Complex multi-scale preparatory processes of stick-slip events on rough laboratory faults

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Abstract

We discuss data of laboratory stick-slip experiments on Westerly Granite samples performed at elevated confining pressure and constant displacement rate on rough pre-fractured faults. The experiments produced complex slip patterns including fast and slow ruptures with large and small fault slips, as well as failure events on the fault surface producing acoustic emission bursts without externally-detectable stress drop. Preparatory processes leading to large slips were tracked with an ensemble of ten seismo-mechanical and statistical parameters characterizing local and global damage and stress evolution, localization and clustering processes, as well as event interactions. We decompose observable complex spatio-temporal trends in AE-derived seismic characteristics identifying effects of persistent and evolving fault roughness at different length scales, multi-scale damage, and local stress evolution approaching large events. The observed trends highlight localization processes on different spatial and temporal scales. The preparatory process of large slip events is facilitated by smaller events marked by confined bursts of AE activity that collectively prepare the fault surface for a system-wide failure by conditioning the large-scale stress field. Our results provide a set of reliable, physics-based characteristics of processes leading to large failure events that may allow for improved earthquake forecasting along natural faults.
(a) 

(b) 

(c) 

(d)
(a) Median proximity $h$

(b) Proportion

(c) Clustering
Figure (a) shows the distribution of macroseismic intensity (MI) over time for different periods (P1 to P5). The horizontal axis represents time in seconds, while the vertical axis represents the macroseismic intensity. The data is represented as a series of points with error bars indicating variability.

Figure (b) illustrates the median fault plane variability over time. The graph compares different time windows (W=100s, W=200s, W=300s) and highlights the variability in fault plane orientation.

Figure (c) depicts the average plunge of the local max principal stress (\( \Psi \)) over time. The graph includes the variability of the plunge with different time windows (W=150s, W=180s). The local stress variability is also shown for comparison.
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events is facilitated by smaller events marked by confined bursts of AE activity that collectively prepare the fault surface for a system-wide failure by conditioning the large-scale stress field. Our results provide a set of reliable, physics-based characteristics of processes leading to large failure events that may allow for improved earthquake forecasting along natural faults.

Plane language summary

We discuss seismic data of rough laboratory fault performed at pressures existing in Earth crust. The laboratory fault was subjected to constant displacement resulting in episodic slips of the fault surface. We observe complex slip pattern including fast/slow ruptures with large/small fault slips. Very small slips on the fault surface were observed only with acoustic emission (AE) activity. The AEs are tiny earthquakes of sub-mm size that produce elastic waveforms recorded with AE sensors. Using parameters derived from AE data we analyzed physical processes leading to large slip of the lab fault surface, an equivalent of the large earthquake. Our parameters characterize local and global damage and stress evolution, damage localization, as well as interactions of small fractures before the labquake. We identify evolving fault roughness at different length scales, and find that the preparatory process preceding lab quakes is facilitated by small earthquakes marked with bursts of AE activity. These bursts indicate ruptures of individual fault patches, which then interact and collectively prepare the fault surface for the labquake. Our results provide a set of physics-based parameters describing complex processes leading to the labquake that may allow for improve earthquake forecasting along natural faults.

1 Introduction

Fault processes leading to large earthquakes in nature have occasionally been observed to produce foreshock activity and aseismic transients, sometimes lasting months or even years prior to the main shock (Kato et al., 2012; Bouchon et al., 2013; Schurr et al., 2014; Durand et al., 2020; Meng and Fan, 2021). Seismic and aseismic precursors signifying fault damage evolution and progressive localization towards large dynamic ruptures are not well understood due to limited availability and resolution of seismic data and widely varying structures and properties of fault zones. The role of precursory observables during the preparatory process before earthquakes and their potential use for forecasting remain controversial (Geller et al., 1997; Bakun et al., 2005; Ogata and Katsura, 2012; Wu et al., 2013; Mignan, 2014, p.201). Existing physical models describing the preparation and nucleation process on large pre-existing faults motivated by field and laboratory studies (Ohnaka, 1992; Ellsworth and Beroza, 1995; McLaskey, 2019; Kato and Ben-Zion, 2021) converge towards a combination of processes including accelerating preslip and, in some cases, cascading foreshocks. However, fault
heterogeneity and structural variability of fault zones result in rich and varying observational phenomena, that often defy clear interpretation. Thus, seismic hazard assessment and earthquake forecasting still largely rely on probabilistic approaches (Ogata, 1999; Lippiello et al., 2019; Hirose et al., 2021; Mizrahi et al., 2023). The observation of a plethora of physical preparatory processes requires high-resolution monitoring of seismic and aseismic bands that are hardly achievable in nature.

Laboratory experiments performed on intact and faulted rock samples with varying loading conditions have provided a wealth of observations characterizing the effects of roughness, gouge material, loading rate, effective normal stress, and stiffness ratio of fault and the loading system on long-term preparatory deformation leading to failure (Latour et al., 2013; Mclaskey and Yamashita, 2017; Leeman et al., 2018; Guérin-Marthe et al., 2019; Scuderi et al., 2020; Gounon et al., 2022; Morad et al., 2022). Motivated by experimental results, various studies (Ohnaka, 1992; Dieterich and Kilgore, 1996; Ben-Zion and Rice, 1997; Ohnaka and Shen, 1999; Latour et al., 2013) suggested to separate the preparatory phase into a quasi-static phase and an accelerating phase producing dynamic slip. This transition is often only loosely defined by onset of a local or system-wide decrease in shear stress leading to abrupt stress drop. In a complex and heterogeneous fault zone the preparation phase may be long-lasting. The transition towards nucleation of a large rupture involves a localization process, distributed creep transients and collective failure of a range of asperities (de Geus et al., 2019; Ben-Zion and Zaliapin, 2020; Yamashita et al., 2021; McBeck et al., 2022). These processes lead to redistribution of stresses along the fault zone at different length scales, reflecting the multi-scale evolution of roughness at the level of granular material forming the fault zone, cm-scale asperities and large-scale structural inhomogeneities.

The multi-scale preparatory processes are typically accompanied by Acoustic Emission (AE) activity that allows monitoring of key seismo-mechanical processes and local stress evolution during the deformation cycle. Parameters derived from AE data showed changes in clustering and localization of AE hypocenters, AE magnitude-frequency distributions, ultrasonic velocities, inter-event triggering and other statistical attributes approaching failure (Main, 1991, 1992; Lockner, 1993; Zang et al., 1998; Goebel et al., 2012, 2013; Kwiatek et al., 2014b; Davidsen et al., 2017, 2017, 2021; Scuderi et al., 2017, p.20). Typically, AE-derived parameters from stick-slip cycles exhibit general trends, which are punctuated and partially reversed by large failure events. Although the observed trends for some parameters during preparatory slip indicate progressive damage and localization, so far, no robust estimate of time to failure could be identified.
Forecasting the origin time of future large earthquakes remains a challenge if not an impossible task.

In recent years earthquake forecasting made a leap using new opportunities provided by Artificial Intelligence (AI) techniques. These techniques demonstrated the ability to predict time to failure in direct shear laboratory tests on smooth faults (Johnson et al., 2021), as well as on analog models, natural and induced seismicity, and synthetic modeling (e.g. Mignan, 2012; Corbi et al., 2019; Johnson et al., 2021; McBeck et al., 2021; Picozzi and Iaccarino, 2021). These studies use a number of potential precursory parameters derived from seismic waveforms or earthquake catalogs, (see e.g. Rouet-Leduc et al., 2017; Lubbers et al., 2018; Hulbert et al., 2019; Picozzi and Iaccarino, 2021). Johnson et al. (2021) noted that successful cross-scale earthquake forecasting requires generalization of predictive models and a better physical understanding of input and output parameters. The former imposes extension of the predictive AI-aided modeling to studies of rough faults, whereas the latter requires a comprehensive linking of AE-derived precursory parameters with observable damage and stress evolution on different spatio-temporal scales.

In this study we employ large AE datasets from laboratory stick-slip experiments involving a series of tests performed on rough pre-fractured faults. The experiments produced complex slip patterns including fast and slow, large and small slips of the fault surface, and confined slips accompanied by AE data bursts. The multi-scale preparatory processes preceding system-wide slip events are analyzed with a set of physics-motivated AE-based features characterizing the seismo-mechanical spatio-temporal processes occurring on the fault. These include parameters describing damage and stress evolution, localization and clustering, event interactions, and local micromechanics and stress heterogeneity. We decompose the observable trends and discuss them in the context of roughness evolution at different spatial scales, a crossplay of local and global damage, and multi-scale stress evolution when approaching a system size event.

2 Data and methods

2.1 Experimental setup

Triaxial stick-slip tests were conducted on cylindrical samples of Westerly Granite with dimensions of 40 mm diameter × 107 mm length (Goebel et al., 2012). Samples were prepared with a 2.5 cm deep notch inclined at 30° to the cylinder axis to guide formation of a shear fracture. The samples were first oven-dried at 100°C and subsequently encapsulated in a rubber sleeve to prevent the intrusion of the confining medium (oil). The specimens were fractured at 75 MPa confining pressure leading to creation of a rough fault surface. To perform a series of subsequent stick-slip experiments, the fault was locked by increasing the confining pressure to 150 MPa. For the initial fracture and subsequent
stick slip tests, the samples were loaded axially using a constant displacement rate of 0.02 mm/min. Subsequent axial loading cycles were applied by advancing the piston at constant displacement rate resulting in an axial strain rate $3 \times 10^6$ s$^{-1}$. Displacement was recorded using a linear variable displacement transducer fixed to the piston and by an external and an internal load cell.

We performed a series of tests on different Westerly granite samples but here we focus on data from one representative experiment stick-slip test (WgN05). The fault roughness in this experiment caused a complex stick-slip pattern with a variety of Slip Events (SE) including five Large Slip Events (LSE) with high stress drops $> 100$ MPa preceded by a varying number of Small Slip Events (SSE) with lower stress drops (Figure 1a).
Figure 1. Overview of mechanical data, AE activity and stick-slip processes at different spatial scales occurring during the experiment. (a,b): AE magnitudes (black dots, left axis) and axial load (red solid curve, right axis). Onsets of large (LSE), small (SSE), and confined slips events (CSE, see Results section for details), the latter not reflected in geomechanical data, are marked with vertical azure lines; (b):
2.2 AE monitoring

Loading and stick-slip events produced AEs, here indicating sub-mm fracturing and frictional processes occurring on the grain scale. AE activity was recorded by sixteen AE sensors with resonant frequency 2 MHz embedded in brass housings and glued directly to the specimen surface, securing an almost complete azimuthal coverage of AE events. The event waveforms were recorded in triggered mode at 10 MHz sampling rate with 16-bit amplitude resolution. Throughout the experiment, repetitive P-wave velocity measurements were performed using ultrasonic transmission providing a time-dependent quasi-anisotropic velocity model composed of five equally-spaced horizontal layers (with associated velocity) and single measurement of averaged vertical velocity (Stanchits et al., 2006). The velocity model was updated every 30 s during the course of the experiment.

2.3 AE Catalog Development

The development of an AE catalog from the experimental data is an upgraded procedure originally developed by Stanchits et al., (2006). Here, we summarize key and new processing steps relevant for evaluating the time-dependent AE characteristics presented and discussed below.

The first P-wave arrivals of AE events were picked automatically using the Akaike Information criterion followed by pick refinement using the modified Convolutional Neural Network picker (Ross et al., 2018) trained on past AE data sets. Based on a time-dependent quasi-anisotropic velocity model, the resolved picks were used to invert for hypocenter locations and origin time using a grid search algorithm paired with the Coyote optimization algorithm (Pierezan and Dos Santos Coelho, 2018). The hypocenter location accuracy is estimated to be about ±2 mm, constrained, in part, by the selected Root-Mean-Square Deviation (RMSD) of travel time residuals (for the following analysis we selected locations with RMSD < 0.5 μs). Then, the first P-wave amplitudes were corrected for hypocentral distance and incidence angle and for the coupling quality of AE sensors using an ultrasonic calibration.
The average AE amplitude and AE magnitude were calculated from
first P-wave amplitudes (Zang et al., 1998):

\[
\overline{A_{AE}} = \frac{1}{n} \left( \sum_{i=1}^{n} (A_i R_i)^2 \right)^{0.5}, (1)
\]

\[
M_{AE} = \log_{10}(\overline{A_{AE}}), (2)
\]

where \(A_i\) and \(R_i\) are corrected first P-wave amplitude and source-receiver distance for sensor \(i\), respectively (cf. Goebel et al., 2012; Dresen et al., 2020). This magnitude estimate reveals relative size
differences between AE events but it is not directly calibrated to the physical size of the events (cf.
Goodfellow and Young, 2014; McClaskey et al., 2014; Yoshimitsu et al., 2014; Blanke et al., 2021).

For each AE event, a full moment tensor (FMT) inversion was performed using the hybridMT software
and first P-wave amplitudes and durations of the first P-wave pulses (Kwiatek et al., 2016; Martinez-
Garzón et al., 2017) corrected for coupling quality and incidence angle (Kwiatek et al., 2014a). The
resulting FMTs were decomposed into isotropic and deviatoric parts (e.g. Vavryčuk, 2001, 2014). From
the deviatoric part of the FMTs, we extracted the P-, T-, and B- axes directions (azimuths and plunges).
A P- (T-, B-) axis plunge equal to 90° and 0° corresponds to the direction of maximum compression \(S_1\)
and the direction perpendicular to it, respectively. The two sets of nodal plane parameters (strike, dip,
rake) were extracted from the deviatoric part of the seismic FMT of each AE event.

The analyzed catalog contains \(N=310,815\) located AEs with \(N(M_{AE}>M_{c,AE})=169,825\) above the
magnitude of completeness \(M_{c,AE} = 1.5\) estimated using the goodness-of-fit method (Wiemer and
Wyss, 2000). The FMTs were quality-constrained using as an uncertainty measure the maximum value
from diagonal elements of the covariance matrix normalized by the average AE amplitude, \(\varepsilon\)
(hybridMT documentation, Kwiatek et al., 2016). Assuming, \(\varepsilon < 0.1\), this resulted in \(N(\text{FMT})=17,963\)
quality-constrained FMTs. The resulting catalog containing origin time, AE location in the local
Cartesian coordinate system of the sample, AE magnitude, FMT parameters including strike, dip, rake,
the MT decomposition and orientation of P-, T- and B- axes, as well as associated location and MT
inversion uncertainties is available in a separate data publication (Kwiatek and Goebel, 2023).

