The inner workings of the earthquake cycle: New insight from integrating geophysical observations and microstructures

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Slip behaviour at and around faults has been shown to be highly dynamic with variability in behaviour occurring both spatially and temporally. This exciting project explores the underlying physical processes that lie at the core of dynamic slip behaviour by probing the rock record of fault slip. In this novel project, you will integrate knowledge obtained from high resolution laser scanning (LiDAR), quantitative microstructural work, and Quaternary fault studies to gain an in-depth understanding of the physical processes acting on a fault and/or fault zone. Results will be far reaching in fundamental science with direct implications for applied science in terms of earthquake hazard evaluation and prediction.

Earthquakes are one of the main hazards that humanity faces, therefore improving our ability to anticipate how fault zones behave through time is of major importance. However, we have still very little understanding of why some faults appear to accommodate different slip modes and others do not, how different slip processes are represented in the rock record, and why faults cycle betwe-en different modes. This project in novel in its cross-disciplinary nature integrating earthquake cycle analysis on real rocks including information on the average fault history using isotopic age dating on fault rocks, patterns of fault surface roughness, and their link to microstructures from natural and experimental fault rocks. In Leeds we have the rare opportunity of this integration as experts in the respective fields are within the same school. In addition, strong personal links to former Leeds staff members (e.g. Dr Jess Hawthorne, now Oxford University) and collaborators (Prof Ken McCaffrey, Durham) strengthen this project.

The earthquake cycle typically consists of three periods of fault slip: (1) coseismic, when earthquake rupture occurs at speeds of 1-2 km/sec and results in a huge release of energy during an earthquake (Heaton, 1990; Rice, 2006); (2) postseismic – during which the fault relaxes and is thought to experience an exponentially decaying rate of stable afterslip (Perfettini and Ampuero, 2008; Ingleby and Wright, 2017); and (3) an interseismic period when the fault is locked and accumulates elastic strain prior to the next earthquake (Marone, 1998; Barbot et al., 2012). In reality, faults are even more complex and may display an additional range of behaviours associated with steady-state creep, pulsing tremor, and slow slip (Hawthorne at al., 2016). On timescales covering multiple earthquake cycles, slip behaviour is even more unpredictable. It is now well-recognised that faults can experience periods of enhanced seismic activity with significantly variable recurrence intervals (Figure 1, Weldon et al., 2004; Cowie et al., 2017). It is not known if this range of fault slip behaviour can occur on all faults, or if it is limited to certain types of faults (e.g. plate boundaries vs. continental settings).

