High-precision seismology to understand slow earthquakes

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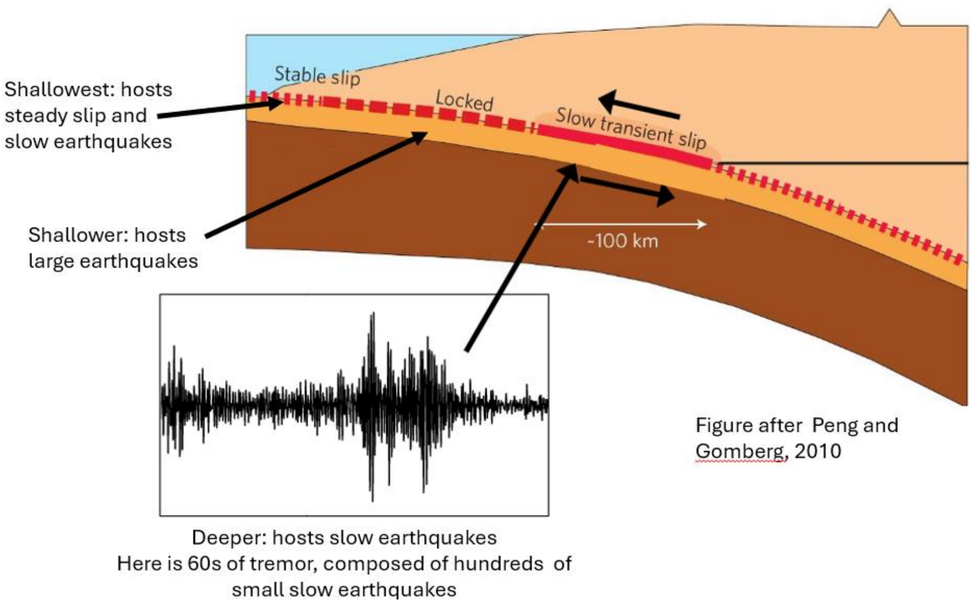
Research theme(s):	• Geophysics and Geodynamics • Geodesy, Tectonics, Volcanology and related hazards
Eligible courses for this project:	• DPhil in Earth Sciences • Environmental Research (NERC DTP) • Intelligent Earth (UKRI CDT)

Overview

Slow earthquakes remain one of the most important unexplained phenomena in fault mechanics. These ruptures are now routinely observed all over the world, often right next to or below large megathrust earthquakes. But we don't know why they happen. We don't know what's happening in the fault zone to keep slow earthquakes, well, slow. In slow earthquakes, faults accelerate but then stall at speeds that are much slower than "normal" seismic ruptures. In this PhD, you'd help figure out why.



The common distribution of slow and fast earthquakes in a subduction zone.

You'd focus your efforts in the DPhil on a particularly abundant type of slow earthquake that creates a phenomenon called tectonic tremor. Tremor, as shown in the figure below, is a low amplitude ground shaking composed of tens to millions of tiny slow earthquakes. Each small rupture lasts around 0.5 seconds and has magnitude equivalent to a M1 or M2 earthquake. We'd like to know what determines that duration and size.

Motivation:

We want to understand the physics of slow earthquakes partly for scientific interest. Slow earthquakes are a significant component of tectonic deformation; they accommodate around half the plate motion at depths around 30 to 50 km.

We also want to try to use slow earthquakes to forecast hazardous faster ruptures. Slow earthquakes often occur right next to large fast earthquakes, and some slow earthquakes have triggered damaging megathrust events. A strong physical understanding of slow earthquakes might let us assess which ruptures are dangerous.

Approach:

Slow earthquakes were discovered almost 25 years ago, and much progress has been made in identifying a range of physical processes that *could* be responsible for their existence. But we have not yet determined which physical process (or processes) is actually responsible. We have been limited in part because (1) we lack extensive enough and precise enough observations of tremor and (2) because we have not carefully tested the proposed models.

So in this PhD, you would

(1) use and develop new techniques to precisely observe tectonic tremor and
(2) use your and others' observations to test proposed models of slow earthquakes.

You could choose to focus more on seismic technique development to improve our imaging of seismic tremor. Or you could use techniques we already have and focus more on model testing, pursuing some of the analyses described below.