2.4 Time series of AE parameters

We analyzed the temporal evolution of a total of 10 parameters (features) derived from the AE catalog
and defined onsets of informative changes of these parameters with regard to global damage and
stress evolution and potential cross-correlations between different proxies. The selected parameters
were utilized to characterize the development of local damage and stress evolution on and around
The fault during the preparatory phases of five LSEs. The predictive AE-modeling of the time-to-failure is a subject of a separate manuscript (Karimpouli et al., 2023, submitted).

The temporal evolution of all AE parameters was calculated using sliding time windows of different lengths (Table 1) to better prospect the development of short- and long-term processes. The calculated parameter values were assigned to the origin time of the last AE event included in each time window. We ignored time windows which overlap with the occurrence of LSEs to avoid mixing precursory AEs with those following LSE. In the following, we describe the 10 different AE parameters listed in Tab. 1 and subsequently used tracking the preparatory processes.

<table>
<thead>
<tr>
<th>No.</th>
<th>Parameter</th>
<th>Symbol</th>
<th>Time windows [s]</th>
<th>Dimension sensitivity</th>
<th>Source/method</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>AE event rate</td>
<td>$\bar{N}$</td>
<td>23.5, 45, 90, 180</td>
<td>time</td>
<td>AE catalog</td>
</tr>
<tr>
<td>2</td>
<td>b-value (maximum likelihood)</td>
<td>$b$</td>
<td>10, 30, 90, 180</td>
<td>time-magnitude</td>
<td>AE catalog</td>
</tr>
<tr>
<td>3</td>
<td>d-value (boxcounting)</td>
<td>$d$</td>
<td>45, 90, 180</td>
<td>space-time</td>
<td>AE catalog</td>
</tr>
<tr>
<td>4</td>
<td>Median proximity</td>
<td>$\tilde{\eta}$</td>
<td></td>
<td></td>
<td>Clustering analysis</td>
</tr>
<tr>
<td>5</td>
<td>Proportion of foreshocks</td>
<td>$p_{FO}$</td>
<td>25, 50, 100</td>
<td>space-time-magnitude</td>
<td>Clustering analysis</td>
</tr>
<tr>
<td>6</td>
<td>Proportion of aftershocks</td>
<td>$p_{AF}$</td>
<td></td>
<td></td>
<td>AE catalog</td>
</tr>
<tr>
<td>7</td>
<td>Proportion of mainshocks</td>
<td>$p_{MA}$</td>
<td></td>
<td></td>
<td>AE catalog</td>
</tr>
<tr>
<td>8</td>
<td>Median fault plane variability</td>
<td>$\bar{\nu}_f$</td>
<td>100, 200</td>
<td>space-time</td>
<td>Focal mechanisms</td>
</tr>
<tr>
<td>9</td>
<td>Plunge of local maximum principal stress</td>
<td>$\delta_{\sigma_1}$</td>
<td>90, 180</td>
<td>space-time</td>
<td>Stress tensor inversion</td>
</tr>
<tr>
<td>10</td>
<td>Local stress variability</td>
<td>$\bar{\nu}_{\sigma ij}$</td>
<td></td>
<td></td>
<td>AE catalog</td>
</tr>
</tbody>
</table>

Table 1: Parameters characterizing the temporal evolution of damage and stress in the sample. Column ‘dimension sensitivity’ generalizes whether the particular parameter senses changes in time, space, magnitude, or their combination.
(1) **AE event rate:** The AE event rate $\bar{N}$ (unit: [1/s]) has been calculated for the catalog of events with $M_{AE} > M_{AE,C}$ as the number of AEs divided by the duration of the moving time window. It represents the intensity of seismic activity across the whole fault surface.

(2) **b-value:** The slope from the magnitude-frequency Gutenberg-Richter (GR) relation indicates the proportion between the number of small and large AE events in a selected population. The b-value is calculated from AE events with magnitudes above the magnitude of completeness $M_{AE} > M_{AE,C}$ using the maximum likelihood method while including a correction for the histogram bin size (e.g., Lasocki and Papadimitriou, 2006). Changes in b-values are thought to be governed by rock damage evolution (e.g., Main, 1991), changes in local stress (Scholz, 1968; Schorlemmer et al., 2005), and geometric complexity and roughness (Goebel et al., 2017).

(3) **d-value:** The fractal dimension $d$ from a population of AE hypocenters has been calculated using the boxcount algorithm (i.e., Minkowski–Bouligand dimension, see Moisy, 2022). We used hypocentral locations [X, Y, Z] of AEs with location quality constrained by the RSMD<0.5 [μs]. The d-value characterizes the geometry of the AE spatial distribution of AE with $d=3$, $d=2$, and $d=1$ corresponding to volumetric, planar and linear Euclidean distribution of AE hypocenters, respectively.

**Clustering of AE events in space, time and magnitude domain:** We identified clusters of AE events according to their space-time-magnitude nearest-neighbor proximity (Zaliapin et al., 2008; Zaliapin and Ben-Zion, 2013a, 2013b). Specifically, we investigated the proximity of an event $j$ to an earlier event $i$ in a combined space-time-magnitude domain (Baiesi and Paczuski, 2004) defined as:

$$\eta_{ij} = \left\{ t_{ij} \left( r_{ij} \right)^d \right\} 10^{-bm_i}, t_{ij} > 0, \infty, t_{ij} \leq 0, \quad (3)$$

where $t_{ij} = t_j - t_i$ and $r_{ij}$ are the temporal and spatial distances between the earthquakes $i$ and $j$, respectively, $b$ is the b-value from the GR distribution, $d$ is the fractal dimension, both estimated as described above, and $m_i$ is the magnitude of the earlier event in time. The scalar proximity $\eta_{ij}$ between events can be expressed as the product of its temporal and spatial components scaled by the magnitude of the earlier event $i$:

$$\eta_{ij} = T_{ij} \cdot R_{ij}, \quad (4)$$

with $T_{ij} = t_{ij} 10^{-qb_{mi}}$ and $R_{ij} = \left( r_{ij} \right)^d 10^{-(1-q)b_{mi}}, 0 \leq q \leq 1$. We fixed $q = 0.5$, providing equal magnitude weights to the scaled temporal and spatial distances. To estimate the spatial distance between events we used hypocentral locations. We denote $\eta_j$ the shortest of the proximities between event $j$ and all earlier events. The distributions of the nearest-neighbor proximities $\eta_j$ in
earthquake catalogs tend to be bimodal (Zaliapin et al., 2008, p.20; Zaliapin and Ben-Zion, 2013a). The mode with larger event proximities $\eta_j$ corresponds to background Poissonian-like seismicity, while potentially appearing mode with smaller event proximities $\eta_j$ indicates clustered events (i.e. foreshocks and aftershocks). The separation threshold between these two modes is here estimated by fitting a Gaussian mixture model (Supplementary Figure S2).

Using the above method, we identify AE clusters that are connected by proximity links smaller than the estimated threshold. Each AE connected to the parent by a link longer than the threshold is considered a background event and starts a new cluster. A single is a cluster that consists of one background event with no associated foreshocks or aftershocks, while multiple-event clusters are called families. The largest event in each cluster is called mainshock; all events within the cluster before or after the mainshock are called fore/aftershocks (see Fig. 6 of Zaliapin and Ben-Zion, 2013a). Due to the short-term saturation of the AE recording system during large slip events LSE1-LSE5 (see more details in the results section), the clustering analyses have been performed separately for each phase P1-P5 (Fig. 1a). This means that early aftershocks from previous slip for phases P2-P5 are not well resolved, biasing the separation between foreshocks, aftershocks and mainshocks shortly after the LSEs.

The temporal changes in AE clustering properties occurring on grain-scales have been analyzed using a sliding time window. We calculated temporal evolution of four parameters, including the median proximity parameter $\tilde{\eta}$:

$$\tilde{\eta} = \text{median}\{\eta_j\}$$

defined as a median of the decimal logarithm scalar proximities (eq. 4) of AEs, and the fraction of AE (5) foreshocks ($p_{FO}$), (6) aftershocks ($p_{AF}$), and (7) mainshocks ($p_{MA}$) in each examined time window (with $p_{AF}+p_{FO}+p_{MA}=1$).

The median fault plane variability parameter $\tilde{\psi}_f$ characterizes the level of heterogeneity in the distribution of the focal mechanisms (Martínez-Garzón et al., 2016; Goebel et al., 2017; Dresen et al., 2020). This is a generalization of rotation angle between pairs of focal mechanisms (Kagan, 2007) applied to an ensemble of focal mechanism solutions. A small 3D rotation angle (<20°) between the P/T/B axes of two mechanisms indicates a high degree of similarity, and 0° deg means they are identical.

We compute the spatial variability of focal mechanism similarity across the laboratory fault and rock sample. Spatial variability is determined from 20 nearest AE neighbors within R<10 mm and the
respective median 3D rotation angle between all focal mechanism pairs (e.g. for 20 AE focal mechanisms there are 190 pairs). This procedure was repeated for each AE event to resolve the spatial heterogeneity/similarity of focal mechanism variability across the whole fault plane. The focal mechanism variability for a particular time window was then estimated as the median of locally calculated values.

\[(9)\] Plunge of local maximum principal stress \(\delta_{\sigma_1}\) and \[(10)\] local stress (orientation) variability \(\Psi_{\sigma_{ij}}\).

Using FMTs we performed a linear stress tensor inversion using the STRESSINVERSE package (Vavryčuk, 2014). We follow the sign convention that compressive stress \(\sigma\) is positive with \(\sigma_1 > \sigma_2 > \sigma_3\). Similarly to median fault plane variability \(\Psi_f\), for each time window, we first calculated the spatial distribution of local stress tensors for each location where at least 40 focal mechanisms were available within a 10 mm distance. The input focal mechanism data were resampled and then inverted 200 times by randomly selecting either of the two nodal planes for each focal mechanism, suppressing the problem of fault plane ambiguity (e.g. Martínez-Garzón et al., 2014) in the input focal mechanism data. From this we obtained the spatial distribution of local stress tensors for a particular time window.

In the following, for each local stress tensor, we extracted the plunge of maximum principal stress \(\delta_{\sigma_1}\) which is given by the eigenvector corresponding to the largest eigenvalue of the input stress tensor.

Finally, we averaged maximum principal stress plunges from the whole fault surface. For plunge of \(\delta_{\sigma_1} = 90^\circ\) the local principal stresses averaged over the sample surface are aligned with the macroscopic vertical loading stress direction \(S_1\).

The second parameter describing the local stress tensors is the tensor variability \(\Psi_{\sigma_{ij}}\), which was calculated with the same procedure as for the focal mechanism variability estimation. For each time window, we calculated the median out of an ensemble of rotation angles between all possible pairs of local stress tensors. Low values of \(\Psi_{\sigma_{ij}}\) parameter suggest that local stress tensor orientations over the fault surface are similar.

### 3 Results

In the following we focus on the analysis of processes leading to the five large slip events (LSEs) with axial stress drop measured in the \(S1\) direction of \(\Delta\sigma > 100\) MPa, slip duration of \(0.2 - 0.4\) s and slip velocity of at least \(1.2 - 1.6\) mm/s (Fig. 1, Supplementary Table S1). The peak slip velocities were not resolved due to the limited sampling rate of the geomechanical data (10 Hz). All LSEs were followed by rapid initial reloading lasting ca. 50 s and a longer period of almost linear stress increase lasting
typically no more than 1000 s. Further axial displacement beyond a yield point was accommodated by
plastic deformation along the fault zone and in its surroundings (cf. Dresen et al., 2020). We attribute
most of the deformation during the loading to shear-enhanced compaction of the granular material
forming the fault gouge (Kwiatek et al., 2014b), as illuminated by the AE activity spreading over the
whole fault surface (Fig. 1e,h).

In addition, structural complexity of the fault surface results in multiple small slip events (SSEs), which
typically occur at elevated axial stress with $S_1 > 400$ MPa. The AE activity associated with these SSEs
is distributed over significant parts or the entire fault surface (Fig. 1d,g). Stress drops of SSEs range
1<$\Delta\sigma<$20 MPa and slip velocities range <0.05-0.2 mm/s (Supplementary Table S1). The lower limit of
SSEs’ stress drops and slip velocity is due to the periodic noise of stress measurements caused by the
servo-controlled MTS loading system.

The macroscopic displacement and stress drop recordings of LSEs and SSEs indicate detectable and
relative movement of fault-bounding blocks across the entire fault surface (Supplementary Movie S1).
Both LSEs and SSEs lead to a temporally higher AE event detection threshold due to low-frequency
noise resulting from comminution and shearing of granular material and debris forming the fault
surface while the fault is slipping (gray area in Fig. 1e). The duration of the AE system saturation time
period lasts 20-120 ms and qualitatively scales with the duration of macroscopic slip and stress drop
magnitude (cf. Supplementary Table S1). The enhanced low-frequency noise is expected to mask very
early AE aftershocks, mostly affecting features (4)-(7) related to clustering properties for the time
windows directly following the LSE.

In addition to LSE and SSE events resulting in measurable axial stress drops, we identified short-lasting
bursts in AE activity due to slips confined in the sample that were mostly not recorded in the
mechanical data (i.e. the externally measured axial stress drop is below $\Delta\sigma < 1$ MPa). These local
Confined Slips Events (CSE) are attributed to local asperity failures providing a significant AE footprint
with very localized AE activity that is most prominent in the early stick-slip cycles (cf. Fig. 1c,f;
Supplementary Movie S1). Each CSE is associated with a large AE event followed by AE aftershocks
and occasionally preceded by AE foreshocks.

In the following, we present and describe selected time series for each of the utilized parameters
describing the evolution of the fault system.
3.1 AE Rates

The AE rates display a short-term (within each phase P1-P5 leading to the LSE) as well as a long-term (across whole experiment) evolution with progressive deformation of the sample (Figure 2b). The long-term evolution is characterized by an overall decrease of AE rates $\dot{N}$. The individual phases P1-P5 preceding LSE1-LSE5 display exponentially increasing $\dot{N}$ when approaching failure (Fig. 2b). LSE nucleation points are defined by large AE events located using P-wave arrivals. Once the elevated noise from saturation of AE system drops to the background level, AE aftershocks are visible, displaying a $1/T^p$ (Omori-type) decrease of AE rates typically lasting no more than about 20 seconds following the actual stress drop (cf. Supplementary Figure S1). The aftershock rates then decrease with consecutive LSEs indicating smoothing of the fault surface.

