins through acquisition and analysis of 7500 LKM of high-quality multi-channel and 880 LKM of ocean bottom seismic data.

- Acquired very long-offset (CDP) and wide-angle seismic data along 170 km long Rewa-Shahdol profile in the Rewa Basin of Central India during 2014-2015 for imaging sub-trappean hydrocarbon-bearing Gondwana sediments and deep crustal study.
- Summary of the entire gas-hydrates activities are given in abstract figure Fig. 2.

Seismic Hazard Assessment

Interaction of various tectonic entities that constitute Indian landmass have made it prone to natural hazards, specially the seismic hazards affecting a major populate of India. Mandated to work for societal cause of mitigating such hazards, (CSIR-NGRI) has been carrying out integrated geophysical investigations for the past four decades. The institute operates over 200 seismological stations which provide high fidelity datasets for earthquake hazard and these are aided by mapping seismically active faults, estimating the sediment thickness and a quantitative study of the amplification of seismic waves in varied geological terrains of India. Some significant results since 2010 are presented below:

- Delineation of potential earthquake source zones is an important step in seismic hazard assessment and mitigation. Preparation of seismo-tectonic

Fig. 2: (Left) The most prospective zones (Krishna-Godavari, Mahanadi and Andaman) and less-explored but potential zones (Kerala-Konkan, Saurashtra, Kerala-Laccadive and Cauvery) of gas hydrates are superimposed on the gas-hydrates stability thickness map along the Indian shelf with the EEZ boundary; (Middle) Seismic section showing BSR and recovered gas-hydrates samples; (Right) Sonic log and saturation of gas-hydrates as a function of depth

maps by correlating seismicity with the geological and structural trends is essential to characterize source zones in terms of active faults characteristics. This can only be achieved if regional and local seismic networks are in place. Seismological waveform data from a network of seismic stations acquired during 2007-2016 were analyzed. These were recorded by a seismological network of stations in Eastern Dharwar Craton (EDC) (Fig. 3). Source locations showed an improvement when data from other regional seismic stations (Koyna network and Shield seismic network) have been added. The errors in hypocentral locations are less than 5 km. A total of 148 microearthquakes were well located in and around the EDC region during the period of network operation. The EDC seismic network with all its functional stations has brought down the threshold limit of earthquake magnitude to 1.0 for those occurring in the EDC and adjoining regions. Reflecting on the history of past significant peninsular earthquakes, it is observed that all of them had occurred on fresh or unknown faults, not known to have ruptured before. The micro-earthquake activity is mainly confined to south eastern part

Fig. 3: Network of seismic stations in the Eastern Dharwar Craton, South India. Addanki = ADK; Bikanur = BKN; Challavanipeta = CHLP; Chotuppall = CUPL; Cuddapah = CUD; Gangavaram = GANGA; Hyderabad = HYB; Killari = KLR; Kothagudem = KGM; Mylavaram = MYLAV; Nagarjunasagar = NJS; Polavaram = PVM; Pulivendala = PULV; Racharala = RCL; Rampur = RPR; Srikalahasthi = SKHT; Sriramsagar = SRS; Srisailem = SRLM; Uravakonda = URV

of Godavari graben, the eastern margin of the Cuddapah basin and the Gundlakama fault.

- Research based on the velocity–depth functions studies are important for earthquake hazard assessment of the densely populated urban centers spread over the Indo-Gangetic Plains (Fig. 4) in terms of predicting strong ground motions due to large earthquakes in the Himalaya. Results of such studies by CSIR-NGRI have shown that the sedimentary thickness in the central part of the Indo-Gangetic Plains varies from 500 m to about 4 km and the shear wave velocities vary from 600 m/s to about 900 m/s indicating they are saturated porous sediments. This inference was possible by using data from over 35 broad band and strong motion velocity meters.
- Despite being in the vicinity of rupture zones of large Himalayan earthquakes, a quantitative study of the amplification of seismic waves in the Indo-Gangetic basin region is still lacking. Using recordings of shallow earthquakes at soft sites and hard reference sites, we computed standard spectral ratios (SSRs). SSRs at sites near the Himalayan foothills, where the sediment thickness is ~4 km, reveal a broadband amplification with a fundamental frequency of 0.13 Hz. The amplification at this frequency

Fig. 4: Sediment thickness beneath strong motion velocity meter stations installed in the Indo-Gangetic Plains. Triangles show locations of high resolution seismic stations of the CIGN. Different colours indicate sedimentary thickness estimated from receiver function analysis using network data

varies between 20 and 60. The fundamental frequency increases to the south as the thickness of the sediments decreases, becoming ~ 0.8 Hz at the southern-most site. The amplification at the fundamental frequencies exceeds 10 at all soft sites.

