Towards Understanding of Triggered Earthquakes

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Triggered Earthquakes

- An earthquake essentially represents the release of elastic strain energy stored in the rocks in the form of seismic waves. The ground motion is the manifestation of seismic wave propagation.
- Anthropogenic engineering activities that act towards releasing pre-existing stress of tectonic origin are named as ‘triggered’ earthquakes.
- Such earthquakes have significant social and economic impacts.
- Such Earthquakes can be triggered by:
  - Impounding of artificial water reservoirs
  - Large scale surface and deep underground mining
  - Fluid injection under high pressure / fracking for hydrocarbons
  - Large underground explosions
  - Petroleum exploration

Reservoir-Triggered Seismicity (RTS)

- Earthquakes triggered by impounding of artificial reservoirs have been reported from about 120 sites through out the world during last 70 years or so.
- Such earthquakes are associated with the potential factors such as rate of loading and un-loading, highest water level reached, duration of retention of high water levels, influence of pore fluid pressure, etc.
- The role of individual parameters in triggering earthquakes has fairly well understood.
- An integrated model for the genesis for RTS is yet to be developed.
- The Koyna earthquake of M 6.3 occurred in 1967 is the largest RTS event. About 200 lives were lost and the Koyna township was severely damaged.

Why Koyna is an Ideal Site?

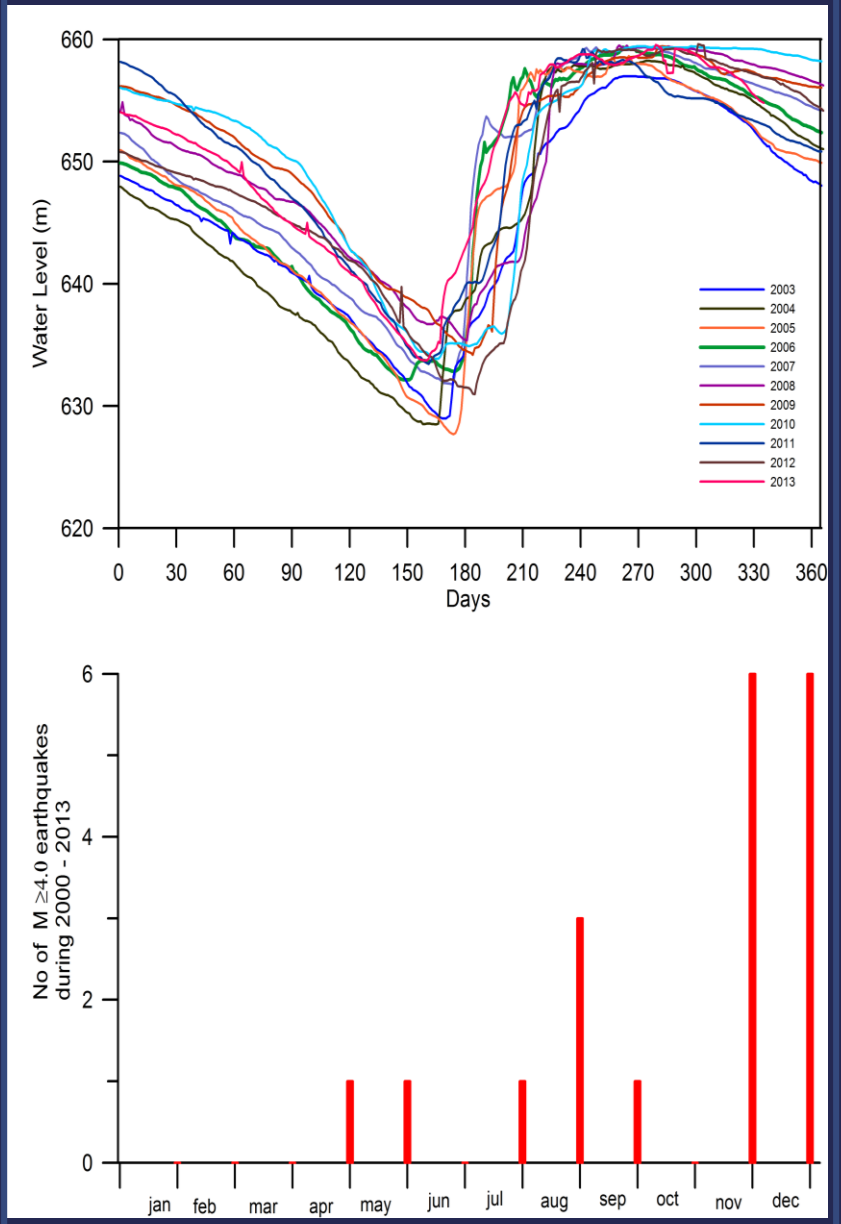
- A world-class site of artificial water reservoir-triggered-seismicity and intra-plate earthquakes: "Lighthouse Project" of ICDP.

a) The largest RTS earthquake so far – M 6.3 on 10 Dec 1967,

b) Persistent seismicity in the vicinity of the reservoir. More than 200 earthquakes have been reported during last 50 years. An earthquake of M 4 occurred on June 4, 2017.

c) Strong association of the earthquake activity with the annual loading and unloading cycles of the Koyna and Warna reservoirs, and