The increase of AE rates $\dot{N}$ during each phase P1-P5 is punctuated by multiple short-lasting bursts of AE activity following SSEs and CSEs characterized by AE rates decreasing as $1/T^p$ over a short period of time (typically < 10 s). No SSEs and all but one CSE show acceleration of AE rates up to failure (cf. Supplementary Figure S1). However, the second CSE ($T=3672.8$ s) in phase P1 shows precursory acceleration of AE rates (Supplementary Figure S1b). The SSEs and CSEs tend to reduce the overall AE rates during phases preceding LSEs (Figure 1b). AE rates are closely related to fault slip and decrease with fault slip rates following slip events irrespective of stress drop magnitude.
Figure 2. Temporal evolution of (b) AE event rates, (c) GR $b$-value, and (d) fractal dimension ($d$-value) calculated using different moving time windows $W$ [s]. For reference, the evolution of AE magnitudes and axial stress is shown in (a) (cf. Fig. 1).
3.2 Gutenberg-Richter b-value

The temporal evolution of the b-value (Fig. 2c) displays a general trend of decreasing b-values associated with AE activity bursts and slip events through each of the phases P1-P5. P1 and P2 show prolonged periods of low b-values approaching LSE failure. This suggests that the b-value acts as a proxy indicating small-scale local ruptures confined in the sample and in general the approach to the system-wide failure.

Beyond phase P2, CSEs and SSEs are less prominent and the temporal trends of the b-value become more uniform. This may reflect a conditioning process of the slip surface, progressive localization and reduction of the fault roughness. Prior to the LSEs, the b-values visibly decrease, and then recover to b=1.4-1.6 during the initial part of the subsequent loading cycle. The amplitude of the b-value recovery following the LSE is likely affected by the saturation of the AE acquisition system which masks smaller aftershocks immediately following LSE, presumably reducing the b-value in early post-slip phases. The trend of the decreasing b-value before the LSEs is also found before some of the CSEs and SSEs. However, it typically becomes more evident if the AEs are additionally spatially constrained to those related to specific patch activation. Overall, the obtained results suggest that localized slips tend to be preceded by a b-value decrease irrespective of the amplitude of macroscopic slip.

3.3 Fractal dimension d

A d-value of about 2.0 corresponds to an AE hypocenter distribution across the fault surface. In contrast, d-values < 2.0 indicate formation of distinct AE lineaments or clusters within the fault zone. The evolution of the d-value during individual stick-slip cycles leads to a general increase of the d-value ahead of each major LSE, signifying the overall increase in the AE activity across the entire fault surface as a consequence of increased contact area between the two faces of the fault. The AE activity immediately following the LSEs is characterized by higher d-values that quickly decrease within the first 50-100 seconds following the LSE. This may be due to fault dilation associated with large slip and a reduction of small-scale asperities in contact reducing AE activity to linear or isolated clusters indicating larger asperities. As loading and shear-enhanced compaction across the fault resumes, the d-value increases again.

Interestingly, over many stick-slip cycles the d-values decrease. Local peak d-values are typically reached just prior to LSEs and they decrease from about 2.0 to 1.7 with consecutive LSEs. Formation of linear AE clusters and depletion in activity in other places of the fault surface correspond to d-values < 2.0 that are observed with progressive slips.
3.4 Clustering properties

The spatial distribution of AE hypocenters allows identifying AE clusters forming at short-scale mm- to cm-scale asperities characterizing the rough topography of the fault surfaces. In addition, all phases P1-P5 show generally similar trends in the evolution of the median proximity $\hat{\eta}$ parameter (Figure 3b), which signifies event clustering in the combined space, time and magnitude domain. During the initial part of each stick-slip loading phase at low axial stress, the median proximity $\hat{\eta}$ is relatively large. This indicates a dominance of diffuse background activity suggesting random distribution of events in time, space and magnitude domains. This agrees with the high proportion of mainshocks (including singles) in the AE catalog (Fig. 3c).

With progressive loading and approaching LSE failure, the event rate increases and median proximity $\hat{\eta}$ displays a transient decrease, indicating a progressive localization of AE activity through each phase ahead of LSEs (Fig. 3b). Concurrently, we observe a decreasing proportion of mainshocks that are superseded by aftershocks and occasionally by foreshocks (Fig. 3c). The long-term proportion of foreshocks clearly does not increase ahead of the LSE. Likewise, the observed increase in aftershocks is linked to the occurrence of more frequent SSEs and CSEs at higher axial stresses, rather than directly to the approach of the LSE.

Some SSEs and CSEs are preceded by a visible short-term drop in the event proximity $\hat{\eta}$ signifying increased clustering, and all CSEs and SSE display strong space-time localization within up to 20 seconds after the slip followed by a transient $\hat{\eta}$ recovery (Figure 3c, Supplementary Figure S3). The amplitudes of these temporal $\hat{\eta}$ changes do not correlate with the macroscopic stress drop amplitudes, at least recovered for SSEs. Accordingly, the short-lasting clustering episodes framing SSEs and CSEs are sometimes preceded by an increased proportion of AE events that are classified as foreshocks, especially in later loading phases. The SSEs and CSEs are always followed by an increased proportion of AE events classified as aftershocks (Supplementary Figure S4).
Figure 3. Temporal evolution of (a) stress and AE activity for reference, (b) Median event proximity $\hat{\eta}$ (low $\hat{\eta}$ indicates clustering of events) and (c) proportion between AE background events (i.e. mainshocks and singles), foreshocks and aftershocks in the catalog (cf. Fig. 1) as derived from clustering analysis.

Time periods directly following LSEs display strong clustering with complete lack of AE foreshocks replaced with AEs classified as mainshocks and aftershocks. The proportion of clustered to background events seems lower on average in comparison to AEs following SSE and CSE, which reflects problems with classification of events in these time periods. Following a LSE, the initially localized AE activity progressively delocalizes typically within 50-100 s before the next cycle starts, initially dominated by background seismicity.
The event proximity measure shows a modest, relative increase with successive stick-slip events, although individual stick-slip cycles still exhibit decreasing proximity values before LSEs. This suggests progressive delocalization of AE events, in particular at the start of a new cycle following LSEs. This seems to be correlated with the generally lower AE rates as well as more random distribution of events in time and space, both due to roughness removal. The proportion between mainshocks, foreshocks and aftershocks does not seem to significantly evolve across several stick-slip cycles.

3.5 Fault plane variability

The observed AEs mostly result from slip and fracture events on the sub-mm scale. Thus, the observed temporal evolution of fault plane variability $\hat{\varphi_f}$ (Figure 4) reflects the small-scale complexity of the microfracturing processes occurring in the sample and along the fault surface during loading. In general, high $\hat{\varphi_f}$ values are observed during the entire experiment, reflecting a broad orientation distribution of focal mechanisms that comprise mostly normal (parallel to fault dip) to strike-slip faulting mechanisms across the whole fault surface. During loading, fault variability mostly increases or fluctuates around a high level but $\hat{\varphi_f}$ often decreases towards failure. Early stages within stick-slip cycles display more heterogeneous distribution of focal mechanisms and the focal mechanism heterogeneity is reduced approaching the respective LSE. Variability evolution $\hat{\varphi_f}$ seems largely unaffected by the occurrence of CSE or SSE events. This agrees with earlier observations of Dresen et al. (2020) and Goebel et al. (2017) indicating alignment of activated microslip planes along defects such as cracks and grain boundaries ahead of a large macroscopic slip. Fault plane variability remains similar for all phases P1-P5, without significant long-term evolution.
Figure 4. Temporal evolution of the (b) local fault plane variability $\hat{\psi}_f(t)$, (c) plunge of the local maximum stress, $\delta_{\sigma_1}(t)$ (filled circles) and local stress tensor variability $\sigma_{ij}(t)$ (dots). For reference, the evolution of AE magnitudes and axial stress is shown in (a) (cf. Fig. 1).

3.6 Maximum principal stress orientation and stress variability

Stress tensor inversion from AE-derived focal mechanisms allows inferring the local orientation of the deviatoric stress tensor and a relative measurement of its eigenvalues. Changes in principal stress orientation in response to loading, averaged over the whole fault plane, are recorded with the $\delta_{\sigma_1}(t)$ (plunge) parameter, whereas heterogeneity of the local stress tensors is reflected in $\Psi_{ij}(t)$ parameter.
In the initial phase P1 the maximum principal stress direction $\delta_{\sigma_1}(t)$ resolved locally stays close to vertical. Subsequently, $\delta_{\sigma_1}(t)$ progressively deviates from the vertical direction as loading increases. Ignoring some short-period outliers, local orientations of the maximum principal stress vary roughly between $90^\circ$ and $40^\circ$ with respect to the vertical sample axis during loading and unloading. Excluding the stick-slip cycle associated with LSE4, we find a progressive rotation of the maximum principal stress during loading while approaching LSE1-5. This rotation is likely due to shear-enhanced compaction and build-up of shear stress during loading near the fault surface, causing a local rotation of the stress tensor. The increasing local shear stresses are released during slip events, leading to back rotation of the local stresses towards the initial stress state that is observed in early part of the phases P2-4, following the LSE1-and LSE3, respectively. The rotation of the principal stress axes in each stick-slip cycle is associated with a slow reduction in spatial heterogeneity of the local stress, as indicated by the decreasing stress variability coefficient $\Psi_{\sigma_{ij}}$.

4 Discussion

Various large earthquakes were found to be preceded by precursory deformation and foreshock seismicity on varying scales in space and time (e.g. Kanamori, 1981; Kato and Ben-Zion, 2021; Sykes, 2021). Recent studies of laboratory data showed that the use of AI techniques and features derived from AEs can open up new avenues towards forecasting laboratory earthquakes on smooth faults. However, the range of observable physical processes involved in the run-up to dynamic rupture and how they interact remain not well understood, regardless of the scale. Likewise, there is limited physical understanding of the extracted data features used by AI techniques and their effectiveness in describing the run-up to failure, especially for rough faults.

In this paper, we employed data from laboratory experiments and used AE-derived seismo-mechanical and statistical parameters to characterize the evolution of local damage, roughness and stress in the immediate vicinity of a rough fault surface. In particular, we investigated whether our parameters contain information that allows tracking the preparation process leading to large slip events. The sizes of AEs recorded in our laboratory experiments range from $M_w$ -7 to $M_w$ -9, being at least 3 units lower than the estimated magnitude of the large stick-slips (Dresen et al., 2020; Blanke et al., 2021). The meta-analysis of (Mignan, 2015) suggests that such AE activity may include key precursory information related to large laboratory earthquakes. Field observations of processes leading to large earthquakes have been categorized as pre-slip, cascade, or localization phenomena, but recent lab studies point towards a case-specific combination of processes (see reviews in McClaskey, 2019; Kato and Ben-Zion, 2021). The physically-motivated parameters used in this study are shown to (I) collectively capture the deviation from long-lasting stable deformation towards a preparatory process of large unstable
failure, and (II) enable high-resolution monitoring of local damage, roughness and stress at different
temporal and length scales, which (III) allows to identify the time in which the fault enters the critical
stage, in which a system-size dynamic rupture may occur at any time.

The stick-slip experiments are performed on a naturally pre-fractured rock sample. The fault surface
displays high initial roughness representing a strongly segmented and juvenile fault in nature. This is
in contrast to a smooth saw-cut surfaces which may be more representative of a fault with large
displacement (cf. Goebel et al., 2017). As in many past experiments (e.g. Harbord et al., 2017), slip
events on a rough fault show a rich mechanical behavior. The large and small macroscopic slips of the
whole or significant portions of the surface display varying durations and amplitudes reflecting fast
and slow slip velocities as well as large and small stress drops (cf. Supplementary Table S1). Smaller
slips confined within the fault surface are highlighted solely by AE activity, but not with external
readings. In consequence, the seismo-mechanical behavior generally shows much stronger or fractal-
like fluctuations compared to saw-cut faults in triaxial stick-slip experiments (Goebel et al., 2017),
double-direct shear experiments containing gouge (e.g. Scuderi et al., 2017; Bolton et al., 2021), or
larger-scale experiments performed in a bi-axial apparatus hosting 3m-scale granite block (McLaskey,
2019). This highlights the need for a careful extraction of meaningful features/parameters from AE
data describing the processes leading to system-size failure.

4.1 Fault roughness, damage and stress evolution

The complex evolution of fault damage, roughness and stress across multiple stick-slip cycles with
progressive shearing is related to grain-scale comminution, gouge production and destruction of
short-scale asperities that ultimately lead to generation of the persisting large-scale topography (cf.
Goebel et al., 2013, 2017; Kwiatek et al., 2014b). Development of roughness at these different scales
is captured with AE source parameters and AE-derived seismo-mechanical and statistical proxies. Smallest grain-scale roughness development is captured with source parameters of individual AEs
events corresponding to fractures of sub-mm size (cf. Dresen et al., 2020; Blanke et al., 2021), as well
as fault plane variability. The short-scale roughness evolution of small mm-to-cm scale asperities is
observed with seismicity rates, b-value, (spatio-)temporal features including clustering and local-
stress field orientation and variability. Finally, the development of the large-scale (>cm) topography is
captured by global properties including d-value, b-value and seismicity rates $\dot{\eta}$.

The complex long-term (across many stick-slip cycles) evolution of fault roughness is primarily
documented in the spatio-temporal AE distribution (d-value) and localized damage indicators (b-value,
AE rate, cf. Fig. 2), as presented in past studies (Goebel et al., 2013, 2017; Kwiatek et al., 2014b; Dresen
et al., 2020). A decrease in local stress variability (Fig. 4c), the new parameter calculated using AE stress tensor inversion, indicates progressive smoothing of the fault surface. Fault roughness evolves substantially up to LSE2 but less in P3-P5. This is likely because after multiple slip events short-scale, small asperities are progressively destroyed but a large-scale fault topography remains, as revealed by post-mortem inspection of the deformed samples. Consequently, the later P3-P5 AE activity is focused on these larger asperities at the expense of a more uniform distribution on the fault. This results in a general $d$-value decrease across many stick-slip cycles converging towards $d=1.6$ close to the peak stresses for the last cycles.

