

Institutional Report

CSIR-National Geophysical Research Institute

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Introduction

CSIR-National Geophysical Research Institute (CSIR-NGRI), a constituent research laboratory of the Council of Scientific and Industrial Research, was established in the year 1961. Over the years, it has nurtured, expertized and established highly specialized facilities for all the major disciplines of geosciences under one roof (<https://www.ngri.org.in/facilities.php>). The multidisciplinary research of the institute is intended to comprehend the complex surface and subsurface structures and processes of the Earth system for refining the knowledge base, and its innovative applications for the betterment of the human society through development of strategies for sustainable management of natural resources like water, energy, and minerals and improve preparedness as well as resilience to geological hazards. With the plausible necessity to synergize science, technology,

and innovation to translate identified research leads for the social and industrial benefits and significant modifications in the government planning and funding, the science plans have been re-formulated at CSIR-NGRI. The new scientific projects including the Fast Track Translational projects, have been interwoven with the reorganized structure of the Institute to optimize resources and synergize them for taking geoscience research to a newer height.

Major Research Themes

The research fields of the institute are structured into seven major R & D Groups and twenty-one activities interlaced with various expertise of geophysical and geological disciplines like Seismology, Seismic, Electrical and Electromagnetic, Geomagnetism, Gravity, GPS Geodesy, Geochemistry, Geology, Hydrochemistry, and Earth processes Modeling.

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The research programs of the Institute have been classified into three broad themes (i) **Earthquake Hazards:** studies of likely impacts due to the catastrophes like earthquakes and tsunamis on surface and subsurface of the Earth which may potentially endanger lives and properties, (ii) **Natural Resources Exploration:** application of geophysical techniques to identify primary geo-resources, like groundwater, hydrocarbons as well as alternate energy sources and minerals, which are the engines of the economic growth (iii) **Geodynamics:** carrying out investigations and modelling of the fundamental aspects of the Earth system and processes. Thus, the focus has been on the research projects addressing critical elements of earth science following the above-based themes.

Salient Achievements During the Last Four Years

The CSIR-NGRI has published more than 600 research papers in the peer-reviewed International Journals, ~90 technical reports, 5 patents, 5 books, and several book chapters. Many scientists of the institute have received national academic awards and were elected as fellows by scientific academies for their excellent scientific contributions and thirty-five research scholars received their Ph.D. degrees from AcSIR and other universities. Several Memorandums of Understanding (MoU) have been signed with leading organizations and institutions of the country in new domains of geophysical applications such as mineral exploration and investigations for tunnel planning required for railways in the Western Ghats and Himalaya; and geotechnical surveys for the LIGO project. Most notable among them is the MoU with AMD (DAE) to carry out Heli-borne Geophysical investigations for uranium exploration, contributing towards the strategic necessities of the country and is the highest valued externally funded project CSIR-NGRI has ever had. The research highlights of the last 4 years under the three themes mentioned above have been listed below.

Earthquake Hazards

- GPS data from observatories across Karakoram fault suggests pure strike-slip motion with a low slip rate varying unsystematically from 0-3 mm/yr. The shallow locking depth of 1-3 km may be inferred as the Karakoram being an aseismic fault.
- Analysis of continuous GPS measurements from 28 sites in the Kumaon–Garhwal Himalaya (KGH) indicate a homogeneous and robust coupling for a width of 85 km on the Main Himalayan Thrust (MHT) beneath the Outer and Lesser Himalaya which does not seem to be affected by the subduction of sediments of the Indo-Gangetic plains or the ridges/faults on the Indian plate. The slip deficit rate of 18 mm/yr is consistent with that in the neighboring western Nepal Himalaya. A high rate of strain accumulation for the past 500 or more years with a homogenous and high coupling on this segment of the MHT may be the cause for the very high seismic vulnerability of this section of the Himalayan region.
- GPS measurements and Synthetic Aperture Radar (InSAR) provided unique observations of crustal deformation in the NW Himalaya. All GPS sites along the Himalaya seem to be strongly influenced by seasonal hydrological and atmospheric loading except the KUNR. Located near the Tehri reservoir, this site additionally exhibits anomalous variations due to seasonal water loading and unloading by the reservoir. The InSAR analysis corroborates that with the seasonal filling of the reservoir, causing a measurable subsidence in its neighborhood (Fig. 1). Further, besides the elastic deformation caused by the seasonal reservoir loading and the insignificant poroelastic deformation caused by accompanied fluid pressure changes, an unaccounted biannual deformation in the east component of the GPS time-series may be attributed to the altered hydrological conditions resulting from the reservoir operations. Understanding the crustal deformation processes due to such anthropogenic sources helps in the segregation of the deformation caused by tectonic, hydrological, and atmospheric effects from that caused by these activities.
- A new seismic network of digital broadband/strong-motion stations has been installed after the occurrence of the 25 April 2015 Nepal earthquake of M_w 7.8, to provide fast and accurate estimates of earthquake hypocentral and source parameters of potentially devastating

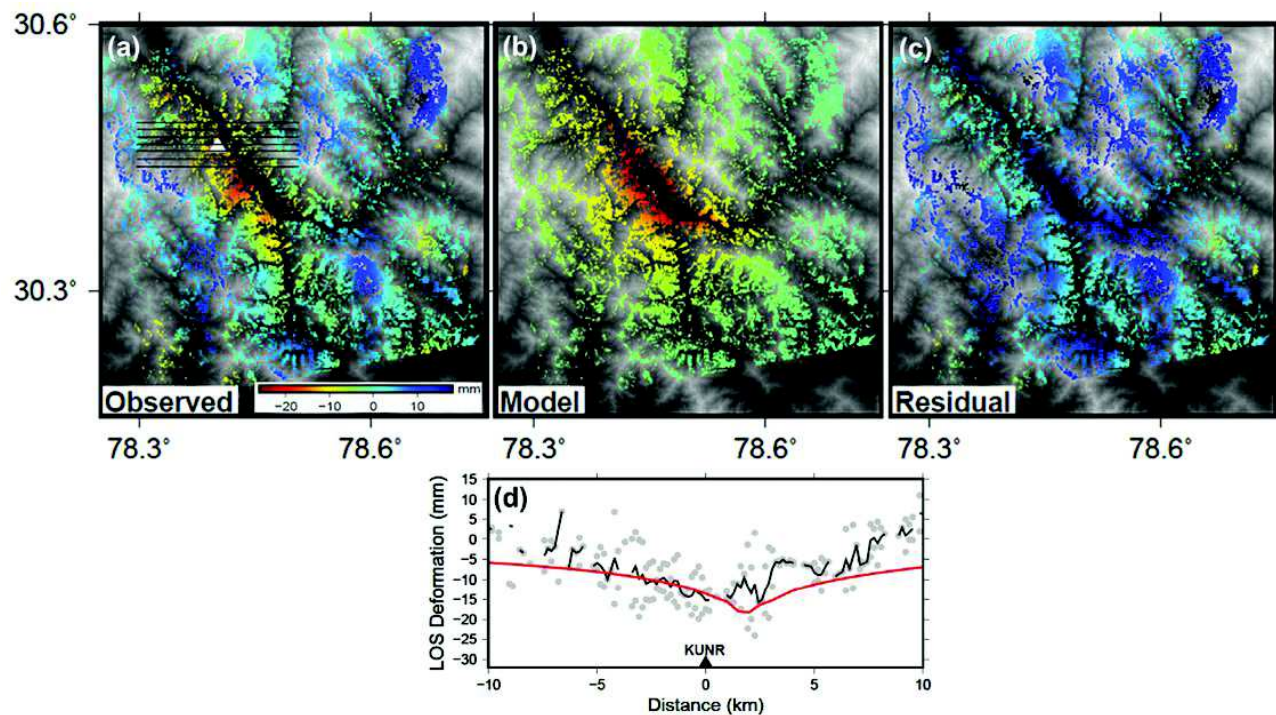


Fig. 1: (a) Observed LOS deformation from InSAR due to difference in water levels in the Tehri reservoir on 22 May 2007 and 22 November 2007, (b) simulated LOS deformation, and (c) the residual between the observed and simulated LOS deformation. (d) West-east profile passing through the KUNR GPS site. Black broken lines and grey dots are the median and scatter in the LOS deformation along a 1-km wide swath across the InSAR image. A red line also shows corresponding simulated displacement due to the reservoir

earthquakes for emergency response applications. This network is also capable of comprehensive characterization of Himalayan seismicity necessary for long-term hazard assessment and mitigation activities. The semi-permanent seismic network now comprises of 87 broadband and 30 strong-motion stations in KGH region (Fig. 2). Out of these, 25 broadband stations have been linked to CSIR-NGRI seismological central observatory server through the GPRS facility for near real-time transmission of data, enabling to locate the earthquakes in near real-time. This seismic network is being developed to monitor earthquakes in and around the most potential seismic zone in the central Himalaya.

- Active fault mapping studies were carried out in the Doon Valley of Uttarakhand for a better understanding of past earthquakes and their effects on the surface. The inferred sedimentary structure, especially the thickness of the soft sediments, varying from a few hundred meters

to about 4 km over the central part of the Indo-Gangetic plains (IGP) and Ground Motion Prediction Equations (GMPEs, Fig. 3) of the IGP and the Himalaya region, form a vital input for the synthesis of horizontal ground motion due to large earthquakes from the Himalaya, thereby, leading to the quantification of seismic hazard in/over this region.

- The outlook of the earthquake genesis in the Nepal Himalaya from imaging of the 25th April 2015 Mw 7.8 earthquake source zone has been obtained using the main earthquake event and its aftershock sequence. The seismic structure of the earthquake source region has been imaged using receiver function analysis of the HiCLIMB and HIMNT seismic networks integrating with the aftershock distribution, crustal structure and co-seismic geodetic studies suggesting that the rupture affected a duplex on the MHT and terminating at blind thrust beneath zone of maximum coseismic uplift (Fig. 4).

