Spatio-Temporal Organization of Earthquakes: Insights from Aseismic Transients and Seismic Triggering in Rock Fracture

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1 Introduction

Recent observations have increasingly detected **large-scale aseismic deformation** preceding certain major earthquakes. In some instances, this slow deformation is associated with **clustered sequences of seismic events** near the hypocenter of the impending mainshock [1]. The spatio-temporal clusters of seismicity may be related to internal stress transfer through **triggering processes**, a potentially key component to earthquake nucleation [2]. However, our understanding of the interaction between aseismic deformation and seismic triggering is limited, primarily due to challenges in observation.

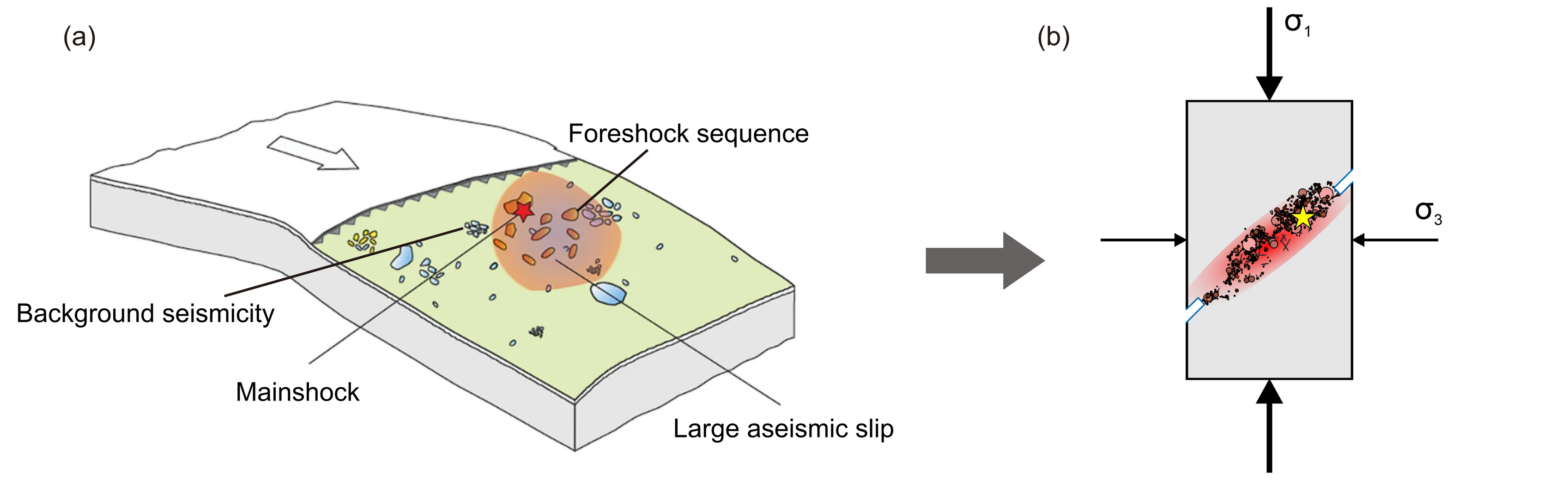

Fig. 1. (a) Schematic of the aseismic slip and earthquake sequences for the 2009 M5.8 earthquake in northern Peru [3]. (b) Schematic of aseismic deformation and acoustic emission (AE) events during the triaxial rock experiment.

2 Methodology

- A triaxial compression test with a **notched** (35° from the loading axis), cylindrical Rotondo **granite** sample confined to P_c **= 50 MPa** (Fig. 2a).
- **Acoustic emissions** (**AE**) recorded using 9 PZT sensors (S1-S9) at 20 MHz sampling rate (Fig. 2b).
- **Distributed strain sensing** (**DSS**) along optical fibers wrapped in the circumferential direction (C1-C3) at a sampling rate of 0.25 Hz (Fig. 2b).