The observed short-term evolution of the AE hypocenter distributions and AE sizes during individual stick-slip phases is complex as expressed by varying AE rates, $d$-values and $b$-values (Figs. 2d, and 3b). The AE rate and $d$-value evolution towards higher values depicts spreading of AE events across the fault (Fig. 2d) imposed by enhanced contact area between the granular material forming the fault zone at increased normal load (Dieterich and Kilgore, 1996) (cf. Supplementary Movie S1). This is associated with a general $b$-value decrease within the stick-slip cycle, interpreted as a signature of increased stress (Schorlemmer et al., 2005; Goebel et al., 2013) or damage accumulation (e.g. Main, 1991). Anti-correlations of $b$- and $d$-values, as observed in our study, have been reported in similar experiments (Main, 1991, 1992). However, the $d$-values and $b$-values are frequently linearly related through $D = 2b$ (Aki, 1981; King, 1983) as found in nature (Wyss et al., 2004) and other laboratory experiments (e.g. Goebel et al., 2017). This suggests interpretation of $b$- and $d$-value correlations and trends remain case-dependent (see also Legrand, 2002) and sensitive to the methodology used. The evolution of the used parameters within one cycle towards the LSE is superposed with high-frequency variations. These originate from activation of short-scale asperities at high levels of axial load, visible as CSE and SSE events and associated transient clusters of AEs (cf. Supplementary Movie S1-S4).
Figure FF5. Surface distribution of AE activity following three slip events from the phase P1 of loading (cf. Fig. 1a-b): (a): CSE T=3414 s (cf. Fig. 1c,f), (b): CSE T=3673 s, (c): SSE T=3963 s (cf. Fig. 1f,h). In (a,b,c) filled circles show AE activity within a 10-second window starting ~12 seconds following the nucleation of a slip event (star). The contour plot marks the density of events between the start of the slip event and the end of the selected time window, indicating the damage accumulation during slip. First, two confined slips (a,b) activate small distinct patches representing cm-length-scale asperities (magenta and green regions in all subfigures). The patches mostly do not overlap suggesting a shift in activity with subsequent slips. This suggests that failing short-scale asperities become inactive and ‘smooth’ at the cm-scales. The smoothed-out region expands ultimately to > 2 cm diameter (c) giving rise to a first small slip event that activates a significant part of the fault surface with AE activity accumulating in a narrow diagonal region (blue region in c). The animations presenting the damage evolution framing the occurrence of three slip events are shown in Supplementary Movies S2-S4.

Post-mortem surface observations suggest that short-scale asperities causing clustered AE activity have been progressively erased but grain-scale roughness remained unchanged. This is supported by general decrease of the local stress variability (short-scale) over several slips (Fig. 4c), although we do not observe significant evolution of the fault plane variability that is governed by grain-scale fracturing. High values of fault plane variability observed during the whole experiment, especially if compared with saw-cut faults (cf. Dresen et al., 2020), reflect complex, inter-granular processes related to shear-enhanced compaction of the granular material forming the fault zone (Kwiatek et al., 2014b). This indicates persistence of grain-scale sub-mm roughness of the stress field. The micromechanical grain-scale roughness evolution leads effectively to smoothing out of the short-scale asperities, and the short-scale stress field, as indicated by the decreasing local stress variability.

Beyond P2 we note that fewer and smaller SSEs occur prior to LSEs. Our observations suggest that with progressive slip and creation of a large-scale fault topography, the stress field across the whole fault surface becomes more uniform. Increased contact area, and smoothing out of short-scale asperities responsible for local stress concentrations results in large-scale homogenization of the stress field while approaching the LSE. This agrees with findings from numerical modeling (Ben-Zion et al., 2003) as discussed further in the next section.

To summarize, we find that grain-scale (<mm) and large-scale (>cm) roughness remain largely unchanged across many slip events in contrast to the short-scale (mm-to-cm) roughness involving asperities distributed initially across the surface that are progressively erased with repeating slips.
4.2 Multi-scale preparatory process and intermittent criticality

Within single stick-slip cycles, the evolving space-time-magnitude correlation $\eta_j$ of AEs indicates formation of distinct clusters (Fig. 3b). Together with progressive $b$-value decrease, increased seismicity rates, the combined parameter evolution indicate accelerating deformation and localization ahead of the LSEs, in agreement with observations from lab tests and field data across different scales (Das and Scholz, 1981; see e.g. Lei and Ma, 2014, p.20; Ben-Zion and Zaliapin, 2020; McBeck et al., 2022). Moreover, the exponentially increasing AE rates indicate accelerated seismic release (ASR), which is a non-universal earthquake precursory behavior (e.g. Bufe et al., 1994; Ben-Zion and Lyakhovsky, 2002; Mignan, 2011). However, the discussed set of parameters does not unequivocally signify the proximity to system-size events (LSEs), as similar trends are observable at smaller spatio-temporal scales before individual SSEs or even CSEs.

At about 85-90% of the maximum axial stress (i.e. hundreds of seconds before LSE, corresponding to the yield stress of the fault), the examined parameters tend to mostly fluctuate around a saturation level with occurrence of SSEs and CSEs. Such saturation level is already observed in the first cycle $P_1$ starting with the first CSE (ca. 1500 seconds before the LSE1) at about 85% peak stress and 75% of failure time $t_f$. In addition, we observe that the length of the saturation period prior to failure shortens with each stick-slip cycle, suggesting that the duration over which stress and seismic parameters fluctuate depends on fault roughness and stress heterogeneity. At the saturation level, $b$-values and $\dot{\eta}$ remain mostly low as both tend to drop significantly in the last part of the loading cycle. Likewise, clustered AE activity including AE foreshock-mainshock-aftershock sequences increases, resulting in a reduced proportion of background events (Fig. 3c). Clustered AE activity clearly associated with SSEs and CSEs, typically consisting of aftershocks and few foreshocks framing the mainshock, suggest stress interaction between events as stress transfer occurs across different length scales of the stress field (see next section).

The external stress fluctuates around a critical state between ~85% and peak stress. This has been described previously as intermittent criticality and was observed in nature and numerical models in combination with ASR and decreasing $b$-value (cf. Ben-Zion et al., 2003; Bowman and Sammis, 2004). In particular, Ben-Zion et al. (2003) showed in simulations of stress and seismicity on a large heterogeneous fault that towards the end of a seismic cycle, a critical (fractal-like) disorder of the stress field heterogeneity is reached over a broad range of scales. This is found in a representative model for the brittle crust (model F, see Ben-Zion et al., 2003), which is characterized by realistic dynamic weakening. In agreement with our results, any stress perturbation at a high stress level may
trigger a small or system wide seismic event. The ultimate size of the event is conditioned on whether the stress level is sufficiently high over a large portion of the fault surface and smooth over this length scale, allowing the event to propagate.

Following Ben-Zion et al., (2003), large-scale correlation of elevated stresses enables the generation of large events over a smoothed portion of the stress field. However, the nucleation of such instability remains a statistical event, as it can be triggered by any small short-scale or even a grain-scale stress perturbation at the right location. The statistical fluctuations before the triggering of large lab earthquakes involve CSE and SSE events. These events lead to stress relaxation across limited portions of the fault and stress transfer to the surrounding. The concentrated stress transfer near previous failure events is evidenced by significant clustering of AE activity forming foreshocks and aftershock sequences at high axial stresses once CSEs and SSEs become more frequent. The redistribution of stress and the stress drops due to CSEs and SSEs may cause the fault to temporarily retreat from the critical stress level. As loading continues, stress recovers and long-range stress correlations are reestablished leading eventually to a system size (LSE) event.

4.4 Earthquake interaction on different length scales

At the beginning of a stick slip cycle, distributed background activity represents >90% of the total AE activity (Fig. 3c). As loading increases, activity rates increase, background activity and $b$-values decrease and there is a progressive spatio-temporal localization of AE events approaching LSEs (Fig. 3b). This is accompanied by increasing slip along the fault. The observed evolution of event proximity and mainshock aftershock distribution may signal AEs triggering close to larger slip events.

Compared to smooth saw-cut faults where shear strain is localized and off-fault damage is minor, increasing fault roughness results in significant off-fault damage and a relatively broad damage zone (Goebel et al., 2017). As a result, shear strain is less localized compared to smooth faults and fault slip starts at lower shear stress. Therefore, precursory slip displays a larger fraction of aseismic deformation compared to smooth faults that unlock only at significantly higher stresses (e.g. Dresen et al., 2020). For rough faults, the increase in shear stress, compaction and contact area of the fault surfaces results in activation of a growing number of asperities leading to CSEs and LSEs. High local stress concentrations ahead of CSEs and SSEs, as well as stress redistribution following these events, produces observable event clustering/triggering (see e.g. Schoenball et al., 2012; Davidsen et al., 2017, 2021; Martínez-Garzón et al., 2018). In agreement with Davidsen et al., (2017, 2021), the local stress concentrations produce AE event interactions. This highlights the importance of local stress intensities
that control the evolution of the investigated parameters and the role of inter-event triggering
(Meredith and Atkinson, 1983; Davidsen et al., 2017).

AE aftershocks following LSEs are scarce in the examined data with respect to those framing SSEs and
CSEs. This is partially because very early AE aftershocks following LSE or SSE are masked by the
saturation of the AE system with continuous noise consisting of abundant overlapping AEs lasting up
to 100 ms (see Supplementary Table S1). However, in large slip events the entire fault blocks are
displaced and strength across the interface is reduced to sliding friction. Since the rupture reaches the
sample size, no stress redistribution beyond the rupture periphery is possible, in contrast to confined
ruptures, reducing the aftershock productivity. As indicated in Goebel et al., (2023), AE aftershocks
following large slip events are controlled by residual elastic strain energy, and also depend on
differences in fault roughness and slip stability.

5 Applications and outlook

Seismic activity rate, accelerated release of seismic moment and energy, and changes of $b$-values have
long been used to characterize precursory deformation preceding mainshocks (e.g. Varnes, 1989;
Bowman et al., 1998; Gulia et al., 2016; Bentz et al., 2019; Picozzi and Iaccarino, 2021). Based on our
experimental observations, we suggest that additional features characterizing different aspects of AE
event organization in space and time, damage, stress and roughness evolution, may assist in
constraining multi-parameter models that are currently being developed for time-to-failure
forecasting.

Typically, very few seismic catalogs have enough (data) resolution to allow following the evolution of
the parameters discussed in our study. However, significant recent progress in enhancing seismic
catalogs using AI techniques (Mousavi and Beroza, 2022) may provide new opportunities. Features
 calculated, for example, from continuous waveform data or seismicity catalogs have been successfully
 used to predict macroscopic fault properties such as shear stress, friction, and time-to-failure in
double-shear experiments performed on a smooth fault (e.g. Lubbers et al., 2018). However, even for
repetitive double-shear experiments with vast amounts of (training) data available, the fault gouge
layer evolves during the experiments, supposedly leading to degradation in time-to-failure prediction
(see discussion in Johnson et al., 2021). This highlights the fundamental roles of fault structural
heterogeneity (roughness), associated stress heterogeneity, and related spatio-temporal and spectral
evolutions for our capability in time-to-failure forecasting. Likewise, fault evolution with cumulative
slip over geological timescales results in progressive localization and fault zones with varying degrees
of structural and mechanical complexity (Tchalenko, 1970; Ben-Zion and Sammis, 2003).
Consequently, precursory deformation may display very different signatures depending on fault structure (Ellsworth and Bulut, 2018; Huang et al., 2020). Our study suggests that a combination of physics-based parameters may pinpoint when a fault system is entering a critical stage. Unsupervised classification techniques could be employed to identify regimes of stable deformation and intermittent criticality states and thus improve the accuracy of seismic forecasts. We note that the final triggering of the system size earthquakes in the intermittent criticality framework remains a statistical event that cannot be precisely predicted.

Conclusions

1. We studied the preparatory processes preceding laboratory earthquakes on rough faults using an ensemble of 10 seismo-mechanical and statistical features. These physics-based parameters describe damage and stress evolution in the fault zone, localization processes, local micromechanics and earthquake interactions, as well as local stress field evolution and stress field heterogeneity.

2. The selected features enable understanding a diversity of processes occurring at different spatial and temporal scales during the preparatory phase preceding system-size laboratory earthquakes, these features can help constraining the input for multi-parameter AI-aided models of earthquake forecasting.

3. The developed set of precursory parameters highlights localization processes preparing system-size earthquakes. However, the parameters are sensitive to length scales of fault surface roughness and associated roughness of the stress field, both rapidly evolving in the course of an experiment. The spatio-temporal evolution of fault surface and stress roughness produce limitations on our ability to monitor and forecast the run-up to large laboratory earthquakes.

4. We identify a transition from stable deformation to an intermittent criticality state allowing the occurrence of large events. This stage is characterized by abundant AE activity highlighting persistent heterogeneity of the stress field at the sub-mm grain-scale. Spatio-temporal AE activity bursts indicate small confined slips in the sample marking a progressive breakdown of asperities. These confined slips superimpose and interact, collectively preparing the fault surface for a system-size slip by progressive smoothing the short- (mm-to-cm) scale stress field. Ultimately, the development of large-scale correlation of elevated stresses enables the propagation of a large slip event over the smoothed portion of the fault, triggered even by a minor stress perturbation.
A system-size earthquake occurring at a state of intermittent criticality is a statistical event that cannot be predicted deterministically. However, using a combination of the parameters described in this study allows identifying the onset time once a fault enters a critical stage. This may be improved with AI classification techniques using cross-scale, physics-based parameters in detection of the critical state of a fault system.

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Open Research

Seismic catalogs, moment tensor catalogs, raw waveform data, geomechanical data and associated information related to stick-slip experiments analyzed in this study are available in separate data publication:


The data publication is available under the temporary link: https://dataservices.gfz-potsdam.de/panmetaworks/review/cf90017dac80dc3ebc19ae2b444c0e750112487de501a98c736154da55493ada/

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Figure 2.
Figure 5.
Complex multi-scale preparatory processes of stick-slip events on rough laboratory faults

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Abstract
We discuss data of laboratory stick-slip experiments on Westerly Granite samples performed at elevated confining pressure and constant displacement rate on rough pre-fractured faults. The experiments produced complex slip patterns including fast and slow ruptures with large and small fault slips, as well as failure events on the fault surface producing acoustic emission bursts without externally-detectable stress drop. Preparatory processes leading to large slips were tracked with an ensemble of ten seismo-mechanical and statistical parameters characterizing local and global damage and stress evolution, localization and clustering processes, as well as event interactions. We decompose observable complex spatio-temporal trends in AE-derived seismic characteristics identifying effects of persistent and evolving fault roughness at different length scales, multi-scale damage, and local stress evolution approaching large events. The observed trends highlight localization processes on different spatial and temporal scales. The preparatory process of large slip
events is facilitated by smaller events marked by confined bursts of AE activity that collectively prepare
the fault surface for a system-wide failure by conditioning the large-scale stress field. Our results
provide a set of reliable, physics-based characteristics of processes leading to large failure events that
may allow for improved earthquake forecasting along natural faults.