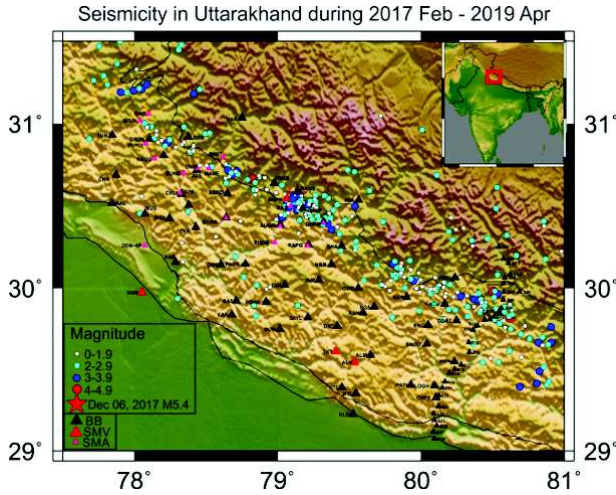


Fig. 2: Location map of newly deployed seismic network in the KGH region (Uttarakhand State). Epicentres of earthquakes, during February 2017 – April 2019, are shown by filled circles. Smaller white filled circles mark events of M0-1.9. Medium size light blue filled circles represent events with M2-2.9 while medium-size filled dark blue circles mark events with M3-3.9. Large filled red circles represent events of M4-4.9. The red filled large star marks the epicentral location of a moderate size earthquake of M5.4, which occurred on 6 December 2017. Filled black triangles mark three-component broadband seismographs while filled red triangles represent four strong-motion velocity meters. Inset shows the Indian sub-continent with the political boundaries of its neighboring countries. The red square marks the study area

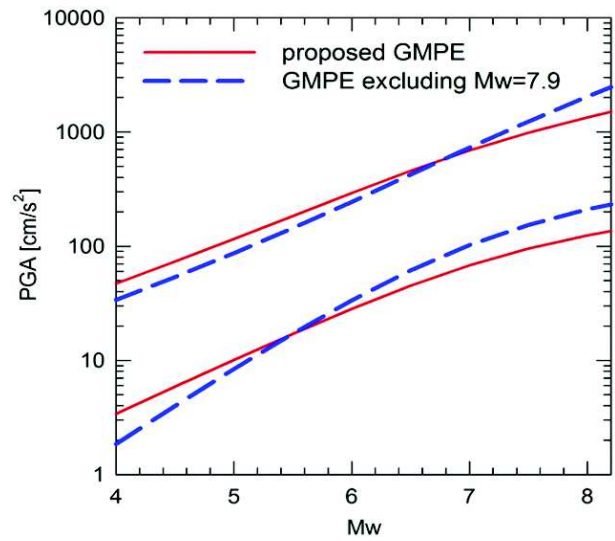


Fig. 3: Acceleration curves for proposed GMPE's with a magnitude

- The joint inversion of P-receiver functions and group velocity dispersion data obtained from 20 broadband mobile seismometers in the Kachchh rift zone has led to the delineation of a noticeable crustal and lithospheric thinning and a 2–6% drop in V_s across the lithosphere-asthenosphere-boundary (LAB). The inferred crustal structure is likely to induce significant flexural deviatoric stresses (~50–100 MPa) in the upper crust,

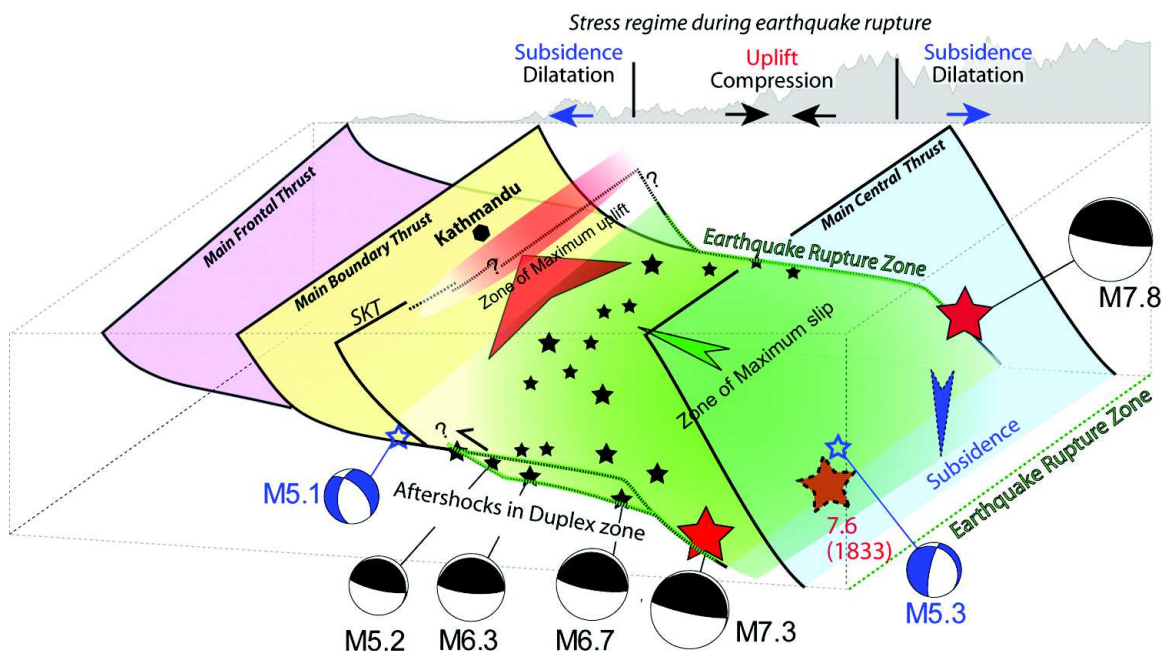


Fig. 4: Schematic section showing rupture pattern during 2015 Nepal Earthquake

thereby bringing the rift zone near to the critical stress level, which provides a new basis to explain the sustained seismicity of the region.

- Seismological studies in the Eastern Dharwar Craton (EDC), using the regional earthquake data from Andhra Pradesh-Telangana and other shield networks, reveal that the seismic activity can be correlated with major structural features such as Godavari graben, Nallamala shear zone and intrusions such as the Closepet granite. The NW-SE oriented faults are perpendicular to the absolute plate motion direction and are conspicuous with neotectonic activity while the shear zones along the east coast show diffused and weak seismicity. Scaling up of micro-earthquake activity monitoring in vulnerable zones will help constrain the depth of seismicity and also the focal mechanisms.
- Investigation of the pore pressure diffusion as a cause for continued seismicity in the Koyna-Warna region (KWR) was carried out through a 3 D fluid flow numerical model. The mathematical model suggests that a vertical fault with a higher vertical hydraulic conductivity in the range of 2–6 m/day facilitates the diffusion of pressure at focal depths of earthquakes though the water level fluctuations in the reservoir are sufficient to trigger earthquakes in the KWR.
- Low-elevation airborne gravity gradient and magnetic (AGGM) surveys carried out in the KWR revealed a higher thickness of basalt along the eastern side of the escarpment in comparison with the western side and the localized density heterogeneities in the vicinity of the hypocentral zone.
- Cores and logs from three exploratory boreholes of approximately 1 km depth in the KWR (Paneri, Phansavale, and Khadi) were analyzed to establish the fracture patterns of the shallow subsurface. The samples from the first two locations showed several slickensides in both basalt and basement sections. The dip amounts and directions of basement fracture patterns over all the boreholes outline a depressional feature in the shallow basement.

- Study of basement rocks from cores of Rasati borehole provides evidence for Neoarchean basement for the Deccan Volcanic flows; in terms of the composition and age (Fig. 5), a correlation found between the gneisses in the KBH-1 borehole and the Neoarchean basement gneisses of the EDC suggests that the EDC possibly extended to these locations. Continued GPS measurements in the region indicate the differential movements of the blocks on either side of the Koyna-Warna fault and explain the differences in the seismicity pattern.

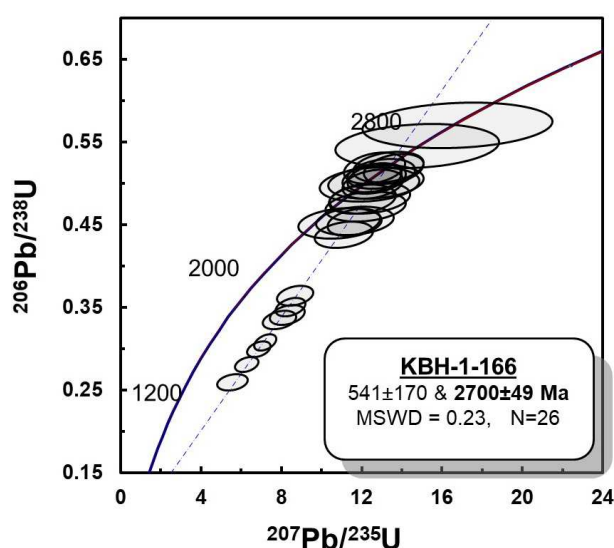


Fig. 5: Concordia diagram for KBH-1 Granodiorite sample

Exploration for Natural Resources

Geological and geophysical studies have been carried out for the exploration of natural resources, including water, hydrocarbons, gas hydrates, coal bed methane, and metallic/non-metallic minerals, essential for every endeavor of human growth, under several project modes. The notable achievements under this theme are briefed here:

Water Resources

- Identification of spatiotemporal variation of hydrological mass patterns through Empirical Orthogonal Function (EOF) analyses of mass estimates from GRACE time-varying gravity data. GRACE mass signal depicts different seasonality among the western, central and eastern parts of the Himalayan region, winter

accumulation over the western region and Alpine and monsoonal accumulation over the central and eastern regions.

- Delineated a mega feature, a paleochannel (pathway of an ancient river) with dimensions comparable to that of the rivers Ganga and Yamuna employing Airborne Electromagnetic (AEM) survey (the multi-moment SkyTEM312) in the Ganga-Yamuna Doab region of Prayagraj-Kaushambi area. The obtained data shows high-resistive linear features extending to a regional scale with a width of up to 4 km. This new finding will open a new dimension for groundwater management in this region and also to the discussion on the presence of an ancient river at Prayagraj.
- Under the aquifer mapping studies in different geological terrains of India, AEM studies carried out in the granitic terrain of Tumkur district, Karnataka led to the introduction of new concepts such as i) precise mapping of water-bearing fracture networks using the information

of depth of investigation (DOI) ii) HYDROLIN that defines underground lineaments consisting of water-saturated fracture networks (iii) TGWH (critical depth called threshold groundwater horizon) below which probability of water-saturated fracture networks of regional extension increases significantly.

- Studies were carried out to help in controlling the indiscriminate pumping, by providing safe pumping rates to the farmers of arsenic affected villages in the Middle Ganga Plains (MGP) through groundwater modelling to map areas that are vulnerable to the leakage reversal in the multi-aquifer system (Fig. 6).

Energy and Mineral Resources

- For characterization of the gas hydrates from seismic attributes, post-stack seismic data from offshore Mahanadi basin is conditioned using background steering and filtered to generate the dip-steered median filter data for extracting the instantaneous amplitude, instantaneous phase,

