

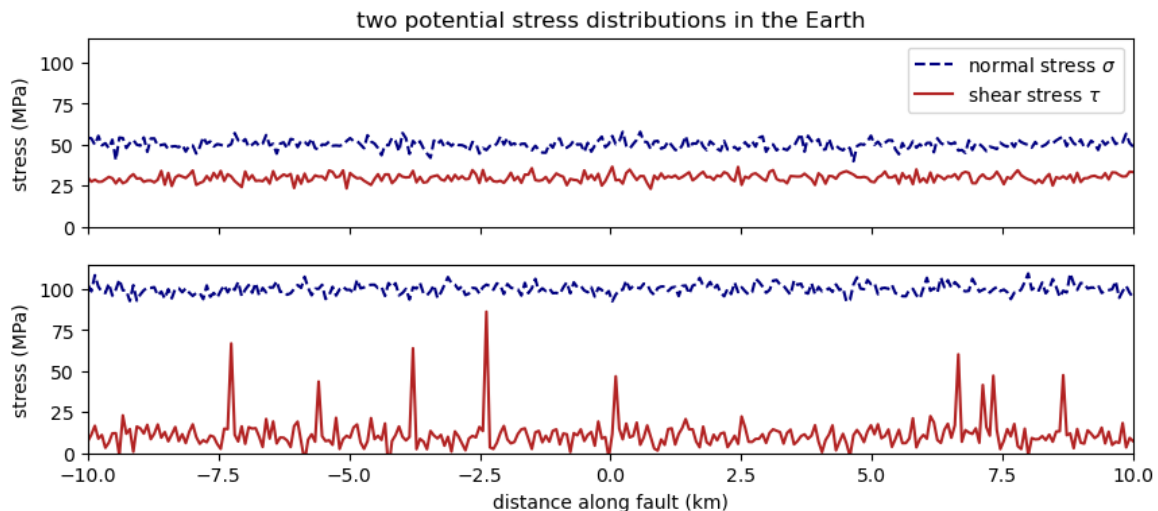
Using earthquakes to constrain stress in the Earth

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Key words:	stress, earthquakes, strength, Earth deformation, rheology, seismology, triggering, signal processing
Research theme(s):	• Geophysics and Geodynamics • Geodesy, Tectonics, Volcanology and related hazards
Eligible courses for this project:	• DPhil in Earth Sciences • Interdisciplinary Life and Environmental Science Landscape Award (ILES LA) • Intelligent Earth (UKRI CDT)

Overview

The magnitude and orientation of stress in the Earth determine how the Earth deforms. It is a first-order feature that one must quantify when considering loads on the Earth's surface, flow within the Earth's crust and mantle, or the nucleation and rupture of earthquakes.

However, the absolute value of stress in the Earth has remained controversial for many decades because most of our observations only provide constraints on stress *changes*. Plausible absolute stress distributions vary widely, as illustrated below.



Observations and models of lithospheric loading, and laboratory measurements of rock friction, suggest that the lithosphere supports significant long-term shear stresses, on the order of hundreds of megapascals. However, alternative observational and modelling approaches imply much lower shear stresses, on the order of megapascals to tens of megapascals. These low stresses are consistent with the presence of the strong dynamic weakening observed in large earthquakes (something) and with observations of earthquake modulation by small-magnitude tidal stresses (something). An outstanding question concerns the relationship between large-scale stress distributions, the mechanics and properties of slip on individual faults, and the degree of lateral and temporal heterogeneity in fault stress over both individual ruptures and entire earthquake cycles.

In this project, you will improve our understanding of stress in the Earth. You will (1) add two new observational constraints on stress state and (2) consider how (or whether) rheological models can accommodate your and others' observations.

Observation 1: Dynamic triggering constraints

The absolute stress in the Earth remains unknown in part because it is difficult to determine the absolute stress at a given location. However, it is relatively straightforward to compute the *change* in stress produced by various perturbations in the Earth. You will examine the changes in stress produced by passing seismic waves: those generated by large ($M > 5$) earthquakes around the world.