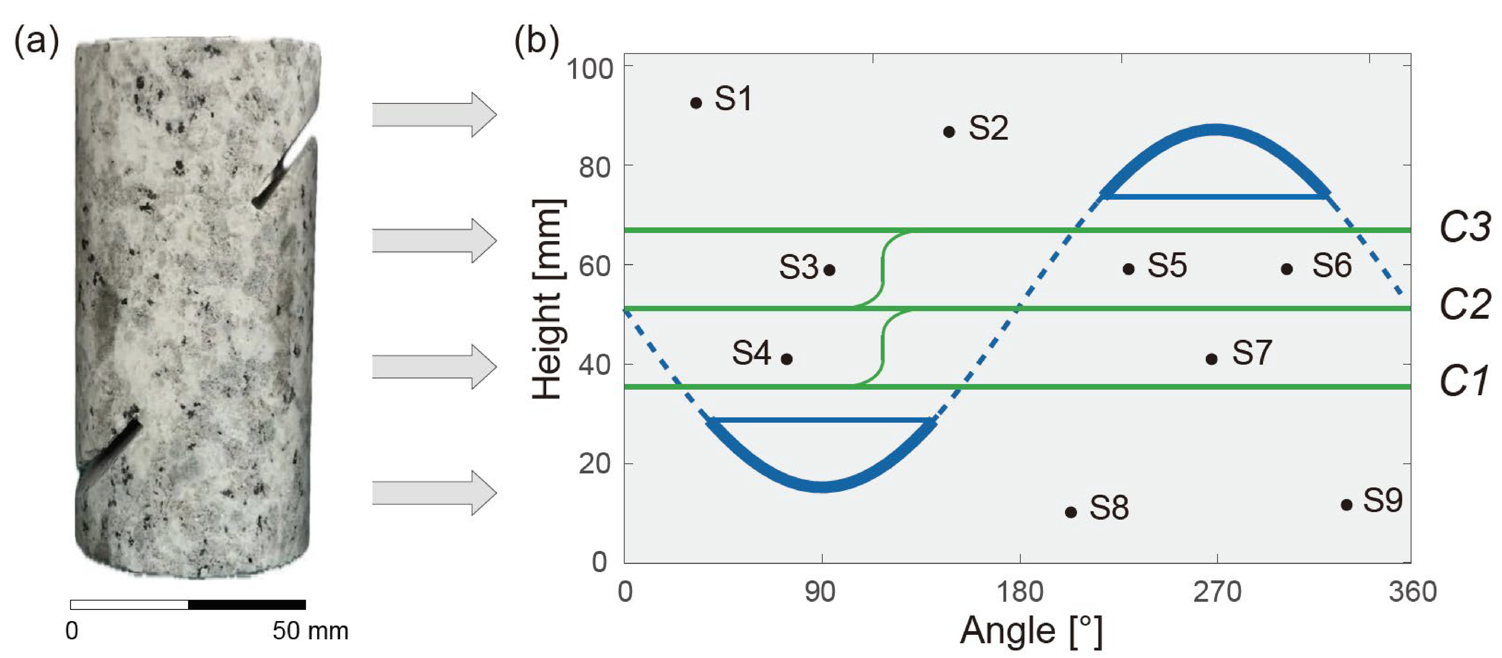

Fig. 2. (a) Rotondo granite sample with a pair of 15 mm deep notches at a 35° from the loading axis. (b) Projection of the PZT (black dots) and DSS (acrylate fiber in green) sensor positions on the sample surface.

3 Triaxial compression test

When we observed an increase in the AE rate, the external axial loading rate was reduced to **0.004 mm/min** to **slow down** the failure process during Phase III.