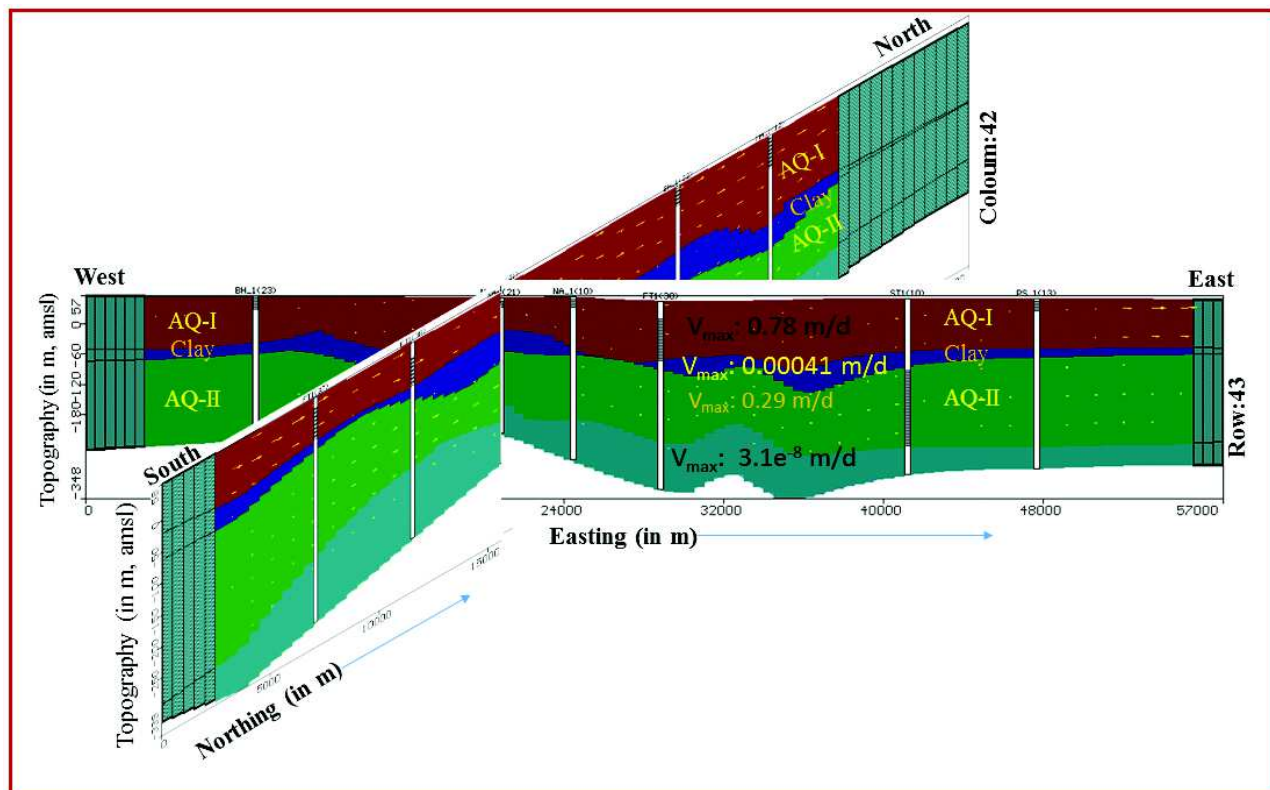


Fig. 6: The maximum groundwater velocity (estimated) and the flow direction of the multi-aquifers system from a part of MGP, Patna. Colours show different lithologies

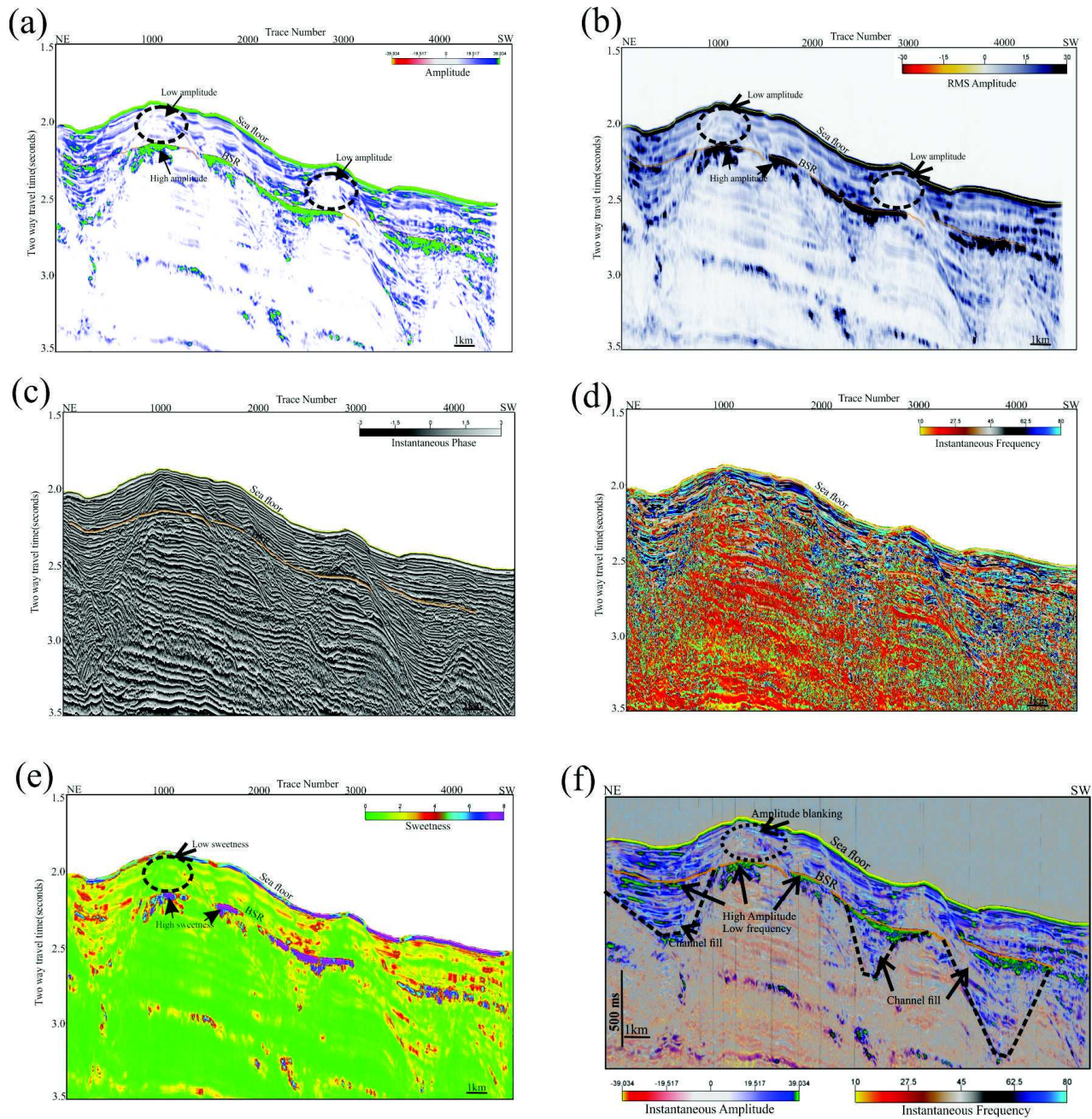


Fig. 7: (a) Instantaneous amplitude, (b) RMS attribute, (c) Instantaneous phase, BSR is characterized by opposite polarity concerning the seafloor event and mimicking the shape of the seafloor, (d) Instantaneous frequency, (e) sweetness, and (f) co-rendered attribute between instantaneous amplitude and instantaneous frequency along the MN-38 line. The hydrate-bearing zones are characterized by low amplitude, low sweetness and high-frequency attributes

instantaneous frequency, RMS amplitude, and sweetness attributes. The low amplitude, high frequency, and low sweetness attributes characterize the presence of gas hydrates whereas, free gas zones are characterized by bright amplitudes associated with low frequency

and high sweetness below the bottom simulating reflector (BSR) as shown in Fig. 7.

- Attempt to resolve the thickness and depth of the coal beds and associated structural features through 3D high-resolution seismic survey in the

Ib valley (Odisha) coalfield by deploying Vibrator (T-15000) as a seismic source show four coal horizons namely Parkhani, Lajkura, Rampur. and Ib. Out of these, the Lajkura coal horizon is found to be the thickest (20-40 m) at a depth of 200-400 m with a total volume of 30 million cubic meters covering an area of about 6 km² in the study region (Fig. 8).

- An acoustic full-waveform inversion (FWI) in the frequency domain with a fixed background density employed to the fine-scale velocity structure of gas hydrate-bearing sediments in the KG basin indicated that the split-spread dataset could resolve subsurface better than the conventional end-on data. 2D & 3D high-resolution seismic surveys (HRSS) were carried out for mapping the coal horizons & associated structural features vital for Coal Bed Methane (CBM) & Shale Gas Exploration in Orissa, Jharkhand and West Bengal.
- The model obtained through ray-trace inversion of wide-angle seismic data has validated the effectiveness of robust elastic finite-difference full-wave modeling for penetration of seismic energy below thick basalts. Dense synthetic seismic data has been generated with the help of elastic finite-difference full-wave modeling using the staggered-grid scheme for the model derived from ray-trace inversion using sparse wide-angle seismic data acquired along with Sinor-Valod profile in the Deccan Volcanic

Province of India.

- Characterized by much higher resistivity than that of host sediments, the presence of pure gas hydrates increases the resistivity of the formation, which might be exploited for the delineation and assessment of gas hydrates. As a characterization of gas hydrate reservoir from seismic data assumes homogeneous distribution, it leads to an overestimation of gas-hydrate saturation. To circumvent this, a method was proposed for the estimation of gas hydrates from 3 D heterogeneous resistivity model simulated using D resistivity log data in the KG basin in the eastern Indian offshore. The simulated resistivity model contains small scale variations of the reservoir and maintains all properties like root mean square fluctuation, characteristic scales, and fractal dimension of the observed log. Volumetric gas hydrate saturation was estimated using the simulated 3 D resistivity model. The porosity used for the estimation of gas hydrates is calculated from the simulated density field generated using the observed density log data. The average gas hydrate saturation is estimated with a pore volume of 9.84% of over 1000 x 1000 x 131 cubic meter volume (Fig. 9).

Airborne Geophysical Surveys

- CSIR-NGRI have a history of more than five decades in airborne geophysical exploration for

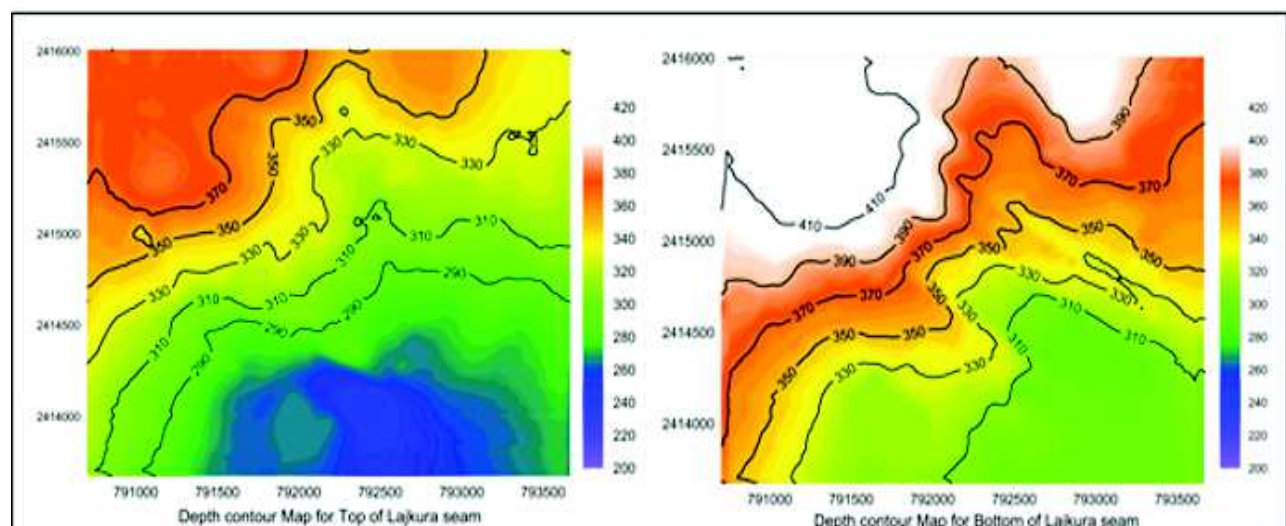


Fig. 8: Depth contour map of Lajkura top and bottom of a coal seam, IB valley coal fields, Belpahar sector, Odisha