- Investigations for the upper mantle anisotropy (UMA) of India using a comprehensive data set of SKS and SKKS waveforms clearly indicate the fast and slow axes of anisotropy (δt) range from 0.3 to 1.7 s, the fast polarization azimuths (Φ) at a majority of stations in the Indo Gangetic Plains and central India coincide with the absolute plate motion of India implying shear at the base of the lithosphere as the dominant mechanism for forging anisotropy.

Earthquake precursory investigations using hydrochemical/isotopic changes in deep groundwater is being carried out in the Reservoir Triggered Seismic zone of Koyna-Warna (Maharashtra) since January 2005. Based on changes observed during M 5.1 earthquake on 14th March 2005 and subsequent changes after the earthquake, probable period of impending earthquake was estimated and it was realized within the estimated period. Further, radiocarbon dates in association with stable isotopes and hydro-chemical data helped to understand the hydraulic linkage between the Koyna–Warna reservoirs (believed to be responsible for induced seismicity) and surrounding groundwater up to the depth of 200 m.

Paleoseismological investigations provide vital inputs for seismic hazard assessment of a region in the form of evidences and chronology of paleoearthquakes. Though CSIR-NGRI has carried out such studies in many parts of India earlier, the locale of intensive current seismicity in NE India known as Kopili Fault Zone, has been documented first time for the seismogenic liquefaction evidences of paleoearthquakes. Age constraints on more than one and a half dozen liquefaction features using Optically Stimulated Luminescence (OSL) and ^{14}C chronology have been inferred to the three time intervals for the occurrence of causative seismic events viz. (i) 250 ± 25 yr. BP, (ii) between 400 to 770 yr. BP and (iii) 900 ± 50 yr. BP, in addition to the known historical earthquakes of 1869 and 1943 in this region. These data enhance our understanding of the

paleoseismic history of this region during the past ~ 1000 years.

CSIR-NGRI has taken up extensive GPS studies for assessment of seismic hazard through understanding of the earthquake occurrence processes in the plate boundary and intraplate regions of the Indian plate. About 75 permanent GPS observatories have been established in the tectonically active regions like Andaman subduction zone, Garhwal-Kumaun Himalaya, Kashmir Himalaya, Indo-Burmese arc, across the Karakoram Fault, and in the Koyna-Warna intraplate region. Besides, there are also permanent GPS observatories throughout India to constrain Indian plate motion and understand the strain accumulation in the plate interior. Most of these sites are connected through VSAT for online data transmission and for archiving the data at Indian National Centre for Ocean Information Services (INCOIS) and National Centre for Seismology (NCS).

As a part of the Indian Scientific Expedition to Antarctica, to estimate the plate motion and to understand the causes of crustal deformation the institute operates one permanent GPS and Seismic observatory at the Indian base station, Maitri. Some significant results of GPS studies by CSIR-NGRI are:

- Using GPS data from the sites located on the Indian plate and along its boundary, Euler pole of rotation of the Indian plate was constrained and it is proposed that the Indian plate moves as a single rigid plate with no significant deformation.
- evidence for strain accumulation in the Andaman region for the 2004 Sumatra-Andaman earthquake, estimated the source parameters of the great earthquakes in the region alongwith their postseismic deformation.
- Low and localized crustal deformation in the plate interior like Koyna-Warna (KW) and Godavari rift (GR) regions has been observed. While in KW region, low to moderate deformation rate ($< 2 \pm 0.5$ mm/year) was seen at a few sites within and close to the fault zones and no resolvable deformation is noticed elsewhere in the Koyna-warna region, it is very low (< 1.5 mm/year) all along the GR. Localized deformation of up to 3.3 ± 0.5 mm/year, is observed at two sites which are characterized

by high level low-magnitude seismicity.