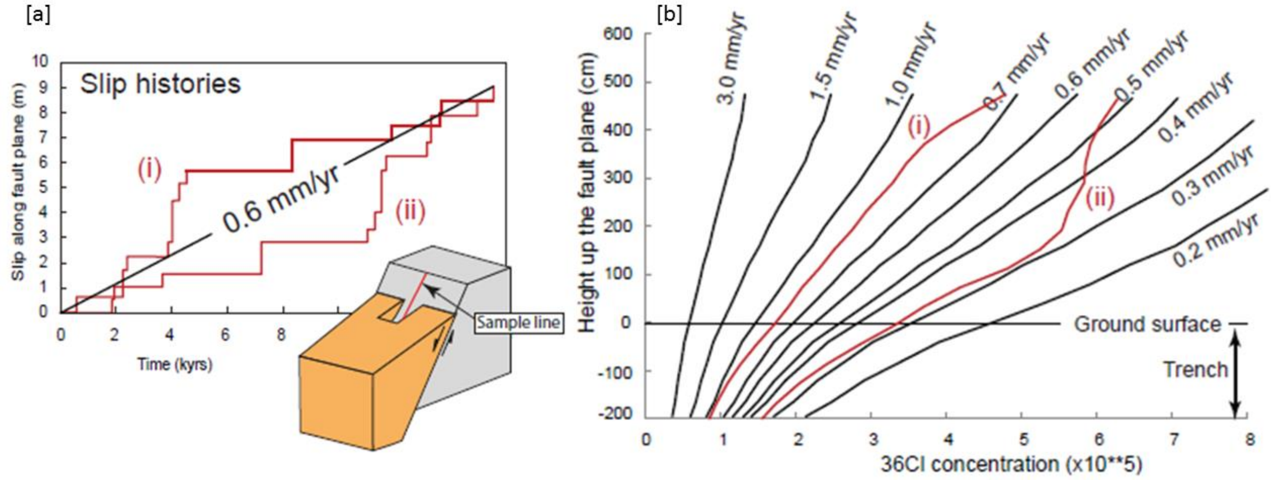


Figure 1:(a) Red lines show examples of two different slip histories that have the same long-term slip rate but highly variable recurrence intervals. (b) Demonstrates how cosmogenic nuclides can be used to model variable fault slip, with sampling strategy indicated in the inset of (a), see Cowie et al., (2017)

The mechanical behaviour of a fault zone is governed by physical and chemical processes occurring on grain-size (micro) scales. Important processes in the development and evolution of faults include stress induced fracturing and frictional sliding, grain communition, crystal plasticity and pressure solution. These processes occur at a variety of timescales where fracturing is instantaneous but crystal plasticity may be continuously active over thousands to millions of years. So far much of our knowledge of these processes has been gained indirectly by fitting theoretical mechanical behaviour to observed slip behaviour. However, microstructures in fault rocks allow direct derivation of the processes responsible for behaviour during slip at a range of rates (e.g. Verbene et al. 2015). Even though it is clear that the microstructures in fault rocks must hold key answers to the underlying questions of fault slip behaviour, the use of microstructures has been hampered by analytical problems as many structures are extremely fine grained and micron to nanometre scale analysis is necessary. In addition, scaling the effects of microscale processes as observed in laboratory experiments to large scale fault rock behaviour of natural faults is not straightforward.

Recent advances in analytical techniques (e.g. Piazolo et al. 2015; Piazolo et al. 2016; Delle Piane et al., 2017) allow us for the first time to investigate microstructures of fault rocks in unprecedented detail, promising to gain the much needed fundamental knowledge of the mechanical and chemical processes governing the rheological behaviour of faults through time and space (e.g. Figure 2). To gain such knowledge it is imperative that analyses be conducted in a framework of well constrained case studies, utilizing the natural laboratory of real faults. In order to do so, we must combine the real-world record of the main types of fault behaviour, made *on geological scales in time and space*, with in-depth microstructural analysis.

Different to laboratory experiments, it is possible to investigate a fault zone over different scales in field-based studies with the background knowledge of a particular fault's behaviour through time. Such work will augment experimental work focussing on the physics of one time-step in the earthquake cycle.

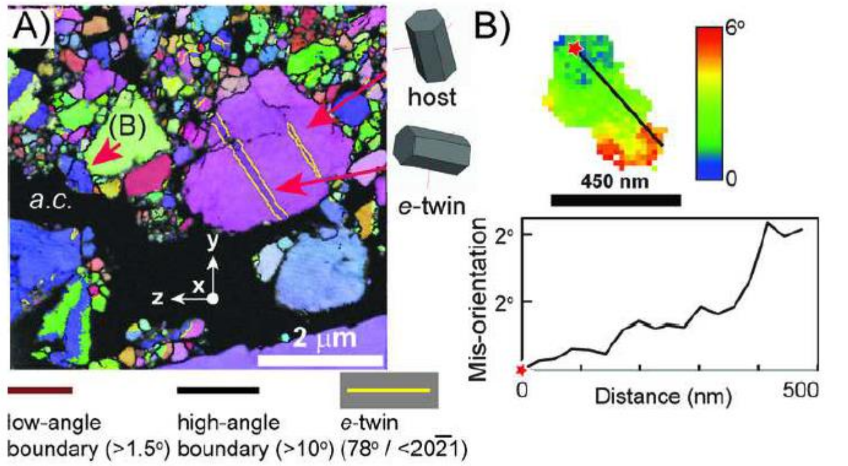
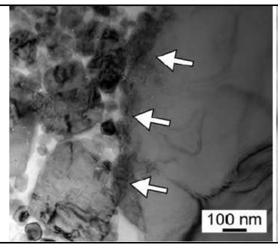


Fig. 2: A & B Example of calcite fault rock investigated using EBSD (Electron Backscatter Diffraction analysis) at the nanometer scale (spatial resolution of 10 nm) to investigate the changes in orientation within the fault rock. This allows us to identify different deformation mechanisms.

