Sci. Dril., 18, 5–9, 2014
www.sci-dril.net/18/5/2014/
doi:10.5194/sd-18-5-2014

Scientific Drilling
Open Access

Probing reservoir-triggered earthquakes in Koyna, India, through scientific deep drilling

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Received: 4 August 2014 – Revised: 19 September 2014 – Accepted: 2 October 2014 – Published: 22 December 2014

Abstract. We report here the salient features of the recently concluded International Continental Scientific Drilling Program (ICDP) workshop in Koyna, India. This workshop was a sequel to the earlier held ICDP workshop in Hyderabad and Koyna in 2011. A total of 49 experts (37 from India and 12 from 8 other countries) spent 3 days reviewing the work carried out during the last 3 years based on the recommendations of the 2011 workshop and suggesting the future course of action, including detailed planning for a full deep drilling proposal in Koyna, India. It was unanimously concluded that Koyna is one of the best sites anywhere in the world to investigate genesis of triggered earthquakes from near-field observations. A broad framework of the activities for the next phase leading to deep drilling has been worked out.

1 Introduction

During 16–18 May 2014, an International Continental Scientific Drilling Program (ICDP) workshop on Scientific Deep Drilling in the Koyna region of western India was held in Koyna. It was jointly organized by the Council of Scientific and Industrial Research (CSIR)-National Geophysical Research Institute (NGRI), Hyderabad and the National Center of Antarctic and Ocean Research (NCAOR), Goa on behalf of the Ministry of Earth Sciences (MoES). This was in continuation of an earlier ICDP workshop held in March 2011 (Gupta et al., 2011) where an exploratory phase of investigations involving compilation and improvement of the hypocentral parameters through operation of additional seismic stations; MT surveys; lidar; airborne geophysical surveys; core drilling at four sites, and modeling of hydraulic connectivity etc. were recommended to be undertaken prior to planning of the deep borehole(s). The purpose of the current workshop was to bring together key experts to discuss results of the exploratory phase, to deliberate on the design of the deep borehole(s), to decide on the instrumentation to be deployed, to build an international science team, and to provide necessary inputs for preparation of a full drilling proposal.

There were 49 participants: 37 from India and the remaining 12 from Canada, France, Germany, Japan, New Zealand, Norway, Spain, and USA. Participants included seismologists, geologists and drilling and instrumentation experts having experience in working on deep drilling sites globally.

The Koyna region, located in the $\sim$65 Ma old Deccan Traps of India (Fig. 1), is globally the most prominent site of artificial water-reservoir-triggered earthquakes, also known as reservoir-induced earthquakes (Gupta, 2011). Soon after the impoundment of the Shivaji Sagar Lake formed by the Koyna Dam in 1962, triggered earthquakes started occurring and have continued until now. This includes the $M = 6.3$ 10 December 1967 earthquake; 22 earthquakes of $M > 5$, and over 200 $M > 4$ earthquakes plus thousands of smaller

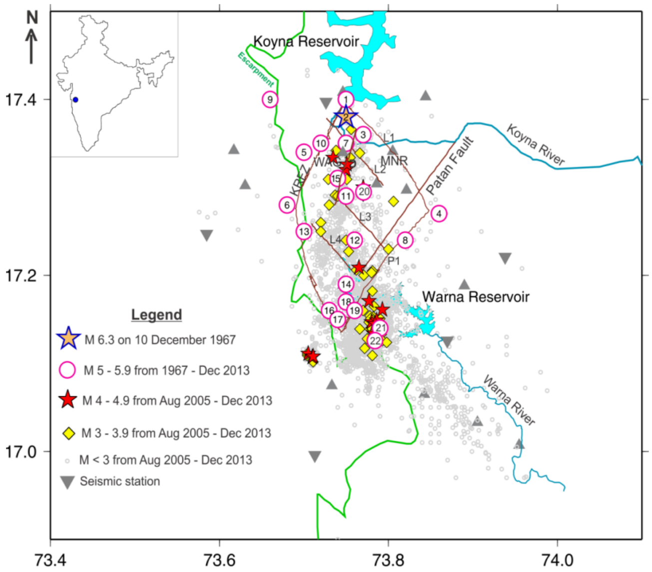

Figure 1. Seismic stations and earthquakes in Koyna–Warna region. KRFZ: Koyna River fault zone; D: Donichiwada Fault; P1: fault parallel to Patan Fault; L1, L2, L3, and L4: NW–SE trending fractures. Inset: Koyna on India's map.

