Ocean Transform Fault Drilling and Water Injection:
An Active Experiment to Trigger a Moderate Earthquake

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Abstract

We propose an experiment to understand the initiation of large earthquakes by inducing seismic events on a shallow fault with water injection. Increasing the fluid pressure near an active fault will reduce normal pressure on a fault and bring it closer to failure, according to the classic Coulomb failure criterion. A study to monitor the water pressure and subsequent triggered earthquakes can help answer some fundamental questions in seismology about the stress levels that cause earthquakes and the physical conditions that are necessary for a large earthquake to occur. This is an effort to repeat the famous Rangely, Colorado experiment that induced earthquakes with water pumping during 1969 to 1973. That experiment influenced much of the early optimism for earthquake prediction and earthquake control in the 1970's, although it has never been repeated.

An appropriate location for such an experiment are mid-ocean transform faults, where there are high levels of seismic activity and moderate (M5 to M6) sized earthquakes that regularly occur at intervals of 5 to 15 years. If we can trigger a moderate seismic event a few years earlier than its expected recurrence time, we can directly observe the physical processes and conditions associated with the initiation of the earthquake.

This experiment represents a new utilization of the drilling platforms for active experiments. These kinds of projects can provide new research directions for IODP.

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Introduction

From the time of the famous Rangely, Colorado example 30 years ago (Raleigh et al., 1967), it has widely been observed that increasing fluid pressure in the vicinity of faults can induce earthquakes. The results from Rangely were one of the main reasons for the optimism in earthquake prediction in the 1970's, although that experiment has never been repeated. More recently very small earthquakes have been induced in the aftershock region of the Kobe earthquake with water injections (Tadokoro et al., 2000). Also, there has been a great interest in the oil industry for inducing tiny seismic events with fluid pumping in wells to recover hydrocarbons in old wells. Finally, filling of water reservoirs often produces small earthquakes, and was apparently responsible for causing the 1967 Koyna, India (M6.5) and 1975 Oroville, California (M5.7) earthquakes. So there are a variety of experiences for triggering earthquakes with fluid pressures, both controlled and uncontrolled.

There has been considerable recent information on the static and dynamic triggering of small earthquakes, although very little is known about the stress levels that trigger larger damaging earthquakes. Is there a difference in the stress levels and physical processes of initiation between small earthquakes that often occur and the rare large earthquake ? If we can actually trigger a moderate size earthquake, we can learn about the initiation process of earthquakes and possibilities for earthquake prediction.

Scientific Motivation

The standard explanation for fluid induced earthquakes, is that increases in pore pressure reduce normal stress on a fault and bring cracks closer to failure, in terms of the Coulomb Failure Criterion. This provides a framework for understanding changes in water pressures in terms of the stress levels associated with earthquakes. Producing local changes in the pore pressure and observing changes in the earthquake occurrence can provide answers to question such as,

What is the level of stress needed to initiate (or trigger) an earthquake ?
In a simple model of earthquakes, an event occurs when the accumulating stress reaches the breaking strength of the fault. However, anticipating this level of stress when the earthquake happens is very difficult

How is the time dependence of increasing stress related to causing earthquakes ?
For large tectonic earthquakes, the stress that causes the event builds up over years to millennia. It is very difficult to say at what point in this process the earthquake occurs. The mid-ocean transforms are one of the places in the world where this stress accumulation and earthquake occurrence is most regular (McGuire et al., 2008).

Are there differences in the initiation of small and large earthquakes ?
What conditions are necessary to initiate a moderate to large size earthquake ?

Small earthquakes are common and occur almost continuously in seismic areas, but very little is known about that rare initiation that grows into a large damaging earthquake. The most interesting observations would be if a relatively large (M5 to M6) event could be induced. With data from this experiment we can begin to understand how large earthquakes are different from small earthquakes.

These are all fundamental questions about earthquakes that have been pondered for decades by seismologists. An project to trigger both small and moderate size earthquakes has the potential for making major advances in understanding the source process of earthquakes and ways that they may (or may not) be predicted.