Plane language summary

We discuss seismic data of rough laboratory fault performed at pressures existing in Earth crust. The
laboratory fault was subjected to constant displacement resulting in episodic slips of the fault surface.
We observe complex slip pattern including fast/slow ruptures with large/small fault slips. Very small
slips on the fault surface were observed only with acoustic emission (AE) activity. The AEs are tiny
earthquakes of sub-mm size that produce elastic waveforms recorded with AE sensors. Using
parameters derived from AE data we analyzed physical processes leading to large slip of the lab fault
surface, an equivalent of the large earthquake. Our parameters characterize local and global damage
and stress evolution, damage localization, as well as interactions of small fractures before the
labquake. We identify evolving fault roughness at different length scales, and find that the preparatory
process preceding lab quakes is facilitated by small earthquakes marked with bursts of AE activity.
These bursts indicate ruptures of individual fault patches, which then interact and collectively prepare
the fault surface for the labquake. Our results provide a set of physics-based parameters describing
complex processes leading to the labquake that may allow for improve earthquake forecasting along
natural faults.

1 Introduction

Fault processes leading to large earthquakes in nature have occasionally been observed to produce
foreshock activity and aseismic transients, sometimes lasting months or even years prior to the main
shock (Kato et al., 2012; Bouchon et al., 2013; Schurr et al., 2014; Durand et al., 2020; Meng and Fan,
2021). Seismic and aseismic precursors signifying fault damage evolution and progressive localization
towards large dynamic ruptures are not well understood due to limited availability and resolution of
seismic data and widely varying structures and properties of fault zones. The role of precursory
observables during the preparatory process before earthquakes and their potential use for forecasting
remain controversial (Geller et al., 1997; Bakun et al., 2005; Ogata and Katsura, 2012; Wu et al., 2013;
Mignan, 2014, p.201). Existing physical models describing the preparation and nucleation process on
large pre-existing faults motivated by field and laboratory studies (Ohnaka, 1992; Ellsworth and
Beroza, 1995; McLaskey, 2019; Kato and Ben-Zion, 2021) converge towards a combination of
processes including accelerating preslip and, in some cases, cascading foreshocks. However, fault
heterogeneity and structural variability of fault zones result in rich and varying observational phenomena, that often defy clear interpretation. Thus, seismic hazard assessment and earthquake forecasting still largely rely on probabilistic approaches (Ogata, 1999; Lippiello et al., 2019; Hirose et al., 2021; Mizrahi et al., 2023). The observation of a plethora of physical preparatory processes requires high-resolution monitoring of seismic and aseismic bands that are hardly achievable in nature.

Laboratory experiments performed on intact and faulted rock samples with varying loading conditions have provided a wealth of observations characterizing the effects of roughness, gouge material, loading rate, effective normal stress, and stiffness ratio of fault and the loading system on long-term preparatory deformation leading to failure (Latour et al., 2013; Mclaskey and Yamashita, 2017; Leeman et al., 2018; Guérin-Marthe et al., 2019; Scuderi et al., 2020; Gounon et al., 2022; Morad et al., 2022). Motivated by experimental results, various studies (Ohnaka, 1992; Dieterich and Kilgore, 1996; Ben-Zion and Rice, 1997; Ohnaka and Shen, 1999; Latour et al., 2013) suggested to separate the preparatory phase into a quasi-static phase and an accelerating phase producing dynamic slip. This transition is often only loosely defined by onset of a local or system-wide decrease in shear stress leading to abrupt stress drop. In a complex and heterogeneous fault zone the preparation phase may be long-lasting. The transition towards nucleation of a large rupture involves a localization process, distributed creep transients and collective failure of a range of asperities (de Geus et al., 2019; Ben-Zion and Zaliapin, 2020; Yamashita et al., 2021; McBeck et al., 2022). These processes lead to redistribution of stresses along the fault zone at different length scales, reflecting the multi-scale evolution of roughness at the level of granular material forming the fault zone, cm-scale asperities and large-scale structural inhomogeneities.

The multi-scale preparatory processes are typically accompanied by Acoustic Emission (AE) activity that allows monitoring of key seismo-mechanical processes and local stress evolution during the deformation cycle. Parameters derived from AE data showed changes in clustering and localization of AE hypocenters, AE magnitude-frequency distributions, ultrasonic velocities, inter-event triggering and other statistical attributes approaching failure (Main, 1991, 1992; Lockner, 1993; Zang et al., 1998; Goebel et al., 2012, 2013; Kwiatek et al., 2014b; Davidsen et al., 2017, 2017, 2021; Scuderi et al., 2017, p.20). Typically, AE-derived parameters from stick-slip cycles exhibit general trends, which are punctuated and partially reversed by large failure events. Although the observed trends for some parameters during preparatory slip indicate progressive damage and localization, so far, no robust estimate of time to failure could be identified.
Forecasting the origin time of future large earthquakes remains a challenge if not an impossible task. In recent years earthquake forecasting made a leap using new opportunities provided by Artificial Intelligence (AI) techniques. These techniques demonstrated the ability to predict time to failure in direct shear laboratory tests on smooth faults (Johnson et al., 2021), as well as on analog models, natural and induced seismicity, and synthetic modeling (e.g. Mignan, 2012; Corbi et al., 2019; Johnson et al., 2021; McBeck et al., 2021; Picozzi and Iaccarino, 2021). These studies use a number of potential precursory parameters derived from seismic waveforms or earthquake catalogs, (see e.g. Rouet-Leduc et al., 2017; Lubbers et al., 2018; Hulbert et al., 2019; Picozzi and Iaccarino, 2021). Johnson et al. (2021) noted that successful cross-scale earthquake forecasting requires generalization of predictive models and a better physical understanding of input and output parameters. The former imposes extension of the predictive AI-aided modeling to studies of rough faults, whereas the latter requires a comprehensive linking of AE-derived precursory parameters with observable damage and stress evolution on different spatio-temporal scales.

In this study we employ large AE datasets from laboratory stick-slip experiments involving a series of tests performed on rough pre-fractured faults. The experiments produced complex slip patterns including fast and slow, large and small slips of the fault surface, and confined slips accompanied by AE data bursts. The multi-scale preparatory processes preceding system-wide slip events are analyzed with a set of physics-motivated AE-based features characterizing the seismo-mechanical spatio-temporal processes occurring on the fault. These include parameters describing damage and stress evolution, localization and clustering, event interactions, and local micromechanics and stress heterogeneity. We decompose the observable trends and discuss them in the context of roughness evolution at different spatial scales, a crossplay of local and global damage, and multi-scale stress evolution when approaching a system size event.

2 Data and methods

2.1 Experimental setup

Triaxial stick-slip tests were conducted on cylindrical samples of Westerly Granite with dimensions of 40 mm diameter × 107 mm length (Goebel et al., 2012). Samples were prepared with a 2.5 cm deep notch inclined at 30° to the cylinder axis to guide formation of a shear fracture. The samples were first oven-dried at 100°C and subsequently encapsulated in a rubber sleeve to prevent the intrusion of the confining medium (oil). The specimens were fractured at 75 MPa confining pressure leading to creation of a rough fault surface. To perform a series of subsequent stick-slip experiments, the fault was locked by increasing the confining pressure to 150 MPa. For the initial fracture and subsequent
stick slip tests, the samples were loaded axially using a constant displacement rate of 0.02 mm/min. Subsequent axial loading cycles were applied by advancing the piston at constant displacement rate resulting in an axial strain rate $3 \times 10^6$ s$^{-1}$. Displacement was recorded using a linear variable displacement transducer fixed to the piston and by an external and an internal load cell.

We performed a series of tests on different Westerly granite samples but here we focus on data from one representative experiment stick-slip test (WgN05). The fault roughness in this experiment caused a complex stick-slip pattern with a variety of Slip Events (SE) including five Large Slip Events (LSE) with high stress drops $> 100$ MPa preceded by a varying number of Small Slip Events (SSE) with lower stress drops (Figure 1a).
Figure 1. Overview of mechanical data, AE activity and stick-slip processes at different spatial scales occurring during the experiment. (a,b): AE magnitudes (black dots, left axis) and axial load (red solid curve, right axis). Onsets of large (LSE), small (SSE), and confined slips events (CSE, see Results section for details), the latter not reflected in geomechanical data, are marked with vertical azure lines; (b):
zoom-in of the time period between 3400 s and 5000 s covering the preparatory processes ahead of the LSE1; (c,d,e): zoom-in of the time window framing the representative confined slip event CSE (c,f), small slip event SSE (d,g) and large slip event LSE (e,h) with AE magnitudes color-coded with time; (f,g,h): Corresponding top-view of the AE activity with red stars marking the location of the AE event initiating the slip. Gray area in (e) denotes short-lasting saturation of the recording system with low-frequency noise from the slip event limiting the detection of individual AE events (see text for details) following the occurrence of LSE. Remaining time windows framing slip events are shown in Supplementary Figure S1.

2.2 AE monitoring

Loading and stick-slip events produced AE-s, here indicating sub-mm fracturing and frictional processes occurring on the grain scale. AE activity was recorded by sixteen AE sensors with resonant frequency 2 MHz embedded in brass housings and glued directly to the specimen surface, securing an almost complete azimuthal coverage of AE events. The event waveforms were recorded in triggered mode at 10 MHz sampling rate with 16-bit amplitude resolution. Throughout the experiment, repetitive P-wave velocity measurements were performed using ultrasonic transmission providing a time-dependent quasi-anisotropic velocity model composed of five equally-spaced horizontal layers (with associated velocity) and single measurement of averaged vertical velocity (Stanchits et al., 2006). The velocity model was updated every 30 s during the course of the experiment.

2.3 AE Catalog Development

The development of an AE catalog from the experimental data is an upgraded procedure originally developed by Stanchits et al., (2006). Here, we summarize key and new processing steps relevant for evaluating the time-dependent AE characteristics presented and discussed below.

The first P-wave arrivals of AE events were picked automatically using the Akaike Information criterion followed by pick refinement using the modified Convolutional Neural Network picker (Ross et al., 2018) trained on past AE data sets. Based on a time-dependent quasi-anisotropic velocity model, the resolved picks were used to invert for hypocenter locations and origin time using a grid search algorithm paired with the Coyote optimization algorithm (Pierzan and Dos Santos Coelho, 2018). The hypocenter location accuracy is estimated to be about ±2 mm, constrained, in part, by the selected Root-Mean-Square Deviation (RMSD) of travel time residuals (for the following analysis we selected locations with RMSD < 0.5 μs). Then, the first P-wave amplitudes were corrected for hypocentral distance and incidence angle and for the coupling quality of AE sensors using an ultrasonic calibration.
The average AE amplitude and AE magnitude were calculated from first P-wave amplitudes (Zang et al., 1998):

\[
\overline{A_{AE}} = \frac{1}{n} \left( \sum_{i=1}^{n} (A_i R_i)^2 \right)^{0.5}, \quad (1)
\]

\[
M_{AE} = \log_{10}(\overline{A_{AE}}), \quad (2)
\]

where \( A_i \) and \( R_i \) are corrected first P-wave amplitude and source-receiver distance for sensor \( i \), respectively (cf. Goebel et al., 2012; Dresen et al., 2020). This magnitude estimate reveals relative size differences between AE events but it is not directly calibrated to the physical size of the events (cf. Goodfellow and Young, 2014; McClaskey et al., 2014; Yoshimitsu et al., 2014; Blanke et al., 2021).

For each AE event, a full moment tensor (FMT) inversion was performed using the hybridMT software and first P-wave amplitudes and durations of the first P-wave pulses (Kwiatek et al., 2016; Martínez-Garzón et al., 2017) corrected for coupling quality and incidence angle (Kwiatek et al., 2014a). The resulting FMTs were decomposed into isotropic and deviatoric parts (e.g. Vavryčuk, 2001, 2014). From the deviatoric part of the FMTs, we extracted the P-, T-, and B- axes directions (azimuths and plunges). A P- (T-, B-) axis plunge equal to 90° and 0° corresponds to the direction of maximum compression \( S_1 \) and the direction perpendicular to it, respectively. The two sets of nodal plane parameters (strike, dip, rake) were extracted from the deviatoric part of the seismic FMT of each AE event.

The analyzed catalog contains \( N=310,815 \) located AEs with \( N(M_{AE}>M_{C,AE})=169,825 \) above the magnitude of completeness \( M_{C,AE} = 1.5 \) estimated using the goodness-of-fit method (Wiemer and Wyss, 2000). The FMTs were quality-constrained using as an uncertainty measure the maximum value from diagonal elements of the covariance matrix normalized by the average AE amplitude, \( \varepsilon \) (hybridMT documentation, Kwiatek et al., 2016). Assuming, \( \varepsilon < 0.1 \), this resulted in \( N(FMT)=17,963 \) quality-constrained FMTs. The resulting catalog containing origin time, AE location in the local Cartesian coordinate system of the sample, AE magnitude, FMT parameters including strike, dip, rake, the MT decomposition and orientation of P-, T- and B- axes, as well as associated location and MT inversion uncertainties is available in a separate data publication (Kwiatek and Goebel, 2023).

2.4 Time series of AE parameters

We analyzed the temporal evolution of a total of 10 parameters (features) derived from the AE catalog and defined onsets of informative changes of these parameters with regard to global damage and stress evolution and potential cross-correlations between different proxies. The selected parameters were utilized to characterize the development of local damage and stress evolution on and around
During the preparatory phases of five LSEs, the predictive AE-modeling of the time-to-failure is a subject of a separate manuscript (Karimpouli et al., 2023, submitted). The temporal evolution of all AE parameters was calculated using sliding time windows of different lengths (Table 1) to better prospect the development of short- and long-term processes. The calculated parameter values were assigned to the origin time of the last AE event included in each time window. We ignored time windows which overlap with the occurrence of LSEs to avoid mixing precursory AEs with those following LSE. In the following, we describe the 10 different AE parameters listed in Tab. 1 and subsequently used tracking the preparatory processes.