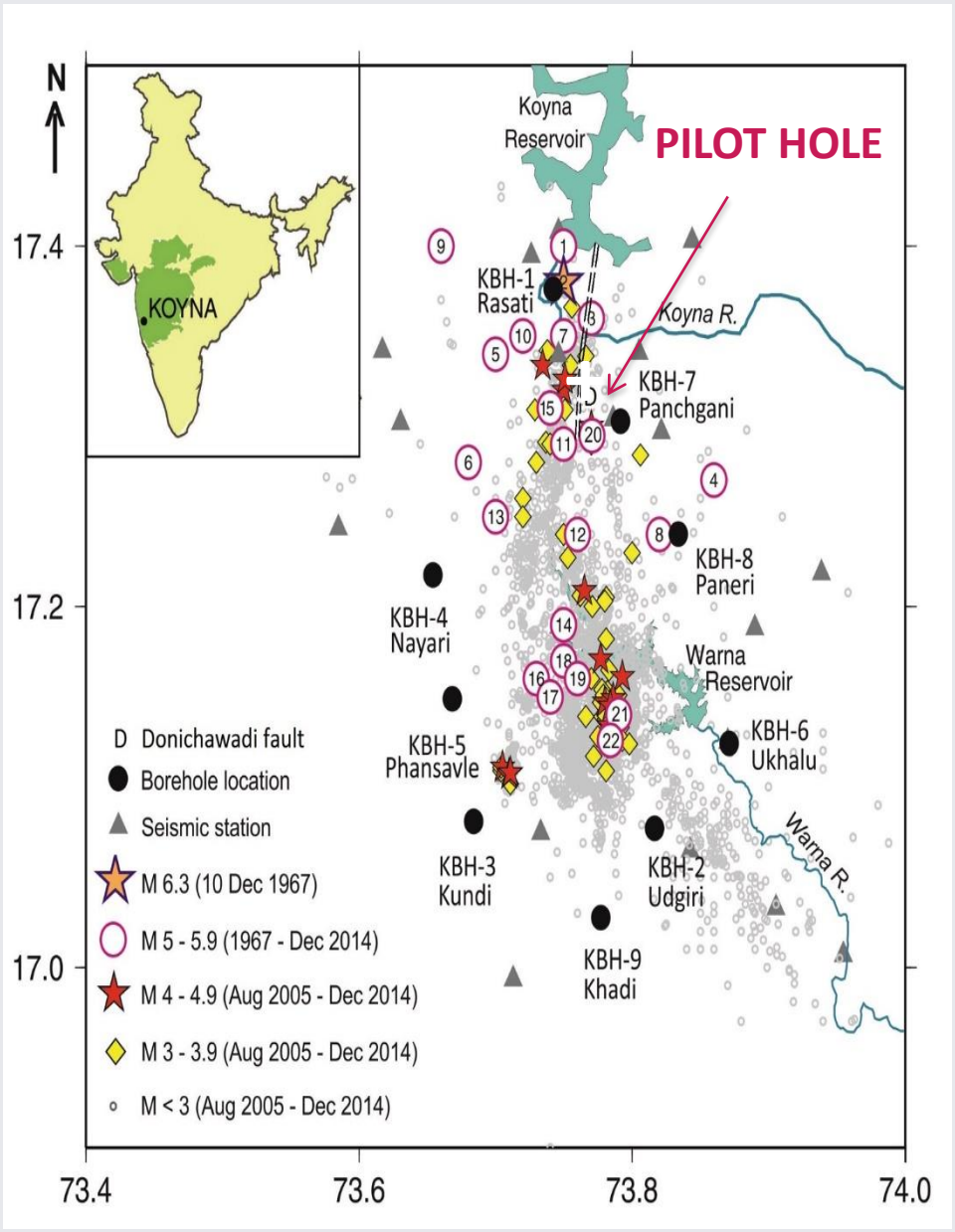
d) Isolated nature of the seismic zone (~30km x 20km x 10km)

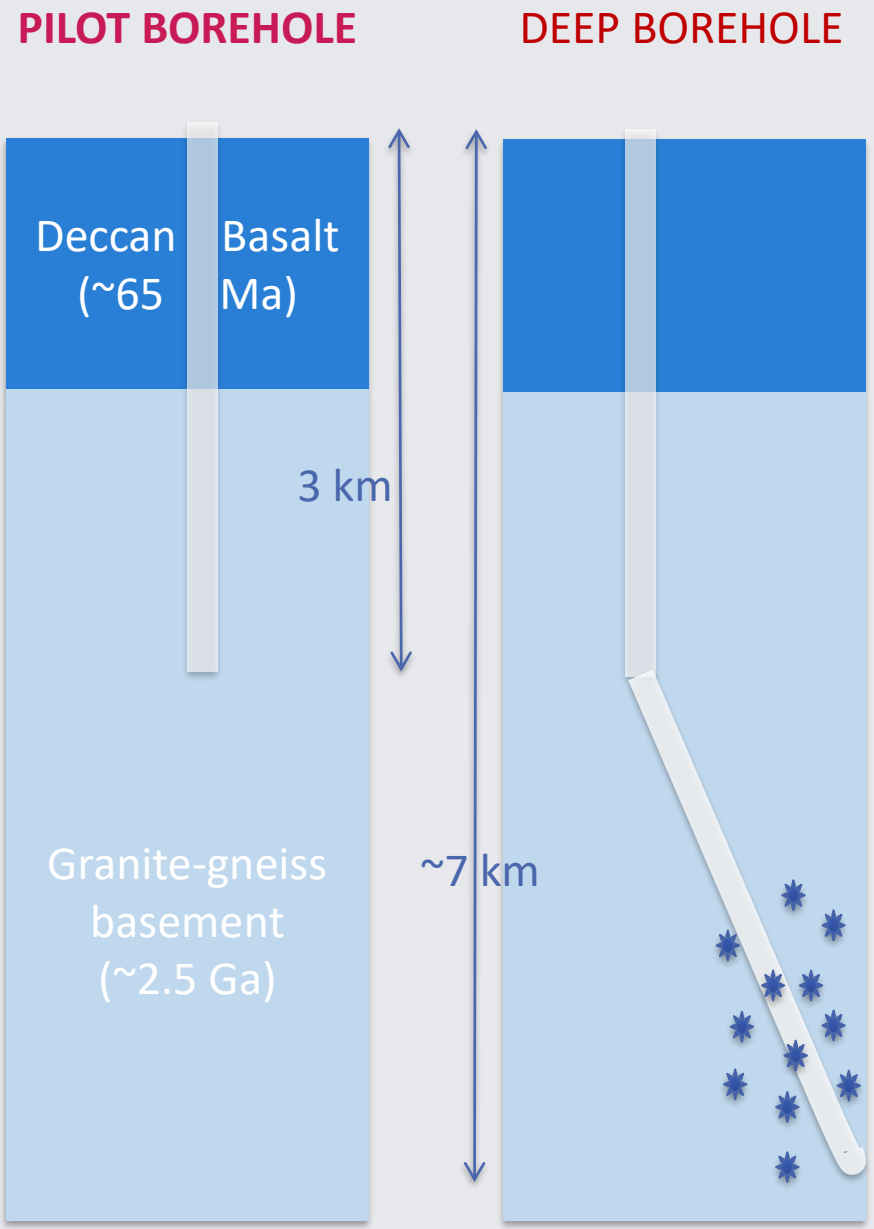


Scientific Drilling in the Koyna Region

- A unique project targeted to:
- To understand and model genesis of RTS.
- Deep drilling, at a appropriate site in the Koyna area, would allow direct characterization of parameters critical to modeling RTS.
- Underground fault geometry (fault-zone Observatory)
- Physical properties of rocks including those in the fault-zone (before, during and after earthquakes)
- Hydro-geologic regime
- Fluid/gas composition
- Temperature and heat flow
- In-situ-stress
- Pore pressure changes in “near field” region