Possible Location for Experiment

Appropriate sites for such an experiment would be transform faults near mid-ocean ridges, such as Blanco on the Juan de Fuca Ridge and Quebrada, Gofar, or Discovery on the East Pacific Rise. In such settings, shallow moderate (M5 to M6) earthquakes occur at repeating intervals of 5 to 15 years (McGuire et al., 2005). The source faults and hypocenters of these strike-slip earthquakes are shallower than for onshore faults because of the high thermal gradient and thus are more easily accessible by drilling to depths of a few kilometers.

An interesting experiment would be to carry out a water injection experiment at one of these sites a few years before the expected earthquakes recurrence, to try to trigger an early occurrence of the event. In addition, earthquakes in this region are often preceded by foreshock sequences. Triggering foreshocks would also provide important information on earthquake initiation processes.

Technical Considerations

A 2 to 3 km deep borehole would be drilled to be close (within a kilometer) to the hypocentral region of a moderate earthquake. Earthquakes along along the transforms occur at shallow depth above the 600 ^{o}C isotherm at depths of about 2 to 5 km (Behn et al., 2007). Fluid pumping can probably increase pore pressure over a fairly large region, so the drilling does not have to be exactly at the (unknown) earthquake hypocenter. The hole needs to be cased and open near the bottom. Water pressurized at various pressures from about 0.001 MPa (about 0.1 psi) to higher values, (possibly 1 MPa, 140 psi) would be pumped into the borehole in order to raise pore pressure in the region of the hypocenter. The upper value for the pumping pressure approach the values of the static stress drops of the earthquakes. This could be an interesting utilization of riser drilling.

An appropriate site in water depths of about 2500 meters can likely be found. However, if the technical capabilities allowed drilling at depths of 3500 to 3800 meters, a much better location could be chosen (Fig. 2).

In most cases, induced earthquakes do not occur immediately after pumping, so there will likely be a several day delay to any induced seismic events.

A complete explanation of the earthquake activity needs understanding of the local fluid, thermal and stress distributions. Depending on the scale of the planned project, several near-fault boreholes to install seismometers along with fluid and strain monitoring instrumentation will also be considered. Also, there would obviously be important information on the physical structure of the fault zone from the borehole cores.

Related Activities

The main objective of this program is to record any changes in the local earthquake activity, so deployment of an array of ocean bottom seismometers (OBS) is an important aspect. There will be needed coordination with US and/or Japan OBS programs, such as NOAA and JAMSTEC. The monitoring program would last from several months before to several months after the water pumping experiment.

Societal Relevance

The results of this experiment can lead to important advances in understanding earthquake prediction and possibly earthquake control. Success in this field has obvious societal relevance for the hundreds of millions of people that live in regions that are prone to large earthquakes. Earthquake prediction has long been an unreached goal in seismology. Understanding the process of triggering and inducing earthquakes is one of few promising paths toward prediction.

Using current technology to actually cause a moderate sized earthquake to happen, should catch the interest of people. This project could be a highlight in outreach activities to the public.

In addition, there would likely be public concern that this type of experiment could produce a large earthquake or tsunami that causes damage. This is the main reason that prohibits this type of experiment on land. A remote mid-ocean ridge site is an ideal location, since even large earthquakes (M7) do not cause any damage when they occur in the mid-ocean ridge region. Also, strike-slip transform faults would minimize the possibility of a tsunami.

Active Experiments

This proposal presents a new use of the drilling capabilities of the IODP platforms that can potentially produce exciting new science results. The mode of ‘Active Experiments’ is a new area of emphasis for IODP expeditions. There have been other proposed active experiments in the IODP programs (e.g. fluid pumping on the Juan de Fuca Ridge), however the present program has predominantly involved collecting cores and physical properties measurements, and more recently some emphasis on (passive) geophysical observatories. Designing and carrying out active experiments for targeted in situ geologic or biological environments, can lead to a variety of innovative directions for IODP.