<table>
<thead>
<tr>
<th>No.</th>
<th>Parameter</th>
<th>Symbol</th>
<th>Time windows [s]</th>
<th>Dimension sensitivity</th>
<th>Source/method</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>AE event rate</td>
<td>$\dot{N}$</td>
<td>23.5, 45 90, 180</td>
<td>time</td>
<td>AE catalog</td>
</tr>
<tr>
<td>2</td>
<td>b-value (maximum likelihood)</td>
<td>$b$</td>
<td>10, 30, 90, 180</td>
<td>time-magnitude</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>d-value (boxcounting)</td>
<td>$d$</td>
<td>45, 90, 180</td>
<td>space-time</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Median proximity</td>
<td>$\tilde{\eta}$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Proportion of foreshocks</td>
<td>$p_{FO}$</td>
<td>25, 50, 100</td>
<td>space-time-magnitude</td>
<td>Clustering analysis</td>
</tr>
<tr>
<td>6</td>
<td>Proportion of aftershocks</td>
<td>$p_{AF}$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Proportion of mainshocks</td>
<td>$p_{MA}$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Median fault plane variability</td>
<td>$\dot{\gamma}_f$</td>
<td>100, 200</td>
<td>space-time</td>
<td>Focal mechanisms</td>
</tr>
<tr>
<td>9</td>
<td>Plunge of local maximum principal stress</td>
<td>$\delta_{\sigma 1}$</td>
<td>90, 180</td>
<td>space-time</td>
<td>Stress tensor inversion</td>
</tr>
<tr>
<td>10</td>
<td>Local stress variability</td>
<td>$\dot{\sigma}_{ij}$</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 1: Parameters characterizing the temporal evolution of damage and stress in the sample. Column ‘dimension sensitivity’ generalizes whether the particular parameter senses changes in time, space, magnitude, or their combination.
(1) **AE event rate:** The AE event rate $\dot{N}$ (unit: [1/s]) has been calculated for the catalog of events with $M_{AE}>M_{AE,C}$ as the number of AEs divided by the duration of the moving time window. It represents the intensity of seismic activity across the whole fault surface.

(2) **b-value:** The slope from the magnitude-frequency Gutenberg-Richter (GR) relation indicates the proportion between the number of small and large AE events in a selected population. The $b$-value is calculated from AE events with magnitudes above the magnitude of completeness $M_{AE}>M_{AE,C}$ using the maximum likelihood method while including a correction for the histogram bin size (e.g. Lasocki and Papadimitriou, 2006). Changes in $b$-values are thought to be governed by rock damage evolution (e.g. Main, 1991), changes in local stress (Scholz, 1968; Schorlemmer et al., 2005), and geometric complexity and roughness (Goebel et al., 2017).

(3) **d-value:** The fractal dimension $d$ from a population of AE hypocenters has been calculated using the boxcount algorithm (i.e. Minkowski–Bouligand dimension, see Moisy, 2022). We used hypocentral locations [X, Y, Z] of AEs with location quality constrained by the RSMD<0.5 [μs]. The $d$-value characterizes the geometry of the AE spatial distribution of AE with $d=3$, $d=2$, and $d=1$ corresponding to volumetric, planar and linear Euclidean distribution of AE hypocenters, respectively.

**Clustering of AE events in space, time and magnitude domain:** We identified clusters of AE events according to their space-time-magnitude nearest-neighbor proximity (Zaliapin et al., 2008; Zaliapin and Ben-Zion, 2013a, 2013b). Specifically, we investigated the proximity of an event $j$ to an earlier event $i$ in a combined space-time-magnitude domain (Baiesi and Paczuski, 2004) defined as:

\[
\eta_{ij} = \begin{cases} 
(t_{ij}(r_{ij})^d 10^{-b m_i}), & t_{ij} > 0, \infty, t_{ij} \leq 0, \end{cases}, \quad (3)
\]

where $t_{ij} = t_j - t_i$ and $r_{ij}$ are the temporal and spatial distances between the earthquakes $i$ and $j$, respectively, $b$ is the $b$-value from the GR distribution, $d$ is the fractal dimension, both estimated as described above, and $m_i$ is the magnitude of the earlier event in time. The scalar proximity $\eta_{ij}$ between events can be expressed as the product of its temporal and spatial components scaled by the magnitude of the earlier event $i$:

\[
\eta_{ij} = T_{ij} \cdot R_{ij}, \quad (4)
\]

with $T_{ij} = t_{ij}10^{-q m_i}$ and $R_{ij} = (r_{ij})^d 10^{-(1-q)b m_i}, 0 \leq q \leq 1$. We fixed $q = 0.5$, providing equal magnitude weights to the scaled temporal and spatial distances. To estimate the spatial distance between events we used hypocentral locations. We denote $\eta_j$ the shortest of the proximities between event $j$ and all earlier events. The distributions of the nearest-neighbor proximities $\eta_j$ in
earthquake catalogs tend to be bimodal (Zaliapin et al., 2008, p.20; Zaliapin and Ben-Zion, 2013a). The
mode with larger event proximities $\eta_j$ corresponds to background Poissonian-like seismicity, while
potentially appearing mode with smaller event proximities $\eta_j$ indicates clustered events (i.e.
foreshocks and aftershocks). The separation threshold between these two modes is here estimated
by fitting a Gaussian mixture model (Supplementary Figure S2).

Using the above method, we identify AE clusters that are connected by proximity links smaller than
the estimated threshold. Each AE connected to the parent by a link longer than the threshold is
considered a background event and starts a new cluster. A single is a cluster that consists of one
background event with no associated foreshocks or aftershocks, while multiple-event clusters are
called families. The largest event in each cluster is called mainshock; all events within the cluster
before or after the mainshock are called fore/aftershocks (see Fig. 6 of Zaliapin and Ben-Zion, 2013a).

Due to the short-term saturation of the AE recording system during large slip events LSE1-LSE5 (see
more details in the results section), the clustering analyses have been performed separately for each
phase P1-P5 (Fig. 1a). This means that early aftershocks from previous slip for phases P2-P5 are not
well resolved, biasing the separation between foreshocks, aftershocks and mainshocks shortly after
the LSEs.

The temporal changes in AE clustering properties occurring on grain-scales have been analyzed using
a sliding time window. We calculated temporal evolution of four parameters, including the (4) median
proximity parameter $\eta$:

$$\eta = \text{median}\{\eta_j\}, \quad (5)$$

defined as a median of the decimal logarithm scalar proximities (eq. 4) of AEs, and the fraction of AE
(5) foreshocks ($p_{FO}$), (6) aftershocks ($p_{AF}$), and (7) mainshocks ($p_{MA}$) in each examined time window
(with $p_{AF} + p_{FO} + p_{MA} = 1$).

The (8) median fault plane variability parameter $\psi_f$ characterizes the level of heterogeneity in the
distribution of the focal mechanisms (Martínez-Garzón et al., 2016; Goebel et al., 2017; Dresen et al.,
2020). This is a generalization of rotation angle between pairs of focal mechanisms (Kagan, 2007)
applied to an ensemble of focal mechanism solutions. A small 3D rotation angle ($<20^\circ$) between the
P/T/B axes of two mechanisms indicates a high degree of similarity, and $0^\circ$ deg means they are
identical.

We compute the spatial variability of focal mechanism similarity across the laboratory fault and rock
sample. Spatial variability is determined from 20 nearest AE neighbors within R<10 mm and the
respective median 3D rotation angle between all focal mechanism pairs (e.g. for 20 AE focal mechanisms there are 190 pairs). This procedure was repeated for each AE event to resolve the spatial heterogeneity/similarity of focal mechanism variability across the whole fault plane. The focal mechanism variability for a particular time window was then estimated as the median of locally calculated values.

(9) Plunge of local maximum principal stress $\delta_{\sigma_1}$ and (10) local stress (orientation) variability $\Psi_{\sigma_{ij}}$.

Using FMTs we performed a linear stress tensor inversion using the STRESSINVERSE package (Vavryčuk, 2014). We follow the sign convention that compressive stress $\sigma$ is positive with $\sigma_1 > \sigma_2 > \sigma_3$. Similarly to median fault plane variability $\Psi_f$, for each time window, we first calculated the spatial distribution of local stress tensors for each location where at least 40 focal mechanisms were available within a 10 mm distance. The input focal mechanism data were resampled and then inverted 200 times by randomly selecting either of the two nodal planes for each focal mechanism, suppressing the problem of fault plane ambiguity (e.g. Martínez-Garzón et al., 2014) in the input focal mechanism data. From this we obtained the spatial distribution of local stress tensors for a particular time window.

In the following, for each local stress tensor, we extracted the plunge of maximum principal stress $\delta_{\sigma_1}$ which is given by the eigenvector corresponding to the largest eigenvalue of the input stress tensor. Finally, we averaged maximum principal stress plunges from the whole fault surface. For plunge of $\delta_{\sigma_1} = 90^\circ$ the local principal stresses averaged over the sample surface are aligned with the macroscopic vertical loading stress direction $S_1$.

The second parameter describing the local stress tensors is the tensor variability $\Psi_{\sigma_{ij}}$, which was calculated with the same procedure as for the focal mechanism variability estimation. For each time window, we calculated the median out of an ensemble of rotation angles between all possible pairs of local stress tensors. Low values of $\Psi_{\sigma_{ij}}$ parameter suggest that local stress tensor orientations over the fault surface are similar.

3 Results

In the following we focus on the analysis of processes leading to the five large slip events (LSEs) with axial stress drop measured in the $S_1$ direction of $\Delta \sigma > 100$ MPa, slip duration of 0.2 − 0.4 s and slip velocity of at least 1.2 − 1.6 mm/s (Fig. 1, Supplementary Table S1). The peak slip velocities were not resolved due to the limited sampling rate of the geomechanical data (10 Hz). All LSEs were followed by rapid initial reloading lasting ca. 50 s and a longer period of almost linear stress increase lasting
typically no more than 1000 s. Further axial displacement beyond a yield point was accommodated by plastic deformation along the fault zone and in its surroundings (cf. Dresen et al., 2020). We attribute most of the deformation during the loading to shear-enhanced compaction of the granular material forming the fault gouge (Kwiatek et al., 2014b), as illuminated by the AE activity spreading over the whole fault surface (Fig. 1e,h).

In addition, structural complexity of the fault surface results in multiple small slip events (SSEs), which typically occur at elevated axial stress with $S_1 > 400$ MPa. The AE activity associated with these SSEs is distributed over significant parts or the entire fault surface (Fig. 1d,g). Stress drops of SSEs range $1<\Delta\sigma<20$ MPa and slip velocities range $<0.05$-0.2 mm/s (Supplementary Table S1). The lower limit of SSEs’ stress drops and slip velocity is due to the periodic noise of stress measurements caused by the servo-controlled MTS loading system.

The macroscopic displacement and stress drop recordings of LSEs and SSEs indicate detectable and relative movement of fault-bounding blocks across the entire fault surface (Supplementary Movie S1). Both LSEs and SSEs lead to a temporally higher AE event detection threshold due to low-frequency noise resulting from comminution and shearing of granular material and debris forming the fault surface while the fault is slipping (gray area in Fig. 1e). The duration of the AE system saturation time period lasts 20-120 ms and qualitatively scales with the duration of macroscopic slip and stress drop magnitude (cf. Supplementary Table S1). The enhanced low-frequency noise is expected to mask very early AE aftershocks, mostly affecting features (4)-(7) related to clustering properties for the time windows directly following the LSE.

In addition to LSE and SSE events resulting in measurable axial stress drops, we identified short-lasting bursts in AE activity due to slips confined in the sample that were mostly not recorded in the mechanical data (i.e. the externally measured axial stress drop is below $\Delta\sigma < 1$ MPa). These local Confined Slips Events (CSE) are attributed to local asperity failures providing a significant AE footprint with very localized AE activity that is most prominent in the early stick-slip cycles (cf. Fig. 1c,f; Supplementary Movie S1). Each CSE is associated with a large AE event followed by AE aftershocks and occasionally preceded by AE foreshocks.

In the following, we present and describe selected time series for each of the utilized parameters describing the evolution of the fault system.
3.1 AE Rates

The AE rates display a short-term (within each phase P1-P5 leading to the LSE) as well as a long-term (across whole experiment) evolution with progressive deformation of the sample (Figure 2b). The long-term evolution is characterized by an overall decrease of AE rates $\dot{N}$. The individual phases P1-P5 preceding LSE1-LSE5 display exponentially increasing $\dot{N}$ when approaching failure (Fig. 2b). LSE nucleation points are defined by large AE events located using P-wave arrivals. Once the elevated noise from saturation of AE system drops to the background level, AE aftershocks are visible, displaying a $1/T^p$ (Omori-type) decrease of AE rates typically lasting no more than about 20 seconds following the actual stress drop (cf. Supplementary Figure S1). The aftershock rates then decrease with consecutive LSEs indicating smoothing of the fault surface.

The increase of AE rates $\dot{N}$ during each phase P1-P5 is punctuated by multiple short-lasting bursts of AE activity following SSEs and CSEs characterized by AE rates decreasing as $1/T^p$ over a short period of time (typically < 10 s). No SSEs and all but one CSE show acceleration of AE rates up to failure (cf. Supplementary Figure S1). However, the second CSE ($T=3672.8$ s) in phase P1 shows precursory acceleration of AE rates (Supplementary Figure S1b). The SSEs and CSEs tend to reduce the overall AE rates during phases preceding LSEs (Figure 1b). AE rates are closely related to fault slip and decrease with fault slip rates following slip events irrespective of stress drop magnitude.
Figure 2. Temporal evolution of (b) AE event rates, (c) GR \(b\)-value, and (d) fractal dimension (\(d\)-value) calculated using different moving time windows \(W\) [s]. For reference, the evolution of AE magnitudes and axial stress is shown in (a) (cf. Fig. 1).
3.2 Gutenberg-Richter b-value

The temporal evolution of the b-value (Fig. 2c) displays a general trend of decreasing b-values associated with AE activity bursts and slip events through each of the phases P1-P5. P1 and P2 show prolonged periods of low b-values approaching LSE failure. This suggests that the b-value acts as a proxy indicating small-scale local ruptures confined in the sample and in general the approach to the system-wide failure.

Beyond phase P2, CSEs and SSEs are less prominent and the temporal trends of the b-value become more uniform. This may reflect a conditioning process of the slip surface, progressive localization and reduction of the fault roughness. Prior to the LSEs, the b-values visibly decrease, and then recover to \( b=1.4-1.6 \) during the initial part of the subsequent loading cycle. The amplitude of the b-value recovery following the LSE is likely affected by the saturation of the AE acquisition system which masks smaller aftershocks immediately following LSE, presumably reducing the b-value in early post-slip phases. The trend of the decreasing b-value before the LSEs is also found before some of the CSEs and SSEs. However, it typically becomes more evident if the AEs are additionally spatially constrained to those related to specific patch activation. Overall, the obtained results suggest that localized slips tend to be preceded by a b-value decrease irrespective of the amplitude of macroscopic slip.

