Preface

CSIR-National Geophysical Research Institute (CSIR-NGRI) was established in the year 1961 to pursue research in geophysics and related geoscience subjects. During the last sixty years, CSIR-NGRI has built an enviable standing both in India and abroad for its research excellence in the geophysical and allied sciences. This is a unique Institute with the state-of-the-art facilities for all the major disciplines of the solid Earth System Sciences under one roof with diversified expertise nurtured over decades. The researchers of the Institute have published more than 100 books, Encyclopedia of Solid Earth Geophysics (1st edition in 2011 and the second edition in 2021), and ~ 5000 papers in the SCI journals. CSIR-NGRI has also contributed to a wide range of India-centric mission mode projects. This Special Issue of the Journal of Geological Society of India presents numerous accomplishments of CSIR-NGRI to commemorate the Diamond Jubilee of its foundation. As part of the Diamond Jubilee celebrations, the Institute has also virtually hosted Joint Scientific Assembly of IAGA-IASPEI (the two associations of IUGG) during 21-27 August 2021 (<http://iaga-iaspei-india2021.in/>), which was attended by more than 850 scientists from 57 countries during this difficult time of corona pandemic.

The first article in this issue, commemorating the Diamond Jubilee of the CSIR-NGRI, authored by Singh, Kumar, Rao and Tiwari deals with the gravity studies undertaken from the very inception of CSIR-NGRI in 1961. It is not out of the place to mention that among all disciplines of geophysics, where stellar contributions have been made in India, discovery and establishment of the concept of isostasy is a major one, and resulted from the measurement made by George Everest, Surveyor General of India, in the vicinity of Himalaya, way back in 1830's. Singh and colleagues have dealt with the Gravity Map series of India: the first maps that compiled the data collected by different agencies and provided a unified picture of gravity anomalies over entire India: a major geophysical contribution from CSIR-NGRI for the benefit of all users. Contemporary computational approaches have been used to provide better-resolved density models under different parts of the Indian plate. A very useful application has been the study of temporal gravity changes inferred from terrestrial and satellite observations of the re-distribution of mass in earthquake prone regions and water storage variability across India. Gravity field studies have been an integral part of CSIR-NGRI's integrated geo-exploration approach to address industry and society related problems.

The results from geomagnetic observations at Hyderabad since 1963 and palaeomagnetic investigations in the diverse geological terrains in peninsular India are summarized by Venkateshwarlu and Arora. It is apparent that the data recorded by CSIR-NGRI observatories have provided the record of magnetic field variability and contributed meaningfully in developing models of the equatorial electrojet (EEJ) and the counter electrojet (CEJ). The authors have also highlighted the comprehensive rock magnetic studies on dykes, traps and sedimentary rocks as well as determination of the palaeopoles from the rocks for inferring the dynamics of the Indian plate.

Harsh Gupta traces the story unfolding after the occurrence of the M 6.3 earthquake in Koyna, near west coast of India and the studies carried out since then. These led to the realization that Koyna is probably the most suitable site globally to study earthquakes in the near field: a most sought-after experiment which would provide the missing inputs to the process of a fault preparing to host an earthquake. This is due to the fact that in the Koyna region earthquakes occur in a small area of 20 km x 30 km, they are shallow (mostly 2 to 9 km depth), there is no other source of earthquakes within 100 km of Koyna Dam, the site is accessible for all kind of experiments and observations and the shallow crust is cool making deployment of measuring devices easy. The proposal was thoroughly examined by the International Continental Drilling Program (ICDP) sponsored international workshop held at CSIR-NGRI and Koyna in 2011. By and large it was agreed that Koyna is a very suitable site for near field investigations. However, several suggestions were made for additional work to be carried out. This was done in the following three years including airborne magnetic and gravity-gradient surveys, detailed LiDAR observations, MT surveys and drilling of deep bore holes penetrating the entire basalt column and going up to 300 m in the underlying granitic basement. Among the major discoveries was the fact that the basement is quite flat at a depth of ~ 300 m below the present sea level, there are no sediments below the basalt-cover and it lies on the granitic basement and several zones of intense fracturing were identified. A network of 6 seismic stations with the 3-component sensors located at depths of ~ 300 m below the basalt layer was also commissioned. This improved earthquake location capability by an order of magnitude. All these results were presented in the second ICDP international workshop held during 2014. A go-ahead was given to put a 3 km deep Pilot Borehole. Based on the proximity to the Donachiwada Fault, that hosted the 1967 M 6.3 earthquake and several M ~ 5 earthquakes and logistics, a site was chosen for the Pilot Borehole. Drilling was initiated in December 2016 and completed in June 2017. Results of experiments conducted during and after drilling were presented in the ICDP Post-operation workshop in 2017. Work is now in progress for designing the proposed ~ 7 km borehole laboratory. Ministry of Earth Sciences (MoES) supported this program.