(c) TEM images of gouge particles produced after 120 mm of shear displacement. Micrometre-sized calcite crystal surrounded by a sub-micrometre matrix. Note the difference in dislocation density (dislocations are seen as grey "wiggles" between the core and the rim of the crystals. (see Delle Piane et al. Geology 2017.)



In this project you will collect a set of fault breccia samples "caught in the act" from active fault zones in several potential field areas. One area of focus will be from the Apennines in central Italy, which recently experienced a devastating earthquake sequence that began with an M_w 6.2 resulting in nearly 300 deaths and relocation of tens of thousands of people. This regions hosts normal faults that are at varying stages of maturity, which have been shown to demonstrate slip rate variability (Figures 1 & 3). You will also have the opportunity to investigate normal faults in southwest Turkey, and other potential regions depending on your interest and progress. Target faults in Central Italy and Turkey have been researched in terms of their seismic activity and their average Quaternary slip behaviour, and the location of ideal field sites is already known. You will have the unique opportunity to combine knowledge gained through microscopic studies with mesoscale features on these faults, using terrestrial laser scanning datasets detailing the metre-scale fault surface, in collaboration with co-supervisor Prof Ken McCaffrey, from Durham University (e.g. Figure 3c). These faults provide the opportunity to investigate structures from the outcrop to the nanoscale, allowing for a process-oriented analysis of fault rock structure.

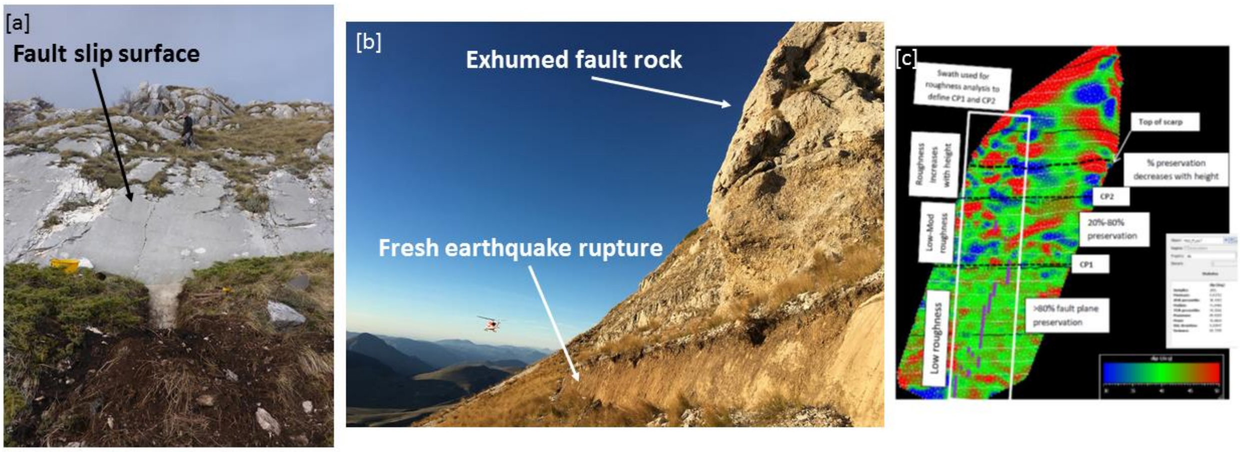


Figure 3: Photos of a preserved fault surface from central Italy (a) and the 2016 earthquake rupture (b). (c) shows a terrestrial laser scan (TLS) derived map of fault surface roughness.

Objectives

In this project, the student will work with leading scientists at Leeds (Laura Gregory and Sandra Piazolo), Oxford (Jess Hawthorne), and Durham (Ken McCaffrey) to integrate the latest techniques in characterising fault zone structures in order to understand the dynamics of the physical processes preserved from the earthquake cycle. The project will address the following questions:

1) *Processes*: What physiochemical processes are involved in fast fault slip, creep, and postseismic afterslip? How do these processes evolve as a fault grows and develops?
2) *Recognition*: How can various earthquake cycle behaviour be identified in natural rocks? What is the link between micro- and meso- scale features of damage on a fault, if any?
3) *Effect*: What is the mechanical effect of the different processes identified in (1)? What is an appropriate mathematical representation of such dynamic behaviour? Based on the latter, can we forecast the timescale and spatial behaviour of fault zones past, present and future?

