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Institutional Report

Government of India, Ministry of Earth Sciences – Borehole Geophysics Research Laboratory, Karad, Maharashtra

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Introduction

Borehole Geophysics Research Laboratory is dedicated to carrying out scientific drilling and related borehole and laboratory investigations to address fundamental questions related to triggered seismicity in an intraplate setting under the Ministry's program titled "Scientific Deep Drilling in the KoynaIntraplate Seismic Zone, Maharashtra." The significant achievements during the quadrennial 2016-2020 include the completion of scientific drilling of a 3 km deep pilot borehole in the Koyna region, downhole geophysical measurements and analyses, core curation, laboratory geological and rock mechanical studies on core samples, development of R&D facilities and capacity building.The studies carried out so far provide new insights into the recurrent low magnitude earthquakes from geological, geothermal, and geomechanicalperspectives of the Koynaseismogenic zone and additionally yielded valuable inputs for further deep drilling and design of a deep borehole observatory in the region.

The work is done, and notable achievements during the quadrennial are summarised in this report.

Scientific Drilling of the Koyna Pilot Borehole

The highlight of the reporting period is the successful drilling of the Koyna pilot borehole KFD1 to a depth of 3 km near Gothane (17º17'57''N, 73º44'19"E), ~10 km SE of Koyna dam (Fig. 1) and the acquisition of downhole geophysical data. KFD1 is located in an area of repeating earthquakes in the Koynaseismogenic zone and proximity to the Donichawadi fissure zone, the surface manifestation of the 1967 M 6.3 Koyna earthquake (Gupta *et al*., 2017a). Passing through 1.25 km thick succession of Deccan basalt flows and continuing 1.75 km into the underlying granite-gneiss basement rocks, the borehole is the deepest drilled through crystalline rock formations in the country. A hybrid drilling technology comprising both air hammer and rotary mud techniques ensured that the drilling and associated measurements, as well as well completion procedures, were accomplished in 6 months from spudding of the borehole. The drilling operations were carried out in three phases. During phase I (December 20, 2016, to January 8, 2017), the borehole was drilled from the surface to 502 m, followed by casing and cementation. During phase II (January 11 to March 12, 2017), the borehole penetrated the basalt-granite intersection at 1251 m and reached a depth of 1503 m, where geophysical logging from 500 m to 1500 m was conducted in the open hole before the borehole was cased and cemented. Finally, during phase III (March 17 to June 11, 2017), the borehole reached the final depth of 3014 m. A photograph of the drill rig and associated equipment is shown in Fig. 2a and a schematic of the borehole configuration are shown in Fig. 2b. Cuttings were collected at 5 m intervals in basalt and 3 m intervals in the basement rock. Additionally, limited cores were collected from discrete depths in the 1500-3000 m section. To keep pace with the drilling, three field laboratories were functional on site: (i) geological laboratory, (ii) mud-logging laboratory, and (iii) online gas and fluid

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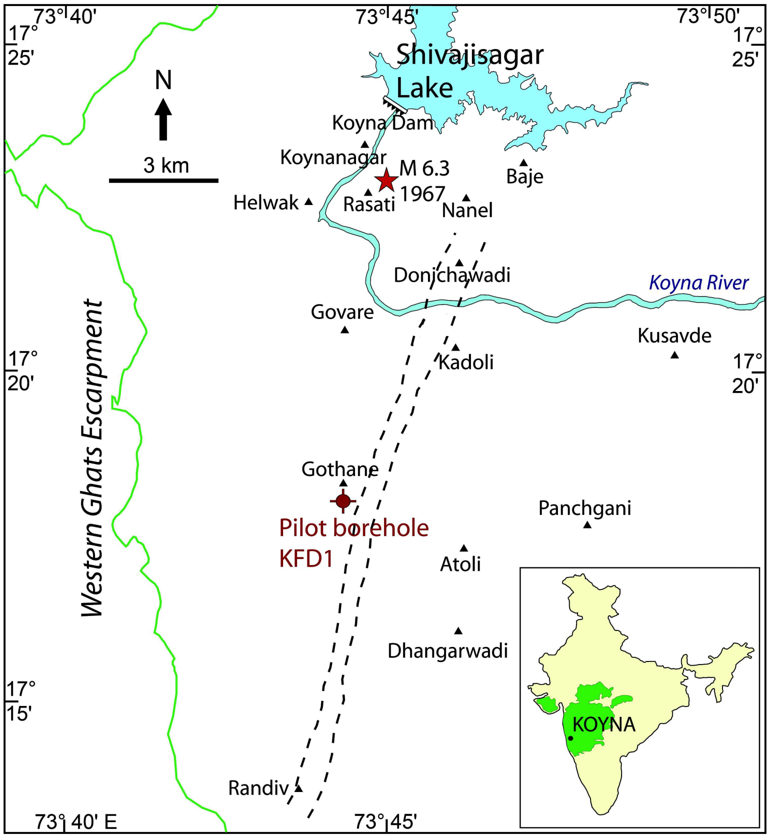

