CONTINUED RESERVOIR TRIGGERED SEISMICITY AT KOYNA, INDIA

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The first scientifically proven site of triggered earthquakes was Lake Mead, USA during 1930s.

Globally, there are over 120 Artificial Water Reservoir sites where triggered earthquakes have occurred.

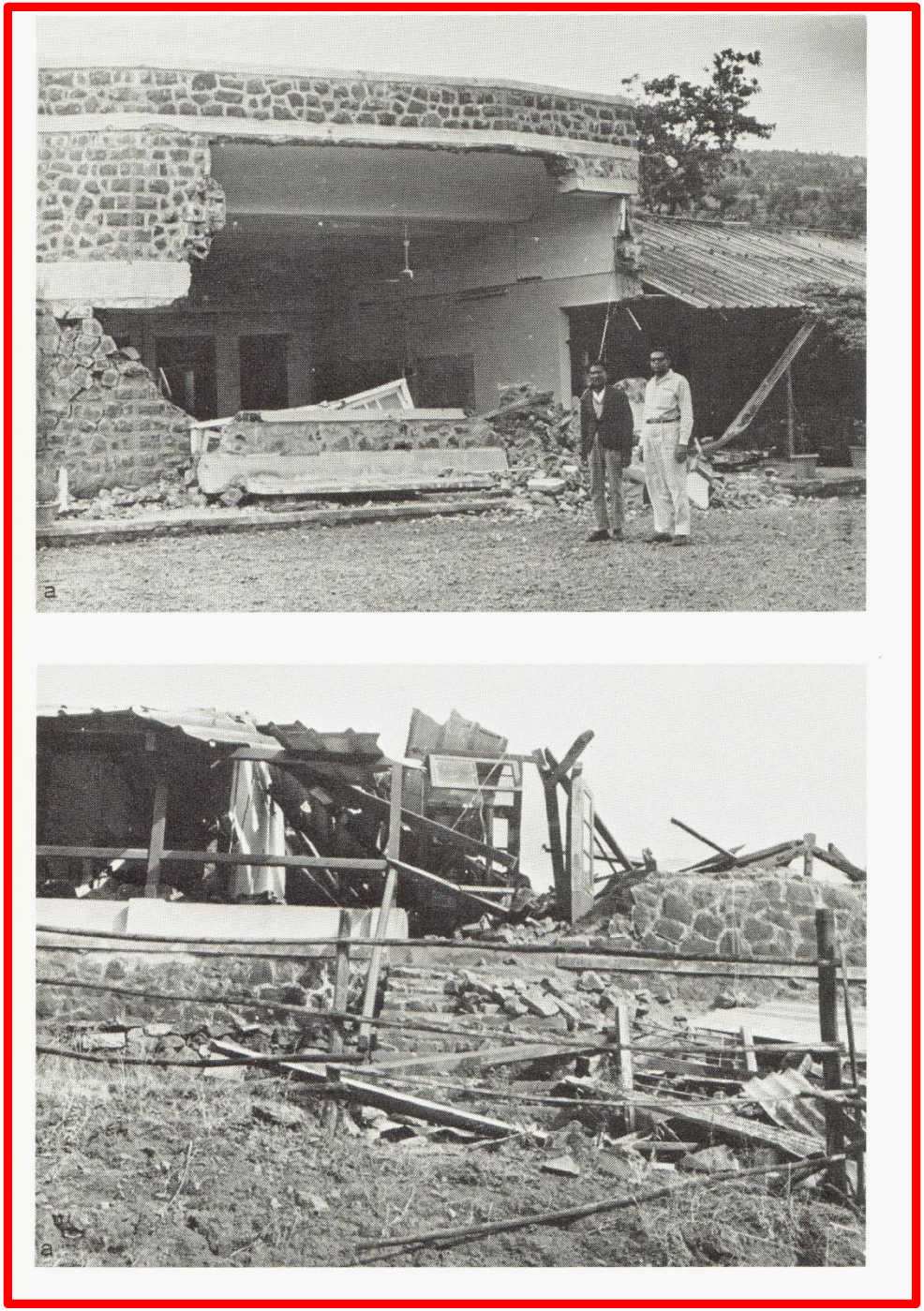
Majority of the sites where triggered earthquakes of $M \geq 5$ occurred are in SCR.

Damaging earthquakes **exceeding magnitude 6** have occurred at:

- Hsingkengfiang (China)
- Kariba (Zambia-Zimbabwe border)
- Kremasta (Greece)
- Koyna (India)

Dec 10, 1967; M 6.3 earthquake at Koyna is so far the largest accepted artificial water reservoir triggered earthquake.

- ***Lives lost 200***
- ***Koyna township destroyed***



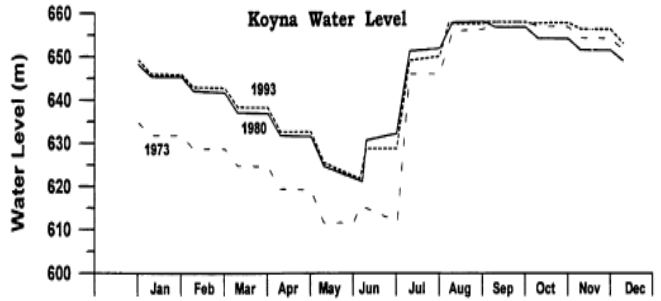
Damage to the houses belonging to the first category

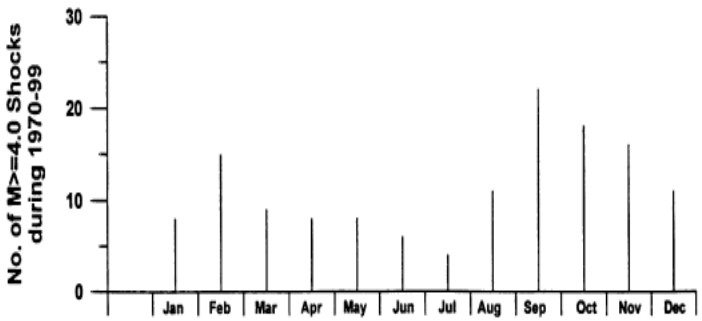
The stone masonry arch bridge on the Helwak-Chiplum road collapsed

Rotational displacement of a pillar at Donchiwadi

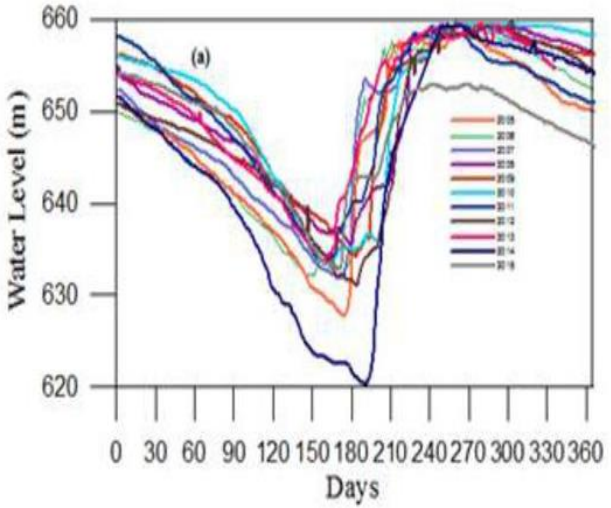
Correlation of water levels with the seismicity of Koyna –Warna