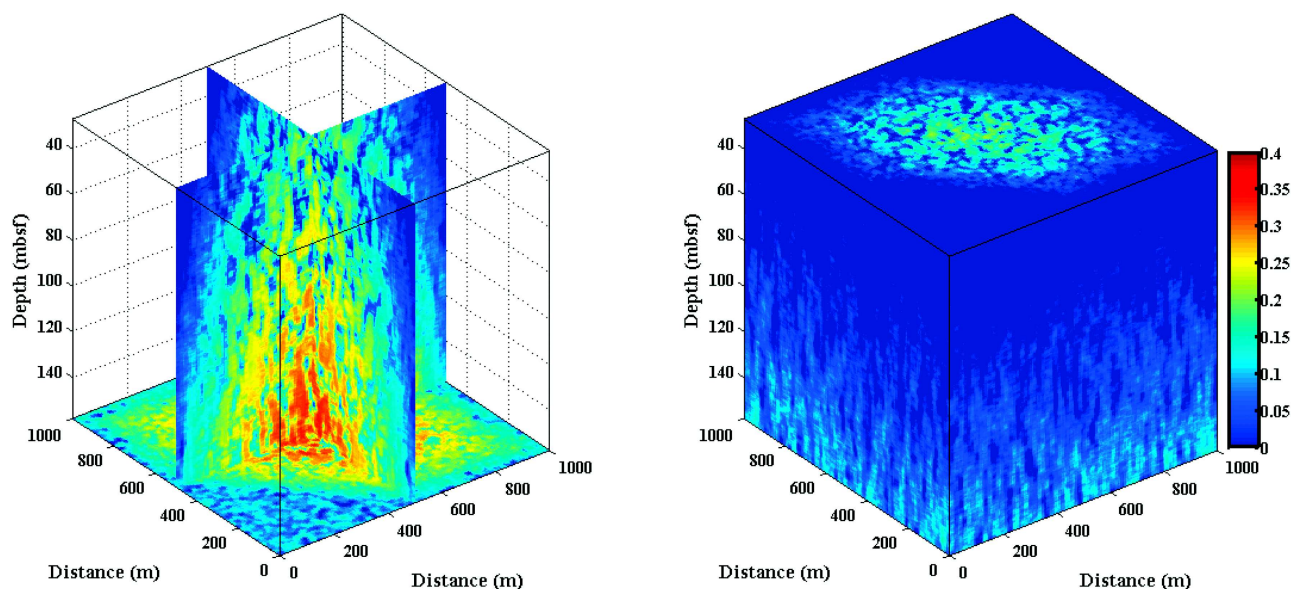


Fig. 9: Left – 3 D cross-sectional view of gas hydrate saturation (left) calculated from simulated heterogeneous resistivity and density. Right – A 3 D volumetric view (1000 m x 1000 m x 131 m) of gas hydrate saturation model over gas hydrate-bearing zone around the borehole NGHP-01-10A

minerals, oil and regional surveys. Starting with the fixed-wing airborne magnetic and radiometric surveys, the Institute has pioneered in low-altitude heliborne multi-parametric geophysical surveys incorporating transient electromagnetic, magnetic and radiometric systems. Using the Versatile Time Domain Electromagnetic (VTEM) system, the Institute has covered about 1,15,000 LKM in the past 9 years for uranium exploration in different parts of the country for Atomic Minerals Directorate, Department of Atomic Energy, Government of India. Since 2016, the Institute has acquired about 41,000 LKM transient electromagnetic, aeromagnetic, and radiometric data over Chhattisgarh and Satpura basins. Integrated interpretation of these multi-parametric geophysical data sets with the geological and available borehole data has helped in identifying new target zones. In 2018, the Institute mapped, for the first time, the deformation structure of the Main Frontal Thrust (MFT) region at Ramnagar, Uttarakhand, by high-resolution heliborne VTEM-Plus system to delineate the near-surface structure at a depth of about 600 m and subsurface signatures of the MFT.

Lithospheric Structure and Geodynamics

- Inferred from regional earthquake travel time data, the seismic character of the Moho beneath the NW Himalaya and Ladakh has been studied along a ~600 km-long profile using 42 regional waveform data recorded on 15 seismographs. The apparent Pn and Sn velocities beneath the NW Himalaya are 8.08 ± 0.04 and 4.64 ± 0.07 km/s respectively for earthquakes occurring south of the profile (downdip, western Indian shield) and 8.70 ± 0.13 and 4.76 ± 0.12 km/s for earthquakes from the north (updip, western Tibet). Similar velocities beneath Ladakh are 7.18 ± 0.07 and 4.32 ± 0.05 km/s for earthquakes due south (downdip, north Indian shield) and 8.50 ± 0.10 and 4.39 ± 0.12 km/s for earthquakes due north (updip, western Tibet). These velocity variations constrain the Moho dip at $\sim 2.4^\circ \pm 0.148^\circ$ beneath the NW Himalaya and $\sim 6.6^\circ \pm 0.548^\circ$ beneath Ladakh. Considering the different dips along with the profile, it is observed that the true Pn (8.37 ± 0.07 km/s) and Sn (4.70 ± 0.1 km/s) velocities are higher for the NW Himalaya than for Ladakh (7.73 ± 0.08 and 4.33 ± 0.09 km/s). The large variation observed between the station pairs near the Indus Zangpo Suture zone may be due to steep dipping ($\sim 7.18^\circ$ to 6.268°) of the Indian Moho. The

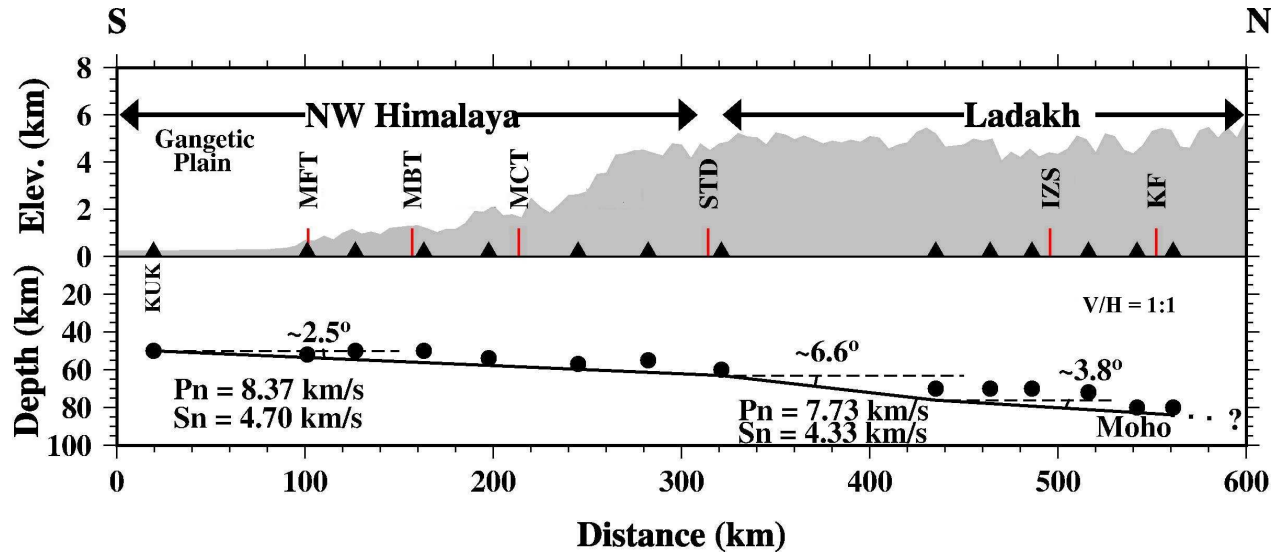


Fig. 10: Variations in the dip of the Indian Moho from the Main Frontal Thrust (MFT) to Karakoram Fault (KF), in the western Himalaya - Ladakh

results show that the Indian Moho is underthrusting at a shallow angle ($\sim 2.58^\circ$) beneath the Himalaya, steepening abruptly ($\sim 6.68^\circ$) further north of the Southern Tibetan Detachment and continues at a shallow angle ($\sim 3.88^\circ$) beneath Ladakh (Fig. 10).

- Imaging of seismic discontinuities of the upper mantle in the western Himalaya through Receiver Function analysis revealed the existence of a thickened mantle transition zone (~ 255 - 262 km) beneath the Gangetic Plain and NW Himalaya than the Tibetan Himalaya due to the presence of cold material within ($\sim 100^\circ\text{C}$ less than normal). Seismotectonics and crustal stress field studies in the KGH suggest that the majority of earthquakes indicate thrust type mechanism. It can be inferred that the strain resulting from the ongoing collision of the Indian Plate with the Eurasian plate is being consumed by thrust fault movement, mainly on the north dipping Munsiri Thrust and south-dipping Tons Thrust.
- Shear-wave splitting parameters measured at four broadband stations in Rajasthan have revealed a mean fast axes orientation of ($39^\circ \pm 9^\circ$) with a mean delay of 1.7 ± 0.3 s, which could be attributed to the frozen lithospheric anisotropy in the direction of the current absolute plate motion of the Indian plate.
- Studies on heat flow, heat production and crustal temperatures over the Archaean Bundelkhand craton reveal similar mantle thermal regimes across the northern and southern parts of the Indian shield, in spite of varying surface heat flow regimes, implying that most of the intra-province and inter-province variations in the Indian shield may be explained by differences in upper crustal heat production.
- A significant intrusive component of the Deccan Large Igneous Province (LIP) in the Narmada, Son Lineament region, has been imaged using a magnetotelluric (MT) data set of 153 stations. 3D modeling of this data set indicated major crustal conductors of different geometries at various depth levels in the crustal column (Fig. 11). These conductive features, correlating well with gravity high anomalies and high seismic velocity zones, are interpreted to be mafic-ultramafic bodies derived from the mantle. It is inferred that these bodies represent the intrusive component of the LIP of the Deccan volcanic episode triggered by the passage of the Indian continent over the Reunion hot spot during the Late Cretaceous. The disposition and the geometry of the subsurface magmatic bodies, which must have served as magma chambers for the outpouring of the Deccan lavas, suggest that they are closely related to the plumbing