Fig. 1: Map of Koyna region showing the locations of the 1967 *M* 6.3 Koynaearthquake (red star) and the pilot borehole KFD1 (after Podugu *et al*., 2019). The trace of the Donichawadi fissure zone (dashed lines) formed during the 1967 earthquake [GSI (1968); Talwani (1997)] is also shown. Inset shows the location of Koyna within the Deccan Traps province (shaded green) on the outline map of India

sampling laboratory, set up in collaboration with International Continental Scientific Drilling Program (ICDP). Drilling Information System was developed in association with ICDP for archiving the drilling as well as geological data.

Downhole Measurements

Downhole geophysical logging in the borehole KFD1 was conducted to constrain physical and mechanical properties of the rock formation. Logging was done in two phases, first in the 12-1/4" diameter open hole section, 500-1500 m, after drilling down to 1500 m and before casing and cementation, and later in the 8-1/2" diameter open-hole section 1500-3000 m after completion of drilling to the final depth. The downhole measurements include electrical resistivity, self-potential (SP), density, neutron porosity, caliper, natural gamma ray, spectral gamma, temperature, and sonic. Additionally, acoustic, as well as microresistivity images of the borehole wall, were acquired. A plot of select geophysical well logs is shown in Fig. 3. In-situ hydrofrac tests were carried out in the basement section below 1600 m depth using a double straddle packer tool lowered into the borehole on a wireline (Fig. 4). Online gas monitoring and sampling were carried out in the granitic basement during drilling to study the concentrations of formation gases including CO_2, CH_4, H_2 and He and detect anomalous gas zones if any.

Laboratory Studies on Core and/or Cuttings

Cores and cuttings obtained from the pilot borehole KFD1, as well as the exploratory boreholes drilled previously to depths up to 1.5 km, have been studied and lithologs prepared. A typical section of core recovered from ~2900 m depth in KFD1 is shown in Fig. 5a and cuttings in Fig. 5b. Petrography and microstructural studies have been carried out primarily in the granitic basement rocks to identify potential deformation features associated with seismic activity in the region.

Further detailed studies are in progress. Geochemical analyses to characterize the basement rocks are underway. Uniaxial compressive strength tests and triaxial tests to distinguish rock strength, elastic properties, and deformation behavior of basement granitoids have been carried out. Measurements of thermo-physical properties of both Deccan basalt and basement granitoids have been completed.

Core Curation

Cores collected from various boreholes in the Koyna region are curated at BGRL. A systematic procedure has been evolved for providing core samples to scientific groups from the country and abroad. A digital core library is under development. Whole-round cores from the Koyna Scientific Drilling Project are optically scanned

Fig. 2: a. A view of the drilling rig and associated equipment at the Koyna pilot borehole site (Photo credit: RakeshRao)

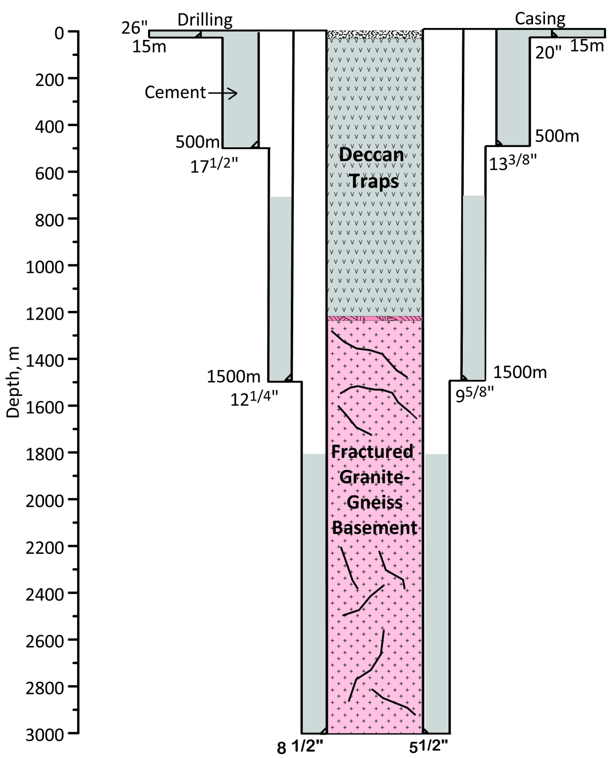

Fig. 2: b. Schematic showing well configuration and general litholog for pilot borehole KFD1