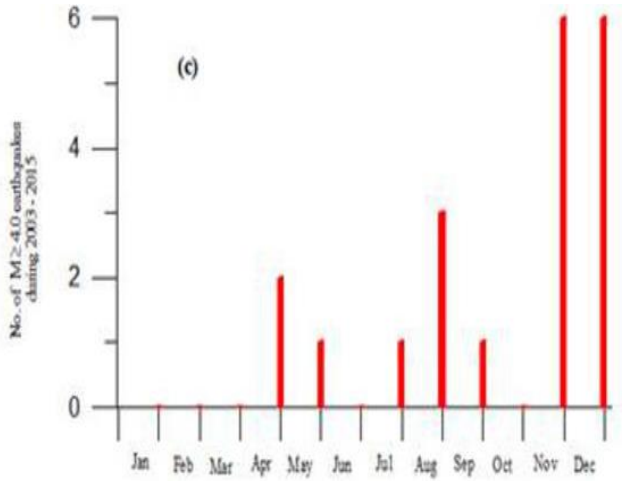
During 1970 - 1999





During 2003 - 2015

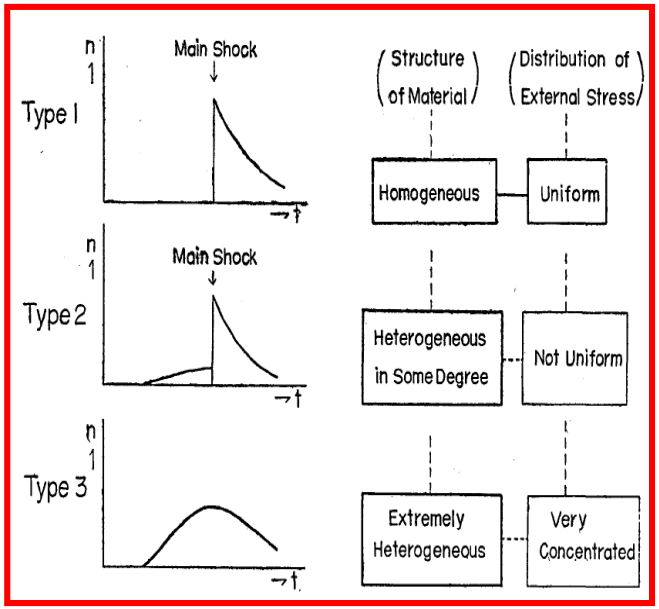


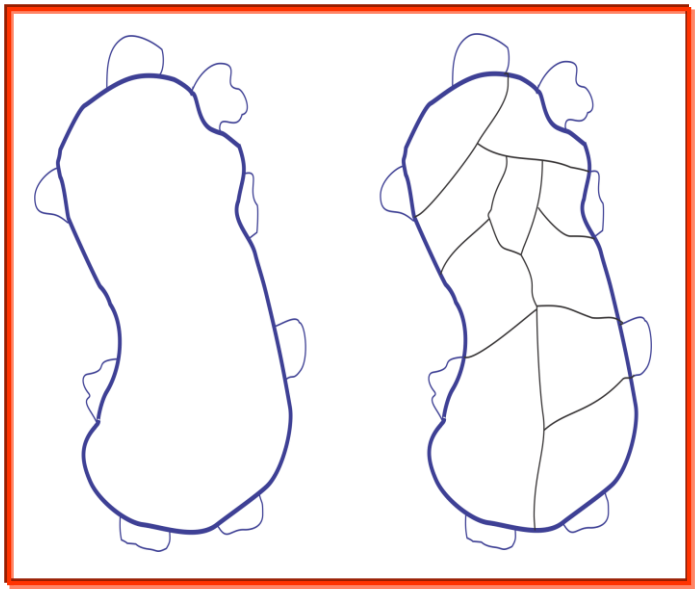


Common Characteristics of RTS

- Log N =a-b m
- Largest aftershock to mainshock magnitude
- Foreshock-aftershock pattern
- Aftershock continue for a long time

Mogi's classification of foreshock-aftershock patterns





Energy released in Koyna region

The Max. Credible Earthquake ($\mathbf{M_{CE}}$) considered for Koyna: **M = 6.8**
Empirical relation used: **Log E = 1.5 M + 11.8**, (M = magnitude)
Using the above relation $\mathbf{E_{MCE} = 10^{22}}$

Energy released so far:

➢ Case 1:

$E = 1 \times E_{M6.3} + 22 \times E_{M\,5.5} + 200 \times E_{M\,4.5}$

$= 10^{(21.25)} + 22x10^{(20.05)} + 200x10^{(18.55)} = 10^{21.94}$

Percentage of $M_{CE} = 10^{21.94} / 10^{22} =$ **87 %**

➢ Case 2:

$E = 1 \times E_{M6.3} + 22 \times E_{M\,5.3} + 200 \times E_{M4.3}$

$= 10^{(21.25)} + 22x10^{(19.75)} + 200x10^{(18.25)} = 10^{21.51}$

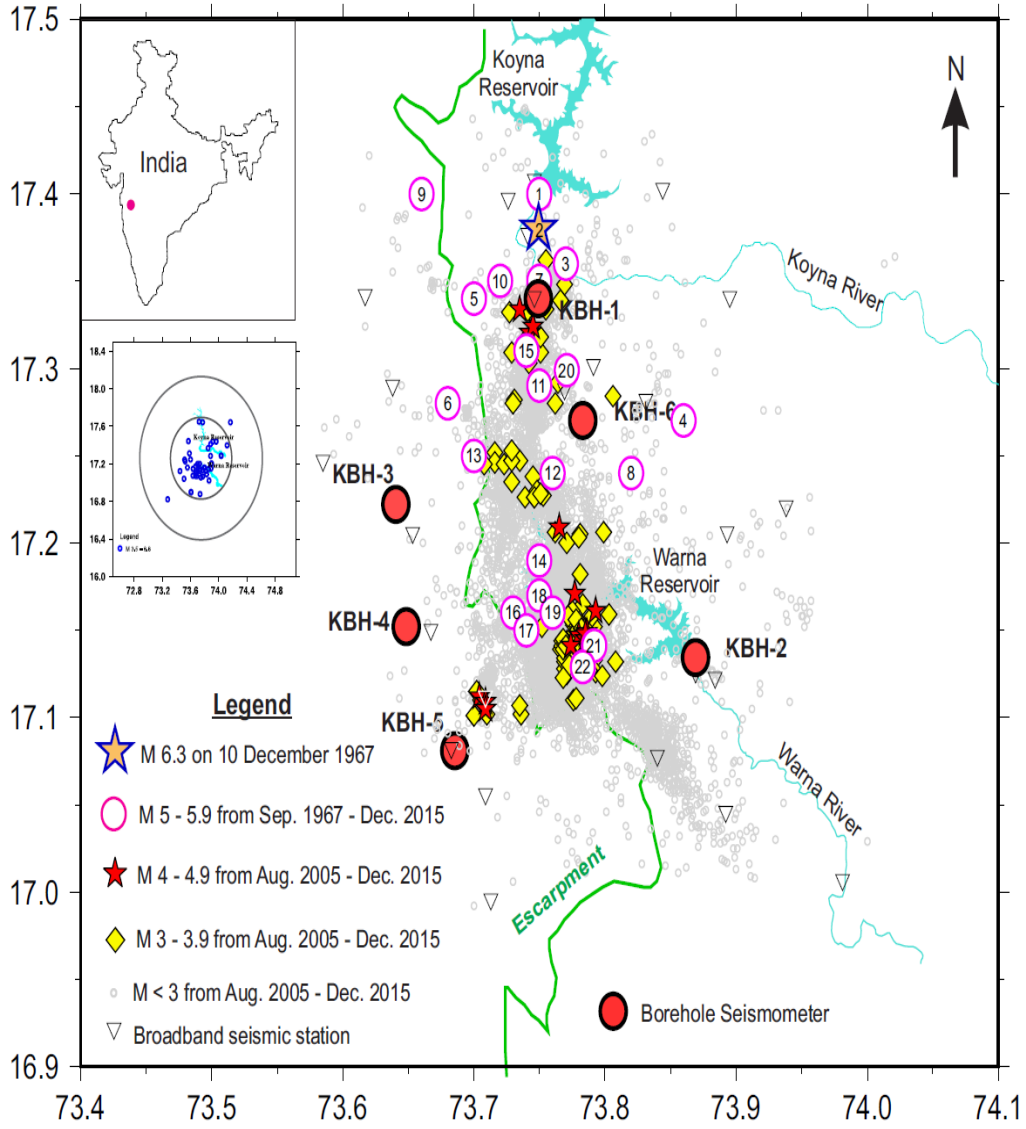
Percentage of $M_{CE} = 10^{21.51} / 10^{22} =$ **32 %**