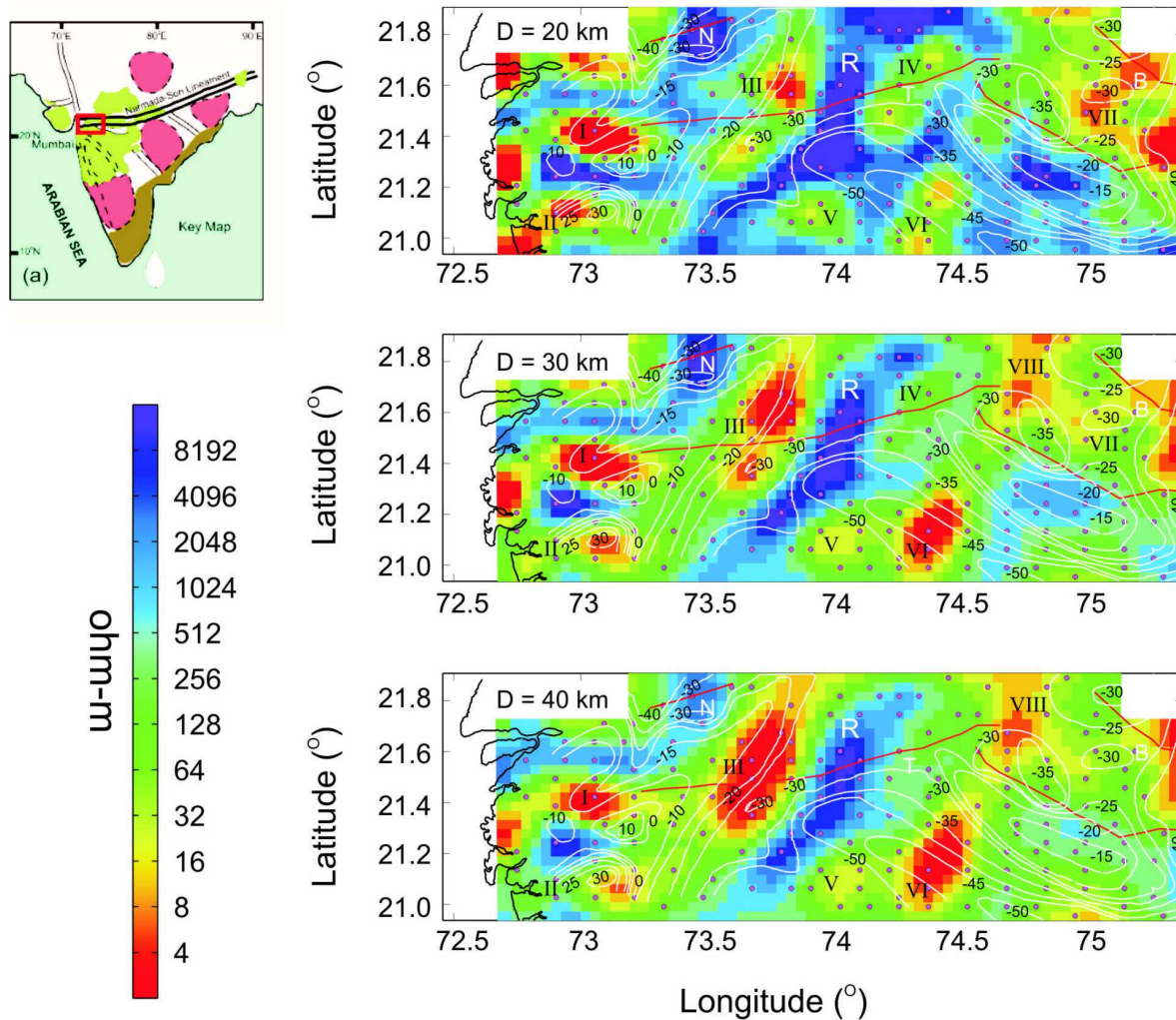


Fig. 11: Horizontal depth section derived from 3D inversion of full tensor MT data at depths 20, 30 km are presented along with gravity contours (white lines) superimposed. Narmada (N), Tapti (T) and Barwani-Sukta (B) faults are marked with red lines

geometry of the LIP of the Deccan volcanic episode.

- Newly acquired gravity data along a lithospheric transect across the eastern part of the Narmada-Son lineament complemented by available gravity data and constraints from seismic sections led to the generation of a 3D crustal density model. The abnormal high gravity anomalies detected in residual and regional anomalies at the sub-crustal and crustal levels are interpreted in terms of high-density mafic intrusion/underplated layer, respectively.
- Basement depth studies in Central India from aeromagnetic data using the spectral scaling method show that the depth to the shallow

magnetic anomalies varies from 1 to 3 km, whereas the magnetic basement depth varies from 2 to 7 km. 3D inversion of residual gravity anomalies in South Rewa Gondwana basin has brought out undulations in the basement delineating two major depressions near Tikhi in the north and near Shahdol in the south. It is found that the gravity method is better suited to demarcate the boundary and delineate the geometry of the Sonakhan Schist Belt, whereas the magnetic method is useful to discriminate against the constituent members of the schist belt due to its bimodal nature of volcanic association in Chhattisgarh Basin.

- Seismologically determined, the crustal and

lithospheric structure of the Singhbhum craton supports a north-ward Archean/Proterozoic subduction model that includes delamination of the lithosphere beneath the oldest Singhbhum granite of 3.6 Ga. The mapped area coincides with the horse-shoe shaped broad Singhbhum synclinorium known as Iron Ore Group (IOG) basin which hosts large iron ore and to a lesser extent, manganese deposits of Precambrian age. This lithospheric feature is inferred to have played an important role in the passage of melts carrying various iron-rich minerals and metals to the uppermost oceanic crust during the Archean plume associated with the magmatic episode.

- Dominant geodynamic processes supporting the formation and evolution of Earth's early crust have been inferred from geochronological data on a new set of Eoarchean detrital zircons from the Singhbhum craton. The U-Pb ages (between 3.95 and 2.91 Ga) of detrital zircons extracted from ~2.9 Ga old quartzites and magmatic zircon from a 3.505 Ga old dacite from the IOG complemented by the recently reported Hadean, Eoarchean xenocrystic (up to 4.24 Ga) and modern detritus zircon grains from the Singhbhum craton, indicate that the Eoarchean detrital zircon represent the crust generated by recycling of Hadean felsic crust formed at ~4.3-4.2 and ~3.95 Ga (Fig. 12a). An increased role for the depleted mantle and the relevance of plate tectonics is signified by the observed prominent shift in Hf isotope compositions at

~3.6–3.5 Ga towards super-chondritic values. These results indicate the role of both depleted and enriched mantle sources involved in crust generation. A short-lived supra-subduction setting around ~3.6–3.5 Ga followed by mantle plume activity during the Paleo-Mesoarchean crust formation in the Singhbhum craton (Fig. 12b) may be inferred, thereby providing an additional repository for Earth's oldest materials.

- Geochemistry and isotopic studies of the Ferropicrites of the Mahakoshal supracrustal belt argue for the existence of a proto-ocean before the amalgamation of the northern cratonic block consisting of Aravalli and Bundelkhand proto-continents, and the southern cratonic block consisting of Singhbhum, Bastar and Dharwar proto-continents, which were still adrift at ~2.1 Ga. On the other hand, the proximity between the depositional ages and the similarities between the geochemical attributes of the basalts in the four volcanic formations [Pitapani, Sitagota, Mangikhuta and Kotima] of the Dongargarh Supergroup, suggest contemporaneous evolution spanning a few tens of million years around ca. 2.5 Ga. The U-Pb age of the mafic volcanic rocks (2471 ± 7 Ma) and the felsic volcanic rocks (2463 ± 14 Ma) reflect Paleoproterozoic volcanic activity in the Kotri belt.
- Field and petrographic studies from the Pithora region of the northeastern part of the Bastar Craton reveal that the syn-plutonic mafic dykes, cusped contacts, magmatic flow textures,

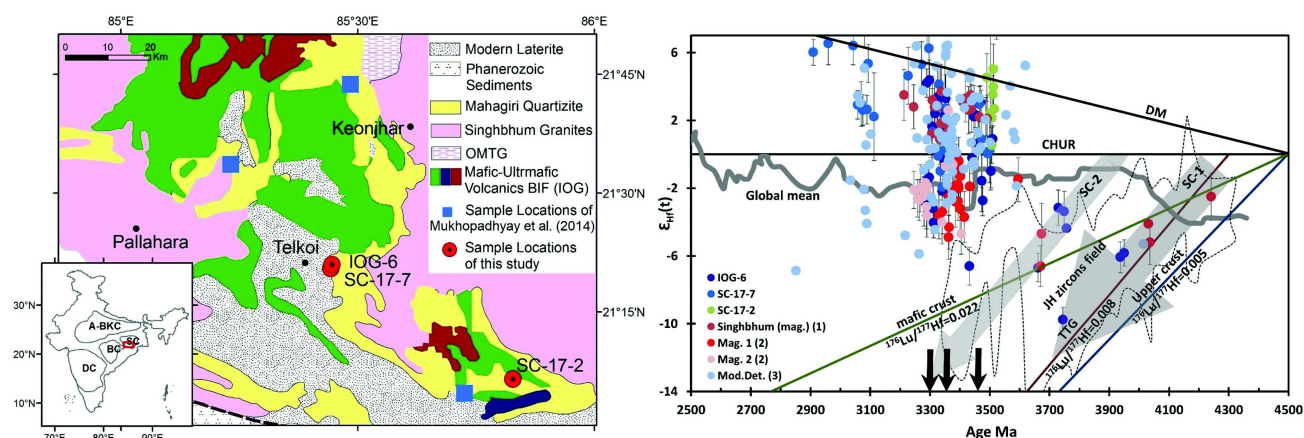


Fig. 12: a) Sample locations in Singhbhum craton. b) Age vs. Hf(t) plot of magmatic and detrital zircons from the Singhbhum craton (data from this work as well as published by others from this area)

mingling and hybridization suggest a coeval emplacement of end-member magmas thereby characterizing the interactions of mafic and felsic magmas.

- Paleomagnetic studies of the ~2.2 Ga Paleo-Proterozoic long mafic dyke from the Gadwal region, Eastern Dharwar craton reveal multi-domain nature with magnetite as the leading remanence carrier. An Integrated approach to delineate the crustal structure beneath the Proterozoic eastern Cuddapah Basin covering Nellore Schist Belt reveals the presence of a thin layer (~ 250 m) of Gondwana sediments with a distinct velocity of 4.20 km/s and a lateral dimension of about 40 km around Vinjamuru region.
- Geochemical and stable isotope signatures of Proterozoic stromatolitic carbonates from the Vempalle and Tadpatri Formations, Cuddapah S upergroup, India are studied in terms of their implications for paleoenvironment and depositional conditions; Spectacular stromatolitic dolomites with varied morphological features preserved in the Vempalle and Tadpatri Formations of the Proterozoic Cuddapah basin exhibit stratifera, columnar, conical, domal and spheroidal/lobate morphologies in which columns are branched at some places (in Tadpatri Formation). Based on their trace elements (as REE+Y) and stable isotopic (C and N) compositions, the Vempalle stromatolites have been classified as three types (a). Vempalle I stromatolites exhibiting pronounced positive Eu anomalies with small scale positive Ce anomalies (b) Vempalle II having slight negative to positive Eu, feeble positive Ce and positive Gd anomalies and (c) Vemaplle III stromatolites displaying positive Ce, Eu and Gd anomalies. The Tadpatri Formation stromatolites have pronounced Gd anomalies with low order positive Ce and Eu anomalies. Significant depletion in $\delta^{18}\text{O}$ is observed in Vempalle and Tadpatri Formations. The Tadpatri stromatolites display variations in negative $\delta^{18}\text{C}$, whereas the Vempalle stromatolites possess both positive and negative $\delta^{18}\text{C}$, thereby reflecting their deviation from the popular belief of the boring billion concepts of displaying Midproterozoic $\delta^{18}\text{C}$ stasis. The flat

REE patterns, Ce, Eu and Gd anomalies, chondritic to superchondritic Y/Ho ratios collectively reflect their deposition in marine water conditions with variable inputs of siliciclastic/terrigenous materials and hydrothermal signatures. These cherty dolomitic stromatolites were deposited in subtidal-intertidal-supratidal zones of a shallow shelf of Proterozoic open ocean under warm, alkaline and anoxic conditions (Fig. 13).