- Discovery of a plate boundary fault with a low seismic hazard in the Indo-Burmese wedge that accommodates part of the motion ($\sim 18 \pm 2$ mm/year) of the relative motion between the India and Sunda plates (~ 36 mm/year). $\sim 20 \pm 3$ mm/year of the relative plate motion of ~ 36 mm/year between the India and Sunda plates is accommodated at the Sagaing fault through dextral strike-slip motion. This motion occurs predominantly through velocity strengthening frictional behaviour, i.e., aseismic slip.
- Estimation of the rate of strain accumulation in different segments along the Himalayan arc and the role of the Karakoram fault in the India-Eurasia convergence. The Oblique motion between southern Tibet and Indian plate is estimated to be 17 ± 2 mm/yr, which is partitioned between dextral motion of 5 ± 2 mm/yr on the Karakoram fault system and oblique motion of 13.6 ± 1 mm/yr with an azimuth of N198°E in the northwest-southeast trending Kashmir Himalayan frontal arc. In the neighbouring Nepal Himalaya, the entire India-Southern Tibet motion of 19–20 mm/yr is arc normal and is accommodated entirely in the Himalayan frontal arc. The Karakoram fault system accommodates about 20% of the southern Tibet and Indian plate convergence and marks the northern extent of the NW Himalayan arc sliver. The Kaurik Chango rift, a north-south oriented seismically active cross-wedge transtensional fault appears to divide the sliver in to two parts causing varying translatory motion on the Karakoram fault on either side of the Kaurik Chango rift.
- Estimated coordinates and velocity (4.6 mm/yr predominantly towards north) of the Indian base station, Maitri, Antarctica. Also, using the available GPS data of other global stations estimated the Euler pole of the Antarctic plate, consistent with the previous studies.
- The ionosphere response to the great intraplate Indian Ocean earthquake of April 11, 2012 (Mw 8.6) and its largest aftershock (Mw 8.2), and the April 25, 2015 Gorkha, Nepal earthquake was analyzed using GPS Total Electron Content measurements.

Basic Research: Studies on the Lithosphere, Earth's Interior and Past Climates

During the past five years, the institute has taken up major programs on basic research with emphasis on the crustal structure and geodynamic evolution of the Indian shield and tectonically active plate boundary regions of the Himalaya and Andaman-Sumatra subduction zone which led to generation of new datasets and results especially from previously less studied regions. This period has also witnessed significant advancements with regard to development of two state of the art analytical methodologies enhancing our research capability pertinent to many contemporary applications in Geochronology and Radiogenic Isotope Geochemistry. All the relevant study areas are shown in Fig. 5. The exciting results from all these studies are summarized below:

- A seismological network in the Singhbhum-Chotanagpur region of the Eastern Indian Shield enabled estimation of lithospheric thicknesses which indicates a Moho depth variation from 37 to 47 km in the Singhbhum-Odisha craton (SOC) and from 41 to 44 km in the Chotanagpur granitic gneissic terrain (CGGT). Archean crust in the SOC is thicker than the Proterozoic crust in the CGGT. The lithosphere-asthenosphere boundary estimates vary from 58 to 100 km in the SOC and 81 to 140 km in the CGGT. Thinning of the lithosphere in the SOC is attributed to the delamination of the lithosphere. Based on SKS/SKKS splitting parameters, the signature of the Pan-African suture has been detected in the CGGT that separates the Archean and Proterozoic provinces.
- A three-dimensional lithospheric density structure of the Singhbhum Protocontinent was estimated by integrated modeling of satellite gravity and geoid anomaly, and topography data. The density model shows that distinct vertical density heterogeneities exist throughout the lithosphere beneath the Singhbhum Protocontinent. The identified crustal structure includes a lateral average crustal density variation from 2800 to 2890 kg/m³ as well as a relatively flat Moho at 35–40 km depth in Singhbhum Protocontinent and Bastar Craton. The Lithosphere-Asthenosphere Boundary (LAB) across the Singhbhum Protocontinent is

at a depth of about 130-140 km. In the regions of Bastar Craton and Bengal Basin, the LAB dips to about 155 ± 5 km depth. The confluence of Mahanadi and Damodar Gondwana basins towards the north-west and the foreland Ganga Basin towards the north are characterized by a deeper LAB lying at a depth of over 170 and 200 km, respectively.

- Segmentation of a subduction zone through tearing is envisaged as an inevitable consequence of the differential rate of slab rollback along the strike of convergent plate boundaries. It is a key feature that controls plate tectonics and seismogenesis in a subduction setting. Globally, lithospheric tears are mostly recognized by seismic tomography and seismicity trends. In one study, seismological evidence for tearing of the Indian oceanic plate at shallow depths along the Andaman arc was presented. The image of the subducted plate using the shear-wave receiver function technique reveals three distinct plate segments. The middle lithospheric chunk has an abrupt offset of ~20 km relative to the northern and southern segments along the entire stretch of Andaman-Nicobar Islands. This abrupt offset at the base of the lithosphere has been interpreted as caused by the tearing of the subducted Indian oceanic plate.
- A magnetotelluric study along a 200-km-long profile across the Sikkim Himalaya reveals 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). The results also suggest 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 in the Sikkim Himalaya could be related to this fault whereas shallow seismicity can be linked to the deformation within the wedge.
- A network of 30 broadband seismological stations is being operated in Arunachal Pradesh.