Considering the average of the above 2 extreme cases,

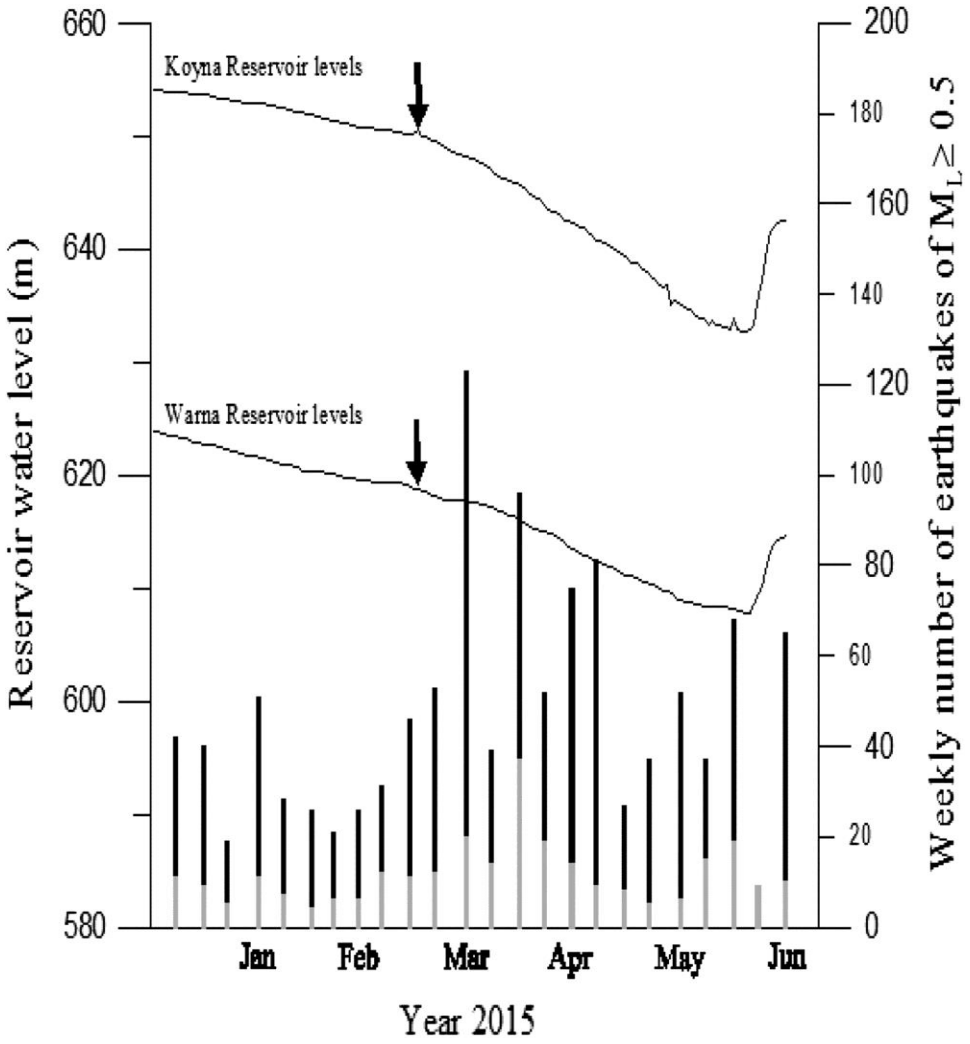
About **60%** of energy may have been released in Koyna

M~5 EVENTS WILL CONTINUE AND THEIR OCCURRENCE WILL BE GOVERNED BY KAISER EFFECT, RATE OF LOADING OF THE RESERVOIRS, HIGHEST WATER LEVELS REACHED AND DURATION OF RETENTION OF HIGH LEVELS

Seismicity of the Koyna-Warna region, existing seismograph network and fault zones



Reservoir water levels at Koyna and Warna with corresponding to earthquakes recorded at Surface and Borehole network during the unloading phase



unloading rate of the Koyna reservoir increases from 0.053 to 0.170 m/day and of the Warna reservoir from 0.065 to 0.106 m/day during the 3rd week of March, 2015.

A UNIQUE SITE TO INVESTIGATE RTS

- Earthquakes occur in a small area (20 km x 30 km)
- Shallow (2-7 km mostly)
- No other source within 50 km of Koyna Dam
- Accessible for experimentation, and
- Continued activity over the past 54 years as of 2016.

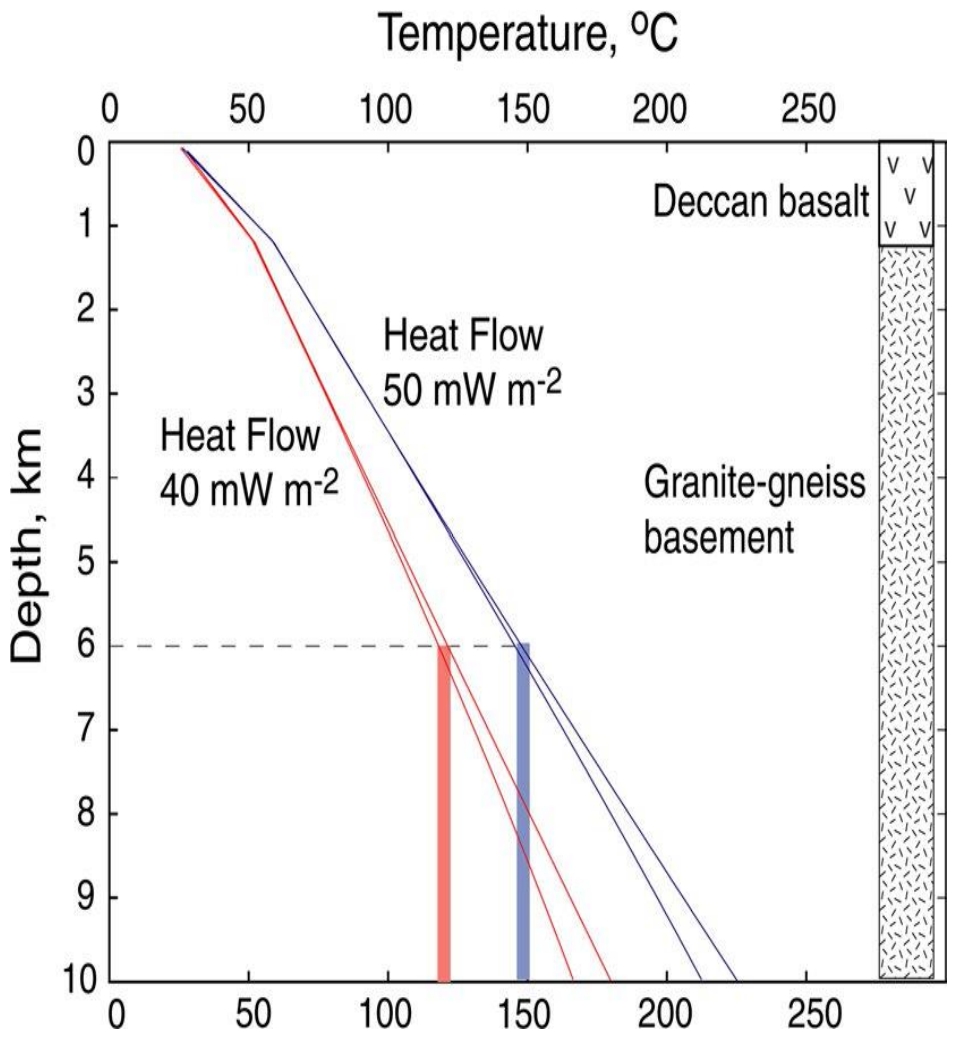
An International ICDP Workshop on Scientific Deep Drilling was organized by the National Geophysical Research Institute (CSIR-NGRI) Hyderabad, India during March 21-25, 2011.