- New U-Pb zircon ages and Hf isotopic compositions for 11 charnockite orthogneisses from the Madurai, Trivandrum, and Nagercoil blocks contributed to the resolution of the age of their magmatic protoliths leading to a better understanding of the accretion of Precambrian continental crust in southernmost India with focus on the younger granulite metamorphic domains. Together with published geochronological data, these new results indicate that the charnockite orthogneisses south of the Palghat-Cauvery suture zone (PCSZ) relate to four distinct episodes of felsic magmatism including ca. 2.62–2.46 Ga in the northern Madurai block (Neoarchean to Siderian Period), ca. 2.05–1.84 Ga in the Trivandrum block and Nagercoil block (Orosirian), ca. 1.0–0.9 Ga in the southern Madurai block, southeast of the Suruli shear zone (early Tonian), and ca. 0.80–0.76 Ga widespread in the southern and eastern Madurai block (late Tonian). Hf isotope analyses of zircons from the charnockite gneisses suggest that the protoliths of the ca. 2.05–1.98 Ga gneisses from the Trivandrum and Nagercoil blocks and the ca. 1.0–0.9 Ga gneisses along the southeastern Madurai block involved a significant juvenile magma component, while the protoliths of charnockite gneisses elsewhere in the Madurai block was formed mainly through recycling of older crust up to ca. 3.2 Ga. The four Spatio-temporal magmatic groups show distinct zircon Hf isotopic signatures indicating predominantly juvenile protoliths in the case of the Orosirian and the early Tonian suites and primarily crustal sources with limited or no mantle component in the case of the Siderian and late Tonian suites. The two-stage zircon Hf model ages (T_{DM}^{C}) are generally consistent with whole-rock Sm-

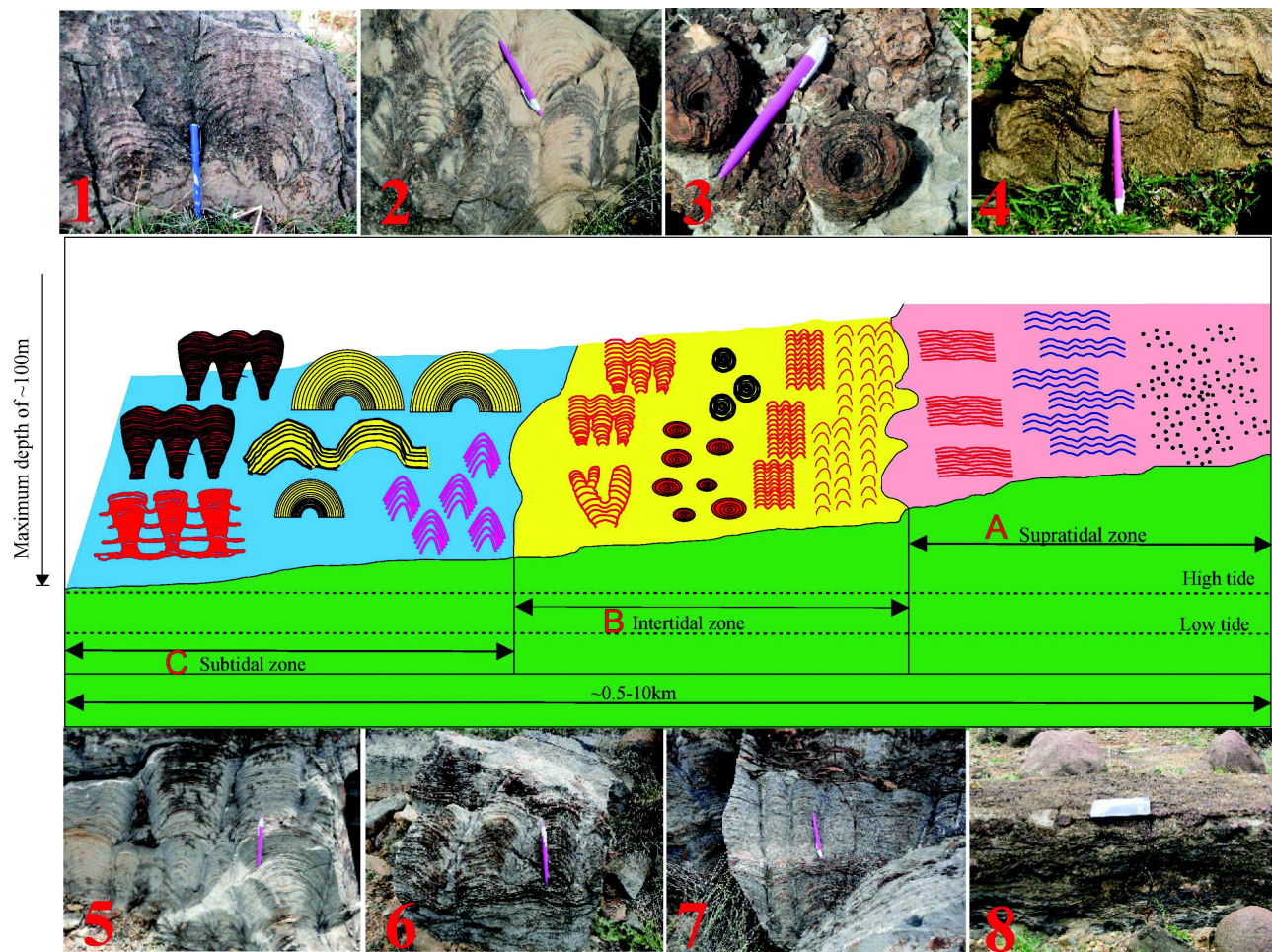
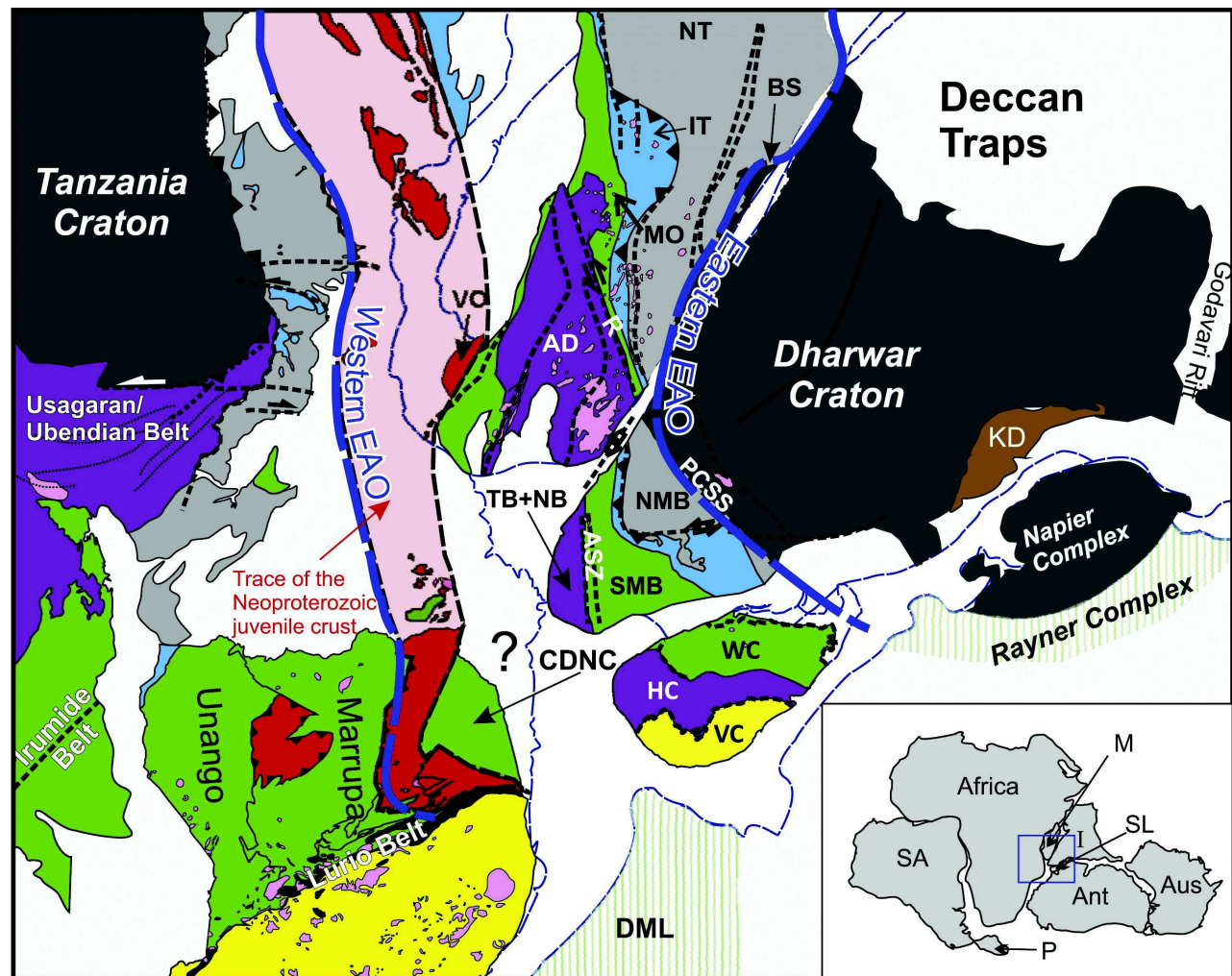


Fig. 13: Schematic diagram showing paleoenvironmental conditions of the Tadpatri and Vempalle stromatolites (not to scale). 1-4 are field photos of Vempalle stromatolites and 5-8 are Tadpatri stromatolites. 1 and 5 are formed in the supratidal zone, 2, 3, 6 and 7 are formed in the intertidal zone; 4 and 8 are formed in the subtidal zone

Nd model ages. This study documents for the first-time juvenile Orosirian magmatism in the Trivandrum and Nagercoil blocks, which are separated from the northern terranes by juvenile Neoproterozoic crust in the Achankovil and southern Madurai blocks. The Madurai block, Trivandrum block, and Nagercoil block of the Southern Granulite terrane were affected by one or two episodes of regional high-grade metamorphism during the protracted interval pertaining mainly to the Ediacaran–Cambrian period, which could mark a final stage in the amalgamation of the Madurai-Trivandrum-Nagercoil blocks to the Dharwar craton along the PCSZ. It is concluded that the merger of these terranes south of the PCSZ with the Archean Dharwar craton coincided with the closure of the Mozambique Ocean towards the

final stage of Gondwana supercontinent formation and development of the East African orogeny (Fig. 14).