using a high-resolution core scanning system to generate 360° (unwrapped) images, which are archived in digital form. First of its kind in the country, the digital core library will support scientific studies and facilitate theme-specific sampling for detailed investigations (Tiwari *et al.*, 2017). A photograph of the core scanner at BGRL is shown in Fig. 6. The cores will be housed in a dedicated core repository, which is under development in Karad.

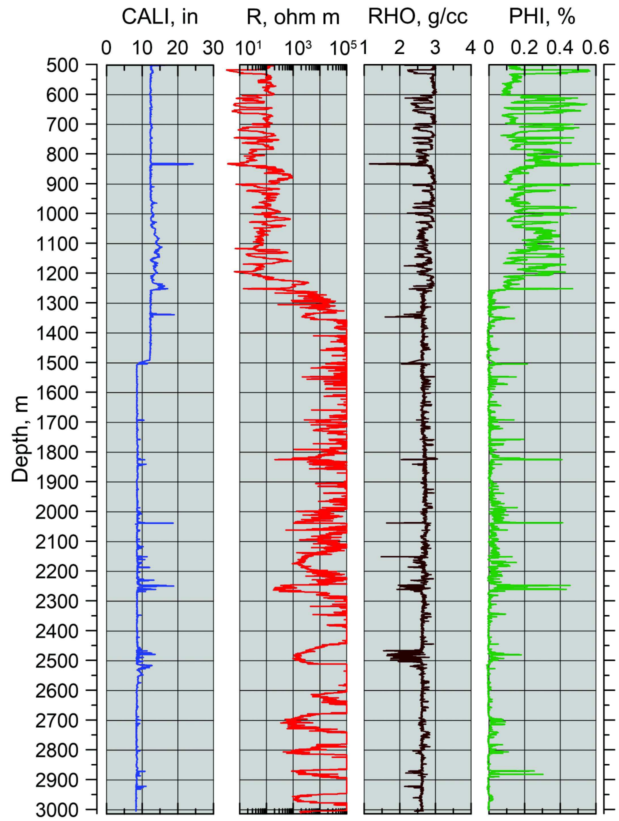

Fig. 3: Plot showinggeophysical logs (CALI: caliper, R: resistivity, RHO: density and PHI: porosity) obtained in the Koyna 3 km deep borehole KFD-1

Modeling Studies

Modeling studies to compute the poroelastic response due to reservoir impounding in the Koyna region have been taken up (Hazarika *et al.*, 2017; Yadav *et al.*, 2017). The evolution of pore pressure beneath the Koyna reservoir as a response to reservoir impoundment was studied by solving a fully coupled poroelastic model using a finite modeling technique. Computations were carried out using a range of permeability to examine its influence on the models. The studies suggest that the initial impoundment of the Koyna reservoir may have altered the pore pressure balance in the vicinity and formed a pore pressure front that gradually propagated beneath the reservoir with time. The model predicts that permeability of the order 10^{-15}-10^{-14} m^2 may be required to generate critical pore pressure changes in the range 0.1-1 MPa up to 10 km depth in the vicinity of the reservoir to facilitate triggering of earthquakes, fiveyears after its impoundment. Although the crystalline basement in the Koyna region comprises