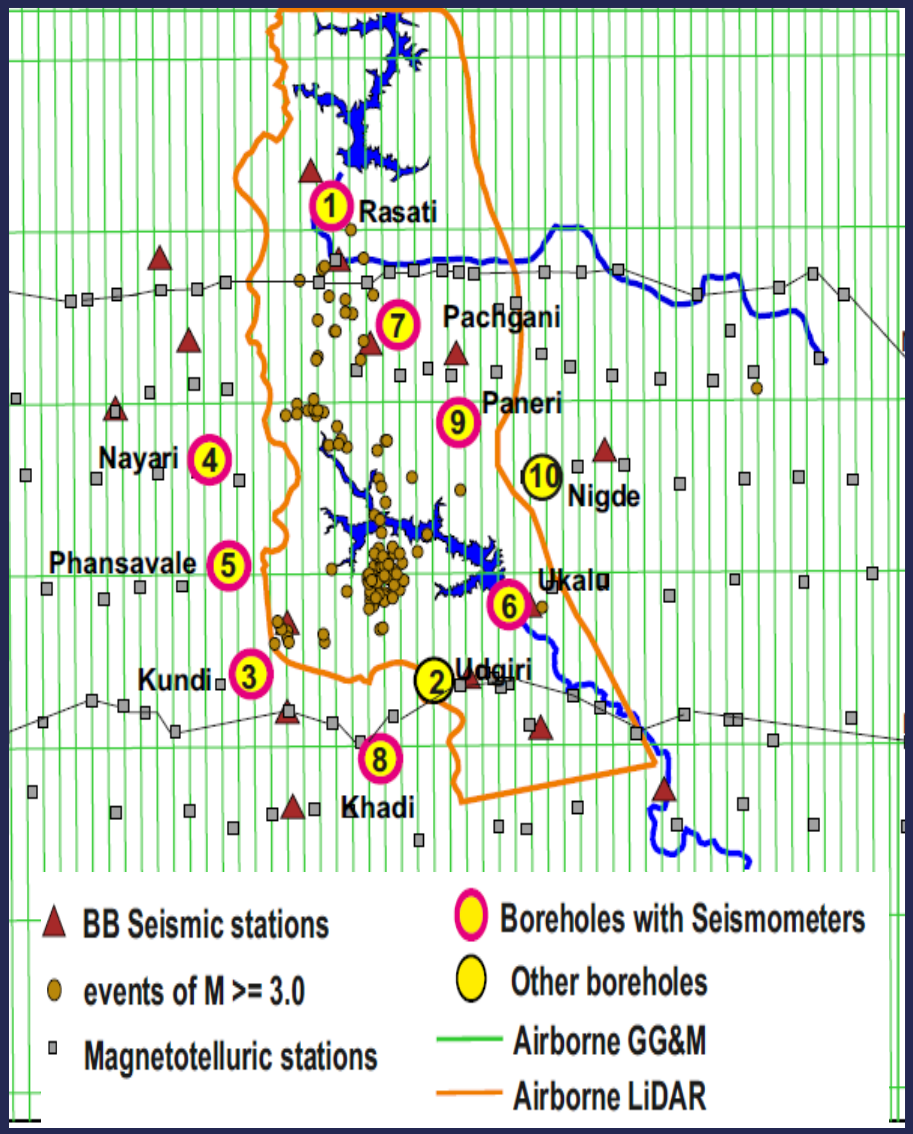
Scientific Drilling – Experimental Plans





Exploratory Drilling & Geophysical Investigations

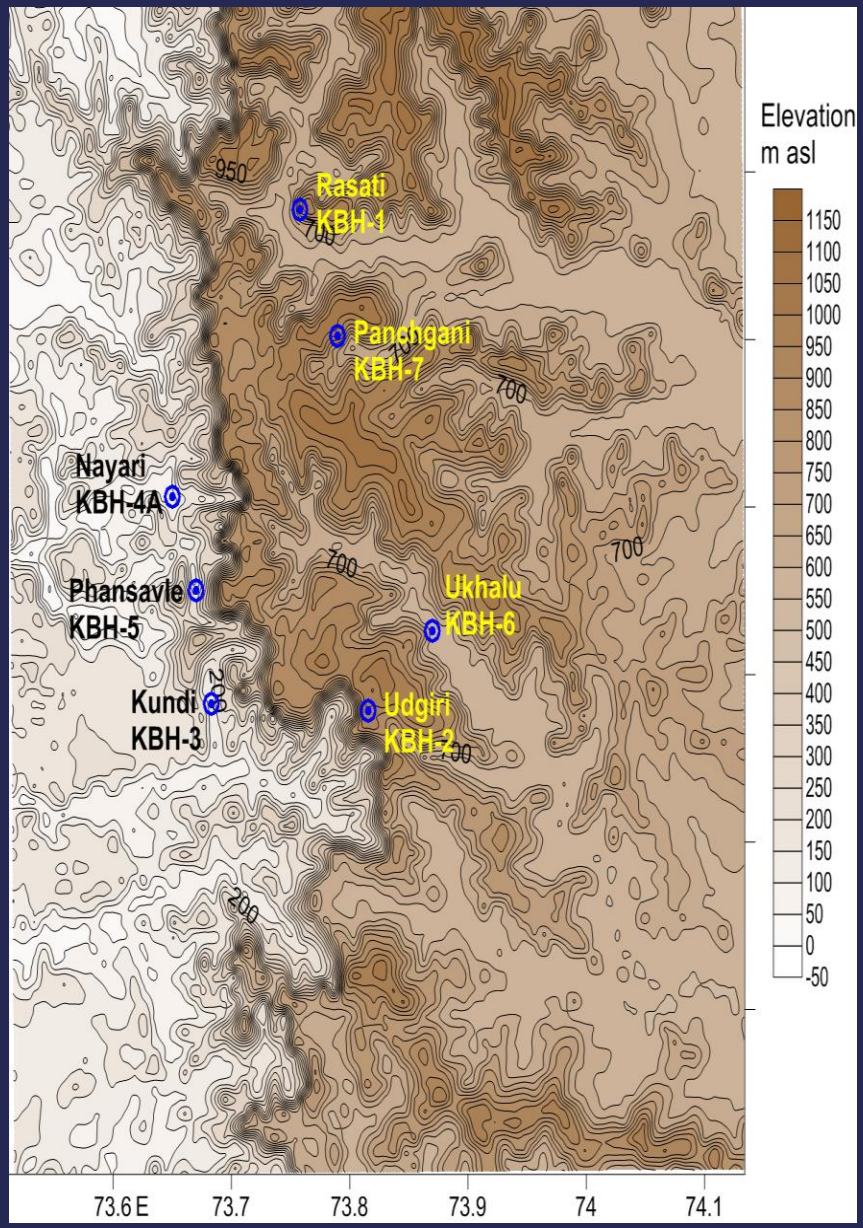
- Exploratory Drilling (9 boreholes)
- Geophysical Logging
- Heat Flow / Geothermal:
- Magnetotellurics
- Airborne Gradiometry & Magnetics
- Airborne LiDAR
- Geological mapping
- Broadband Seismology
- Borehole Seismology (in 6 boreholes)



New Information from Drilling

- Direct information from drilling (10 km of cores):
- Max. Thickness: 1251 m, 46 lava flows. Directly overlying granite basement.
- Nine giant plagioclase basalt flows are present.
- Basement granitoids are composed of granite-gneiss, granite and migmatite gneiss, The presence of strained quartz and unstrained plagioclase feldspar in the basement granitoids.
- Absence of infra-Trappean sediments
- Undulations in basement, ~200 m
- Identification of fault/fracture zones and other deformations with seismic activity.