The results based on both P- and S-receiver functions reveal the Moho variation from 50 km in the Himalaya to 75 km beneath the Tibet with a consistent low velocity zone above the Moho. The presence of mantle anisotropy has also been delineated through shear-wave splitting observations in SK(K)S phases along two distinct directions in eastern Arunachal Himalaya.

- Deformation patterns in the NE Himalaya have been inferred from geological studies within Main Boundary Thrust (MBT)-Himalayan Frontal Thrust (HFT) wedge in the Dikrang river section, marked by active geomorphic landforms like uplifting terraces, back-lifted Itanagar surface. The active deformation in mountain front is marked by northward migration of younging terraces with the growth of duplex and partitioning of Tipi thrust
- The Moho depth variation was mapped along a 600 km long profile from the west to the east coast of South India covering the passive continental margin, and the Western Ghat escarpment created during India-Madagascar separation at ~85 Ma; Archean Western and Eastern Dharwar cratons and Proterozoic basin. The image was generated through three different approaches: H- V_p/V_s stacking, common conversion point migration and inversion of teleseismic receiver functions at 38 locations. The Moho depth along the profile varies smoothly between 34 and 41 km, except beneath the Western Ghat and at the contact of east and Western Dharwar Craton (WDC), where it is offset by up to ~8 km. The study suggests (i) possible differential uplift of the Western Ghat, as a consequence of India-Madagascar separation and prominent role of deep crustal structure in the location of the escarpment, compared to the surface process, and (ii) presence of long-lived steeply dipping fault separating the two distinct Archean crustal blocks indicative of mechanically strong continental lithosphere beneath the Dharwar craton.
- Significant lateral variations in shear wave velocity and Moho depth have been obtained for the Archean crust beneath the Dharwar

craton, using earthquake waveform data recorded over 50 broadband seismographs. The inversion and modeling of receiver function data reveal a Moho depth of 38–54 km in the WDC, 40–46 km in the SGT, and 32–38 km in the EDC. The average shear wave velocity (V_s) of crust beneath the WDC is ~ 3.85 km/s as compared to ~ 3.6 km/s in the EDC. A highly variable thickness (16–30 km) of mafic cumulate ($V_s \geq 4.0$ km/s and $V_p \geq 7.0$ km/s) beneath the WDC, in contrast with a thin one (< 5 km) beneath the late Archean EDC has been inferred.

- An integrated modeling of the topography, gravity and geoid anomalies, and geothermal data from the southern India was carried out along three long profiles with constraints available by seismic data under the assumption of local isostatic equilibrium. The results reveal a crustal configuration with the Moho depth varying from ~ 40 km beneath the Dharwar craton, and ~ 39 km beneath the Southern Granulite Terrain (SGT) to about 15–20 km beneath the adjoining oceans. The lithospheric thickness varies significantly from ~ 70 –100 km under the adjoining oceans to ~ 130 –135 km under the southern block of SGT including Sri Lanka and increasing gradually to ~ 165 –180 km beneath the northern block of Southern Granulite Terrain and the Dharwar craton.
- The deep density structure of the crust and upper mantle suggests crustal underthrusting of the Indian and the Asian plates in the Hindu Kush–Pamir section unlike that in the Ladakh–Karakoram region, where underthrust Indian lithosphere underplates beneath the Asian plate. The density model supports a hypothesis of slab breakoff of Indian and Eurasian plates in the Ladakh–Karakoram segment, and of the Indian plate in the Hindu Kush–Pamir region, whereas the Eurasian plate drastically underthrusts deeper (c. 200 km), causing deep seismicity in the Hindu Kush–Pamir section.
- The lithospheric resistivity structure of the southern section of the WDC, which hosts the oldest supracrustal rocks (Holenarsipur Belt), and the adjoining Mesoarchean Coorg Block was studied using broadband and long-period magnetotelluric data. The rigorous 2D analysis and subsequent inversion modeling of the data

yielded crustal conductive zones within the Coorg Block, which might be related to the relatively young (933 Ma) metamorphic processes identified in the area and/or the possible fluid infiltration during the Cretaceous passage of Reunion plume in the proximity of the Coorg area. The e-LAB estimate shows quite thick (~ 190 km) cratonic lithosphere at the eastern segment of the WDC indicating a preserved cratonic keel at some locations in the Dharwar craton. The ~ 125 km thick resistive lithosphere seen beneath the Coorg area proclaims a cratonic nature of this block.

