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Recent Attention on Induced Earthquakes

- Fluid pumping Pawnee Oklahoma Earthquake (M5.8, 2016)
- Geothermal Basel, Switzerland Earthquakes (M3.4, 2006)
- Natural gas Spain (M4.7, 2013)
- Earthquakes triggered by filling of reservoirs
 - 1961 Kurobe Dam, Japan (M4.9)
 - 1967 Koyna, India (M6.5)
 - 1975 Oroville, California (M5.7)



We want to trigger a M5~M6 earthquake on a mid-ocean transform fault !

Key Scientific Questions

- 1. What is the level of stress needed to initiate an earthquake ?
- 2. Are there differences in the initiation of small and large earthquakes ?(Can we predict a large earthquake ?)
- 3. Understanding of the earthquake cycle

Mid-ocean Transform Fault



Ocean transform earthquakes are shallow, so can drill to seismogenic zone

M5 to M6 earthquake occur regularly at repeat times of 5 to 15 years

Safety factors,

Mid-ocean sites far from land Strike-slip reduces chance of tsunami



Rangely, Colorado Experiment 1969-1973



Fig. 7. Frequency of earthquakes at Rangely. Stippled bars indicate earthquakes within 1 km of experimental wells. The clear areas indicate all others. Pressure history in well Fee 69 is shown by the heavy line; predicted critical pressure is shown by the dashed line.

- This experiment showed that increase in fluid pressure can trigger earthquakes, as explained by the Coulomb failure criterion
- These results influenced much of the early optimism for earthquake prediction in the 1970's
- It has not been recently repeated because it is difficult to find an appropriate site to induce earthquakes



Coulomb Failure Function

$$\mathsf{CFF} = \tau - \mu(\sigma_n)$$

$$\mathsf{CFF} = \tau - \mu(\sigma_{\mathsf{n}} - \Delta \mathsf{P})$$

Pumping water into the fault zone to raise the pore pressure (ΔP) can trigger earthquakes



Induced versus Triggered Earthquakes

'Induced' earthquakes are directly caused by human activity. If there was not this human activity the earthquakes would not occur.

'Triggered' earthquakes are natural earthquakes that would occur at some time, but are caused to happen earlier by human activity



Larger earthquakes are usually considered 'Triggered'

- 1967 Koyna, India (M6.5)
- 1975 Oroville, California (M5.7)
- 2011 and 2016 Oklahoma Earthquakes (M5.7, 5.8)



Possible ocean sites for Triggering Experime













R/V Chikyu riser *p*umping pressures of 30 to 40 MPa (4400 to 5800 psi). Pressure limit is the strength of packer.

Volume (using 2 pumps) is 2x 6 barrels/minute.



Experiment to trigger a M5 – M6 event on an oceanic transform fault

- Understand initiation process Is it different for small and large events?
- What are the stress level need to trigger a moderate earthquake?
- Can we trigger earthquakes during different times of the earthquake cycle?