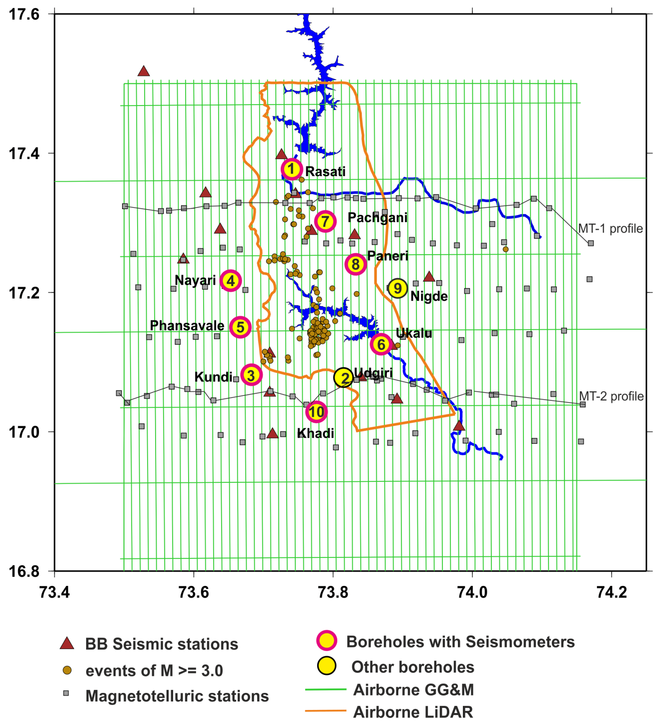

Figure 2. Map of the study area. Green lines indicate the airborne gravity gradiometry and magnetic data flight lines. An orange line encloses the airborne lidar acquisition area. Grey squares indicate MT sites. Red triangles are broadband seismological stations. Numbered circles indicate the locations of exploratory boreholes which are being drilled and logged. Borehole 2 could not be logged; 9 and 10 are planned. Boreholes in Rasati and Kundi have been instrumented with three component seismometers at depths of 1522 and 1134 m, respectively. The remaining six boreholes are to be instrumented in the next few months. Brown filled circles indicate earthquakes of magnitude greater than 3 for the period 2005 to 2013.

earthquakes. Filling of the nearby Warna Reservoir in 1985 caused further expansion of the triggered earthquake zone. A strong association of earthquake activity is observed with the annual loading and unloading cycles of the two reservoirs (Gupta, 2002). The entire earthquake activity is limited to an area of about 20 km × 30 km, with the focal depths of most of the earthquakes lying between 3 and 8 km. There is no other earthquake source within 50 km of the Koyna Dam. Accessibility to the epicentral zones makes the Koyna/Warna site well suited for earthquake-related near-field observations. An earthquake of $M = 3.2$ occurred on 15 May 2014 in the Koyna region, a day prior to the commencement of the workshop.

2 Proceedings of the workshop

The first day of the workshop was dedicated to discussing the scientific questions that need to be addressed. Several of these are taken from the SAFOD program (Zoback et al., 2011). These include the following:

1. What is the fluid pressure and permeability within and adjacent to the fault zone?
2. What are the composition and origin of fault-zone fluids and gases?
3. How do stress orientation and magnitude vary across fault zones?
4. How do earthquakes nucleate?
5. How do earthquake ruptures propagate?
6. How do earthquake source parameters scale with magnitude and depth?
7. What is the role of water reservoirs in triggering earthquakes?
8. What is the 3-D/4-D nature of the fault zone?

Although several studies have clearly established the association of continued triggered earthquakes in Koyna with the precipitation-driven loading and unloading of the Koyna and Warna reservoirs, the triggering mechanism is not well understood. Our knowledge about the physical properties of rocks and fluids in the fault zones and how they affect the buildup of stress for extended period is limited by the lack of data from the near-field region.

Existing geological, hydrological and geophysical studies in the region provide a good initial framework to study the regional tectonic setting but lack critical inputs needed to explore the physical mechanisms that connect the reservoir water level changes to the occurrence of earthquakes. The clear evidence provided by past seismic activity makes a compelling case for bringing new scientific tools to probe the triggered seismicity in the Koyna area. The proposed scientific deep drilling and setting up of a deep borehole observatory is aimed to study pre-seismic, co-seismic and post-seismic changes in physical properties in the "near-field" of earthquakes and provide answers to the abovementioned questions. By instrumenting the deep borehole for long-term monitoring of critical parameters such as seismicity, temperature, fluid/gas and pore pressure, it would be possible to obtain unprecedented new information on the temporal changes of those parameters in the near-field of earthquakes before, during and after an earthquake.

Studies carried out since 2011 in the preparatory phase were reviewed, including detailed airborne magnetic and gravity-gradient surveys, MT surveys, drilling and logging of six boreholes going to depths of ~ 1500 m, heat flow measurements, seismological investigations including the deployment of two borehole seismometers, and lidar surveys (Fig. 2).