Pandey and Kumar have presented the innovative work carried out in the area of paleoseismology and neotectonics. They discussed the evolution of the ¹⁴C facility from its foundation in the seventies and development of new dating tools, which have allowed the researchers to construct chronology of past major earthquakes in the Shillong Plateau and in other earthquake prone regions. The paper also describes that the research focus in recent times is on landscape modelling to understand Earth surface processes, including mass wasting, in tectonically active terrains of the Himalaya and the Western Ghats and the Late Quaternary deformation partitioning in the Himalayan front.

Srinagesh and Pavan Kumar have provided a summary of the

observational seismology initiated at CSIR-NGRI with the establishment of the seismological observatory similar to the World-Wide Standard Seismograph Network (WWSSN) a program of United States Geological Survey (USGS). It was started on 11 December 1967 to record the aftershocks of the Koyna earthquake of M 6.3. They provide a review of all the field investigations and laboratory studies of significant earthquakes that occurred in India since 1967. These include 3 earthquakes in western Himalaya, 6 earthquakes in central Himalaya, 2 earthquakes in eastern Himalaya and 10 earthquakes in peninsular India. In 1989 CSIR-NGRI seismological observatory was equipped with a very broadband-seismographs of GEOSCOPE international network. Currently, CSIR-NGRI is operating over 200 seismic stations all over the country. The earthquake catalogues obtained for various source regions and the associated fault plane solutions form a major input in the Probabilistic Seismic Hazard as it would help in understanding the Probable Earthquake Hazard of the study region and also siting of vital and critical installations based on the background seismic activity.

Prantik Mandal has investigated the structure of the seismically active Kachchh region which hosted the disastrous 26 Jan 2001 earthquake that claimed ~ 20,000 human lives. Using S-to-P conversion and joint inversion of P-receiver functions and surface wave dispersion data, a seismogenic crustal volume of 50 km x 50 km x 45 km has been inferred. A marked crustal and asthenosphere thinning below the Kachchh rift zone is discovered. Three high velocity anomalies have been mapped below the Wagad uplift, Kachchh rift and Banni regions which are interpreted as mafic plutons. $M \geq 5$ earthquakes are located in the vicinity of the contact of high and low velocity zones. An 8 to 18% increase in V_p/V_s velocities ratio is inferred indicating presence of fluids. The author suggests mapping of the wave velocities to infer locales which are likely sites of the future earthquakes.

Kumar, Mandal and Kumar have deliberated on the seismic structure of the crust and lithospheric mantle of the Indian shield using controlled source seismic (reflection/refraction) and passive seismology. The review and synthesis of seismic/seismological results by the authors outline the crustal velocity variations, basement, Moho depth configurations and thickness of the lithosphere under different geological provinces. They have also discussed about the interpretations of these variations for the geodynamic models of cratonic assemblage, hazard scenario and resource prospects.

Manglik, Gupta and Tiwari have reviewed the crust and upper mantle structure related studies undertaken at CSIR-NGRI for the Himalayan collision belt. One of the earliest results was the discovery of an extremely thick crust of 65 to 70 km below the Himalayan and Tibet Plateau region inferred from surface wave studies way back in 1967. This was found to be true from the later detailed controlled source seismic observations. Upper mantle P-wave velocity structure down to 230 km was inferred for the Hindu Kush region by analysis of travel times of deep earthquakes. A few years later, the first ever trans-Himalayan deep seismic sounding (DSS) study by CSIR-NGRI provided further definitive evidence for crustal thickening and spatial variation of the Moho within the Kashmir Himalaya. In the years to follow dense seismic networks were deployed, both in network and profile mode, in northeast India covering the Shillong Plateau, the eastern Himalaya, the Indo-Burmese Arc and the Assam valley, and in

the northwest Himalaya covering mainly the Kumaun and Garhwal sectors. These studies yielded information about the Moho disposition, crust and upper mantle velocity structure, nature of the décollement surface, upper mantle discontinuities and the mantle transition zone, and seismic anisotropy. A good number of gravity and magneto-telluric studies have also been carried out by CSIR-NGRI to decipher the density structure, mechanical strength of the lithosphere and electrically conductive zones, respectively, and their possible correlation with seismicity.