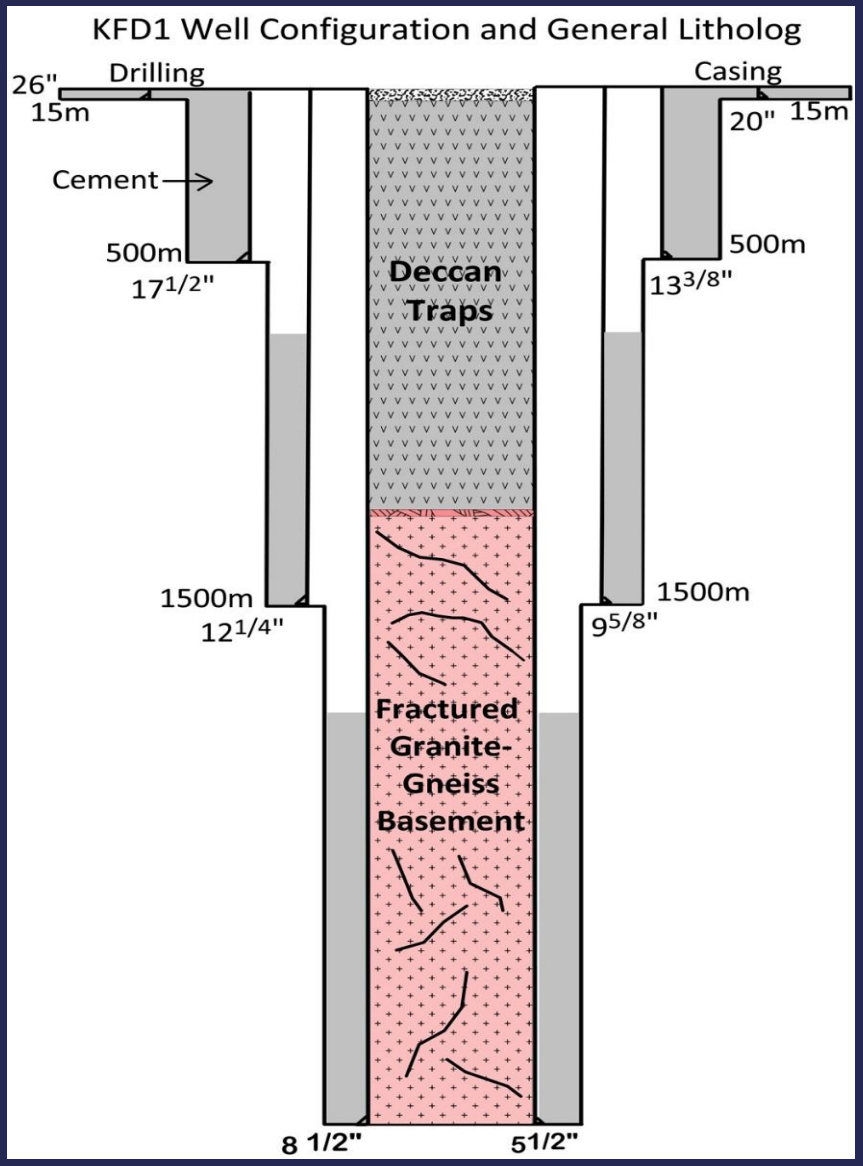
- Gupta et al. 2015, Mishra et al. 2017, Misra et al. 2017)



Information from Geophysical Surveys & Drilling

- Subsurface temperature regime and heat flow:
- At 1.5 km: 56^{o}C. Modeled up to 10 km. 80^{0} and 130-150^{0} C at 3 & 6 Km.
- Physical properties of basalt and basement rocks
- The presence of weak planes oriented in other directions than pre-existing cleavage planes, probably induced by ongoing seismic activity.
- Secondary mineralization along older fissures and fractures is indication of percolation of water through fractures.
- Fault and Fluid Zone: Low conductivity (100-1400 ohm.m)
- 3D subsurface density models have been developed. Seismicity has been associated with density/velocity anomalies.
- Rock strength is locally weakened at different depths by successive seismic activities, stress accumulation within rock mass is unlikely to be high enough to produce large earthquakes.

Pilot Borehole (KFD-1)



- 3 km, completed on June 11, 2017.
- Vertical, within ~3 degrees
- Casing and cementation to 3 km
- Cuttings and cores collected.
- Online gas sampling and analysis
- Down-hole geophysical logging
- Electrical and acoustic images
- Temperature regime
- In-situ stress from hydrofrac tests, 9 places between 1600-2400 m
- Fault Zone Observatory
- Air-hammer drilling (up to 1500 m) and Rotary Mud Drilling (1500-300m).
- Perforated casing for stress measurements