Among the most significant results are those obtained from the six boreholes on the thickness of the Deccan Traps basalt and its relation to the basement and the geophysical environment to be encountered in deeper drilling. These holes were continuously cored and penetrate through the Deccan Traps into the Archean basement. It was found that the basal flows rest directly on basement with no intervening sedimentary layers. The basement contact is almost horizontal indicating very little topography of the basement across the Western Ghats escarpment. It was also inferred that the temperature at a depth of 5 km will be around 130 to 150 °C, confirming earlier estimates. Seismic waveform modeling and double difference approach to earthquake relocation have helped in better understanding the hypocentral distribution and fault geometry. To achieve desired accuracies of a few tens of meters, seismometers need to be placed below the basalt cover. This has led to the plan of putting eight borehole seismometers with good azimuthal coverage around the earthquake zone. Two of them are already in operation and six more are planned to be installed in the months to come.

As part of the workshop, talks were given addressing a deep borehole observatory plan, earthquake nucleation, geochemical control on fault reactivation, stress regime in the Indian subcontinent, borehole seismology, role of fluids in triggering earthquakes, temperature monitoring in boreholes, and physical properties from well logs and laboratory measurements. Posters on the investigations were displayed to encourage discussions throughout the 3 days of the workshop. The day ended with a visit to the Panchgani drilling site (Fig. 4).

The second day was dedicated to discussions in the following three breakout groups:

a. main hole(s) drilling, down hole measurements and sampling,

b. main hole(s) completion plan, observatory design and installation plan, and

c. sample management, distribution and laboratory studies.

Coordinators for each of these three groups led the discussions and managed to converge on practical plans. International collaboration was another issue that was discussed on the second day. The day ended with boating on Koyna Lake.

On the third day, a presentation was made on ICDP participation, training and equipment setup maintained by trained personnel of the Operational Support Group (OSG). Available facilities include the following:

- online gas monitoring while drilling
- Slim Wave™ Geophone Chain
- core scanning and logging
- data management system.

The schedule for the use of these facilities has to be made well in advance.

The coordinators of the three breakout groups presented their recommendations to the entire workshop, which were discussed in detail.

3 Outcome of the workshop

All the participants appreciated the progress made since the first ICDP workshop held in March 2011. The sites of the pilot hole(s) and the main bore hole(s) were tentatively agreed upon (Fig. 3). A broad framework for the future work was chalked out. It was concluded that Koyna is the best site for addressing the questions that need to be resolved for an improved understanding of reservoir-triggered earthquakes and that answers can be found through deep drilling. The major outcome of the workshop may be summarized as follows:

1. Details of geophysical, geological, airborne studies and borehole measurements carried out during the preparatory phase of the past 3 years and their broad results form a solid basis for upcoming investigations in this area. Based on gravity, magnetic, seismic and MT data, a 3-D structure of the region has been worked out, which has been validated from the information obtained from the six boreholes drilled down to ~ 1500 m depth and other geoinformation.

2. The results of recording of two borehole seismometers at depths of 1134 and 1522 m, several hundred meters into the basement, have been very encouraging. It is seen that earthquakes of $M < 1$, which are almost a part

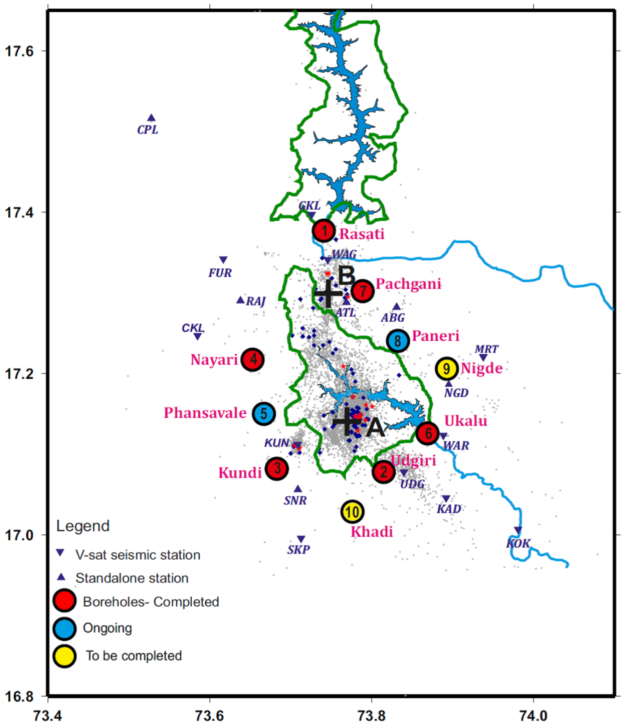

Figure 3. Locations of exploratory boreholes vis-à-vis seismic clusters. Black crosses mark proposed locations of pilot boreholes. The grey, blue and red dots represent epicenters of seismic activity over the last 9 years in increasing order of magnitude from 1.8 to 5.5. Green lines mark boundaries of reserve forest areas surrounding the Koyna (north) and Warna (south) reservoirs.

of the noise on the surface station, are clearly recorded by the borehole seismometers. Six additional borehole seismometers are suggested to be deployed to help to constrain the geometry of the active fault and provide information critical for fine-tuning the location of the pilot and main borehole(s).