Workshop Participants:

26 International
50 India

Total support, and a few suggestions for further work before setting up the borehole observatory

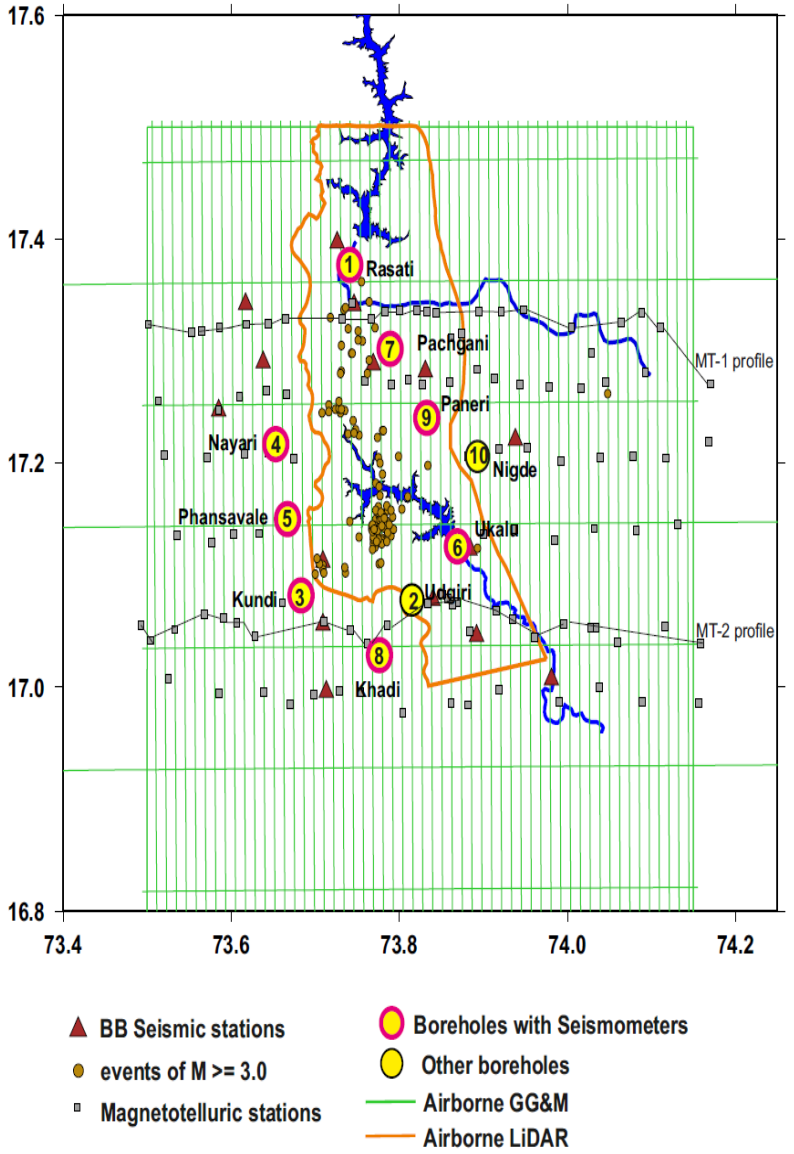
Photograph from the Koyna drilling site. In the foreground, scientists and the drilling crew hold a spectacular 4.5 m - long core of massive basalt recovered from the borehole KBH-1.



Temperature-depth profiles in the upper crust in the Koyna area computed using a range of heat flow and heat production scenarios. Heat flow range is 40–50 mW m^{-2}. A low heat production (0.2 µW m^{-3}) for basalt and a range of heat production for granite–gneiss (0.5–1.5 µW m^{-3}) has been considered. Estimated temperature at 6 km depth is in the range of 130–150 °C.

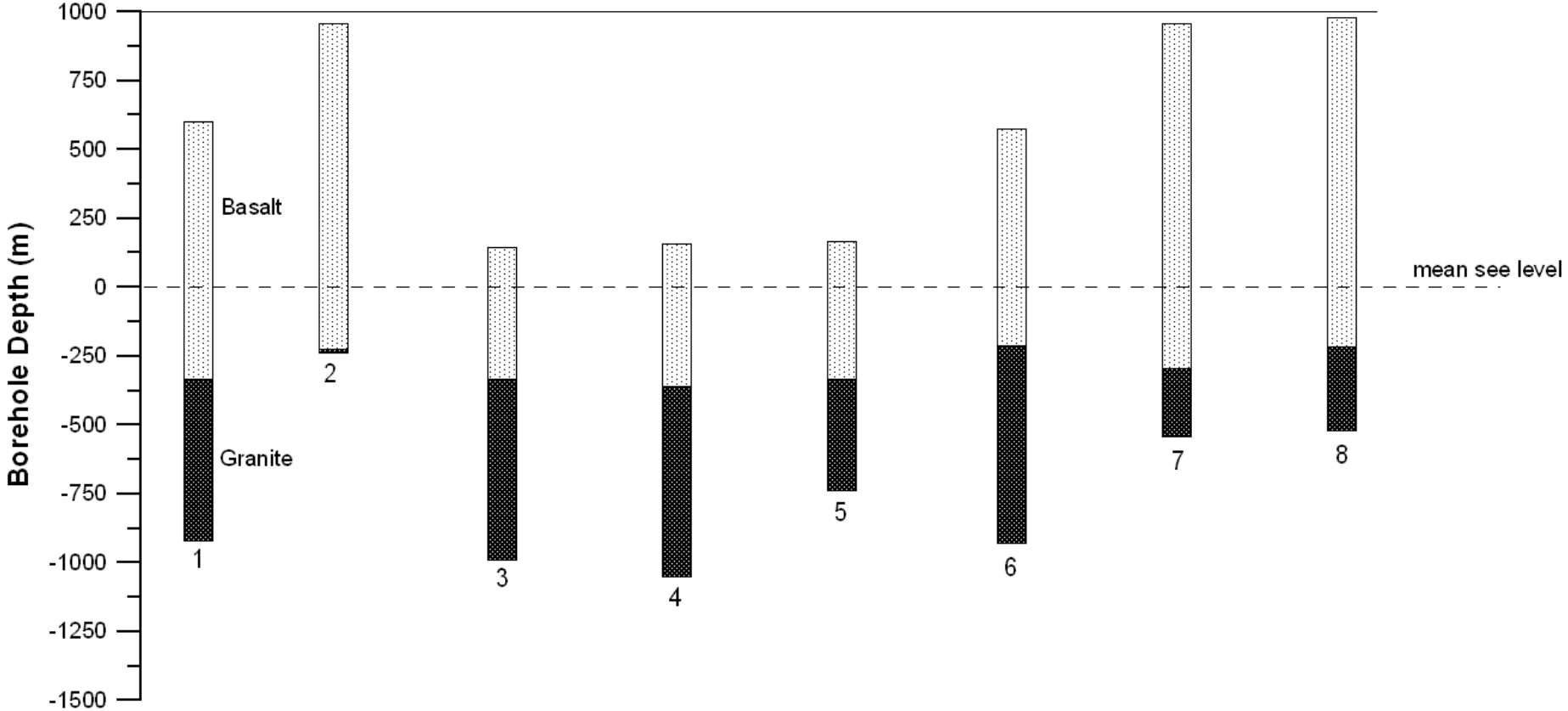
MAJOR WORK COMPLETED

- Air borne gravity -gradient + magnetic survey
- Drilling of 9 bore holes (each ~1500 m)
- Air borne LiDAR surveys
- Six bore-hole seismometers
- MT
- Heat Flow
- ICDP Workshop