Roy, Kumar and Srinagesh have made use of shear wave splitting measurements to comprehend mantle deformation beneath India. They used ~ 2500 published shear wave splitting measurements from over 350 broad-band seismic stations. The fast polarization azimuths are predominantly oriented parallel to absolute plate motion. The observed deviation is inferred in terms of differences in lithospheric evolution processes. The inferred deviation is stronger in southern India compared to central and north India.

Rajewar, Mohana Lakshmi, Mohanty, N. Pandey, A. Pandey, Chaurasia and several others with Vineet Gahalaut have over-viewed Global Navigational Satellite System (GNSS) related studies undertaken at CSIR-NGRI. The studies initiated with the establishment of the first Global Positioning System (GPS) permanent GNSS stations at CSIR-NGRI in 1995. There was a major expansion in the studies in 2003 with the installations of stations in the NE India, Himalayan Arc, Andaman Subduction Zone, and the stable and failed rift regions of the Indian plate. The observations are interpreted in terms of tectonics and temporal plate motion. GNSS observations have a capability to comprehend ionospheric variations in terms of earthquake processes.

Labani Ray has summarized geothermal measurements and determination of heat flow to estimate the crustal thermal structure in different geological provinces of India and also helped in the exploration of geothermal energy potential of the disparate regions. She has reported relatively low heat flow in the Archaean Dharwar and Bundelkhand cratons and fairly high heat flow values in the Proterozoic Aravalli Craton, Proterozoic segments of the Singhbhum Craton, and the Archaean-Proterozoic Bastar Craton. The heat flow studies carried out across India have revealed variability in the heat flow and provided a refined crustal thermal model which are interpreted for geodynamic evolution, seismogenesis and so on.

Vijay Kumar, Bhaskar Rao, Babu and Sreenivas have thrown light on the development of Analytical Laboratory Facilities for Geochronology and Isotope Geochemistry at CSIR-NGRI and highlighted the contributions of these laboratories towards Precambrian geodynamics and lithospheric evolution studies. They argued how Zircon U-Pb age-Hf Isotope Systematics on the Archaean Singhbhum and Dharwar cratons and the Archean-Proterozoic Southern Granulite Terrains have facilitated to infer (a) juvenile crust formation in these geological provinces and (b) possible onset of plate tectonic processes in the Singhbhum and Western Dharwar cratons during early Paleoproterozoic.

Ram Mohan, Srinivasa Sarma, Khanna, Satyanarayanan and Keshav Krishna have described the establishment of geochemical

facilities at CSIR-NGRI and nation-wide usage of these facilities by the students and researchers for the studies related to comprehend evolution history of the Indian Shield and metallogeny. The analytical facilities have helped the researchers at CSIR-NGRI to probe the evidence for early life; decipher the depositional environment and provenance of clastic sediments of the Dharwar Craton and several other footprints of geodynamic processes during Precambrian.

Patro and Sarma have outlined the beginning of magnetotelluric (MT) method for crustal electrical imaging and the leadership role played by CSIR-NGRI in MT/LMT studies in India. Starting with the successful mapping of subtrappean sedimentary basin in the northwestern Saurashtra, the MT measurements were carried out in most of the geological terrains of India that led to the delineation of the crustal/lithospheric electrical signature for their geodynamic interpretations and in the geothermal areas for natural energy resources.

Behera, Kolluru and Singh have addressed the all-important problem of looking for Mesozoic sediments below the Deccan Volcanic Province (DVP) using a combination of seismic and gravity field observations. Globally, almost 50% of oil fields are hosted by the Mesozoic sediments. However, in India the huge Deccan Volcanic Province covers these possible locales of Mesozoic sediment occurrence. A few selected deep seismic profile data in the DVP were subjected to ray-trace inversion of travel time data to robust tomographic inversion and advanced seismic imaging techniques to obtain seismic sections and velocity models. These help in delineating thick Mesozoic sediments south of Kachchh, north-western part of Saurashtra, and the western segment of Deccan Syncline hidden below the high velocity basalt trap layer. Over the past three decades this approach has been successfully applied to address the difficult problem of revealing hidden Mesozoic sediments. This has been of immense help to petroleum industry sector, particularly the Oil and Natural Gas Commission (ONGC) and Oil Industry Development Board (OIDB).