3. For a better comprehension of the mechanism of earthquake occurrence and the part played by reservoirs in triggering earthquakes, it was recommended to have two pilot and two main boreholes, hosting comprehensive sets of monitoring instruments. Originally only one pilot bore hole and one main bore hole were planned (A in Fig. 3). However, an additional pilot bore hole and a main borehole (B in Fig. 3) located close to the second-most active seismic cluster in the Koyna region, were recommended. Operation of two bore well observatories would provide exceptional opportunities to address the questions posed earlier.

   The well scheme for the 3000 m deep pilot hole (Table 1) was proposed. The following is a suggested drilling approach:

   – pre-conditions
     – no high-pressure zone
     – no influx of gas, hydrocarbons, corrosive fluids
     – no mud-loss zone
     – no high temperature environment
     – anticipated rate of progress from core drilling 1–2 $m\,h^{-1}$
   – drilling objective
     – react to potential mud losses in and at the base of basalt; increase the drilling performance drastically over core drilling (3–4 $m\,h^{-1}$).
   – rig specification
     – 300 t hook-load capacity
     – 2$\times$ triplex mud pumps (1000 kW each)
     – top-drive desirable (else rotary table)
     – 3000 m of 5 in. DP+5 in. HWDP+6 1/4 in./8 1/4 in./9 1/2 in. DC
   – drilling techniques
     – classic rotary drilling: with mud motors or turbine, 3R-insert bits, polycrystalline
     – diamond bit (PDC) or impregnated bits
     – air hammer: fast, environmental issues (noise at surfaces $>$ 80 db, plus air pollution). Rotary mud-drilling is less noisy.
     – having an option to switch any time over from air drilling to mud rotary drilling, logging, casing and cementation.
   – mud system: water-based polymer mud (SG = 1,2)
   – directional drilling: max tolerable verticality: $\sim 1.5^\circ$ inclination.
   – coring: on-demand spot coring is possible any time, not needed in basalt, is not primary task in pilot hole, might be if penetrating fault zone

4. An outline of the logging and other measurements along with possible instrumentation for the pilot boreholes was discussed in detail. Commencement of drilling the pilot borehole(s) must be as early as possible. Necessary instrumentation and equipment also need to be procured.

5. International collaboration is welcome and will be established through bilateral agreements for investigation of specific research problems with approval of MoES and/or ICDP.

6. An Integrated Data Management System and GIS platform will be put in place to enable external participation and optimize interpretations.

Table 1. Well scheme.

Hole diameter	Casing size	Setting depth
17.5 in.	13.38 in.	400 m
12.25 in.	9.63 in.	1400 m*
8.5 in.	5.5 in.	3000 m

*Option of one contingency casing 7 in. liner after 9 5/8 in. casing to mitigate uncertainties/surprises. All casing, drill bits and other consumables are of API standards.

Figure 4. Participants at the Panchgani drill site.

7. Permissions necessary to put experiments and drilling in the reserve forest area should be obtained on a priority basis.

8. A full drilling proposal for the main borehole(s) is foreseen to be prepared in due time to meet the 15 January 2015 deadline of submission to the ICDP.

4 Broad schedule for the future work

- Submitting a proposal to ICDP for the main boreholes by 15 January 2015. Details need to be worked out.

- Drilling of two 3 km deep pilot boreholes by summer of 2015 (leap-frog with two rigs).

- Concurrent planning of deep main borehole(s), firming the specifications by the summer of 2015 and drilling from October 2015 through December 2017.

- Plan for an international meeting and visit of the facilities in December 2017 to coincide with 50 years of Koyna $M = 6.3$ earthquake of 10 December 1967.

The workshop provided an excellent opportunity to discuss with the global community the work carried out in the preparatory phase since the first ICDP workshop of March 2011 and to firm up the future plan of action. There was much appreciation of the work reported and concurrence on the future course of work.

Acknowledgements. We are grateful to all the participants for their contribution to the workshop at a short notice. We thank Hans Kuempel and Art McGarr for providing constructive reviews. Brian Horsfield and Uli Harms facilitated the workshop. The workshop was funded by the Ministry of Earth Sciences, Government of India and the International Continental Scientific Drilling Program (ICDP), Potsdam.

Edited by: T. Wiersberg
Reviewed by: A. McGarr and H.-J. Kuempel

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