DISCOVERIES

- Practically no sediments below basalt
- Thickness of basalt column related to the surface elevation
- Almost flat basement
- Temperatures ~ 130°C at 5 km depth
- Nucleation phase


Borehole Depth (m)
1000
750
500
250
0
-250
-500
-750
-1000
-1250
-1500
Basalt
Granite
mean see level
1
2
3
4
5
6
7
8

While SAFOD (San Andreas Fault Observatory at Depth) is located on a long seismically active plate boundary, DEEPAK (DEEP scientific drilling At Koyna) would be for the first time in the plate interior zone, with no seismic activity within 50 km radius.

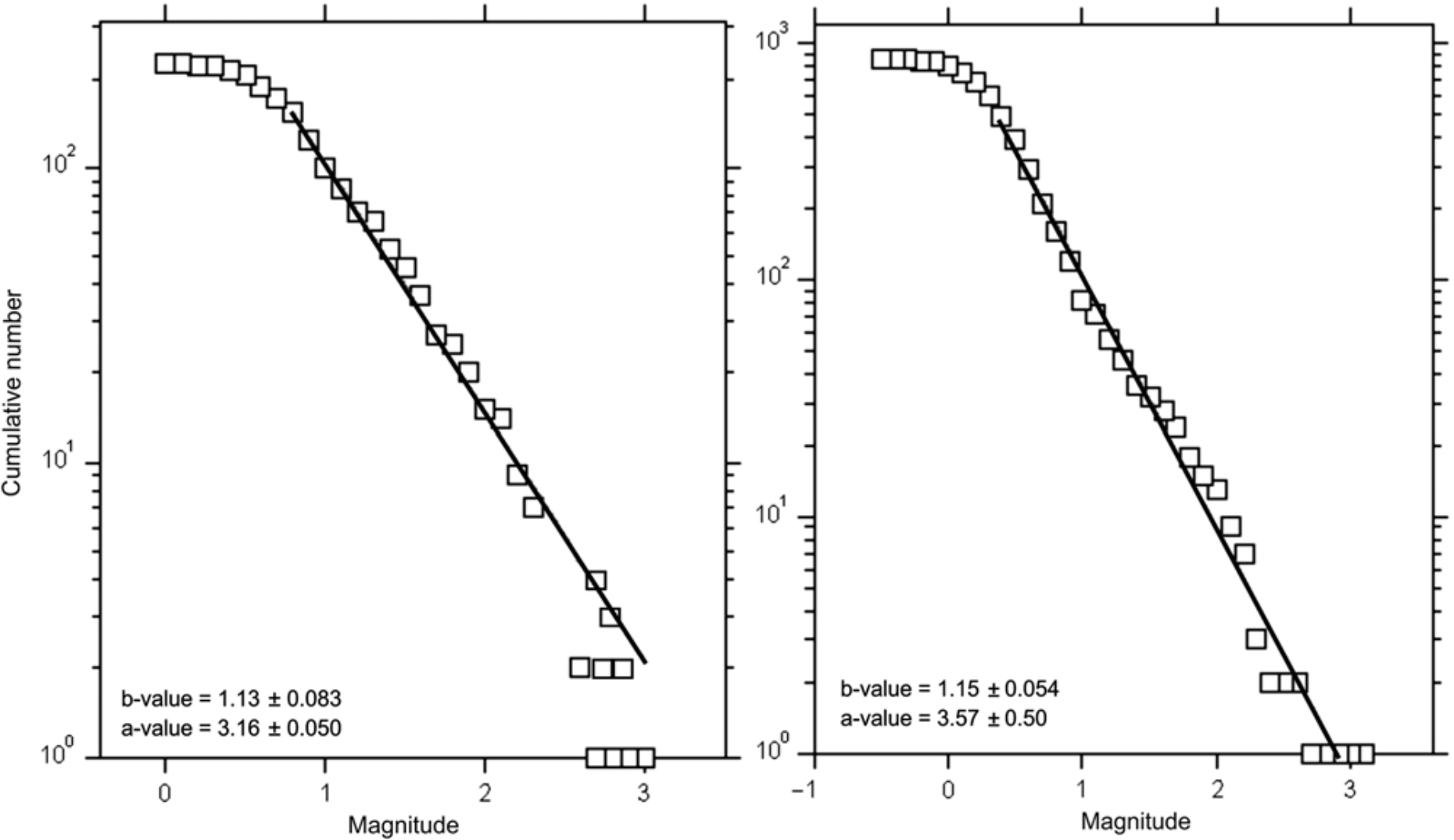