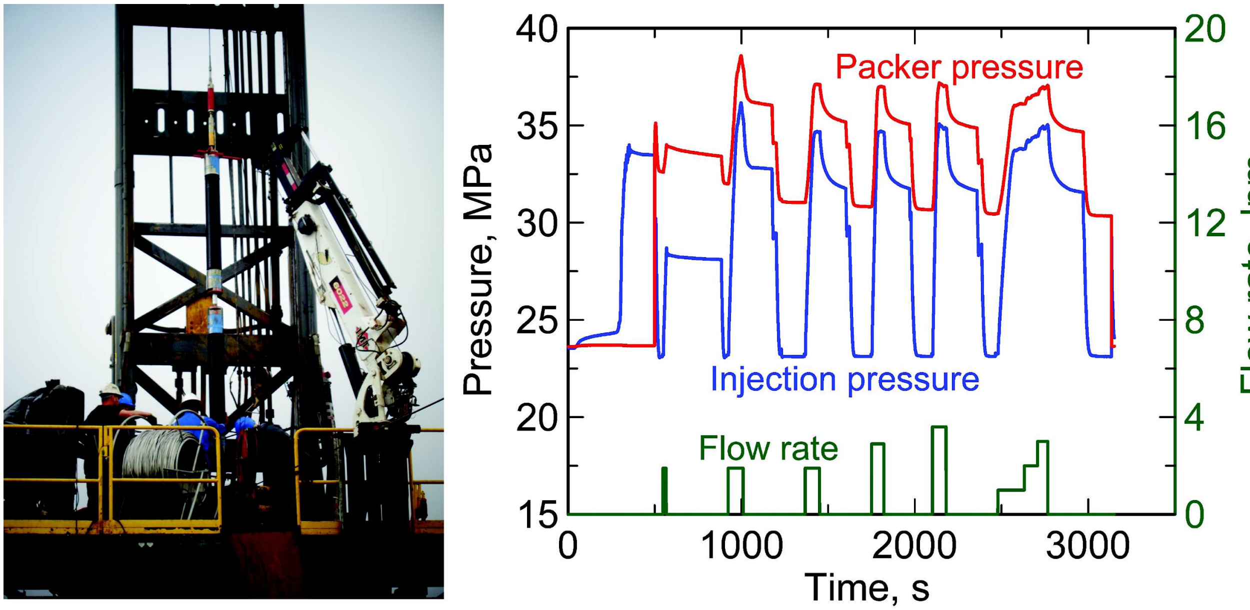

Fig. 4: Field set-up for hydraulic fracturing test (left) and pressure-time curves (right)

poorly permeable granitic rock, the occurrence of fracture zones, as evidenced by core samples and geophysical logs, may provide potential pathways for water channelization. Besides permeability, other factors such asfrictional strength and stress orientations may play a significant role in facilitating movement along faults. Studies on 3D modeling of pore pressure and stress regimes to explain the persistent seismicity in the region during the past five decades have been initiated.

International Workshop

An International Workshop on "Scientific Deep Drilling in Koyna" was conducted in association with ICDP during Oct 14-16, 2017, at Pune. The objectives of the Workshop were to review pilot borehole operations and associated studies, identify critical knowledge gaps and plans for future work. There were 65 participants, including 19 experts from France, Germany, Italy, Canada, Japan, Czech Republic, South Korea, Spain, Switzerland and the USA. The 3-day workshop included a field visit to BGRL-MoES Core Repository under development at Karad, where the borehole cores from a pilot borehole and exploratory boreholes were displayed (Fig. 7). The recommendations from the workshop are valuable for future scientific investigations in the Koyna region and the development of collaborative programs.

Salient Results

1. The succession of Deccan lava flows has been established from studies on core samples in the Koynaseismogenic zone. The trap thickness varies between 412 m and 1251 m, as obtained from the scientific drilling up to 3 km depth in the region (Gupta *et al*., 2017b; Roy, 2018). The succession comprising of a few tens of lava flows is directly underlain by granitic basement, with no infra-trappean sediments in between. A 1251.20 m long drill core recovered earlier at Panchgani, located close to the Koyna pilot borehole, represents the longest basalt core so far obtained in the region. Tentatively, 46 lava flows have been identified from the mesoscopic examination of the core, which opens up possibilities of integration with the streams exposed at the surface in the Koyna and the surrounding region and constrains the stratigraphy of the Deccan Traps in the area (Mishra *et al*., 2017).

2. The basement rocks underlying the Deccan Traps in the Koyna region up to a depth of 3 km comprise mainly of cratonic (Tonalite/Trondjhemite/granodiorite) gneisses of peninsular India, occurring as interlayer of granite, granite gneiss and varying proportion of migmatite gneiss. Granites are undeformed and massive.