Brittle Deformation Associated with Seismic Activity

Granular flow

Slickenlines

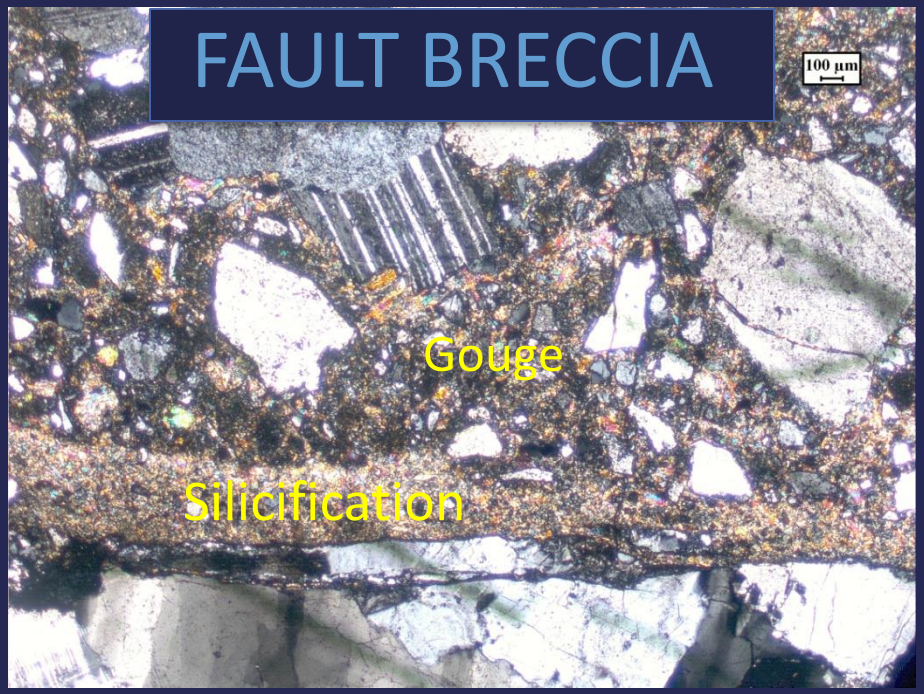
Injected veins

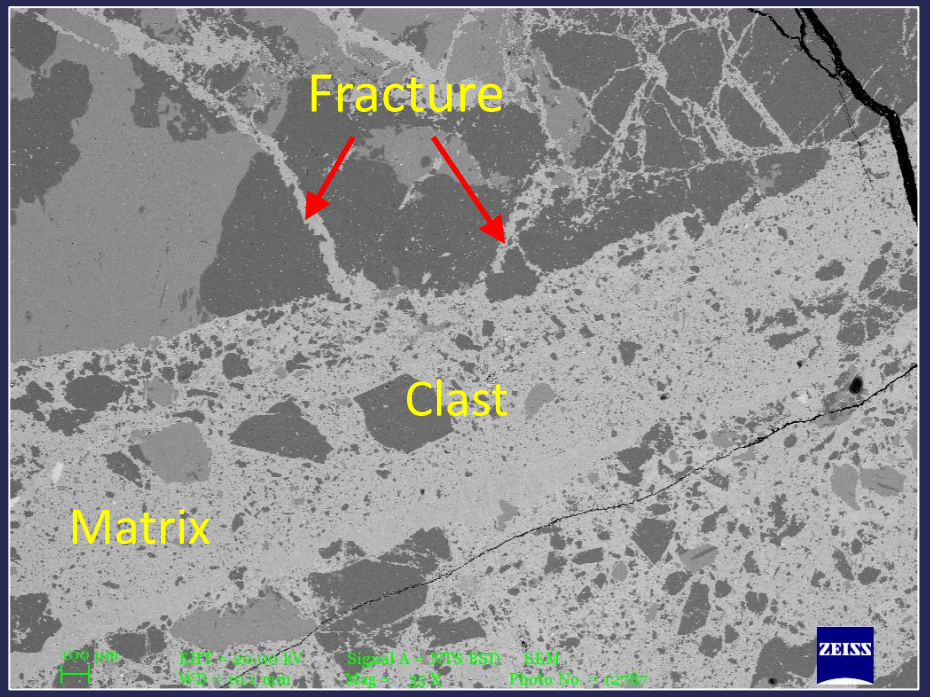
Pseudotachylite

Shattering

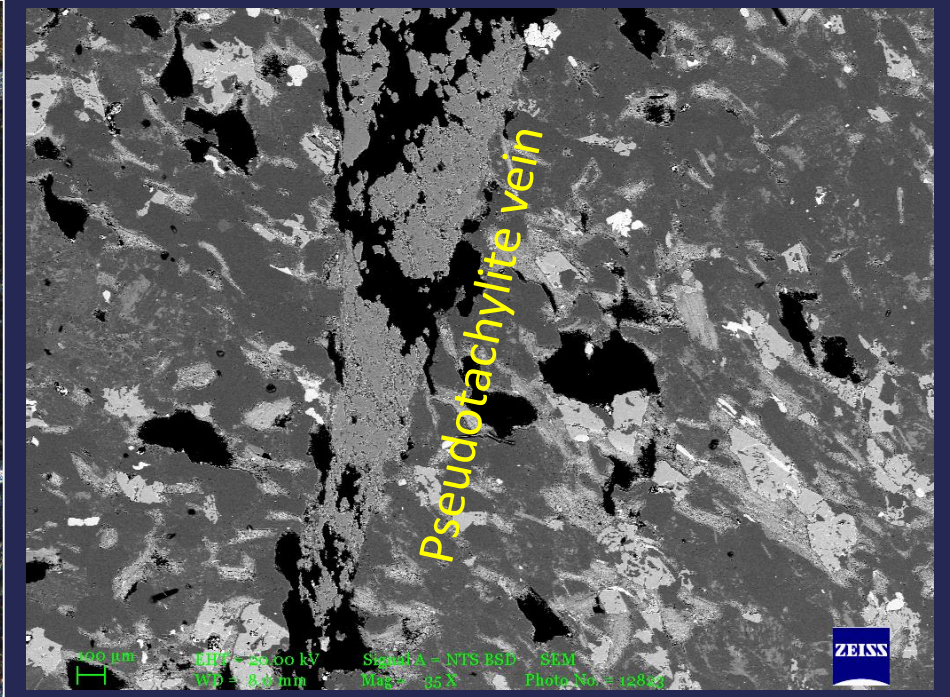
(Misra et al. 2017)