SECOND ICDP INTERNATIONAL WORKSHOP, KOYNA, 16-18 MAY 2014

India: 37 ; Outside India: 12

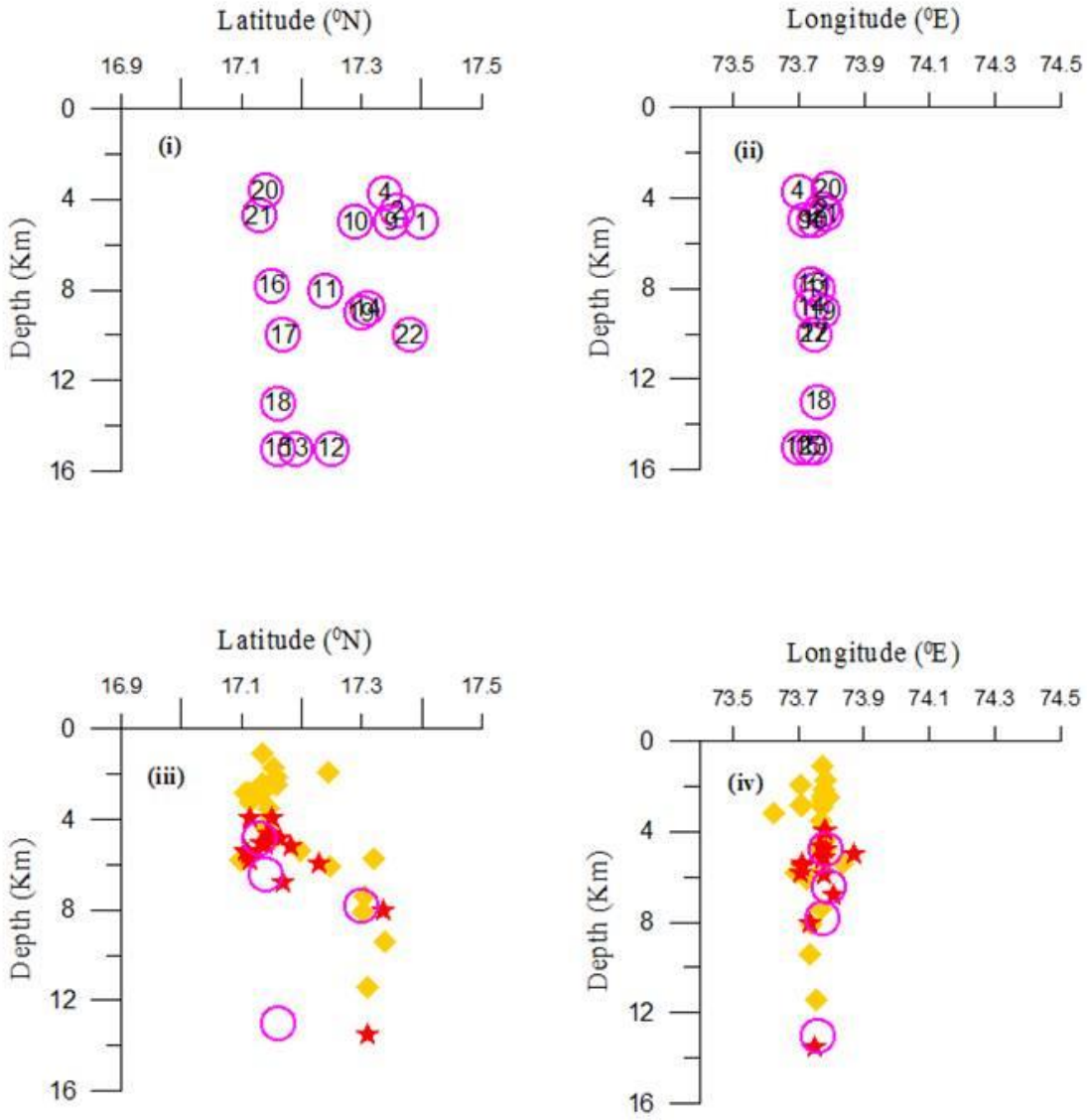
Key Questions

1) What is the fluid pressure and permeability within and adjacent to fault zone?
2) What are the composition and origin of fault-zone fluids and gases?
3) How do stress orientation and magnitudes 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 and the mechanism?
8) What is the 3D/4D nature of the fault zone?

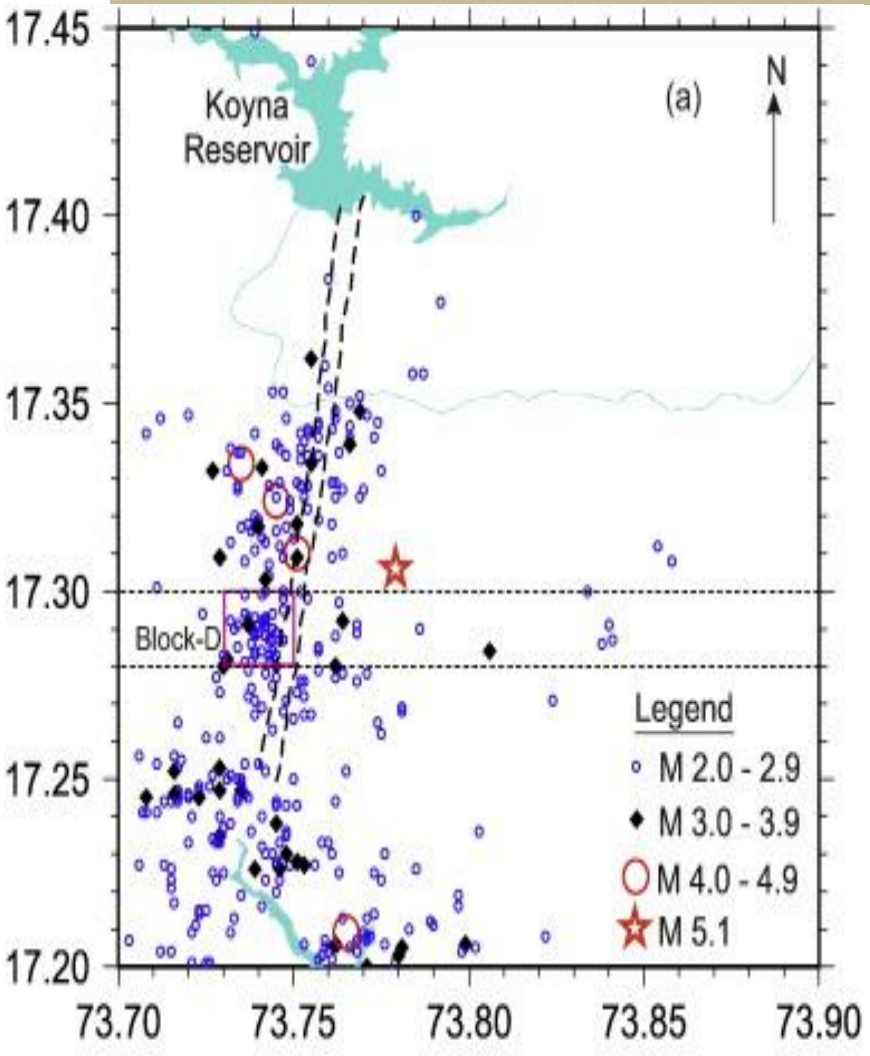
Earthquake frequency–magnitude distribution curves using Surface and borehole network