- The crustal and the upper mantle lithospheric electrical structure of the SGT were evaluated using data space Occam 3-D inversion of the MT data. The results for the SGT reveal basically a highly resistive (several thousands of Ohm meters) upper crustal layer overlying a moderately resistive (a few hundred Ohm meters) lower crustal layer which in turn is underlain by the upper mantle lithosphere whose resistivity shows significant changes along the traverse. It is inferred that the Archean Dharwar craton/ Neoproterozoic SGT terrain boundary lies south of the Palghat–Cauvery shear zone. The lithospheric upper mantle electrical structure of the SGT up to the depth of 100 km may be broadly divided into two distinctly different segments, viz., northern and southern segments. The northern lithospheric segment, over a major part, is characterized by a thick resistive upper mantle, while the southern one is characterized by a dominantly conductive medium suggesting a relatively thinned lithosphere in the southern segment. The results also showed that the Achankovil shear zone is characterized by a well-defined north dipping conductive feature.
- 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. Only two out of 16 sites retained a pristine magnetization that yielded suitable directions and paleointensity estimates. The results indicate a

mean field intensity of $9.2 \pm 7 \mu\text{T}$ yielding a VDM value of $1.3 \pm 1 \times 10^{22} \text{ Am}^2$. 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).

- The Koyna-Warna region of India is one of the best worldwide examples of reservoir-induced seismicity, with the distinction of having generated the largest known induced earthquake (M 6.3 on 10 December 1967) and persistent moderate-magnitude ($>M$ 5) events for nearly 50 years. On the basis of the alignment of earthquake epicenters over an ~ 50 -year period, lateral variations in focal mechanisms, upper-crustal tomographic velocity images, geophysical data (aeromagnetic, gravity, and magnetotelluric), geomorphic data, and correlation with similar structures elsewhere, it was suggested that the Koyna-Warna area lies within a right step between northwest trending, right-lateral faults. The right-lateral faults extend well beyond the immediate Koyna-Warna area, possibly suggesting a more extensive zone of seismic hazards for this region.
- Zircon U-Pb geochronology, Hf-isotope and trace element compositions of over 20 rock units in different Precambrian formations were studied to decipher the age of magmatic crystallization, metamorphism and sedimentation. Important rock units studied include charnockite orthogneisses from Southern Granulite Terrain, granitoids and greenstone belt metasediments from the Dharwar and Bastar cratons, clastic sediments from the Cuddapah, Kaladgi, Bhima, Vindhyan, Delhi-Aravalli supracrustal basins, kimberlites and lamproites from the southern and central India. These data contribute a wealth of new information on the Precambrian evolution of the Indian Shield. Important results include evidence for upto ca. 3.5 Ga orthogneisses in the Western Dharwar craton; observation of up to 3.7 Ga old detrital zircons in greenstone metasediments of the Western and Eastern Dharwar cratons; clear evidence for four episodes of granite magmatism in the southernmost part of the southern granulite terrain including juvenile magmatism during the Orosirian (~ 2.05 to 1.8 Ga) and Tonian (1.0 -

Fig. 5: The study areas of the work related to Basic Research: Studies on the Lithosphere, Earth's Interior and Past Climates. AC–Aravalli Craton; ACSR–Achankovil Shear Zone; BB–Bhima Basin; BC–Bastar Craton; BUC–Bundhelkhand Craton; CB–Chhattisgarh Basin; CB–Cuddapah Basin; CIS–Central Indian Shear Zone; CITZ–Central Indian Tectonic Zone; CPG–Closepet Granite; EDC–Eastern Dharwar Craton; EGMB–Eastern Ghat Mobile Belt; IB–Indravati Basin; KB–Kaladgi Basin; KWRR–Koyna & Warna Reservoir Regions; PCSZ–Palghat Cauvery Shear Zone; SC–Singhbhum Craton; SGT–Southern Granulite Terrain; SMB–Singhbhum Mobile Belt; VB–Vindhyan Basin; WDC–Western Dharwar craton (Modified after Sahu *et al.*, 2013, JGSI, Spl Vol. 137-165)

0.72 Ga) Periods and a common granulite facies metamorphism at ~ 510 Ma. Discovery of new kimberlites in southern and central India and the discovery of native gold in the Mesoarchean chromitites, Tagadur, Karnataka.