FAULT BRECCIA





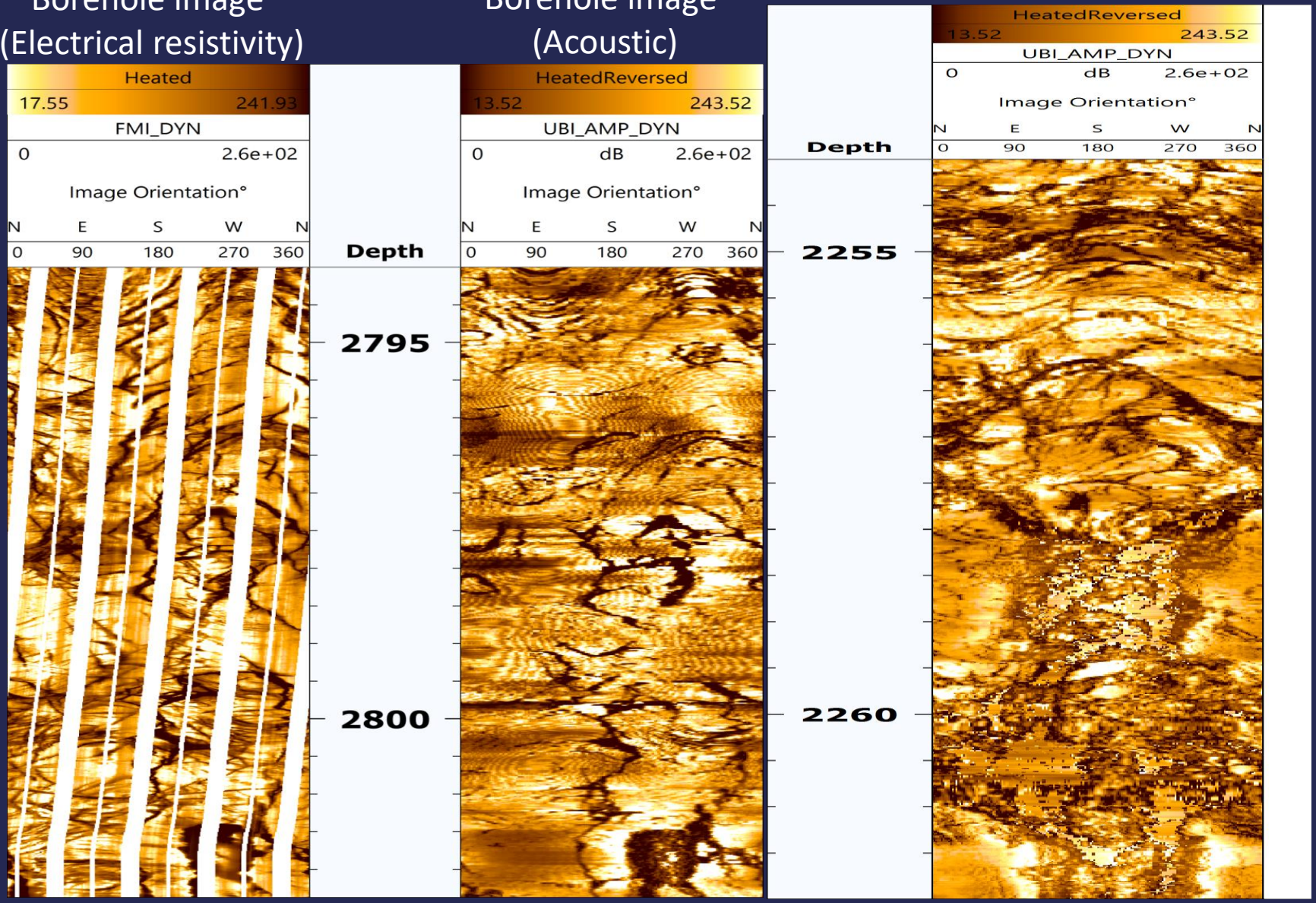
PSEUDOTACHYLITE



Fractured Horizons at Depth

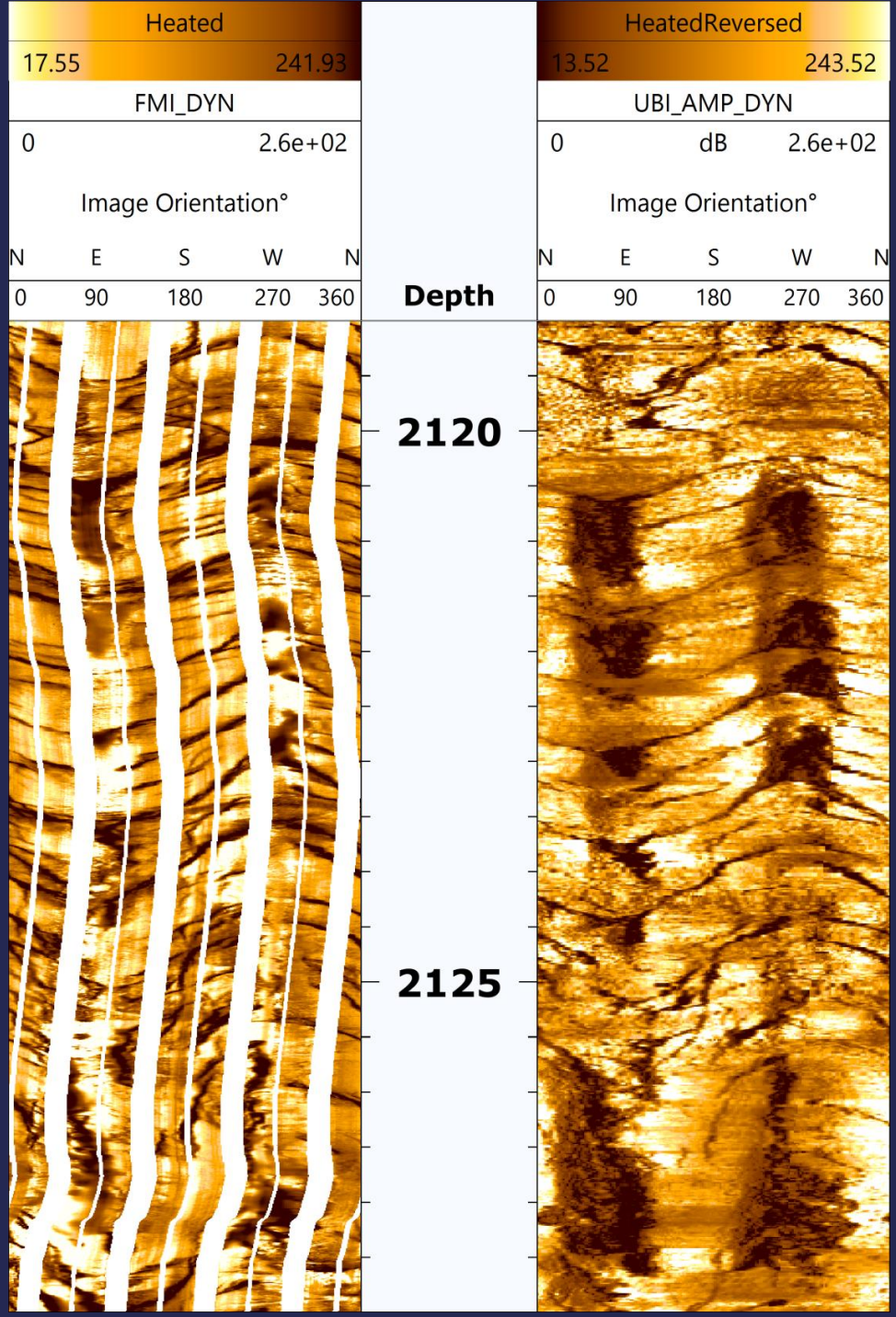
Borehole image
(Electrical resistivity)

Borehole image
(Acoustic)