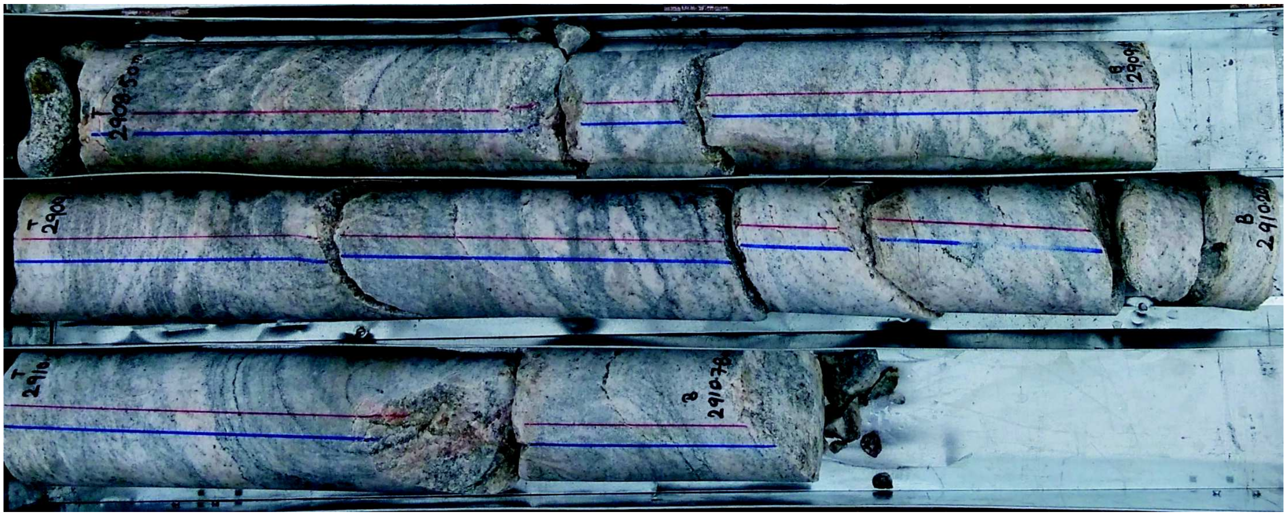

Fig. 5a: A section of granite-gneiss core recovered from KFD1 and stored in a metal box

Fig. 5b: Photograph showing typical drill cuttings of granite-gneiss retrieved from KFD1 and stored in plastic jars

Petrography of granite reveals dominantly quartzofelspathic composition. At places, potash felspars are present within pink granite. The minerals show interlocking arrangements within grains and no preferred alignment, typical of igneous textures. Granite gneiss and migmatite gneiss are comprised of hornblende,biotite and clinopyroxenes interlayered with segregated quartofeldspathic minerals defining the gneissosity (Misra *et al*. 2017). A Neoarchean age (~2700 Ma) for the basement granitoids has been reported (Bhaskar Rao *et al*., 2017).

3. The granitoids show segregation bandings of felsic and mafic minerals, which are reoriented and transposed by sheared fabrics. This evidence of ductile deformation is over-printed by brittle deformation represented by fractures and fault rocks. Local occurrences of pseudotachylite veins provide direct proof of seismic energy release along fault zones. Other deformation features are present as fault breccia and cataclasites in zones of intense brittle deformations, granular flow of brecciated and pulverized clasts, fault gouge, slickenlines on slickensides, clast-cortex aggregates and crystal plastic deformations of quartz grains (Misra *et al*., 2017).

4. Fractures within the fault zones are filled with secondary precipitation, which is frequently ferruginous but also comprises carbonaceous, siliceous and clay minerals. Occurrences of epidotes and sericitized feldspars along the fractures constitute direct evidence of hydrous alteration. These observations provide strong support for water channelization through the fractures in granitoid rocks at depth (Misra *et al*. 2017).

5. Physical and mechanical properties of the basement granitoids have been determined from downhole measurements up to a depth of 3 km. The granitic basement is characterised by mean density of 2.65±0.1 (sd) g/cc, low porosity in the range 0.1 to 1%, P-wave velocity in the range 5.8 to 6.2 km/s, S-wave velocity in the range 3.4 to 3.8 km/s, Poisson's ratio 0.22 to 0.24 and Young's modulus 78 to 90 GPa (Goswami *et al*., 2019a).

Fig. 6: Photograph of Core Scanning System at BGRL

Fig. 7: Display of cores from Koyna Scientific Drilling Project at BGRL-MoES, Karad

6. Fault damage zones have been identified at multiple depths between 2000 m and 3000 m in the Koyna pilot borehole based on anomalous geophysical properties, significant stress-induced shear wave velocity anisotropy and rotation in fast polarised shear wave orientation (Goswami *et al*., 2019a).