Technique development: blind source separation in seismology

A recorded tremor signal, like any seismic signal are a function of two things: the source that generates the seismic waves and the path that the seismic waves travel from source to receiver.

tremor signal = slow earthquake sources * path from source to receiver

Tremor is hard to analyse because both of these components are complex; the source could consist of hundreds of local slow earthquakes, and the path reflects earth structure at sub-km length scales.

To analyse tremor, then, you may start with two existing template-based tools. These approaches take signals from known sources---perhaps local earthquakes or previously identified tremor---and compare them with target data to identify, locate, and analyse new tremor sources. You may create or enhance tremor maps in a range of locations depending on interest. There is tremor with interesting features in Costa Rica, Cascadia, New Zealand, and Alaska, among other locations.

If you are interested in technique development, you may go one step further and address a major challenge with template-based tools: how do you find a template—a reference signal—in the first place? Or equivalently, how do you extract the features of the tremor signal created by the path from the features created by the complex slow earthquake distribution? To date, this problem has been solved by intuitive visual inspection of the data and by brute force. However, the problem can also be framed as a blind source separation problem, as is common in speech processing, and our group has been working to develop source separation tools appropriate for complex but repetitive signals like tremor. Significant progress is possible here, which would let you identify a wide range of seismic signals with high precision, including tremor.

Testing physical models of tremor

As you identify and analyse tremor, you will use the observations to decipher the physical processes that limit the slip speeds in these enigmatic slow earthquakes. You may assess the physical processes proposed to explain slow earthquakes using one or more of the tests below.

Tidal and atmospheric modulation

First, you might examine the response of slow earthquakes to external forcing: to loads on the fault created by oceanic tides or by variation in atmospheric pressure. Some models, such as shear-induced dilatancy, predict that the fault should respond differently to short-period loads like the 12-hour tide than to long-period loads like 20-day atmospheric pressure changes.

LFE properties

Alternatively, you might examine the detailed properties of the slow earthquakes that constitute tremor. To do so, you'd have carefully collect data from many ruptures. But with these collected data, you could assess, for instance, how slow earthquake size increases with duration, whether faults open as they slip, how the porosity of the fault zone changes with time, and how slow earthquake complexity changes with size.

Fault connectivity

Slow earthquake complexity can be created by a range of sources: complex frictional properties, complex fault structures, or spatial variations in water pressure. You may be particularly interested in how all this complexity allows slow earthquake ruptures to migrate along the fault. You may use your tremor maps to probe how ruptures evolve or stall, and you may assess whether ruptures are likely to connect updip, to where large and hazardous earthquakes nucleate.

Timeline

The timeline of this PhD would depend on which projects you are interested in focusing on, and whether you wish to focus more on seismic technique development or on thinking deeply about mechanisms to test models of slow earthquakes. One sample timeline could be as follows.

Year 1: training and literature review in seismic data analysis and slow earthquakes, first set of tremor locations

Year 2: improve tremor detection and locations, write location/detection paper, begin modulation analysis

Year 3: assess physical processes in the context of modulation, write modulation paper, begin analysing fault connectivity

Year 4: finalise fault connectivity analysis, write fault connectivity paper and finalise thesis

Training & Skills

The student will develop strong skillsets in two areas throughout the PhD. First, they'll develop technical skills, learning (and developing) seismic, mathematical, and computational techniques. These could be analytical as well as computational and will likely combine signal processing and machine learning approaches. Second, the student will develop a deep understanding of earthquake mechanics and slow earthquakes, so that they will be able to rigorously test hypotheses about earthquake processes.

Guidance and training will be available from supervisors as well as formal coursework. The student will benefit from a strong seismology group in the department and from the potential to discuss online and visit supervisor A. Thomas and her group in the US. The student will be able to develop connections with other students in the UK and internationally. Attendance at a summer school in earthquake mechanics is highly likely, dependent on availability.

The student will also be trained in written and in-person communication and present their work at various conferences.

References & Further Reading

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Further Information

Contact: If you're interested, please do get in touch with Prof. Jessica Hawthorne (jessica.hawthorne@earth.ox.ac.uk) to have a chat about which aspects of the project you think you'd like to focus on.