- New results were obtained using bulk Sr, Nd, Pb, Hf and Fe isotopic systematics characterizing a wide range of rock types such as Mid-Ocean Ridge basalts from the Carlsberg and Central Indian ridge systems, clastic sediments from the deep Indian Ocean, marine Mn-Fe nodules and encrustations and paleosols of different ages on land. These data were used to infer element sources, marine bio-geochemical processes, continental weathering and provenance relevant to several outstanding problems of marine

geology and paleo climates in deep time.

- The *in-situ* trace element analysis of dated zircons at a spatial resolution of $<50\ \mu\text{m}$ has provided constraints on nature of the parent rock, especially in the case of *ex-situ* zircons. The major and trace element distribution in a Martian Meteorite (shergottite) helped in modeling the aspects of melting and differentiation of the Martian depleted mantle. A systematic study of over 30 trace element compositions including PGE in Glass cosmic spherules helped in constraining the nature of element fractionation and fragmentation during the atmospheric entry of micrometeoroids reaching temperatures around $\sim 1700^\circ\text{C}$.
- A concerted U-Pb baddeleyite age, paleomagnetic and geochemical study of several dyke swarms in different parts of the Dharwar, Bundelkhand and Singhbhum cratons has led to identifying a giant radial dyke swarm exposed widely in central and southern India. Dated at $\sim 2367\ \text{Ma}$ this dyke swarm could be extremely useful for Paleoproterozoic continental reconstruction.
- Rb-S rhyolite and U-Pb zircon ages, Sr-Nd-Pb isotopic compositions and paleomagnetic data on the alkaline complexes including the Sung Valley, Jasra and Samchampi from Assam and Meghalaya, suggest that alkaline activity in the region is younger than the Rajmahal-Sylhet-Bengal (RSB) flood basalts, at least by about 10 Ma, and could also be genetically unrelated to it and the Kerguelen plume. This is in contrast to earlier reports which include these alkaline complexes as part of the RSB large igneous province.
- Evidence for the Hadean and Eo-archean crust is reported from the fringe of Coorg Block, one of the oldest crustal blocks of Peninsular India. Zircon U-Pb ages and Lu-Hf isotopes from a suite of meta-igneous rocks from the Coorg Block record multiple pulses of magmatism at ca. 3.5, 3.2, 2.7 and 2.5-2.4 Ga. Those metasedimentary rocks accreted along the margins of the Coorg Block show multiple zircon population with mean $^{207}\text{Pb}/^{206}\text{Pb}$ ages at 3.4, 3.2, 3.1, 2.9, 2.7, 2.6, 2.5, 2.2, 2.0, and 1.3 Ga. Both, +ve and -ve Hf_i values, coupled with

older crustal model ages (T_{DM}^{C}) for the zircons of igneous rocks from Coorg Block suggest that the magma derived from Meso- to Eo-archean, comprises juvenile and reworked components. The oldest T_{DM}^{C} value (4031 Ma) is recorded by zircon grain in a ferruginous quartzite. The T_{DM}^{C} values of the zircon population in the metasedimentary suite range from 3126 to 3786 Ma, derived from dominantly felsic crust. The data suggest vestiges of Neo-hadean primordial continental crust with episodic crustal growth during the Eo-archean, Meso-archean and Neo-archean building the continental nuclei in Peninsular India, and contribute to the understanding of crustal evolution in the early history of the Earth.

- Multiple spectral and statistical analyses of a 700 year long temporal record of groundwater recharge from the dry lands, Badain Jaran Desert (Inner Mongolia) of Northwest China reveal a stationary harmonic cycle at $\sim 200 \pm 20$ year. Interestingly, the underlying periodicity in groundwater recharge fluctuations is similar to those of solar-induced climate cycle “Suess wiggles” and appears to be coherent with phases of the climate fluctuations and solar cycles. Matching periodicity of groundwater recharge rates and solar and climate cycles renders a strong impression that solar-induced climate signals may act as a critical amplifier for driving the underlying hydrographic cycle through the common coupling of long-term Sun-climate groundwater linkages.
- A high resolution record of the Indian summer monsoon (ISM) is generated using a $\delta^{18}\text{O}$ time series from a stalagmite collected from the Valmiki cave in southern India. This record covers a time span of ~ 1000 years from 15,700 to 14,700 yr BP (before 1950 AD) with an average sampling resolution of ~ 5 years. High amplitude $\delta^{18}\text{O}$ variation in this record reflects abrupt changes in ISM activity during the last deglaciation and suggests an age for the onset of termination at $\sim 14,800$ yr BP in the Indian sub-continent.
- An attempt was made to understand the surface and deep water characteristics of northeast Indian Ocean (NEIO) region by using carbon