When the surface waves produced by large earthquakes pass through a local fault, they change the shear and normal stress on that fault. Sometimes those stresses can instantaneously trigger local earthquakes. You will assess which stresses trigger local earthquakes: are the shear stresses or normal stresses more important?

By determining whether the shear or normal stresses are more important, you will be able to constrain a key parameter of earthquake modelling: the friction coefficient during nucleation. You may assess whether earthquakes begin near the peaks or troughs in the lower panel above and thereby determine which stresses are available for continued earthquake growth.

You should note, however, that the dynamic triggering produced by passing seismic waves is small, and there is likely to be significant random variability. So for this analysis to work, you will have to examine *lots* of earthquakes and carefully consider the statistics of triggering. You will likely compute

surface wave stresses for tens_ or hundreds of thousands of local earthquakes and use a variety of statistical approaches to measure the stresses' influence.

Observation 2: Earthquake depths beneath the ocean

As a second way to determine stress in the Earth, you will determine where earthquakes occur: where there is enough stress to permit brittle rupture. Some analyses of earthquake depths in continental interiors have provided important estimates of the total strength of Earth's lithosphere (something). However, continental interiors are often complex, recording multiple large geological events. This makes them hard to model and interpret.

You will thus focus on estimating earthquake depths (and thereby the brittle stress distribution) in a slightly simpler environment: beneath oceanic transform faults and in oceanic intraplate settings. These portions of the Earth's lithosphere have recorded fewer geological events since their creation, making them ideal for assessing our first-order rheological models (something).

Unfortunately, local observations are rare_ in the oceans. We therefore need to determine the depths of earthquakes beneath the ocean using more distant observations---those made on land. There is no current usable method available to determine those depths for the plentiful small earthquakes that occur, so you will develop a new approach. You will remove much of the complexity in the Earth by comparing pairs of earthquakes. Then you will identify seismic waves from the earthquakes that travel in a variety of directions: waves that travel straight downward to the station (P or S) and waves that first travel up and bounce off the surface of the Earth (pP, pS, or sS).

You may use a variety of tools to identify the timing of these waves. You will likely bring together existing coherence-based signal processing (something), a brute force grid search, and a neural-network based algorithm. You will thus be able to estimate the depths of earthquakes on transform faults around the world and determine plausible regional lithospheric strengths.

Reconciling observations with rheological models

As you make and complete your observations, you will use them to deepen our understanding of stress in the Earth. You may, for instance, consider the observations' implications for (1) rheological models of long-term earth deformation and (2) models of earthquake growth.

You may assess which rheological parameters are plausible. You may consider which rock types, temperatures, and pore pressures could exist at a range of depths in the Earth. Or you may consider how deformation rate could increase with stress in order to match both observed stresses in the Earth and observed stresses and deformation rates in laboratory experiments.

You may also assess how variable stress could be in the Earth. That stress variation could determine long-term rheology as well as the potential for earthquakes that nucleate in high-stress regions to grow into neighbouring low-stress regions.

Timeline

Year 1: Literature survey and preparatory coursework. Data gathering and processing for dynamic triggering observations.

Year 2: Dynamic triggering analysis. Consider implications for earthquake nucleation. Write-up. Begin theory and synthetics for earthquake depth determination.

Years 3: Finalise methodology for depth determination. Determine earthquake depths on transform faults. Compare implied stress distributions with inferences from other techniques.

Year 4: Consider how the range of observations can or cannot be reconciled by existing rheological models. Final write-up.

Training & Skills

The project will require an interdisciplinary skill set including geology, geophysics, signal processing, and statistics, along with a motivation to think deeply about the observations and the literature. Incoming students will not begin with all these skills, however, and training will aim to fill gaps and enhance in knowledge and skills. For example, the student might take a graduate-level course in scientific computing, and may follow other courses in mathematics, materials science or Earth science as appropriate. Attendance at a summer school is expected, depending on availability.

The student will also learn through weekly project meetings with the supervisors. A key focus will be on scientific writing and illustration for publication.

Other courses on professional skills are available through the University. Attendance is encouraged.

References & Further Reading

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Further Information

If you're interested in this project, get in touch with Jessica Hawthorne (jessica.hawthorne@earth.ox.ac.uk) as you're preparing your application.