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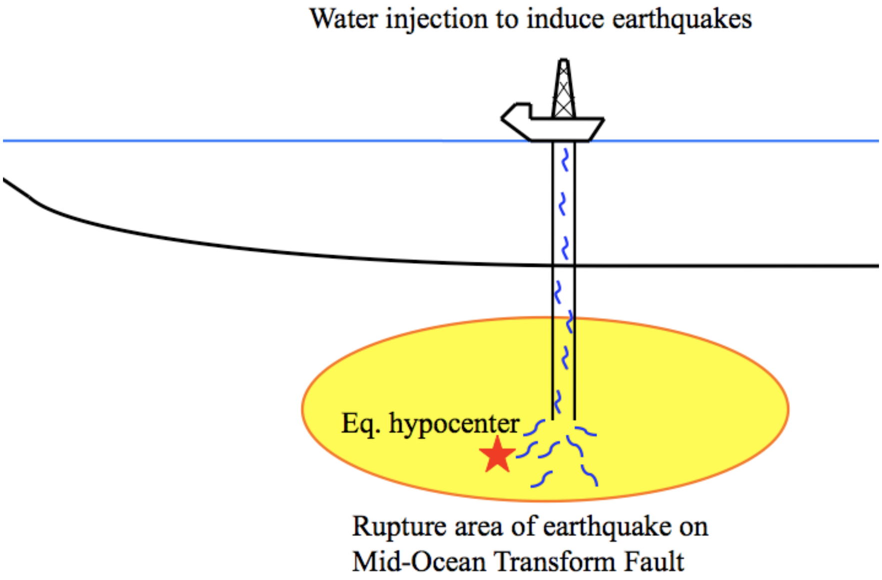

Figure 1. Schematic of water injection experiment to induce earthquakes.

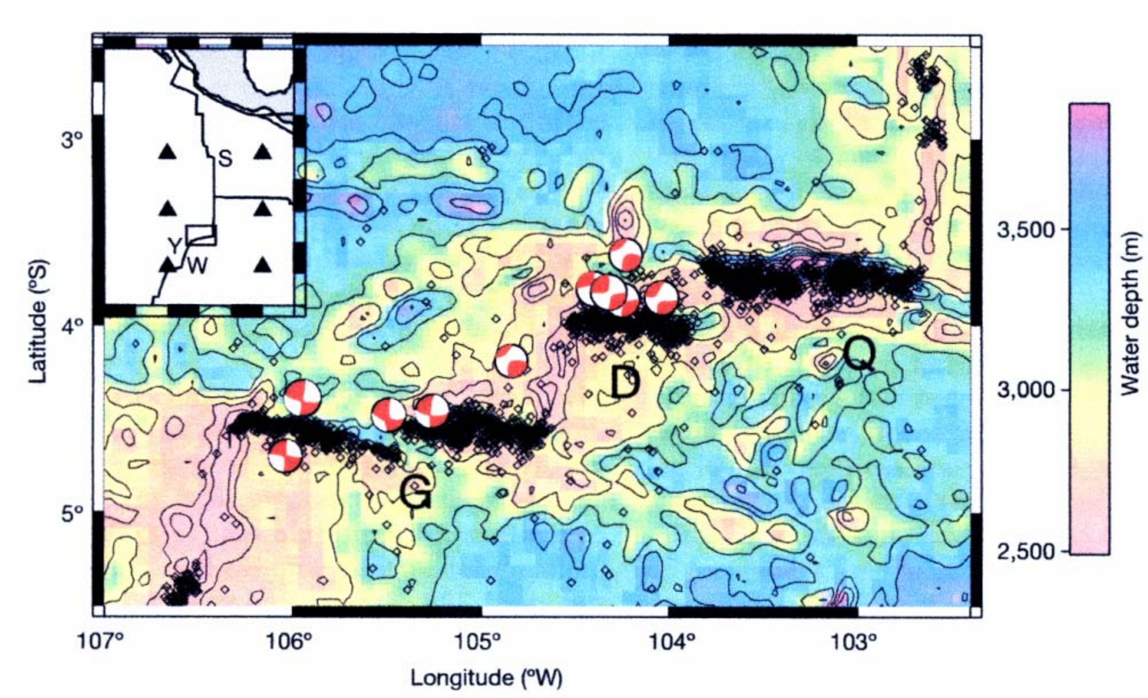

Figure 2. Seismicity near the on transform faults of the East Pacific Rise. (McGuire et al., 2005).