In order to answers the question posed above, it will be necessary to combine different techniques and approaches.

1. Investigate small scale features in samples close to or on the fault using the latest field based (e.g. fault zone laser scanning) and analytical (e.g. nanoscale electron microscopy, microtomography) techniques. The field area in central Italy with faults of known Quaternary fault slip rates (e.g. Cowie et al. 2017) will be the initial focus but we anticipate expansion of the field area to southwestern Turkey and/or the western USA.
2. Develop models of process dynamics derived from field and sample analysis. Link structures observed at all scales through careful sample selection.

3. Integrate key parameters derived from microstructural analyses into fault slip modelling/physical calculations and compare the results with observed fault behaviours. (e.g. Hawthorne et al. 2016)
4. Conduct well-constrained experiments of fault slip in the laboratory collaborating with project partner Prof Shengwen Qi at the Chinese Academy of Sciences, followed by subsequent in-depth analysis of experimental samples (e.g. Piazolo et al. 2015).
5. Develop and test hypotheses linking the observations from the rock record into fault slip behaviours, relying on what we already know from the earthquake and Quaternary records on the faults you have studied.

We expect the balance between these approaches to vary depending on the specific interests of the student. There is the potential to develop novel methods of integrating what you may observe in the rock record with physical models of fault slip; a challenging but important endeavour.

Potential for high impact outcome
Active tectonics and the resulting earthquake hazard is a pressing issue facing many countries. We are in a unique position at Leeds to bring together a range of observational, modelling and field approaches to answer important unresolved questions about the earthquake cycles. The research topic has immediate relevance to improving our understanding of the link between faulting and timescale and nature of seismic hazard. There will be ample opportunities to deliver the results of the project at international conferences in addition to UK meetings. Through in-country collaborators, there will be the opportunity to communicate the earthquake hazard to local authorities and civil protection planners.

The project sits in an emerging research field with important fundamental research to be done but also important societal implications. Consequently, we anticipate the project will generate several papers being suitable for submission to high impact journals.

Training

You will be part of an active group of researchers and students at SEE that focus on earthquake dynamics including experts in active faulting and microstructural investigation of rocks and minerals. Specifically, the student will work under the supervision of Dr. Laura Gregory and Prof Sandra Piazolo within the Tectonics and Geodynamics group in the Institute of Geophysics & Tectonics at the School of Earth & Environment at Leeds. The Institute also hosts the Centre for the Observation and Modelling of Earthquakes, Volcanoes and Tectonics (COMET), which provides a large group of researchers engaged in active tectonics research with whom the student can interact. This project provides a high level of specialist scientific training in: (i) analysis of geophysical data in terms of earthquake cycle, (ii) geological field skills, (iii) laboratory analysis including state-of-the-art microstructural and –chemical analysis (from outcrop to nanometer scale) (iv) data processing and interpretation of laser scanner data and (v) Deformation modelling related to earthquake cycle. Microscale analysis will be using the most advanced analytical suite currently available in the UK housed in the new Bragg Centre, a £96 million investment in engineering and physical sciences at the University of Leeds. The successful PhD student will have access to a broad spectrum of training workshops put on by the Faculty that include an extensive range from scientific computing through to managing your degree and preparing for your viva.

Student profile

The student should have a strong interest in active tectonics challenges, a desire to undertake laboratory and fieldwork overseas, and a strong background in a quantitative science (earth sciences, geophysics, geology, physics, natural sciences). Willingness and excitement for taking up the challenge to work at the boundary of geophysics, mechanics and microstructural analysis utilizing a combination of technique (field analysis, in-depth microstructural analysis, experiments and/or numerical modelling) is a prerequisite. This is a multidisciplinary project but we welcome students with enthusiasm for any relevant field as the project is flexible based on your interests.

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