Physics-based earthquake forecasting for CO₂ storage

Potential Supervisors
- Jessica Hawthorne (https://www.earth.ox.ac.uk/people/dr-jessica-hawthorne/)
- Tom Kettlety (https://www.earth.ox.ac.uk/people/tom-kettlety/)
- Mike Kendall (https://www.earth.ox.ac.uk/people/professor-mike-kendall/)

Key Words
- Geophysics
- Seismology
- Earthquakes
- Hazard
- Machine Learning
- Modelling

Overview

CO₂ sequestration and storage are likely to become a significant component of climate change mitigation. And engineering efforts have recently made swift progress in improving our ability to inject and keep CO₂ fluids in the ground. However, over the past few decades, it has also become apparent that when we inject large quantities of fluids into the ground, the fluids often trigger earthquakes.

A major challenge then, is to store CO₂ in a way that triggers only small, innocuous earthquakes. We thus need to know the relationship between CO₂ pressure and earthquake rate, and we need to monitor and interpret the details of earthquake evolution.

Unfortunately, most well-established earthquake hazard estimates are dominated by empirical approaches. To first order, they assume that earthquakes occur where they occurred before. When we inject CO₂ into the ground, we change the conditions, and earthquakes are unlikely to occur where they were before. Thus we need to understand the physical relationship between injected CO₂ and earthquake rate.

Your challenge will be to advance the state of the art in this area. You will
- Develop a geomechanical model for CO₂ storage in one of several locations projects – perhaps Decatur, Quest, or In Salah. Here you will track the spatial and temporal variations in rock properties, fluid volumes, and fluid properties.
- Couple the output of the geomechanical model to simple models of fault failure, to achieve a first order forecast of induced seismicity for a CO₂ storage site.
- Further develop the seismicity forecast by incorporating more understanding of fault physics, adding information gleaned from laboratory experiments and tectonic earthquakes.

Further Considerations

To appropriately manage induced seismicity risks, uncertainties on dozens of input parameters need to be accounted for. There are many mechanisms controlling induced seismicity, both geological (stress anisotropy, fault orientation, fault density, fault cohesion, fault friction) and operational (fluid volumes, fluid compressibility). This introduces many sources of uncertainty in any assessment of induced-seismicity risk. Seismic and other geophysical surveys can image faults and provide some constraint on some of the above site characteristics, which can then be used to bound a model. However, many of these fault triggering effects are governed by physical processes that take place on features far below the resolution of any seismic survey. For example, notable cases of operationally impactful induced seismicity have taken place on faults that were undetectable in reflection seismic data (e.g., Clarke et al., 2019; Kettlety et al., 2021).

To account for risks from uncertain sources, probabilistic methods must be used. This has been a standard process in risk assessment for natural seismicity for many decades. To do this for induced seismicity, one needs to couple geomechanical models of the reservoir and the induced seismicity behaviour – based on observed microseismic characteristics – to a probabilistic fault failure framework, producing probably-based forecasts of induced seismicity hazard. This can then provide a spatial and temporal forecast of seismicity probability density. You will assess and calibrate these uncertainties as you compare the forecasts to evolving seismicity, so that you can develop further confidence in models that work and discard models that don't match the data.

Several methods to do this have been recently proposed: Bourne and Oates (2017); Cremen and Werner (2021); Bommer (2017); Edwards, Bourne and Oates (2019); Smith, Heimessen, et al. (2022); and Dempsey and Suckale (2017). These methods generally develop a simple model of the
reservoir. The geomechanical model of stress changes can be bespoke, or more general. For CO₂ storage, new models need to be developed to account for the properties of the CO₂, and how it interacts with the subsurface. Determining exactly what physics are more important to include in the geomechanical model and the failure model are key questions in this approach. Data from full scale demonstration projects – Decatur, Quest, and In Salah – will be used to develop and test the performance of these forecasting methods.

Finally, as you consider more sophisticated fault models, you may consider numerous simulations of fault slip—on a range of plausible fault networks. Your goal will be to assess which of these simulations match the data and what their future earthquake rates will be. Given the number of models run, you will use machine learning tools to condense the range of simulations into a tractable number of parameters, and then you will assess which parameters actually need to match the observations in order to develop an accurate seismicity forecast.

**Timeline**

**Year 1**: develop understanding of CO₂ storage and earthquake mechanics, develop geomechanical model

**Year 2**: develop earthquake forecast with simple seismicity model

**Year 3**: develop earthquake forecast with more information from frictional mechanics

**Training & Skills**

In this project, you would learn a broad range of techniques in geomechanical modelling, earthquake mechanics, machine learning, and seismology. You would work at the boundary between understanding fundamental mechanics and developing tools that can be implemented in industry. You will likely attend classes or summer schools and follow self-developed reading courses or journal clubs with your working groups.

Depending on interest, there are various possibilities for collaborations within Oxford and with researchers at other institutions in the UK, US, and Europe. You will interact with researchers working models and on geological and geophysical observations and will attend conferences and workshops in the UK, Europe, and the US.

Finally, you will develop your ability to write and present your work so that you can have more fruitful interactions your colleagues.

**References & Further Reading**


**Further Information**

Contact: Tom Kettlety (tom.kettlety@earth.ox.ac.uk) and Jessica Hawthorne (jessica.hawthorne@earth.ox.ac.uk)

This project would be suited to a student interested in seismic hazard and physical understanding of the Earth, with an ambition to approach complex datasets. Such a student could have a wide variety of backgrounds, from physics to geology, engineering, or computer science. There will be opportunities to further develop your knowledge in unfamiliar areas. Please get in touch if you’re interested in a project along these lines.