Satyavani, Uma, Kishore, and several others with Vedanti have written about the geophysical exploration of the unconventional hydrocarbon resources. It is globally recognized that the conventional hydrocarbon resources are fast-depleting and it is extremely important to look for unconventional resources like Gas hydrates, Coal Bed Methane, and Shale gas. Innovative techniques need to be developed to map these resources and find ways and means to make environmental friendly use of them. The work carried out since early 1990's showed a huge presence of gas hydrates within the exclusive economic zone of India. It was also estimated that a mere 10% production of this huge resource could meet India's hydrocarbon resource demand for the next 100 years. However, the technology for the appropriate extraction and use of this resource needs to be developed. Seismic exploration studies were carried out in various lignite and coal fields in Rajasthan, West Bengal, Jharkhand, Andhra Pradesh and Odisha. Several prospective basins have been explored by CSIR-NGRI in the last two decades using seismic reflection data. An overview of this effort is presented in this article.

Satyanarayana and Vasudevan have briefly described the design and development of geophysical instruments at times when there were

very few commercial equipment available for field investigations. These activities include field-scale development of Resistivity meter, Seismic refraction timer, Proton Precession Magnetometer (PPM), Time domain Electro Magnetic System (GS-100), Flux Gate Magnetometer, Magnetic susceptibility meter, Metal detector, Pulsed Transient Airborne EM System, Rubidium Vapour Magnetometer, Magneto telluric sounding System, EM Enslin unit, Salinity meter, Automatic water level and quality meter, Borehole logger, etc. The know-how of some of these instruments was transferred to private industries for upscaling.

Tiwari, Mondal and Chandra have provided an overview of the studies for the assessment of groundwater resources in India undertaken over the past six decades by the CSIR-NGRI. It is pointed out that groundwater related research has been undertaken from the very inception of CSIR-NGRI, six decades ago. In the process new techniques and instruments have been developed by the scientists to address the locale specific problems. It is realized that the groundwater, which is a major resource of fresh water, has been extensively used for irrigation, industrial and domestic requirements. Over one-half irrigation requirements are met with ground water. The ever-increasing requirement of groundwater calls for detailed aquifer mapping and development of optimum production approaches taking into consideration varied hydrological and climatic conditions. Electrical and Electromagnetics are two very effective geophysical approaches used in deciphering aquifer characteristics. The authors point out that very significant developments have been made by CSIR-NGRI in improving applicability of these two approaches for groundwater exploration and assessment. Additionally, a number of instruments were designed and developed at CSIR-NGRI to meet ever increasing demand. Technical know-how has been successfully transferred to entrepreneurs for rapid utilization and reproduction.

Nandan, Surinaidu and Dinesh Kumar have shown a good example of managed aquifer recharge (MAR) in the granitic terrain through community participation. They have presented that the MAR structures such as percolation tanks, constructed at suitable locations based on geophysical and geohydrological information play a vital role in improving the groundwater availability and thereby the socio-economic conditions in semi-arid granitic terrain.

Dimri and Bansal have discussed about the scaling approach for the estimation of source depths from gravity and magnetic data. It was noticed that the scaling distribution of sources are found in many applications for estimating the depth to the top of anomalous sources from gravity and magnetic data. The discussed non-linear approach was extensively used in different geological environments. It is inferred that a single value of the scaling exponents may not work for all the depth and over a large region as scaling exponents are not constant but vary with the lithology and crustal heterogeneities of the region.

Shrivastava, Begum and Jakkula have summarized tsunami related work undertaken at CSIR-NGRI after the occurrence of the mega Mw 9.2 Sumatra earthquake of 26 December 2004 and the resultant tsunami that claimed over 250,000 human lives in south and south-east Asia. They have developed models to estimate tsunami run-ups along the Indian coast in response to tsunamigenic earthquakes

occurring in the Sumatra-Andaman seismic zone and Makaran coast seismic zone in the Arabian Sea. They have addressed questions pertaining to propagation of tsunami waves over the ridges, islands and approaching the east and west coast of India and the run-ups distances for a variety of tsunami sources.

The advances in geo-time series modelling presented by Tiwari and Rekapalli discussed about the nonlinear Geophysical methods and other tools, which can be used in geophysical data analyses using Machine Learning and Artificial Intelligence, demonstrating the methods with a few field examples.

Harsh Gupta has provided information about the 2nd Edition of the Encyclopedia of Solid Earth Geophysics published by Springer in 2021. The Editorial Board has 4 members from CSIR-NGRI in addition to the Editor-in-Chief. There are a total of 256 articles

spread over 1950 pages in two volumes. The publication of this 2nd edition commemorates the Diamond Jubilee of CSIR-NGRI.

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