- A comprehensive study of thickness and composition of the crust; and the nature of crust-mantle boundary beneath Southern Indian Shield (Fig. 15a) has been carried out using P-wave receiver function from 119 seismic stations data covering geological domains like mid to late Archean Dharwar craton, Archean and Proterozoic metamorphic terrains, Proterozoic basin, rifted margins and escarpments, and Deccan volcanics. Except for the Western Dharwar (~ 40 km into 50 km in the south) and Southern Granulites (40-45 km), all other geological domains have a crustal thickness in the range of 33-40 km (Fig. 15b). Most of the



Basement rocks U-Pb age (Ga)

- | | |
|---|---|
| Late post-tectonic granitoids (ca. 0.65–0.5 Ga) | Paleoproterozoic Muva Supergroup intruded by Paleoproterozoic (2.0–1.8 Ga intrusives) |
| Neoproterozoic (ca. 0.85–0.75 Ga) juvenile crust | Paleoproterozoic metasedimentary sequences (Muva Supergroup) |
| Late Mesoproterozoic to Early Neoproterozoic (ca. 1.0–0.85 Ga) basement rocks and Neoproterozoic metasedimentary sequences and possible occurrences in Antarctica | Neoarchean (~2.5 Ga) crust reworked during the Neoproterozoic (ca. 0.85–0.5 Ga) |
| Mesoproterozoic (ca. 1.2–1.1 Ga) basement rocks | Archean (>2.5 Ga) cratons |
| Major structures | |
| Outline of the East African Orogen (EAO) | |

Fig. 14: Geological sketch showing different Precambrian terranes and major shear/suture zones in a Gondwana reconstruction and their potential correlation with terranes in southern India. The major geological blocks, formations, and structures include NT-Antananarivo block; IT-Itermo Group; MO-Molo Group; AD-Androyen block; VO-Vohibory block; CDNC-Cabo Delgado nappe complex; BS-Betsimisaraka suture; R-Ranotsara shear zone; PCSS-Palghat- Cauvery shear system; ASZ-Achancovil shear zone; the eastern and western limits of East African orogen (EAO); NMB-northern Madurai block; SMB-southern Madurai block; TB+NB-Trivandrum and Nagercoil blocks; WC-Wanni complex; HC-Highland complex; DM-Dronning Maud Land; KD- Krishnagiri domain. The inset shows a tight fit of Gondwana fragments: M-Madagascar, SL-Sri Lanka, I-India; P-Patagonia; SA-South America; Ant-Antarctica; Aus-Australia. Please see text for references; VC-Vijayan complex

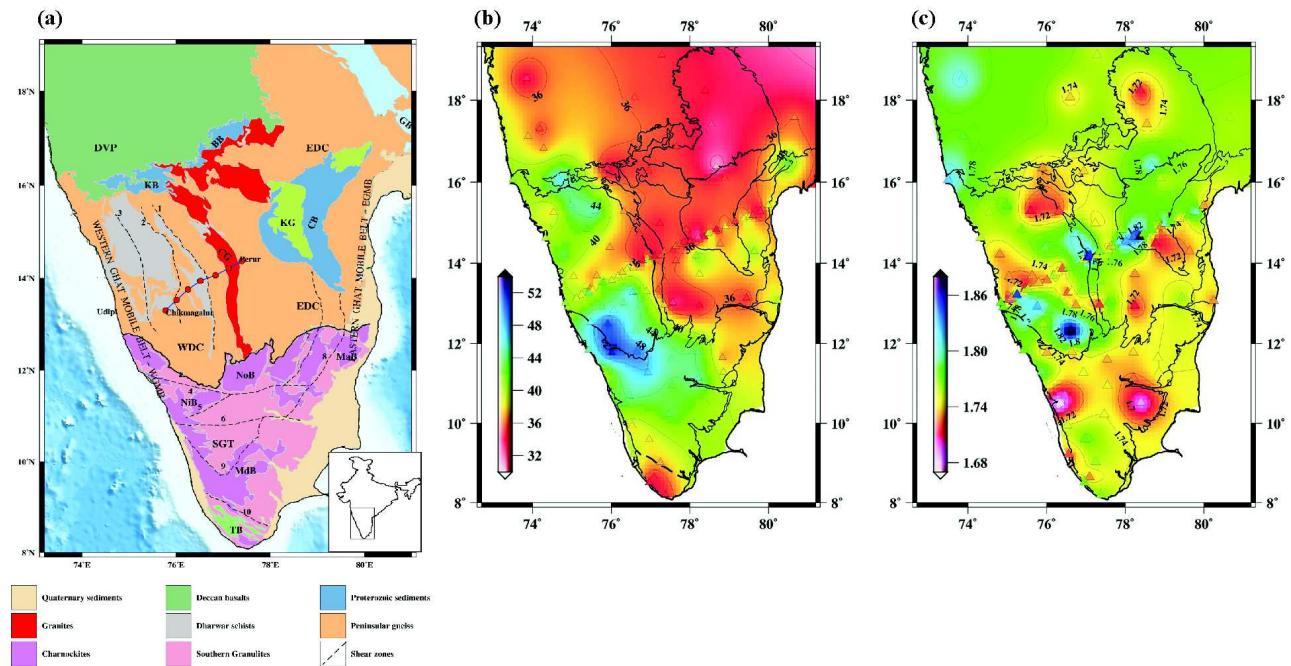


Fig. 15: a. Geology map of the South Indian Shield (also showing Perur-Chikmagalur deep seismic profile) (b) Moho depth and (c) Vp/Vs. variation maps of South India

crustal blocks have low to moderate Vp/Vs. (1.72-1.76) representing a felsic to intermediate composition. The Archean granulite terrain with high Vp/Vs. (1.76-1.81) indicates more mafic crust beneath them (Fig. 15c). When accounted for the paleo burial depth of 15-25 km, the study suggests a possible Himalaya-Tibet like scenario beneath the mid-late Archean in southwestern Dharwar and north granulite terrain showing progressive densification of deeper crust leading to a gradational crust-mantle transition that is otherwise sharp elsewhere. The study suggests a more homogenized and felsic nature of the Precambrian crust beneath the terrains formed after 2.6 Ga, possibly due to the delamination of the mafic lower crust. These results do not suggest any distinction between late Archean and Proterozoic crusts. The Deccan volcanism at 65 Ma does not appear to have altered the crustal character beneath it and is similar to the adjacent late Archean east Dharwar craton. The western Ghat escarpment and the coastal plain formed due to separation of India from Madagascar are underlain by the mafic lower crust.

- A new deep crustal seismic reflection profiling,

the DHARSEIS experiment was conducted along with a 200 km long Perur-Chikmagalur profile across the Archean Dharwar craton (Fig. 15a), to understand the crustal evolutionary processes during the Neoproterozoic. The seismic images obtained using the common reflection surface (CRS) stack method show distinctly different reflectivity patterns in the Mesoproterozoic Western Dharwar Craton (WDC) and the Neoproterozoic EDC. The WDC consists of a simple structure with a significant part of the crust (6 to 28 km) displaying a gently dipping reflection fabric and a subhorizontal reflection fabric from 28 to 40 km except beneath the Chitradurga schist belt. On the other hand, the EDC displays a complex reflectivity pattern, contrary to the simple crustal structure suggested by various other studies. A dipping Moho, oppositely dipping reflection fabric and a thrust fault are the major crustal features in the EDC. The present seismic study imaged a west-dipping reflection fabric extending from 34 to 43 km in the EDC, which is interpreted to represent an upper-mantle subduction zone (Fig. 16).

- The in-situ stress orientations of the Indian plate compiled from the borehole breakouts, hydro-

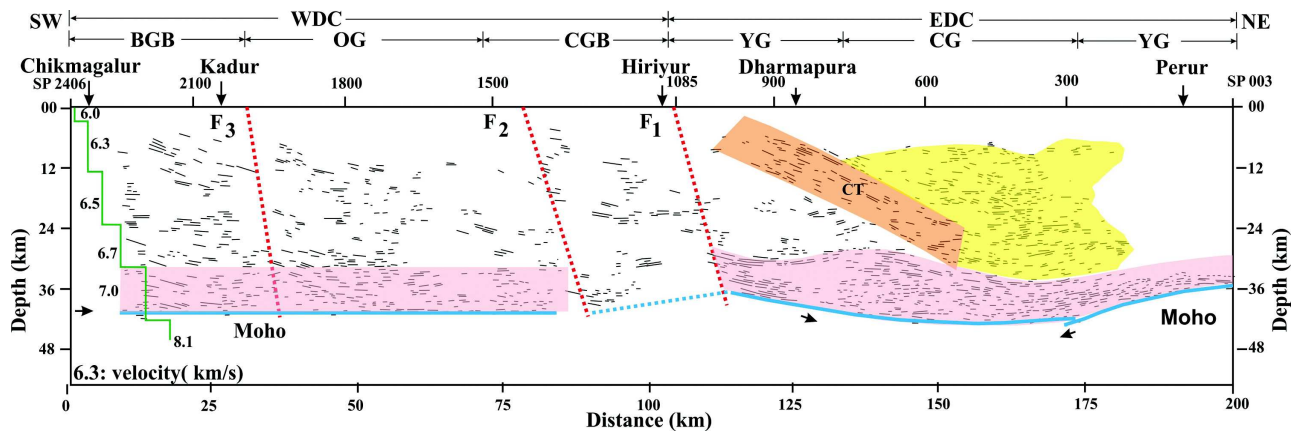


Fig. 16: The panel shows the corresponding line drawing of reflections obtained from the CRS depth migrated section with a 1D velocity model superimposed on it

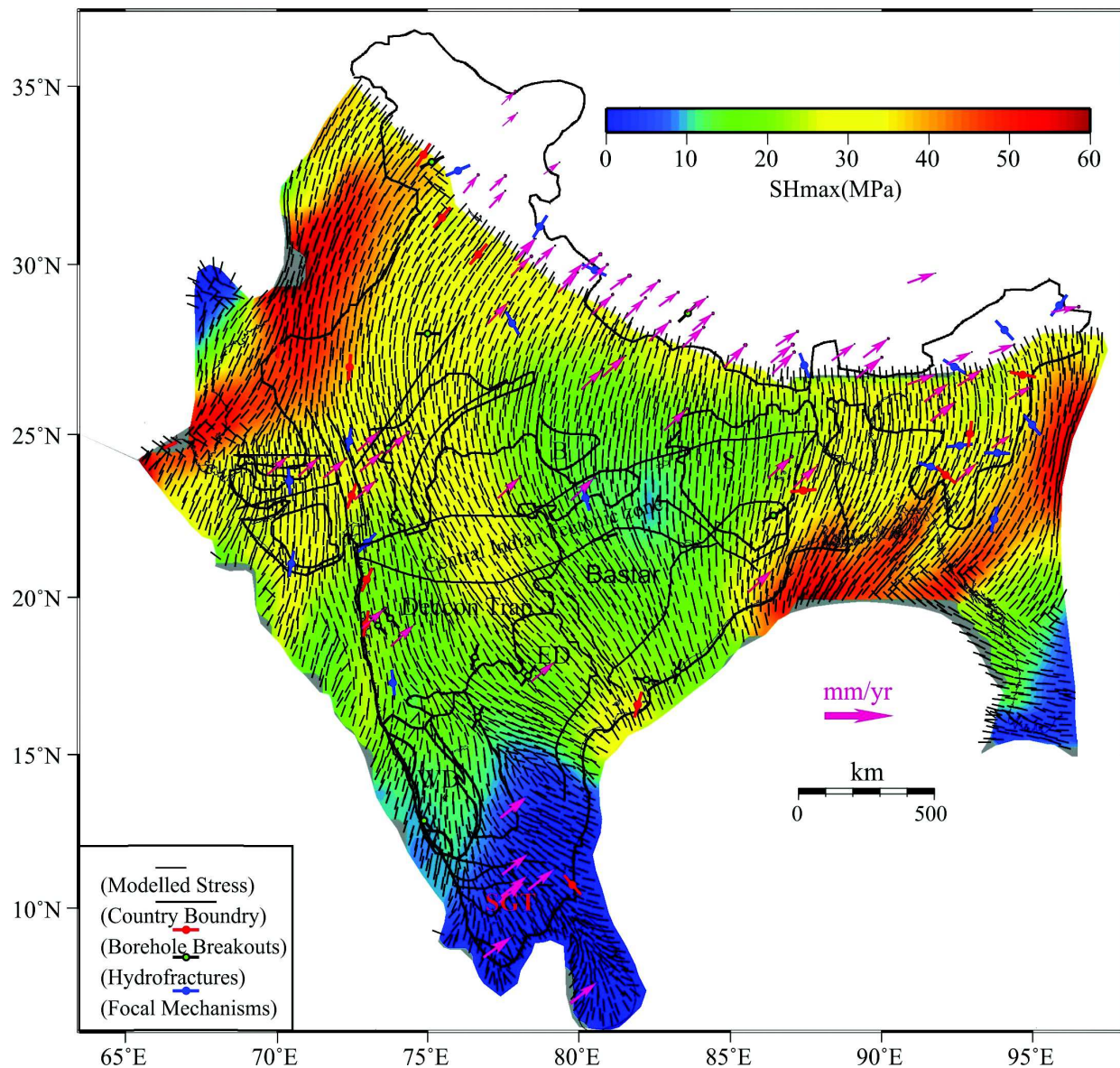


Fig. 17: Numerical simulation of maximum principal stress of the Indian continent