3.3 Fractal dimension d

A d-value of about 2.0 corresponds to an AE hypocenter distribution across the fault surface. In contrast, d-values < 2.0 indicate formation of distinct AE lineaments or clusters within the fault zone. The evolution of the d-value during individual stick-slip cycles leads to a general increase of the d-value ahead of each major LSE, signifying the overall increase in the AE activity across the entire fault surface as a consequence of increased contact area between the two faces of the fault. The AE activity immediately following the LSEs is characterized by higher d-values that quickly decrease within the first 50-100 seconds following the LSE. This may be due to fault dilation associated with large slip and a reduction of small-scale asperities in contact reducing AE activity to linear or isolated clusters indicating larger asperities. As loading and shear-enhanced compaction across the fault resumes, the d-value increases again.

Interestingly, over many stick-slip cycles the d-values decrease. Local peak d-values are typically reached just prior to LSEs and they decrease from about 2.0 to 1.7 with consecutive LSEs. Formation of linear AE clusters and depletion in activity in other places of the fault surface correspond to d-values < 2.0 that are observed with progressive slips.
3.4 Clustering properties

The spatial distribution of AE hypocenters allows identifying AE clusters forming at short-scale mm- to cm-scale asperities characterizing the rough topography of the fault surfaces. In addition, all phases P1-P5 show generally similar trends in the evolution of the median proximity $\hat{\eta}$ parameter (Figure 3b), which signifies event clustering in the combined space, time and magnitude domain. During the initial part of each stick-slip loading phase at low axial stress, the median proximity $\hat{\eta}$ is relatively large. This indicates a dominance of diffuse background activity suggesting random distribution of events in time, space and magnitude domains. This agrees with the high proportion of mainshocks (including singles) in the AE catalog (Fig. 3c).

With progressive loading and approaching LSE failure, the event rate increases and median proximity $\hat{\eta}$ displays a transient decrease, indicating a progressive localization of AE activity through each phase ahead of LSEs (Fig. 3b). Concurrently, we observe a decreasing proportion of mainshocks that are superseded by aftershocks and occasionally by foreshocks (Fig. 3c). The long-term proportion of foreshocks clearly does not increase ahead of the LSE. Likewise, the observed increase in aftershocks is linked to the occurrence of more frequent SSEs and CSEs at higher axial stresses, rather than directly to the approach of the LSE.

Some SSEs and CSEs are preceded by a visible short-term drop in the event proximity $\hat{\eta}$ signifying increased clustering, and all CSEs and SSE display strong space-time localization within up to 20 seconds after the slip followed by a transient $\hat{\eta}$ recovery (Figure 3c, Supplementary Figure S3). The amplitudes of these temporal $\hat{\eta}$ changes do not correlate with the macroscopic stress drop amplitudes, at least recovered for SSEs. Accordingly, the short-lasting clustering episodes framing SSEs and CSEs are sometimes preceded by an increased proportion of AE events that are classified as foreshocks, especially in later loading phases. The SSEs and CSEs are always followed by an increased proportion of AE events classified as aftershocks (Supplementary Figure S4).
Figure 3. Temporal evolution of (a) stress and AE activity for reference, (b) Median event proximity $\eta$ (low $\eta$ indicates clustering of events) and (c) proportion between AE background events (i.e. mainshocks and singles), foreshocks and aftershocks in the catalog (cf. Fig. 1) as derived from clustering analysis.

Time periods directly following LSEs display strong clustering with complete lack of AE foreshocks replaced with AEs classified as mainshocks and aftershocks. The proportion of clustered to background events seems lower on average in comparison to AEs following SSE and CSE, which reflects problems with classification of events in these time periods. Following a LSE, the initially localized AE activity progressively delocalizes typically within 50-100 s before the next cycle starts, initially dominated by background seismicity.
The event proximity measure shows a modest, relative increase with successive stick-slip events, although individual stick-slip cycles still exhibit decreasing proximity values before LSEs. This suggests progressive delocalization of AE events, in particular at the start of a new cycle following LSEs. This seems to be correlated with the generally lower AE rates as well as more random distribution of events in time and space, both due to roughness removal. The proportion between mainshocks, foreshocks and aftershocks does not seem to significantly evolve across several stick-slip cycles.

3.5 Fault plane variability

The observed AEs mostly result from slip and fracture events on the sub-mm scale. Thus, the observed temporal evolution of fault plane variability $\hat{\psi}_f$ (Figure 4) reflects the small-scale complexity of the microfracturing processes occurring in the sample and along the fault surface during loading. In general, high $\hat{\psi}_f$ values are observed during the entire experiment, reflecting a broad orientation distribution of focal mechanisms that comprise mostly normal (parallel to fault dip) to strike-slip faulting mechanisms across the whole fault surface. During loading, fault variability mostly increases or fluctuates around a high level but $\hat{\psi}_f$ often decreases towards failure. Early stages within stick-slip cycles display more heterogeneous distribution of focal mechanisms and the focal mechanism heterogeneity is reduced approaching the respective LSE. Variability evolution $\hat{\psi}_f$ seems largely unaffected by the occurrence of CSE or SSE events. This agrees with earlier observations of Dresen et al. (2020) and Goebel et al. (2017) indicating alignment of activated microslip planes along defects such as cracks and grain boundaries ahead of a large macroscopic slip. Fault plane variability remains similar for all phases P1-P5, without significant long-term evolution.
Figure 4. Temporal evolution of the (b) local fault plane variability \( \hat{\Psi}_f(t) \), (c) plunge of the local maximum stress, \( \delta_1(t) \) (filled circles) and local stress tensor variability \( \sigma_{ij}(t) \) (dots). For reference, the evolution of AE magnitudes and axial stress is shown in (a) (cf. Fig. 1).

3.6 Maximum principal stress orientation and stress variability

Stress tensor inversion from AE-derived focal mechanisms allows inferring the local orientation of the deviatoric stress tensor and a relative measurement of its eigenvalues. Changes in principal stress orientation in response to loading, averaged over the whole fault plane, are recorded with the \( \delta_1(t) \) (plunge) parameter, whereas heterogeneity of the local stress tensors is reflected in \( \Psi_{ij}(t) \) parameter.
In the initial phase P1 the maximum principal stress direction $\delta_{\sigma_1}(t)$ resolved locally stays close to vertical. Subsequently, $\delta_{\sigma_1}(t)$ progressively deviates from the vertical direction as loading increases. Ignoring some short-period outliers, local orientations of the maximum principal stress vary roughly between 90° and 40° with respect to the vertical sample axis during loading and unloading. Excluding the stick-slip cycle associated with LSE4, we find a progressive rotation of the maximum principal stress during loading while approaching LSE1-5. This rotation is likely due to shear-enhanced compaction and build-up of shear stress during loading near the fault surface, causing a local rotation of the stress tensor. The increasing local shear stresses are released during slip events, leading to back rotation of the local stresses towards the initial stress state that is observed in early part of the phases P2-4, following the LSE1-and LSE3, respectively. The rotation of the principal stress axes in each stick-slip cycle is associated with a slow reduction in spatial heterogeneity of the local stress, as indicated by the decreasing stress variability coefficient $\Psi_{\sigma_{ij}}$.

4 Discussion

Various large earthquakes were found to be preceded by precursory deformation and foreshock seismicity on varying scales in space and time (e.g. Kanamori, 1981; Kato and Ben-Zion, 2021; Sykes, 2021). Recent studies of laboratory data showed that the use of AI techniques and features derived from AEs can open up new avenues towards forecasting laboratory earthquakes on smooth faults. However, the range of observable physical processes involved in the run-up to dynamic rupture and how they interact remain not well understood, regardless of the scale. Likewise, there is limited physical understanding of the extracted data features used by AI techniques and their effectiveness in describing the run-up to failure, especially for rough faults.

In this paper, we employed data from laboratory experiments and used AE-derived seismo-mechanical and statistical parameters to characterize the evolution of local damage, roughness and stress in the immediate vicinity of a rough fault surface. In particular, we investigated whether our parameters contain information that allows tracking the preparation process leading to large slip events. The sizes of AEs recorded in our laboratory experiments range from $M_W$-7 to $M_W$-9, being at least 3 units lower than the estimated magnitude of the large stick-slips (Dresen et al., 2020; Blanke et al., 2021). The meta-analysis of (Mignan, 2015) suggests that such AE activity may include key precursory information related to large laboratory earthquakes. Field observations of processes leading to large earthquakes have been categorized as pre-slip, cascade, or localization phenomena, but recent lab studies point towards a case-specific combination of processes (see reviews in McLaskey, 2019; Kato and Ben-Zion, 2021). The physically-motivated parameters used in this study are shown to (I) collectively capture the deviation from long-lasting stable deformation towards a preparatory process of large unstable
failure, and (II) enable high-resolution monitoring of local damage, roughness and stress at different
temporal and length scales, which (III) allows to identify the time in which the fault enters the critical
stage, in which a system-size dynamic rupture may occur at any time.

The stick-slip experiments are performed on a naturally pre-fractured rock sample. The fault surface
displays high initial roughness representing a strongly segmented and juvenile fault in nature. This is
in contrast to a smooth saw-cut surfaces which may be more representative of a fault with large
displacement (cf. Goebel et al., 2017). As in many past experiments (e.g. Harbord et al., 2017), slip
events on a rough fault show a rich mechanical behavior. The large and small macroscopic slips of the
whole or significant portions of the surface display varying durations and amplitudes reflecting fast
and slow slip velocities as well as large and small stress drops (cf. Supplementary Table S1). Smaller
slips confined within the fault surface are highlighted solely by AE activity, but not with external
readings. In consequence, the seismo-mechanical behavior generally shows much stronger or fractal-
like fluctuations compared to saw-cut faults in triaxial stick-slip experiments (Goebel et al., 2017),
double-direct shear experiments containing gouge (e.g. Scuderi et al., 2017; Bolton et al., 2021), or
larger-scale experiments performed in a bi-axial apparatus hosting 3m-scale granite block (McLaskey,
2019). This highlights the need for a careful extraction of meaningful features/parameters from AE
data describing the processes leading to system-size failure.

4.1 Fault roughness, damage and stress evolution

The complex evolution of fault damage, roughness and stress across multiple stick-slip cycles with
progressive shearing is related to grain-scale comminution, gouge production and destruction of
short-scale asperities that ultimately lead to generation of the persisting large-scale topography (cf.
Goebel et al., 2013, 2017; Kwiatek et al., 2014b). Development of roughness at these different scales
is captured with AE source parameters and AE-derived seismo-mechanical and statistical proxies.

Smallest grain-scale roughness development is captured with source parameters of individual AEs
events corresponding to fractures of sub-mm size (cf. Dresen et al., 2020; Blanke et al., 2021), as well
as fault plane variability. The short-scale roughness evolution of small mm-to-cm scale asperities is
observed with seismicity rates, b-value, (spatio-)temporal features including clustering and local-
stress field orientation and variability. Finally, the development of the large-scale (>cm) topography is
captured by global properties including d-value, b-value and seismicity rates $\dot{\eta}$.

The complex long-term (across many stick-slip cycles) evolution of fault roughness is primarily
documented in the spatio-temporal AE distribution (d-value) and localized damage indicators (b-value,
AE rate, cf. Fig. 2), as presented in past studies (Goebel et al., 2013, 2017; Kwiatek et al., 2014b; Dresen
et al., 2020). A decrease in local stress variability (Fig. 4c), the new parameter calculated using AE stress tensor inversion, indicates progressive smoothing of the fault surface. Fault roughness evolves substantially up to LSE2 but less in P3-P5. This is likely because after multiple slip events short-scale, small asperities are progressively destroyed but a large-scale fault topography remains, as revealed by post-mortem inspection of the deformed samples. Consequently, the later P3-P5 AE activity is focused on these larger asperities at the expense of a more uniform distribution on the fault. This results in a general d-value decrease across many stick-slip cycles converging towards $d=1.6$ close to the peak stresses for the last cycles.

The observed short-term evolution of the AE hypocenter distributions and AE sizes during individual stick-slip phases is complex as expressed by varying AE rates, d-values and b-values (Figs. 2d, and 3b). The AE rate and d-value evolution towards higher values depicts spreading of AE events across the fault (Fig. 2d) imposed by enhanced contact area between the granular material forming the fault zone at increased normal load (Dieterich and Kilgore, 1996) (cf. Supplementary Movie S1). This is associated with a general b-value decrease within the stick-slip cycle, interpreted as a signature of increased stress (Schorlemmer et al., 2005; Goebel et al., 2013) or damage accumulation (e.g. Main, 1991). Anti-correlations of b- and d-values, as observed in our study, have been reported in similar experiments (Main, 1991, 1992). However, the d-values and b-values are frequently linearly related through $D = 2b$ (Aki, 1981; King, 1983) as found in nature (Wyss et al., 2004) and other laboratory experiments (e.g. Goebel et al., 2017). This suggests interpretation of b- and d-value correlations and trends remain case-dependent (see also Legrand, 2002) and sensitive to the methodology used. The evolution of the used parameters within one cycle towards the LSE is superposed with high-frequency variations. These originate from activation of short-scale asperities at high levels of axial load, visible as CSE and SSE events and associated transient clusters of AEs (cf. Supplementary Movie S1-S4).
Figure FF5. Surface distribution of AE activity following three slip events from the phase P1 of loading. (cf. Fig. 1a-b): (a): CSE T=3414 s (cf. Fig. 1c,f), (b): CSE T=3673 s, (c): SSE T=3963 s (cf. Fig. 1f,h). In (a,b,c) filled circles show AE activity within a 10-second window starting ~12 seconds following the nucleation of a slip event (star). The contour plot marks the density of events between the start of the slip event and the end of the selected time window, indicating the damage accumulation during slip.

First, two confined slips (a,b) activate small distinct patches representing cm-length-scale asperities (magenta and green regions in all subfigures). The patches mostly do not overlap suggesting a shift in activity with subsequent slips. This suggests that failing short-scale asperities become inactive and ‘smooth’ at the cm-scales. The smoothed-out region expands ultimately to > 2 cm diameter (c) giving rise to a first small slip event that activates a significant part of the fault surface with AE activity accumulating in a narrow diagonal region (blue region in c). The animations presenting the damage evolution framing the occurrence of three slip events are shown in Supplementary Movies S2-S4.