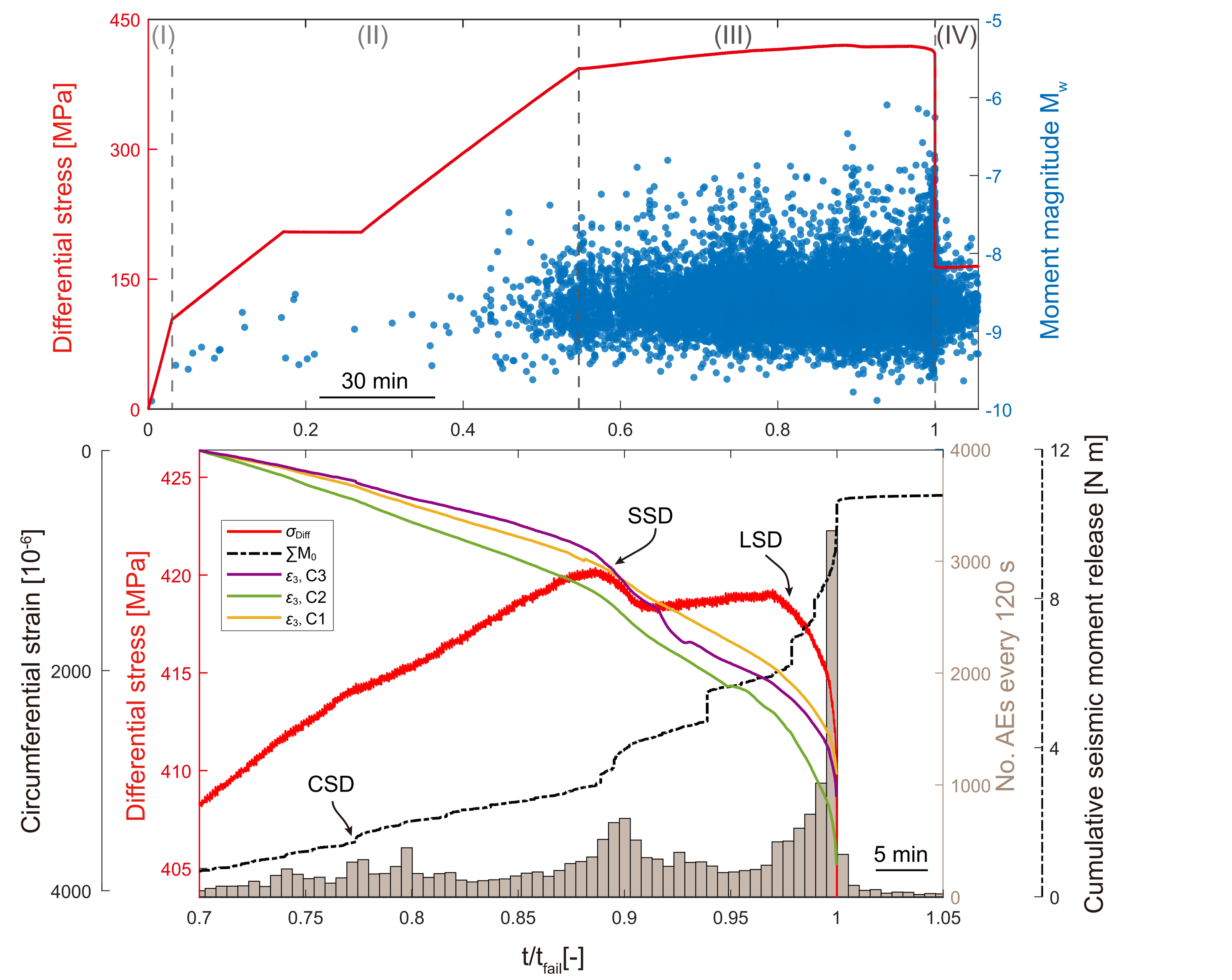

Fig. 3. (**Top**) Differential stress (red line, left axis) and the moment magnitude of the AEs (blue dots, right axis) as a function of time. (**Bottom**) Differential stress (red line, left axis), mean strain for each DSS line (yellow line: bottom level; green line: middle level; purple line: top level; left axis), number of AEs at two-minute intervals (histogram bars, right axis) and cumulative seismic moment (dashed line, right axis) during Phase III.

4 Acoustic emission results

The faulting process shows an intermittent, burst-like behavior of AE activity.

A short-lasting AE burst at $t/t_{fail} \approx$ 0.77 highlights a **small confined slip** (**CSD**) event that was not recorded in the macroscopic mechanical data [2] (Fig. 3). Small AE clusters are shown in the lower and middle part of the future fault plane (Fig. 4a).

An AE burst is correlated in time with a **small stress drop** (**SSD**) following the peak stress. This AE cluster spreads towards the upper part of the fault surface (Fig. 4b).

The subsequent **large stress drop** (**LSD**) is illuminated by the AE activity spreading across the fault surface (Fig. 4c).