7. Study of formation gases during the drilling of the Koyna pilot borehole revealed gas-rich zones characterized by anomalous helium concentrations up to 12.8 ppmv, more than sevenppmv above the atmospheric level. Helium isotope measurement confirms that the helium gas comprises of radiogenic and atmospheric helium, but no mantle helium. He-rich zones correlate well with the fault damage zones identified from geophysical logs and are characterized by high fracture density as revealed from borehole images. The helium concentrations are consistent with those previously observed over the surface fissures near Kadoli, suggesting a southward extension of the Donichawadi fault zone up to pilot borehole site and confirming that the fault zone is permeable even after 50 years of the 1967 Koyna earthquake (Podugu *et al*., 2019).

8. The in-situ stress regime of the Koyna region has been inferred from the analysis of geophysical logs down to a depth of 3 km. The Koynaseismogenic zone is characterised by critically stressed strike-slip to normal faulting environment (Goswami *et al*., 2019b).

9. The thermal regime beneath the Koynaseismogenic zone has been established from deep holetemperature measurements and thermal conductivity measurements on drill core samples in the laboratory. The temperature at a depth of 3 km is ~78^{o}C. The region is characterised by low heat flow, typical of the thermal regime in the adjoining Achaean Dharwarcraton. The new data lead to an estimate of 130^{o}±20^{o} C at 6 km depth. Although temperature considerations allow for a deeper ($\geq$25 km) seismic-aseismic transition, the vast majority of earthquakes occur in the uppermost 10 km.

10. The basement granitoids are characterised by low and variable rock strength (15 MPa to 130 MPa). Because rock strength is locally weakened at different depths in the Koynaseismogenic zone by successive seismic activities, stress accumulation within the rock mass is unlikely to be high enough to produce large earthquakes. A large number of low magnitude earthquakes in the Koyna region during the past few decades may be attributed to low and variable rock strength of the basement granitoids (Goswami *et al*., 2017a,b).

11. New information on rock types up to depth of 3 km, deformation features in the granitic basement, physical and mechanical properties of the basement granitoids, hidden fault damage

zones from in-situ geophysical and geochemical datasets, in-situ stress and temperature provide a functional characterization of the geological, geothermal and geomechanical regime in the Koynaseismogenic zone. When combined with seismological observations, the new datasets provide focussed targets for further seismic monitoring by the installation of a multi-level seismometer array up to 3 km depth and design of deep borehole observatory at a depth of 5-7 km in the region.

12. A numerical modeling framework for studying the evolution of pore pressure and subsurface stress distribution in response to reservoir loading has been prepared. A preliminary study indicates the role of permeability required to induce critical pore pressure changes capable of triggering earthquakes in a critically stressed region (Hazarika *et al*., 2017).

13. A vital offshoot of the scientific drilling experiment is the discovery of microbial life within the deep, hot (~80ºC) biosphere and their role in carbon and another element cycling. The study, carried out by a team of scientists from the Indian Institute of Technology, Kharagpurin collaboration with BGRL/MoES,provides new insights intothe evolution of life and their function in this planet and beyond (Dutta *et al*., 2018, 2019a,b).

Future Plans

Significant progress has been made in different components of the Koyna scientific deep drilling project, such as the completion of the pilot phase, the establishment of a research laboratory, the development of deep drilling and measurement plans and the initiation of several laboratory experiments and modeling studies. The work carried out so far provide a base to carry out further studies that include seismological monitoring in the pilot borehole, scientific deep drilling to 5-7 km depth and downhole measurements, establishment of deep fault zone observatory to study temporal changes in physical, mechanical and chemical properties before, during and after occurrence of earthquakes, development of advanced laboratory facilities for undertaking geological and geophysical measurements on fault zone rocks obtained from deep drilling, acquisition of seismological and other field data sets from deep borehole observatory (long-term monitoring), data analysis, data integration and modeling to comprehend the genesis of reservoir triggered earthquakes in an intraplate tectonic setting, education and outreach.

Contributors

The work summarized in this report was carried out by a team of scientists, namely, Surajit Misra, Vyasulu V. Akkiraju, Nagaraju Podugu, Deepjyoti Goswami, Thomas Wiersberg, Pinki Hazarika, Amrita Yadav, Satrughna Mishra, Sanjay Tiwari, Anup Sutar, Vishnu, C S, Sunil Rohilla, MatsyendraShukla and Pinaki Sar, who were ably assisted by Srihariprasad G, Digant Vyas, Ashish Warhade, Dinesh Nikalje, Pallavi Tembhurnikar and Vikrant Bartakke.

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