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# Shear failure of a granite pin traversing a sawcut fault

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ABSTRACT

Fault heterogeneities such as bumps, bends, and stepovers are commonly observed on natural faults, but are challenging to recreate under controlled laboratory conditions. We study deformation and microseismicity of a 76 mm-diameter Westerly granite cylinder with a sawcut fault with known frictional properties. An idealized asperity is added by emplacing a precision-ground 21 mm-diameter solid granite dowel that crosses the center of the fault at right angles. This intact granite 'pin' provides a strength contrast that resists fault slip. Upon loading to 80 MPa in a triaxial machine, we first observed a **M** -4 slip event that ruptured the sawcut fault, slipped 40 μm, but was halted by the granite pin. With continued loading, the pin failed in a swarm of thousands of **M** -6 to **M** -8 events known as acoustic emissions (AEs). Once the pin was fractured to a critical point, it permitted complete rupture events (**M** -3) on the sawcut fault (stick-slip instabilities). Subsequent slip events were preceded by clusters of foreshock-like AEs, all located on the fault plane, and the spatial extent of the foreshock clusters is consistent with our estimate of a critical nucleation dimension $h^*$. We also identified an aseismic zone on the fault plane surrounding the fractured rock pin. A post-mortem analysis of the sample showed a thick gouge layer where the pin intersected the fault, suggesting that dilatancy of this gouge propped open the fault and prevented microseismic events in its vicinity. Recorded microseismicity separates into three categories: slip on the sawcut fault, fracture of the intact rock pin, and off-fault seismicity associated with pin-related rock joints. We found that pin fracture events were exclusively implosive (anticrack) even though the shear process zone was overall dilatant. This shows how aseismic effects can lead to unexpected seismic manifestations of certain faulting processes.

## 1. Introduction

Improvements in high speed digital data acquisition have led to increasing numbers of high quality observations of small seismic events in both laboratory and field studies. Earthquakes **M** 3 to **M** -4 have been used to image hydraulic fractures[1,2] and geothermal reservoirs,[3,4] study mining-induced seismicity,[5,6] and gain insight into the nucleation processes of larger crustal earthquakes.[7,8] Laboratory experiments (0.1–1 m scale), and in-situ experiments (10 m scale) conducted in underground laboratories (e.g. [9]) are used to study faulting processes and associated microseismicity under more idealized conditions. Such experiments can include mechanical measurements of fault slip, stresses, and forces—quantities that are largely unknown at depth—enabling a link between underlying mechanical processes and their seismic manifestations.

In laboratory rock mechanics experiments, seismic events can be broadly classified as either "stick-slip" events or acoustic emissions (AEs). Stick-slip events rupture the entire sample and are accompanied by measureable drops in stress supported by the sample. In this paper, we refer to stick-slip events as dynamic slip events (DSEs). DSEs are thought to be analogous to earthquakes,[10] but their dynamics depend, at least in part, on the stiffness of the loading machine (e.g. [11]). AEs are smaller seismic events that are typically confined to the interior of a laboratory sample. They can be caused by microcrack formation, slip events, sudden compaction, and other mechanisms (e.g. [12–14]) and they are used to study the mechanics of fracture and faulting processes on the mm scale in materials ranging from rocks to reinforced concrete.[15] Recent progress in sensor calibration showed that AEs range from **M** -5 down to about **M** -8.[1,16–18] While the seismic moments $M_0$ of AEs are truly tiny, their stress drops—reflecting the events' duration relative to $M_0$—are consistent with scaling relationships observed for larger natural earthquakes.[19,20] This provides some support for a long-standing assumption that AEs can provide insight into the mechanics of larger faulting processes (e.g. [21,22]).

This paper presents a laboratory experiment that explores heterogeneity in a simulated fault system. A limited number of laboratory AE

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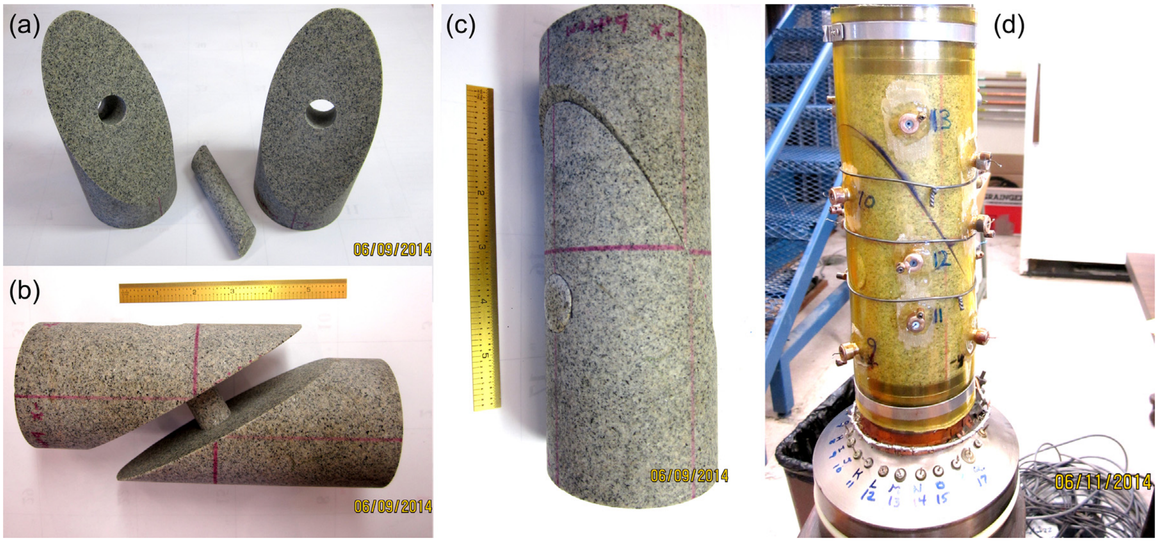