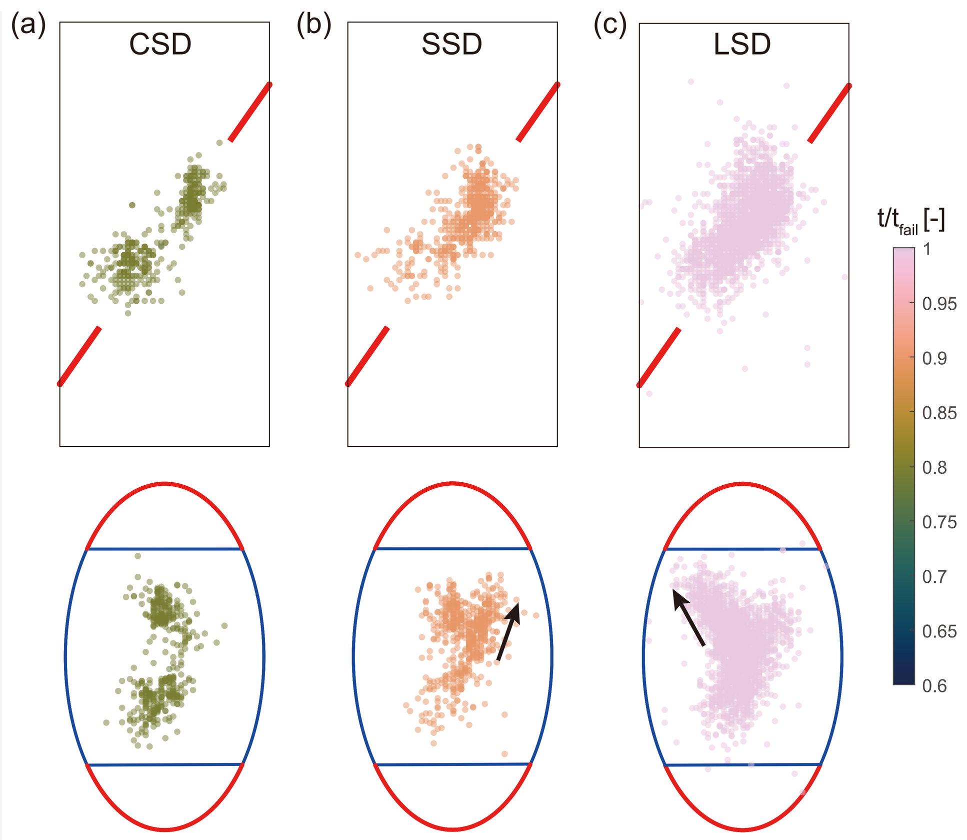

Fig. 4. Sequence of AE locations obtained within a 60 s window starting ~15 s following the nucleation of a slip event. The slip events are shown in parentheses. The top row shows the locations in the depth plane, and the bottom row shows the same locations projected on the fault plane. The black arrows indicate the direction in which the AE clusters are spreading.

5 Seismic Triggering and Aseismic Transients

We follow the space-time-magnitude nearest-neighbor approach to test for the clusters of AE events (Fig. 5):

$$\tau_j = t_{ij} \times 10^{-bm_i/2}, \quad R_j = r_{ij}^{\,d} \times 10^{-bm_i/2}$$

$$\Downarrow$$

$$\eta_j = \tau_j \cdot R_j$$

This allows us to identify the triggered events (22%) and background seismicity (78%).

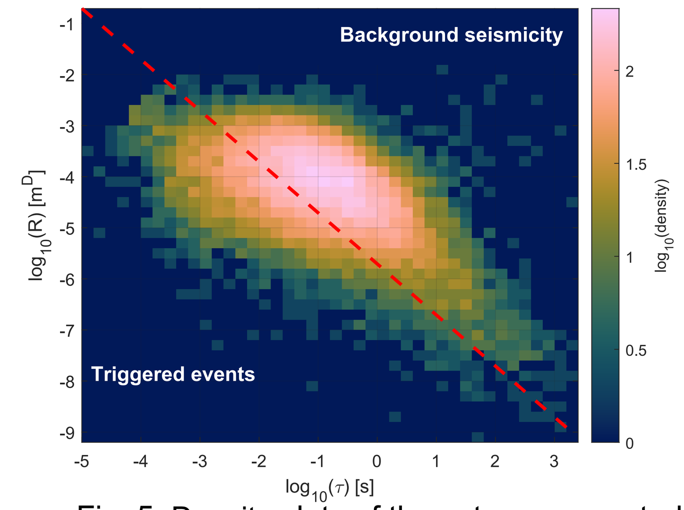

Fig. 5. Density plots of the set η represented in log τ – log R space.

Strain accumulates near the end of notches. The nucleation of SSD is associated with the **build-up of strain rate** accompanied by the **seismic swarms** (Fig. 6 a, b), indicating the formation of the **damage zone**. This is followed by a sharp contrast between positive and negative strain rates, indicating the growth of shear cracks emanating from the notches. The front of the **strain transients** propagates outwards, further inducing a step-like increase in seismic moment released by background events. This triggers **foreshock sequence** and **aseismic strain acceleration**, interpreted as the nucleation of the dynamic rupture.