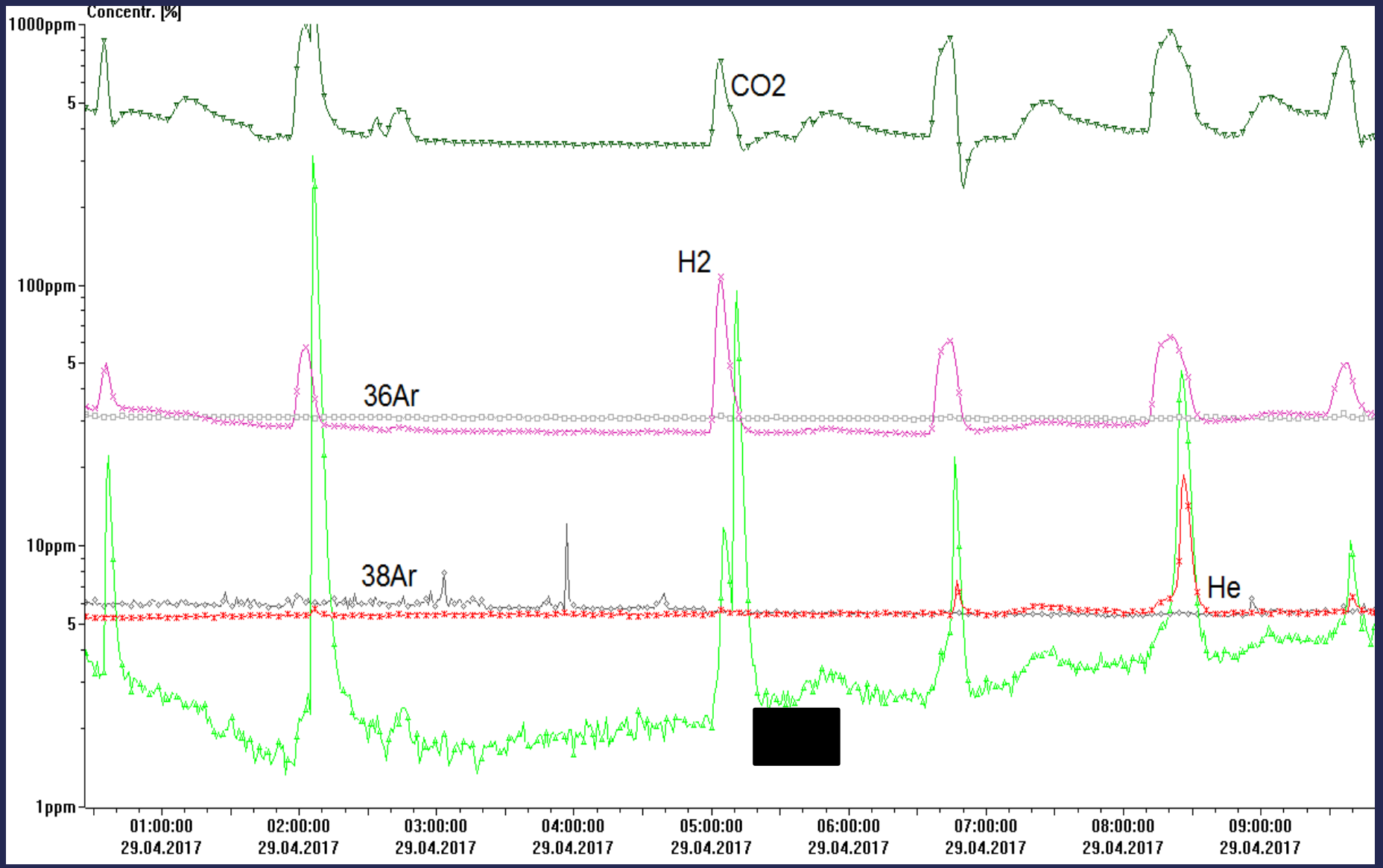


Breakouts

- ✓ Breakouts take place in the borehole wall when the circumferential stress around the borehole wall overcomes the compressive strength of the rock formation.+
- ✓ It always occurs in the direction of minimum horizontal stress



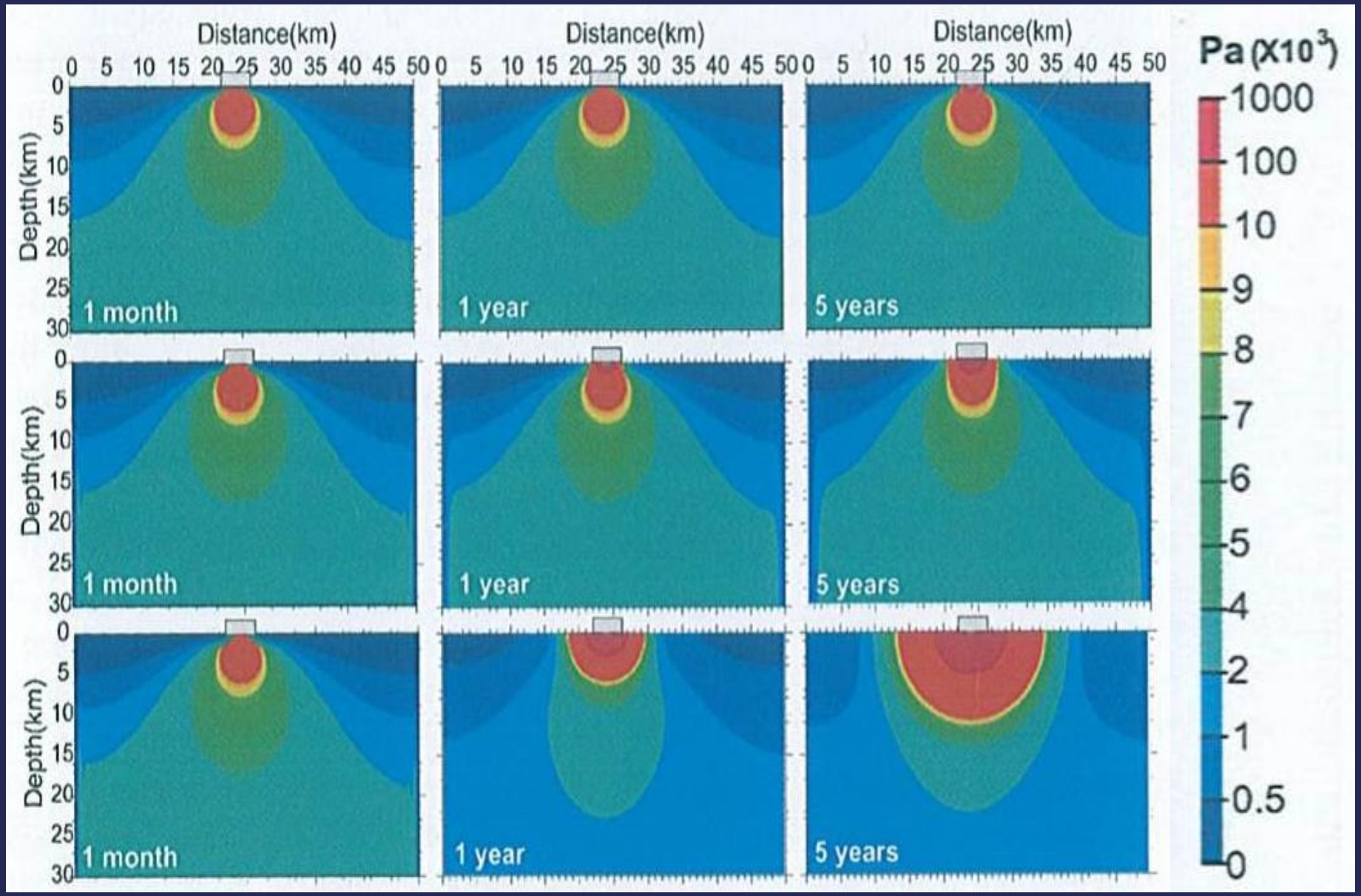
Online Gas Analysis



Conclusions so far …

- Five zones of faults/ fractures were identified.
- Vertical fractures filled with siliceous material.
- Evidence of strike-slip fault.
- Strain-stress analysis indicate significant variability in deformation behavior due to heterogeneity induced by frequent earthquakes in the region.
- Low and variable strength and elastic properties of basement granitoids indicate that rock strength has been modified by the recurrent seismic activity.
- It also implies that rocks are not strong enough to produce large earthquakes.
- Useful for deciding location of main borehole.

RTS Modelling



Other Studies

- Deccan volcanism and mass extinction
- Paleo-magnetism
- Thermal structure and the state of stress in the lithosphere
- Geothermal potential
- Record of climate change
- Geomicrobiology
- ……

*Geo*microbiological Experiment

Cores from deep subsurface

(Interior sub-core)