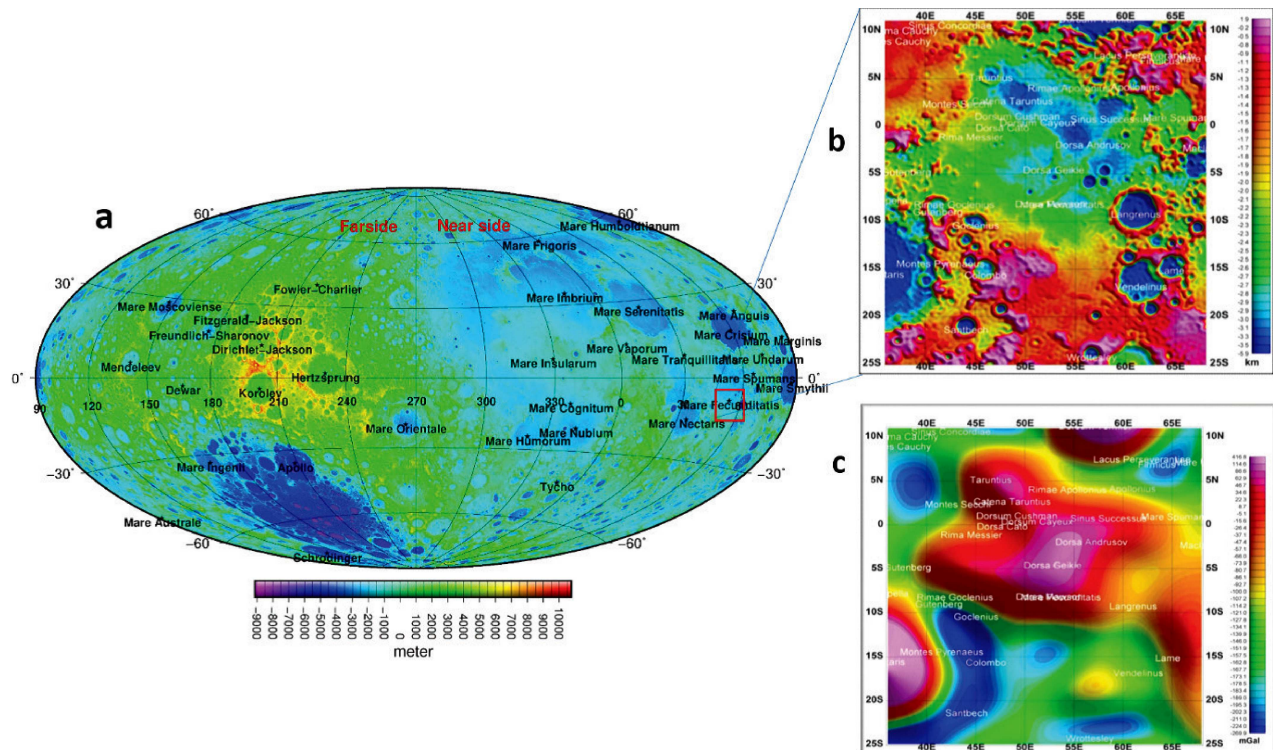


Fig. 18: (a) Global topographic map of the Moon showing the outline of the study region by a rectangular red box. This map is plotted in Hammer's projection centered at 270°E longitude, showing the near and far sides of the Moon on either side. (b) Topographic map (c) Regional gravity anomaly map of the mare fecundities region. These maps are plotted in Mercator projection (origin at 180°E and 0°N)

fracture, and focal mechanism are limited and are not following the GPS derived plate velocity. Therefore, a 2D numerical simulation is conducted (Fig. 17) to understand the present day stress distribution over the Indian sub-continent introducing the material heterogeneity in terms of the computed effective elastic thickness. This study shows that the stresses in the NW Indian regions are more influenced by the Himalayan collision reaction forces, while those in southern regions are influenced by the material heterogeneity.

- Studies of the Earth's magnetic field using new data and new techniques illustrate the behavior of pulsations at low latitude sites. The characteristics of these events lead to the inference that the modes were compressional, which could be driven by K-H instability or solar wind dynamic pressure, as compressional modes can propagate to low latitude with little attenuation.

Planetary Studies

The Gravitational Field of the Moon has been determined by the tracking of radio signals emitted by orbiting Spacecraft data by inverting the gravity anomalies. Observations from the GRAIL mission have provided high precision and resolution gravity data of the Moon. Apart from several exciting features, the global topographic map (Fig. 18a) shows that the near side of the Moon (right half of the map) is at a lower elevation than the far side (left half) on average. The near side also has a thinner lunar crust, most of the lunar maria and mare basalts. The low areas (blue) are the floors of large impact basins. The large blue patch on the lower left is the South Pole-Aitken basin, the largest known impact basin in the solar system at 2500 km across and 12 km deep. The ancient SPA basin is scarcely visible in photographs because it is overprinted by more recent craters of various sizes. We have studied surface and subsurface density structures of mare fecundities region using the gravity anomalies and topography (Fig. 17b). The high positive gravity anomalies (Fig.

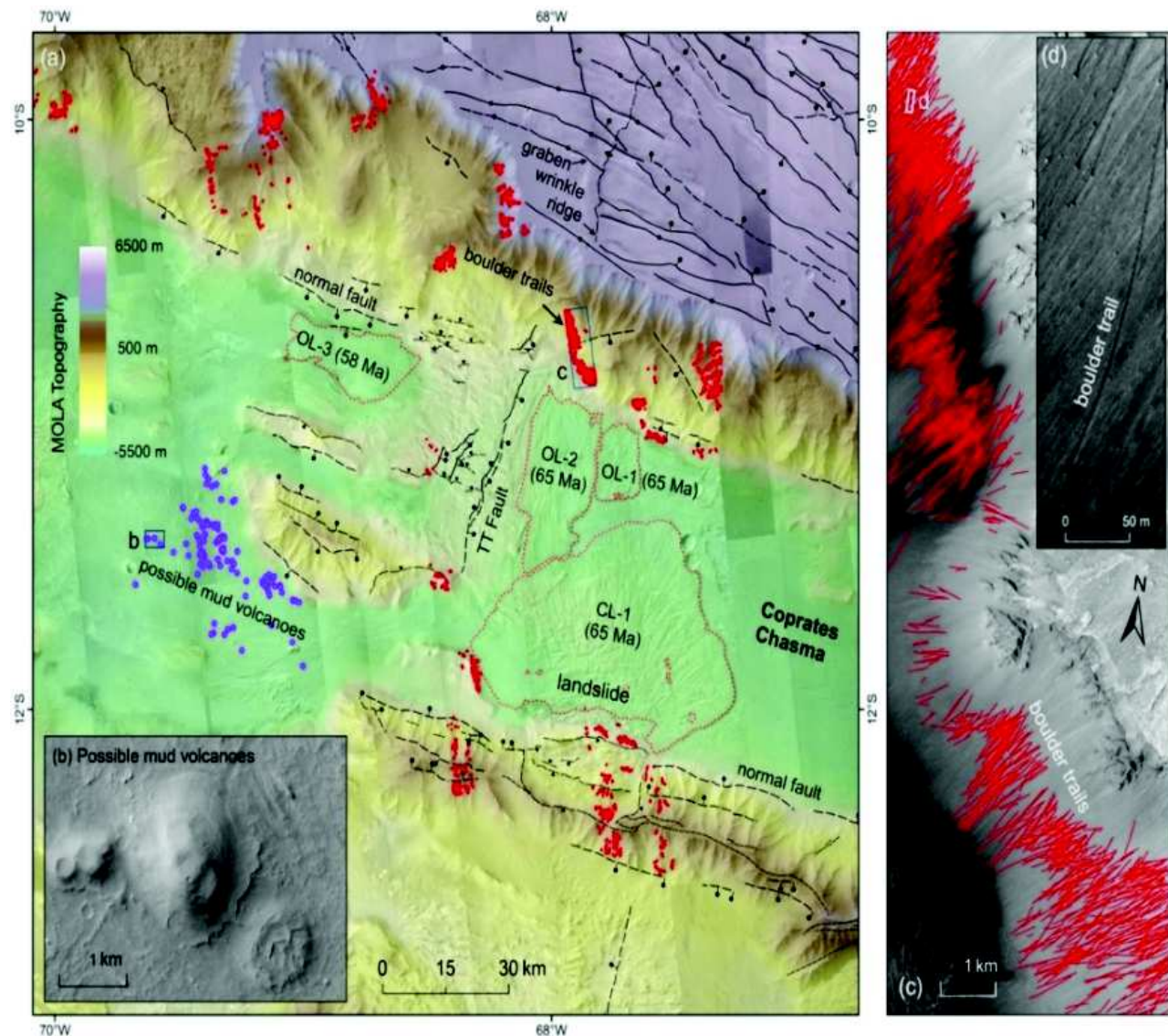


Fig. 19: Surface features of Valles Marineris canyon, Mars with background of MOLA topography superimposed on CTX imagery: (a) The interior of Coprates Chasma exhibiting the landslides with IDs (OL = Ophir Labes and CL = CopratesLabes) and model formation ages labeled; different types of faults, the boulder falls exhibiting the trails (red clusters), and mud volcanoes (blue open circles) are also shown. (b) Blow up of possible mud volcanoes, (c) the boulder trails (red polylines), sand dunes on HiRISE image and (d) illustrates a few boulders fall trails with boulders at their terminal ends

3.46c) observed in the proximity of wrinkle ridges of the region are attributed to plausible deep-seated intrusives beneath this region.

- Geomorphologic observations and crater size-frequency age determinations gleaned from high-resolution orbiter data demonstrate that the Valles Marineris region (Fig. 19) of Mars is seismotectonically active. The evidence suggests that the reactivated dip-slip faults cross-cut the

chasmata walls and floors with a total vertical displacement of 2 km, forming the fault bound trough. More than 16000 boulder-fall occurrences with pristine trails are observed along the chasmata wall, with an average slope of 25 degrees that are interpreted to be triggered by seismic shaking from the shallow marsquakes.

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primarily taken from the CSIR-NGRI Annual/Bi-Annual Reports (<https://www.ngri.org.in/annual-report.php>) and the publications listed therein.