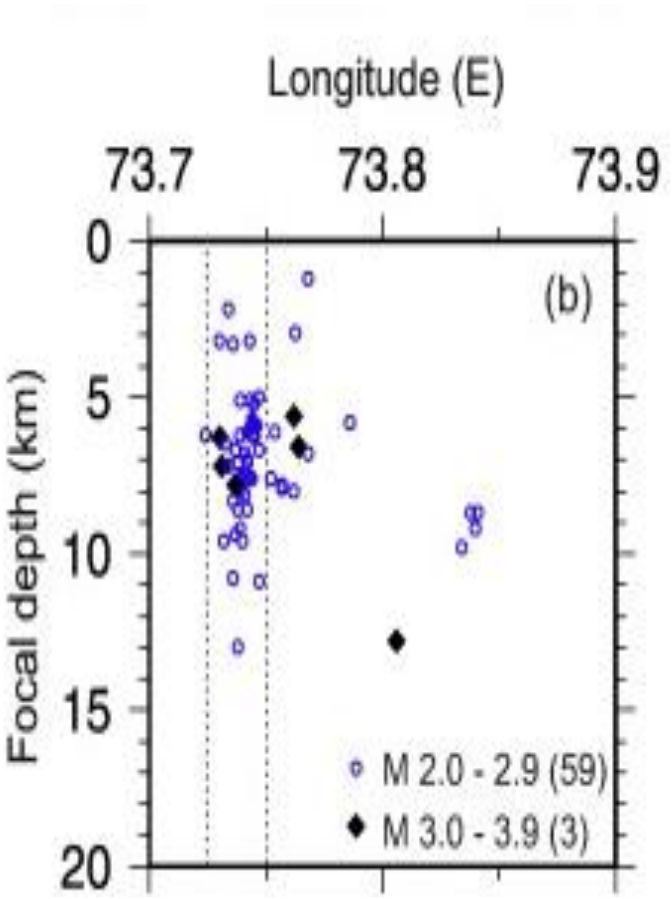


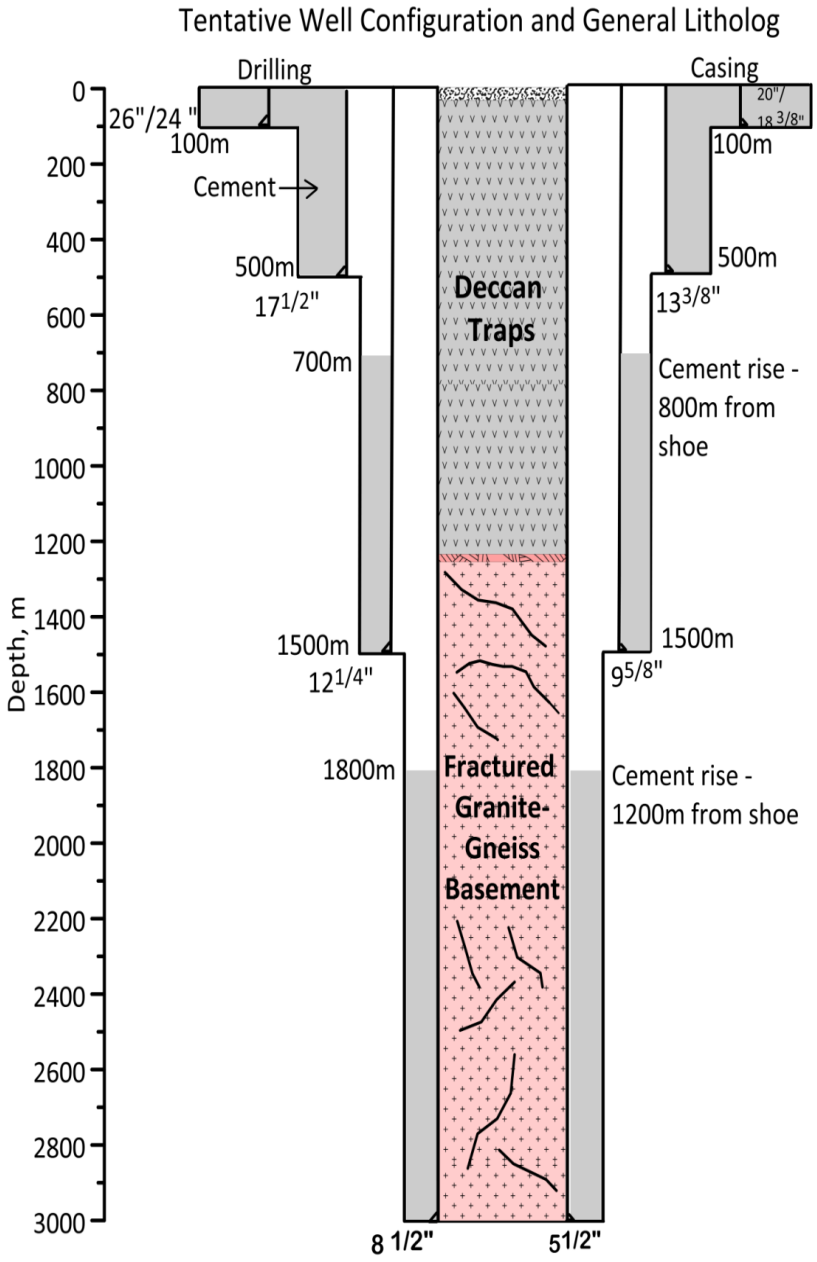
Depth section of earthquakes along latitude and longitude



Earthquakes of magnitude ≥ 2.0 (August 2015 – Dec 2015) & depth section of events of block D: the Pilot Borehole location







Well Configuration for the pilot boreholes
Drilling to start by 30 November, 2016


7
sgd
5
A
B
MP09CL1350

Progress of Pilot Borehole

- 1500 m on 1st March 2017
- Basement at 1247 m (Panchgani 1252 m)
- Several zones with immense fluid loss
- Geophysical logging completed
- OLGA set up
- Casing done to 1500 m
- Cementing completed
- Cores to be obtained at depths below 1700 m
- Air hammer/mud rotatory drilling resumes on 17th March
- 3000 m perhaps by 15th May
- EOS
- Post operation workshop scheduled on 14, 15, 16 Oct 2017

COST

It is estimated to cost about Rs 300 crores (US $ 70 millions) over a 5 year period.

Acknowledgements:

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Jim Mori, Bill Ellsworth, Hans Joachim Kuempel, Marco Bohnhoff ……(International)


Thank
you…

Borehole Geophysics Research Laboratory, Karad


BGRL - temporary premises)


2016 SAG Meeting Field Trip
Deccan Traps, India


SAG Visit to BGRL, Karad

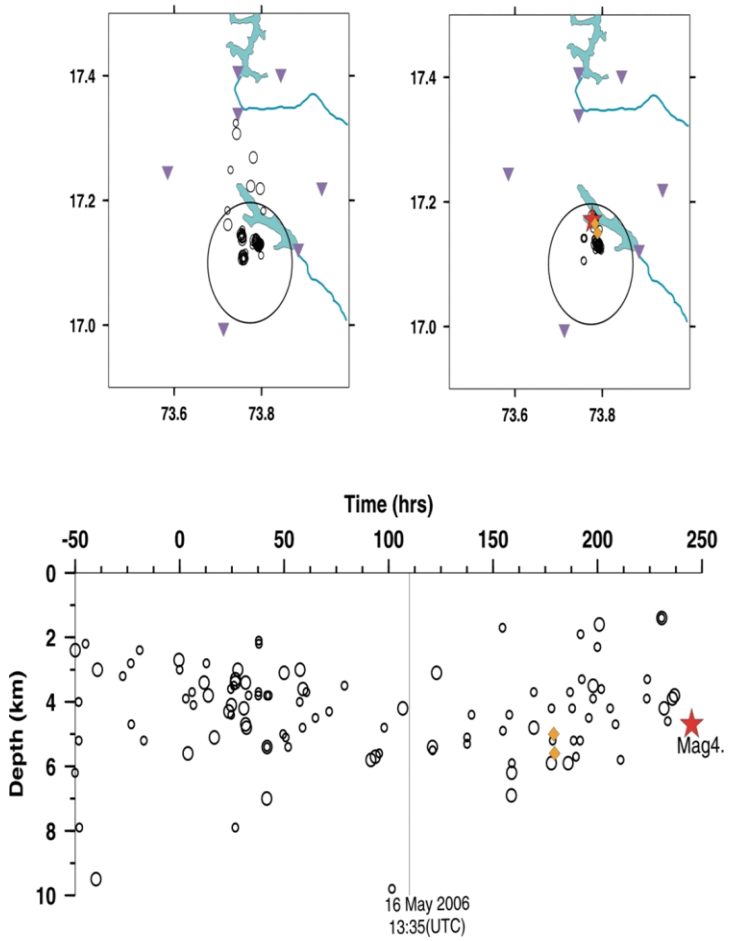

BGRL Core Repository (under construction)

Forecast of an M~4 earthquake in the Koyna region

"On the basis of the data available from 7 seismic stations operating in the Koyna region, we have identified a nucleation, which started on 12th May, 2006. This may lead to the occurrence of an M~4 earthquake in the next 15 days. This shallow earthquake (focal depth < 8 km) will occur within a radius of 10 km centered at 17.1^{0}N, 73.8^{0}E. On the basis of our previous experience of studying nucleation-preceding earthquakes in the Koyna region, we expect this earthquake to occur over the next 15 days time (till 31st May, 2006), with a 50% probability."