Extraction of DNA

Purification, QC

Analysis of function genes

Analysis of 16S rRNA genes

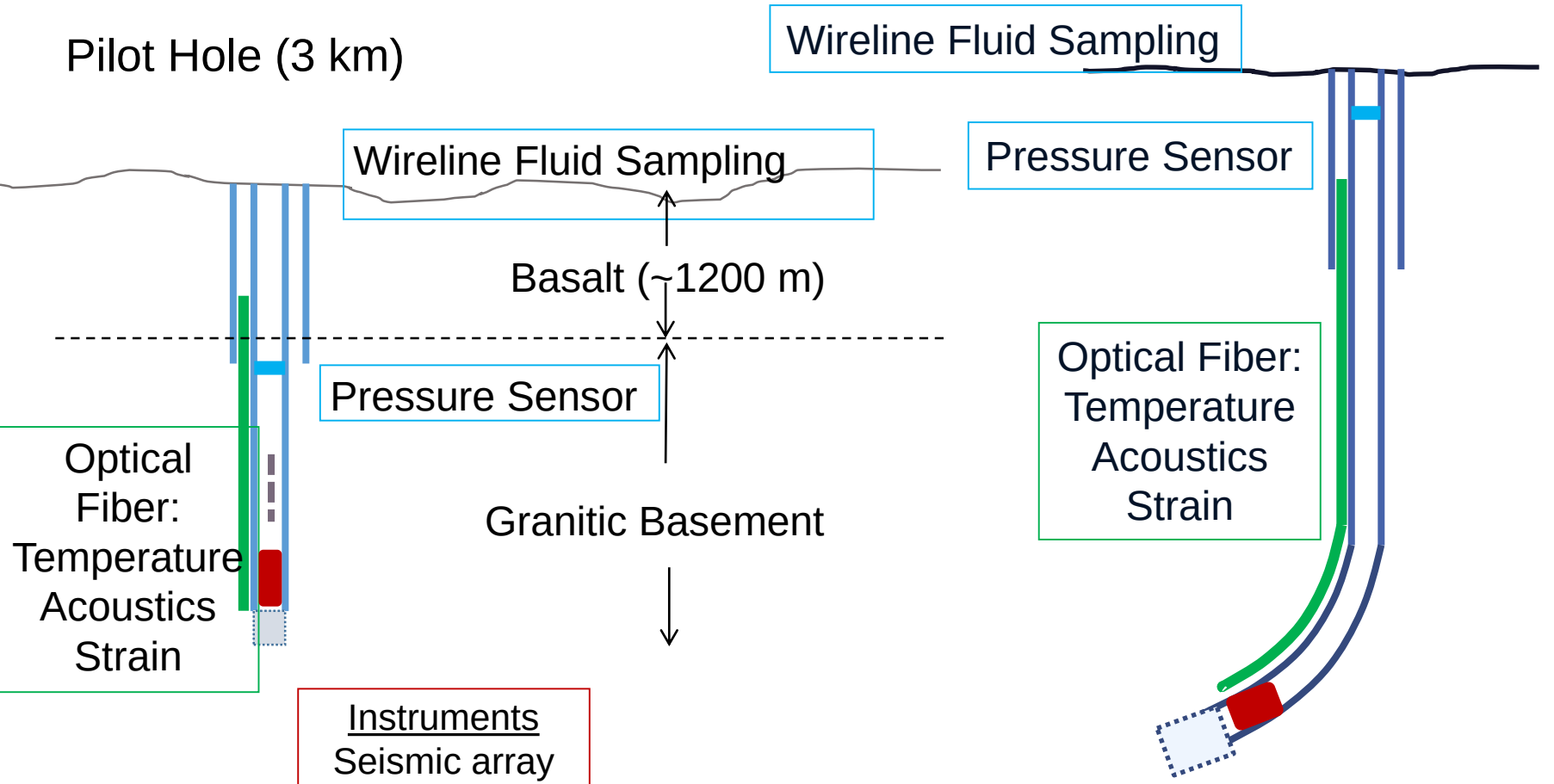
Microbial community analysis

- Microbial networks
- Key stone species
- Metabolic role

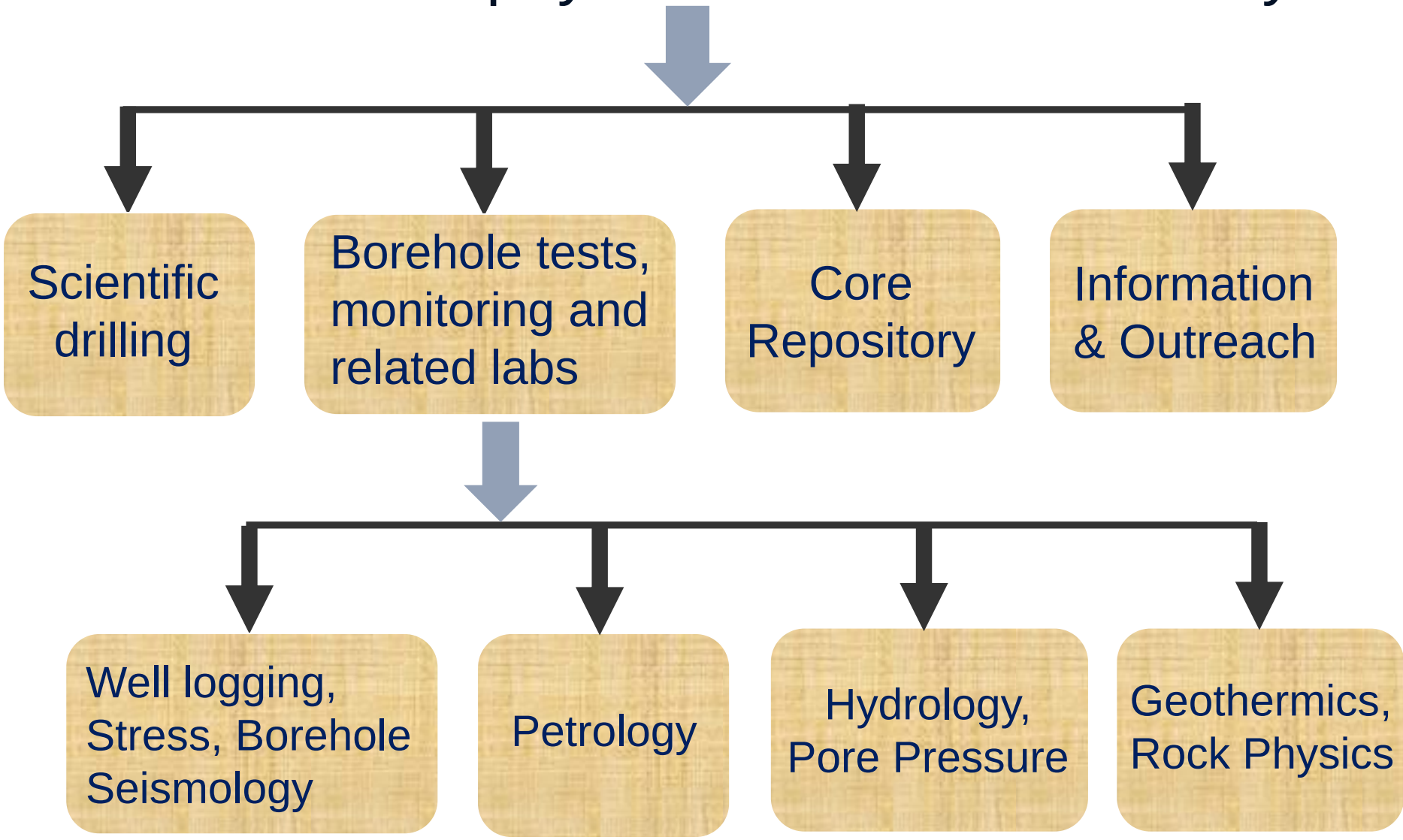
Geochemical parameters relevant to microbial processes

(Source: P. Sar; IIT Kharagpur

Future Plans for Measurements



Borehole Geophysics Research laboratory



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