**Fig. 1.** The "pin" sample used in this study was a 76.2 mm diameter cylinder of Westerly Granite with a 30° sawcut simulated fault surface and a 20.68 mm diameter pin of intact westerly granite placed in a 20.78 mm hole oriented perpendicular to the sawcut. The sample was instrumented with an array of seventeen piezoelectric AE sensors (d) to record the locations and focal mechanisms of tiny seismic events associated with the rock deformation processes.

tests have studied deformation on 'natural' fault surfaces, i.e. fractured surfaces with cm-scale roughness.[22–24] However, rock mechanics experiments commonly employ planar faults (saw cut) that have been ground flat to simulate a more mature fault or to determine frictional properties related to minerology and surface contacts. Samples with saw cut faults have lower strength than intact samples, and typically initiate slip suddenly and with little warning. Using both mechanical and seismic (AE) data, studies on saw cuts have explored fault surface roughness, asperities, and the initiation and propagation of dynamic rupture,[24–27] but they lack variation in local shear strength due to macroscopic fault irregularities (jogs, bends, stepovers or branches) or along-strike variations in lithology and pre-stress. (Note, an early study did, in fact, observe contained rupture on a 2 m fault that had large-scale heterogeneous pre-stress.[28]) This is a class of fault heterogeneity that is difficult to achieve with a triaxial experiment (~ 80 MPa) where sample size is limited.

Our sample was designed to include an idealized asperity embedded in an otherwise standard laboratory sawcut fault. The asperity is a central pin of intact rock, as shown in Fig. 1. The pin makes up about 4% of the total fault surface area and provides a shear strength contrast of more than a factor of 2. We directly compared the results to our previous work on an identical sample without a pin.[26] We used the pin sample to test whether a 4% asperity would stop dynamic rupture and whether the remnants of the asperity would affect subsequent ruptures. AE analysis was used to explore the seismic manifestations of the above effects.

Seismic sources (both earthquakes and AEs) are typically represented with a seismic moment tensor (MT). The information contained in the MT has been used to map regional stress fields (e.g. [29–31]) and to discriminate between explosions, tectonic quakes, and mine collapse events (e.g. [32,33]) including for verification of nuclear test ban treaties.[34] While MT studies are routine for great earthquakes and temblors large enough to be recorded by an array of stations with wide azimuthal coverage, they are less common for microseismicity. The potential of MT analysis of AE data has long been known, but uncertainties associated with velocity models, sensor response, and low signal-to-noise ratio muddy results. It is typically unknown whether the scatter commonly observed in MT-based results is due to limited accuracy of MT solutions or if it reflects true variation in source properties. In our experiments, the locations and orientations of the pin and fault were prescribed, and different event types could be cleanly separated in time and space, so we are able to test the validity of MT solutions on the mm scale.

When loaded, our pin sample produced a variety of types of AEs including predominantly double-couple, foreshock-like events associated with slip on the sawcut fault and other events associated with fracture of the intact granite pin. When sheared, the pin did not rupture as a single event. It failed as a swarm of thousands of AEs. On the whole, this shear process zone experienced dilatancy, and a thick layer of fault gouge was developed. Remarkably, all associated AEs had clear compaction (implosive) mechanisms indicating that dilative processes were aseismic.

## 2. Experimental procedure

Tests were performed on a cylinder of room-dry Westerly granite that was 76.2 mm in diameter and 175 mm long, as shown in Fig. 1. The sample contained a saw cut simulated fault inclined at 30° to the vertical axis and a 20.68 mm diameter cylinder of intact Westerly granite placed in a 20.78 mm diameter hole that intersected the fault at a 90° angle. The sample was jacketed in a 4.5 mm-thick polyurethane sleeve, and an array of 17 piezoelectric AE sensors (6.35 mm diameter) were separated from the rock surface by 1 mm brass fixtures. These fixtures had curved surfaces that were machined to match the sample curvature and were glued directly to the rock (Fig. 1d). The sample was then placed in a pressure vessel of a triaxial deformation apparatus and loaded at constant confining pressure $p_c = \sigma_2 = \sigma_3 = 80$ MPa. As depicted in Fig. 2a, axial stress $\sigma_1$ was applied with a hydraulic ram that advanced a steel piston against the bottom of the sample column. The diameter of the granite pin was precision ground to provide a close but non-interference fit inside its hole, with a clearance of approximately 100 µm. The pin was assembled in the sample without using cement or glue that might inadvertently change the rock properties in the vicinity of the fault. Based on simple finite element models, we expected confining pressure $p_c = 80$ MPa to elastically reduce the hole diameter by about 60 µm. Due to its orientation, it is likely that the hole was also distorted, and this provided a modest clamping force on the pin. Axial displacement, $z_{LP}$, axial stress $\sigma_1$, and $p_c$ were measured outside the pressure vessel and recorded continuously at 1 Hz sampling rate. The parameters $p_c$ and $z_{LP}$ were computer controlled using servo valves, and we imposed a constant axial shortening rate $d(z_{LP})/dt = 5$ µm/s. The total area $A_T$ of the sawcut, including the circular cross-section of the pin, is 9122 mm$^2$. The cross-sectional area of the pin $A_{pin} = 336$ mm$^2$, or 3.7% of the fault area. Shear stress ($\tau$) and normal stress ($\sigma_n$) resolved