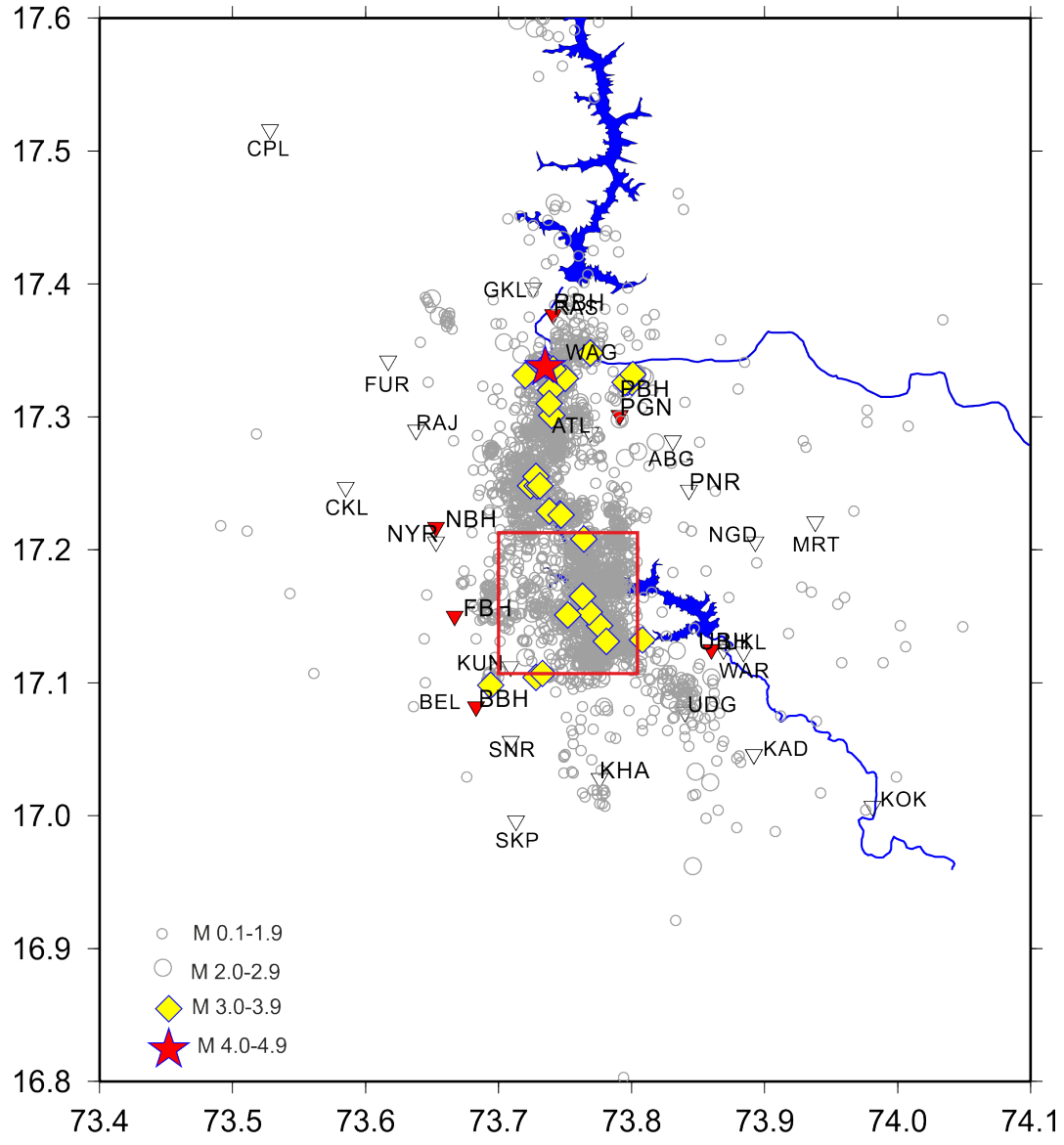
-JOUR.GEOL.SOC.INDIA, VOL.68, JULY2006, Gupta et. al.

Successful Forecasts

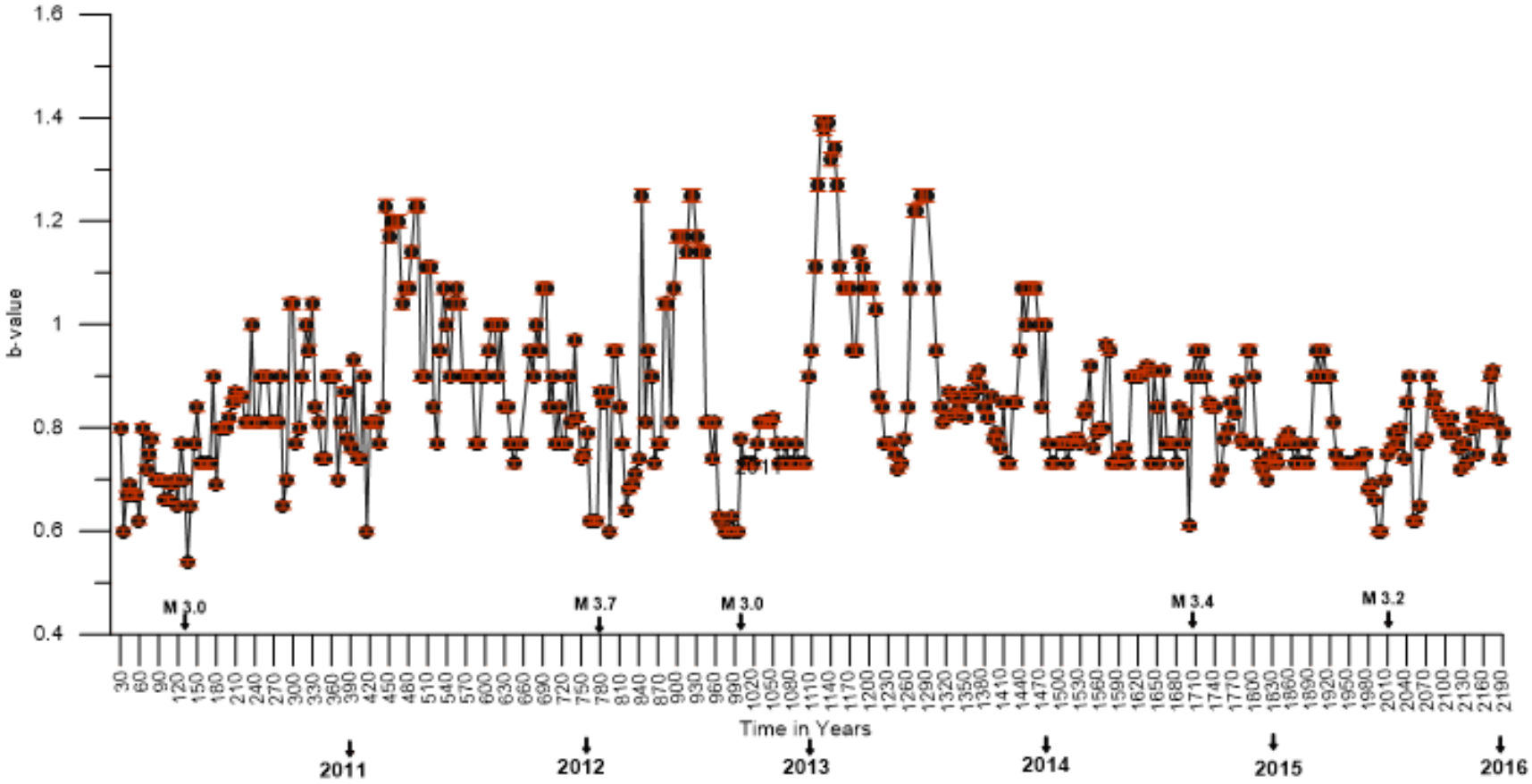


An earthquake of M 4.2 occurred in the Koyna region on ***21st May 2006*** *at 20:29:01.2 UTC. The epicenter of this earthquake (17.171^{0}N, 73.777^{0}E), lies within 10 km of the predicted epicenter. The depth is 4.7 km.* ***So the forecast has come true.***

Nucleation time: 250 hrs



Seismicity of the Koyna-Warna region during 2011-2016



Temporal variation of b-values at Warna region during 2011-2016

M 7.9 May 12, 2008 Wenchuan earthquake, China was triggered by 156 m deep Zipingpu dam on Min river located about 21km away from the epicenter?

Flooding of river near San Andreas fault, California may have triggered two M~6 earthquakes in the past (Dalton, 2010)

Advertisement in EOS

- Advertisement in EOS
- Post operation workshop scheduled on

We know precious little about the composition of the fault at depth, the state of in-situ stresses or pore pressure within the fault zone, how the fault zone fluids originate, the fault zone processes and their dependence on time.