and oxygen isotopes from planktonic and benthic foraminifera from an undisturbed AMS-dated core to infer glacial to Holocene changes in surface and deep waters. Variations in $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values of planktonic and benthic foraminifera are suggestive of large changes in the surface and deep water characteristics during the last ~60 ka. Changes in the local hydrological cycle appear to have controlled $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values of foraminiferal shells. Strong Indian summer monsoon precipitation at 7-6 ka BP and a sudden decrease at ~5 ka BP may have influenced the planktonic foraminifera $\delta^{18}\text{O}$ values.

- The paleoclimatic signatures in the form of dune sediments in a limited area in the eastern margin of the Cuddapah basin were explored. These inland sand dunes are mainly of aeolian origin with several first- and second-order streams facilitating erosion and accumulation of the sands from the source rocks. Morphological and sedimentary characters indicate two generations of dunes (i) the older dunes comprising dark brown highly oxidized, fine sand with gullying and dissection and (ii) the younger dunes consisting of pale-yellow fine sand. The percentages of silica and heavy minerals indicate that the source rock for the dune sands is mainly Cuddapah quartzite, with contribution from the Nellore Schist Belt. OSL dating of 47 samples yielded ages from the present to 90 ka, suggesting a long aggradational history. The ages cluster into seven groups, 90 ka, 45–48 ka, 30–33 ka, 21 ka, 11 ka, 4.6 ka, 1.7 ka and recent (16–200 yr), reflecting short-lived arid phases in an otherwise semi-humid landscape. Future modeling exercise may possibly integrate this information to understand the atmospheric dynamics over the past 50 ka.

Other Significant Contributions

The institute has also been actively involved in the Planetary Geosciences activities with focus on the Moon, Mars and Venus. Some significant studies and results are mentioned below.

- Shallow moonquakes are thought to be of tectonic origin. However, the geologic structures responsible for these moonquakes are unknown. The analysis of Lunar Reconnaissance Orbiter

and Chandrayaan-1 images carried out by the institute revealed four lobate scarps in different parts of the Schrödinger basin. The scarps crosscut small fresh impact craters (<10-30 m) suggesting a young age for the scarps. A 28 km long scarp (Scarp 1) yields a minimum age of 11Ma based on buffered crater counting, while others are 35–82Ma old. The topography of Scarp 1 suggests a range of horizontal shortening (10–30 m) across the fault. Two scarps are associated with boulder falls in which several boulders rolled and bounced on nearby slopes. A cluster of a large number of boulder falls near Scarp 1 indicates that the scarp was seismically active recently. A low runout efficiency of the boulders (~2.5) indicates low to moderate levels of ground shaking, which has been interpreted as related to low-magnitude moonquakes in the scarp.

- The lunar surface is characterized by asymmetric distribution of its volcanic deposits. The nearside contains about 90% of the mare basalts, while there are a few on the farside with some are in the South Pole Aitken (SPA) basin, which is the largest and oldest impact basin on the Moon. The geological mapping using Lunar Reconnaissance Orbiter (LRO) and Chandrayaan-1 Moon Mineralogy Mapper (M3) data of 143 km Antoniadi impact basin provides new insights into volcanic processes in the southern SPA. Antoniadi has excavated the SPA floor as deep as 9 km. Distribution of secondary craters around Antoniadi shows that the basin was formed by oblique impact with the direction of 50° counter-clockwise from 178°E longitude.
- Boulder fall occurrences of Cerberus Fossae region of Mars were most likely caused by Zuni-impact related surface vibrations, but not by paleo-marsquakes as previously thought.

A new multidisciplinary research facility in the field of bio-geophysics has been initiated at the institute. It combines three pristine research disciplines microbiology, geophysics and geochemistry. Current research activities of bio-geophysics laboratory are focused on detection, monitoring, and development of cost effective techniques for remediation of contaminants in soil, landfill leachate water and wastewaters.