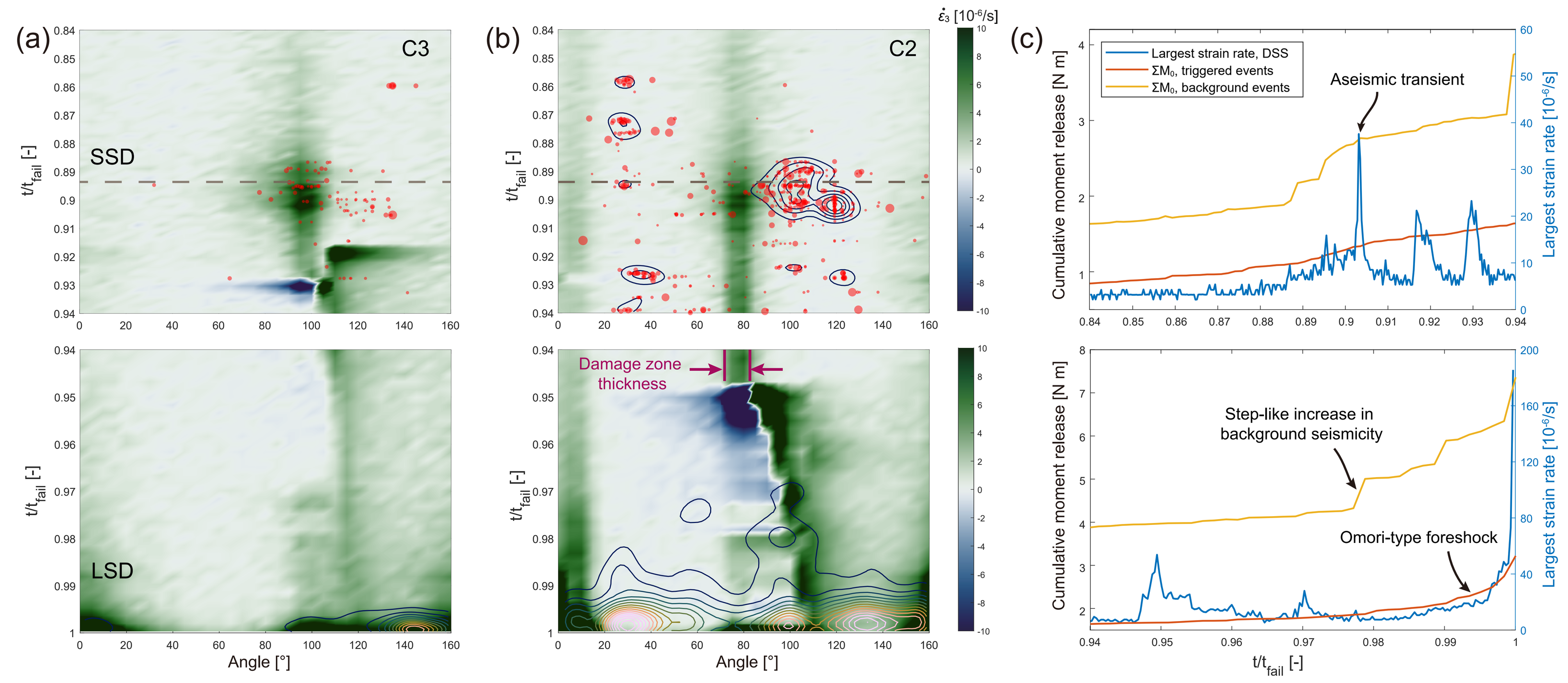

Fig. 6. (a, b) Strain rate based on DSS data for circumferential cable C3 (a) and C2 (b) with triggered events superimposed. The contour plot marks the density of events. (c) Cumulative moment release of background seismicity (orange line, left axis) and triggered events (red line, left axis), largest strain rate (blue line, right axis).

5 Conclusion and Future Work

Our data suggest that **aseismic strain accumulation produces progressive local weakening to trigger AE bursts and strain transients associated with the fault nucleation** (Fig. 4 and 6). Once formed, the build-up strain migrates from the fault zone and the AEs delocalize to **homogenize the stress among the fault surface**. This further triggers the strain transients in the neighboring volume, resulting in an acceleration of foreshock activity and aseismic strain leading to a large rupture (Fig. 6). We will further examine the effect of fluids on fracturing process in future experiments.

References

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