Major R&D Facilities at CSIR-NGRI

Airborne Geophysics

Magnetic, radio metric and electromagnetic (frequency and time domain) facilities for multi-parametric airborne geophysical surveys for mineral exploration.

Deep Earth Probes

High fidelity controlled source seismic instrumentation together with broadband seismic units for campaign mode investigations, magnetotelluric and deep resistivity probes, absolute micro-gravity and field gravity stations and magnetometers.

Shallow Surface Geophysics

3D Seismic Data Acquisition System with Vibrators, Induced Polarization and frequency/time domain EM equipment, Ground Penetrating Radar (GPR), high resolution gravity, magnetic instruments.

Seismological Observatory

Broadband (120s-50Hz) Seismological Observatory, Regional networks covering northeastern India, Peninsular India and Andaman Islands for continuous earthquake monitoring in realtime.

GPS/GNSS, Geodetic Network

Network of GPS stations linked to international arrays for study of the Indian plate motion and applications for tectonic geodesy.

INTERMAGNET Magnetic Observatory

Continuous mode recording of fluctuations of the geomagnetic field and near real time space weather observations.

Geothermal Observatory

Measurement of air temperature, relative humidity, solar radiation, precipitation, wind speed, direction and subsurface temperature variations upto a depth of around 30 m, for climate change applications.

Geochemical Analytical Facilities

Fully automated X-ray fluorescence spectrometer (XRF), Atomic absorption spectrometer, High

Resolution Inductively Coupled Plasma Mass Spectrometer with laser ablation system (LA-HR-ICP MS), Electron probe micro analyzer (EPMA) and Scanning Electron Microscope with Energy Dispersive Spectrometer (SEM-EDS), Sulfur Analyzer, Wet chemical laboratory connected with microwave digestion system, high pressure asher system and fire-assay laboratory.

Geochronology and Radiogenic Isotope Analytical Facilities

Thermal Ionization Mass Spectrometer, Multi Collector-Inductively Coupled Plasma Mass Spectrometers and Laser Ablation M-ICPMS for Rb-Sr, Sm-Nd, K-Ca, Pb-Pb and *in situ* U-Pb zircon geochronology.

Stable Isotope Laboratories

Gas source mass spectrometers, GCMS-MS, element samplers and analyzers supporting T, H, O and C-isotopic studies for applications in isotope hydrology, hydrocarbon exploration, study of paleo-climates and geo-environment.

High-pressure experiments for rock mechanics and engineering geophysics applications

Optically Stimulated Luminescence (OSL) and ^{14}C dating facilities

LAM-MC-ICPMS National Facility

Future Plans

CSIR-NGRI is in the process of formulating future scientific programs as per the research themes mentioned below:

Integrated management of groundwater resources; Protect and restore wetlands, rivers, aquifers and lakes

§ Designing suitable recharge structures for sustainable water management and implementation through local communities in drought affected villages of Anantapur district of Andhra Pradesh

§ Assessment of sea water intrusion in Godavari Delta to understand its impact on social and economic aspects

§ Validated interpretation of the existing

geophysical data both from heliborne and ground surveys. A performance matrix of various geophysical techniques as applied in the different geological terrains. 3-D Resistivity model of the representative aquifers.

§ Protect and restore wetlands such as preliminary assessment of environmental degradation of Koringa Mangrove ecosystem and Kolleru Lake

To improve the assessment of earthquake hazard for sustainability of the built environment

- Estimates of response of plate boundary and plate interior lithosphere to the changes in stress; elucidate the mechanical and rheological properties of faults and surrounding rocks
- Space-time clustering of earthquakes for evaluating baseline measurements in the Himalaya and Peninsular shield and paleo-seismological studies
- Attenuation relationships, ground motion prediction equations for the Himalaya and Indo-Gangetic Plains
- Solutions to geotechnical problems through near-surface geophysical studies as per the need of stakeholders

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To scientifically harness the clean energy and mineral resources for robust growth of the nation

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- Quantification of gas hydrates by rock physics modeling and estimation of pore-pressure for KG offshore
- Fine-scale 3-D structure for coal in Jharsuguda, Odisha
- Locations of possible uranium deposits in Chhattisgarh by heliborne surveys
- Finer scale mantle heterogeneities of the lithospheric mantle in terms of formation and destruction of crust leading to magmatism and metallogeny
- Need based geophysical support for mineral exploration to public sector and private companies

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