Post-mortem surface observations suggest that short-scale asperities causing clustered AE activity have been progressively erased but grain-scale roughness remained unchanged. This is supported by general decrease of the local stress variability (short-scale) over several slips (Fig. 4c), although we do not observe significant evolution of the fault plane variability that is governed by grain-scale fracturing. High values of fault plane variability observed during the whole experiment, especially if compared with saw-cut faults (cf. Dresen et al., 2020), reflect complex, inter-granular processes related to shear-enhanced compaction of the granular material forming the fault zone (Kwiatek et al., 2014b). This indicates persistence of grain-scale sub-mm roughness of the stress field. The micromechanical grain-scale roughness evolution leads effectively to smoothing out of the short-scale asperities, and the short-scale stress field, as indicated by the decreasing local stress variability.

Beyond P2 we note that fewer and smaller SSEs occur prior to LSEs. Our observations suggest that with progressive slip and creation of a large-scale fault topography, the stress field across the whole fault surface becomes more uniform. Increased contact area, and smoothing out of short-scale asperities responsible for local stress concentrations results in large-scale homogenization of the stress field while approaching the LSE. This agrees with findings from numerical modeling (Ben-Zion et al., 2003) as discussed further in the next section.

To summarize, we find that grain-scale (<mm) and large-scale (>cm) roughness remain largely unchanged across many slip events in contrast to the short-scale (mm-to-cm) roughness involving asperities distributed initially across the surface that are progressively erased with repeating slips.
Within single stick-slip cycles, the evolving space-time-magnitude correlation $\eta_j$ of AEs indicates formation of distinct clusters (Fig. 3b). Together with progressive $b$-value decrease, increased seismicity rates, the combined parameter evolution indicate accelerating deformation and localization ahead of the LSEs, in agreement with observations from lab tests and field data across different scales (Das and Scholz, 1981; see e.g. Lei and Ma, 2014, p.20; Ben-Zion and Zaliapin, 2020; McBeck et al., 2022). Moreover, the exponentially increasing AE rates indicate accelerated seismic release (ASR), which is a non-universal earthquake precursory behavior (e.g. Bufe et al., 1994; Ben-Zion and Lyakhovsky, 2002; Mignan, 2011). However, the discussed set of parameters does not unequivocally signify the proximity to system-size events (LSEs), as similar trends are observable at smaller spatio-temporal scales before individual SSEs or even CSEs.

At about 85-90% of the maximum axial stress (i.e. hundreds of seconds before LSE, corresponding to the yield stress of the fault), the examined parameters tend to mostly fluctuate around a saturation level with occurrence of SSEs and CSEs. Such saturation level is already observed in the first cycle P1 starting with the first CSE (ca. 1500 seconds before the LSE1) at about 85% peak stress and 75% of failure time $t_f$. In addition, we observe that the length of the saturation period prior to failure shortens with each stick-slip cycle, suggesting that the duration over which stress and seismic parameters fluctuate depends on fault roughness and stress heterogeneity. At the saturation level, $b$-values and $\eta$ remain mostly low as both tend to drop significantly in the last part of the loading cycle. Likewise, clustered AE activity including AE foreshock-mainshock-aftershock sequences increases, resulting in a reduced proportion of background events (Fig. 3c). Clustered AE activity clearly associated with SSEs and CSEs, typically consisting of aftershocks and few foreshocks framing the mainshock, suggest stress interaction between events as stress transfer occurs across different length scales of the stress field (see next section).

The external stress fluctuates around a critical state between ~85% and peak stress. This has been described previously as intermittent criticality and was observed in nature and numerical models in combination with ASR and decreasing $b$-value (cf. Ben-Zion et al., 2003; Bowman and Sammis, 2004). In particular, Ben-Zion et al. (2003) showed in simulations of stress and seismicity on a large heterogeneous fault that towards the end of a seismic cycle, a critical (fractal-like) disorder of the stress field heterogeneity is reached over a broad range of scales. This is found in a representative model for the brittle crust (model F, see Ben-Zion et al., 2003), which is characterized by realistic dynamic weakening. In agreement with our results, any stress perturbation at a high stress level may...
trigger a small or system wide seismic event. The ultimate size of the event is conditioned on whether
the stress level is sufficiently high over a large portion of the fault surface and smooth over this length
scale, allowing the event to propagate.

Following Ben-Zion et al., (2003), large-scale correlation of elevated stresses enables the generation
of large events over a smoothed portion of the stress field. However, the nucleation of such instability
remains a statistical event, as it can be triggered by any small short-scale or even a grain-scale stress
perturbation at the right location. The statistical fluctuations before the triggering of large lab
earthquakes involve CSE and SSE events. These events lead to stress relaxation across limited portions
of the fault and stress transfer to the surrounding. The concentrated stress transfer near previous
failure events is evidenced by significant clustering of AE activity forming foreshocks and aftershock
sequences at high axial stresses once CSEs and SSEs become more frequent. The redistribution of
stress and the stress drops due to CSEs and SSEs may cause the fault to temporarily retreat from the
critical stress level. As loading continues, stress recovers and long-range stress correlations are
reestablished leading eventually to a system size (LSE) event.

4.4 Earthquake interaction on different length scales

At the beginning of a stick slip cycle, distributed background activity represents >90% of the total AE
activity (Fig. 3c). As loading increases, activity rates increase, background activity and $b$-values
decrease and there is a progressive spatio-temporal localization of AE events approaching LSEs (Fig.
3b). This is accompanied by increasing slip along the fault. The observed evolution of event proximity
and mainshock aftershock distribution may signal AEs triggering close to larger slip events.

Compared to smooth saw-cut faults where shear strain is localized and off-fault damage is minor,
increasing fault roughness results in significant off-fault damage and a relatively broad damage zone
(Goebel et al., 2017). As a result, shear strain is less localized compared to smooth faults and fault slip
starts at lower shear stress. Therefore, precursory slip displays a larger fraction of aseismic
deformation compared to smooth faults that unlock only at significantly higher stresses (e.g. Dresen
et al., 2020). For rough faults, the increase in shear stress, compaction and contact area of the fault
surfaces results in activation of a growing number of asperities leading to CSEs and LSEs. High local
stress concentrations ahead of CSEs and SSEs, as well as stress redistribution following these events,
produces observable event clustering/triggering (see e.g. Schoenball et al., 2012; Davidsen et al., 2017,
2021; Martínez-Garzón et al., 2018). In agreement with Davidsen et al., (2017, 2021), the local stress
concentrations produce AE event interactions. This highlights the importance of local stress intensities
that control the evolution of the investigated parameters and the role of inter-event triggering (Meredith and Atkinson, 1983; Davidsen et al., 2017).

AE aftershocks following LSEs are scarce in the examined data with respect to those framing SSEs and CSEs. This is partially because very early AE aftershocks following LSE or SSE are masked by the saturation of the AE system with continuous noise consisting of abundant overlapping AEs lasting up to 100 ms (see Supplementary Table S1). However, in large slip events the entire fault blocks are displaced and strength across the interface is reduced to sliding friction. Since the rupture reaches the sample size, no stress redistribution beyond the rupture periphery is possible, in contrast to confined ruptures, reducing the aftershock productivity. As indicated in Goebel et al., (2023), AE aftershocks following large slip events are controlled by residual elastic strain energy, and also depend on differences in fault roughness and slip stability.

5 Applications and outlook

Seismic activity rate, accelerated release of seismic moment and energy, and changes of $b$-values have long been used to characterize precursory deformation preceding mainshocks (e.g. Varnes, 1989; Bowman et al., 1998; Gulia et al., 2016; Bentz et al., 2019; Picozzi and Iaccarino, 2021). Based on our experimental observations, we suggest that additional features characterizing different aspects of AE event organization in space and time, damage, stress and roughness evolution, may assist in constraining multi-parameter models that are currently being developed for time-to-failure forecasting.

Typically, very few seismic catalogs have enough (data) resolution to allow following the evolution of the parameters discussed in our study. However, significant recent progress in enhancing seismic catalogs using AI techniques (Mousavi and Beroza, 2022) may provide new opportunities. Features calculated, for example, from continuous waveform data or seismicity catalogs have been successfully used to predict macroscopic fault properties such as shear stress, friction, and time-to-failure in double-shear experiments performed on a smooth fault (e.g. Lubbers et al., 2018). However, even for repetitive double-shear experiments with vast amounts of (training) data available, the fault gouge layer evolves during the experiments, supposedly leading to degradation in time-to-failure prediction (see discussion in Johnson et al., 2021). This highlights the fundamental roles of fault structural heterogeneity (roughness), associated stress heterogeneity, and related spatio-temporal and spectral evolutions for our capability in time-to-failure forecasting. Likewise, fault evolution with cumulative slip over geological timescales results in progressive localization and fault zones with varying degrees of structural and mechanical complexity (Tchalenko, 1970; Ben-Zion and Sammis, 2003).
Consequently, precursory deformation may display very different signatures depending on fault structure (Ellsworth and Bulut, 2018; Huang et al., 2020). Our study suggests that a combination of physics-based parameters may pinpoint when a fault system is entering a critical stage. Unsupervised classification techniques could be employed to identify regimes of stable deformation and intermittent criticality states and thus improve the accuracy of seismic forecasts. We note that the final triggering of the system size earthquakes in the intermittent criticality framework remains a statistical event that cannot be precisely predicted.

Conclusions

1. We studied the preparatory processes preceding laboratory earthquakes on rough faults using an ensemble of 10 seismo-mechanical and statistical features. These physics-based parameters describe damage and stress evolution in the fault zone, localization processes, local micromechanics and earthquake interactions, as well as local stress field evolution and stress field heterogeneity.

2. The selected features enable understanding a diversity of processes occurring at different spatial and temporal scales during the preparatory phase preceding system-size laboratory earthquakes, these features can help constraining the input for multi-parameter AI-aided models of earthquake forecasting.

3. The developed set of precursory parameters highlights localization processes preparing system-size earthquakes. However, the parameters are sensitive to length scales of fault surface roughness and associated roughness of the stress field, both rapidly evolving in the course of an experiment. The spatio-temporal evolution of fault surface and stress roughness produce limitations on our ability to monitor and forecast the run-up to large laboratory earthquakes.

4. We identify a transition from stable deformation to an intermittent criticality state allowing the occurrence of large events. This stage is characterized by abundant AE activity highlighting persistent heterogeneity of the stress field at the sub-mm grain-scale. Spatio-temporal AE activity bursts indicate small confined slips in the sample marking a progressive breakdown of asperities. These confined slips superimpose and interact, collectively preparing the fault surface for a system-size slip by progressive smoothing the short- (mm-to-cm) scale stress field. Ultimately, the development of large-scale correlation of elevated stresses enables the propagation of a large slip event over the smoothed portion of the fault, triggered even by a minor stress perturbation.
A system-size earthquake occurring at a state of intermittent criticality is a statistical event that cannot be predicted deterministically. However, using a combination of the parameters described in this study allows identifying the onset time once a fault enters a critical stage. This may be improved with AI classification techniques using cross-scale, physics-based parameters in detection of the critical state of a fault system.

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Open Research

Seismic catalogs, moment tensor catalogs, raw waveform data, geomechanical data and associated information related to stick-slip experiments analyzed in this study are available in separate data publication:


The data publication is available under the temporary link: https://dataservices.gfz-potsdam.de/panmetaworks/review/cf90017dac80dc3ebc19ae2b444c0e750112487de501a98c736154da55493ada/

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Kwiatek, Grzegorz; Goebel, Thomas (2023): Acoustic Emission and Seismic moment tensor catalogs associated with the triaxial stick-slip experiment performed on the Westerly Granite Sample. GFZ Data Services. https://doi.org/10.5880/GFZ.4.2.2023.003. Temporary link to data publication:


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Table S1
Movies S1 to S4

Introduction

The supplementary information contains additional figures presenting detailed information on AE evolution framing large, small, and confined slip events (Figures S1, S3, S4), separation of the AE activity into background and clustered activity using Gaussian mixture model (Figure S2), table containing supplementary information on basic properties of the slip events (Table S1), as well as the animations of surface distribution of the AE activity during the whole experiment (Movie S1), and the temporal zoom-ins for the first three slips discussed in the original manuscript (Movies S2-S4).
Figure S1: Zoom-in of the time windows framing the slip events with AE magnitudes color-coded with time in the post-slip-event phase. Each subplot is centered on the onset of the corresponding CSE, SSE or LSE. The nucleation event is shown with an azure star. The cumulative number of events is shown with a magenta line.
Figure S2: Illustration of AE catalog separation (using gaussian mixture model) into background and clustered seismicity in rescaled time - rescaled distance space for five phases P1-P5 of the experiment (cf. Figure 1).

(a) 

(b) 

(c) 

(d) 

(e)
Figure S3. Zoom-in of the time windows framing the slip events showing evolution of median proximity parameter (with shortest window length W=25s) with time. Each subplot is centered on the onset of the corresponding CSE, SSE or LSE. The nucleation event is shown with an azure star. The cumulative number of events is shown with a magenta line.
Figure S4. Zoom-in of the time windows framing the slip events showing changes in proportion of AE aftershocks (with shortest window length $W=25s$) with time. Each subplot is centered on the onset of the corresponding CSE, SSE or LSE. The nucleation event is shown with an azure star. The cumulative number of events is shown with a magenta line.
**Supplementary Table S1.** Overview of basic parameters related to large slip events (LSEs) and small slip events (SSEs). For SSE, slip duration and slip velocity is hardly recoverable due to the noise of stress measurements caused by the servo-controlled MTS loading system.

<table>
<thead>
<tr>
<th>Time [s]</th>
<th>Slip# (slip type)</th>
<th>Stress drop [MPa]</th>
<th>Slip duration [s]</th>
<th>AE detection disturbance [ms]</th>
<th>Slip velocity [mm/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>3963</td>
<td>SSE (slow)</td>
<td>2</td>
<td>~6-8</td>
<td>&lt;25</td>
<td>&lt; 0.05</td>
</tr>
<tr>
<td>4312</td>
<td>SSE (fast)</td>
<td>27</td>
<td>0,40</td>
<td>70-90</td>
<td>0.2</td>
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<tr>
<td><strong>4975</strong></td>
<td><strong>LSE1</strong></td>
<td><strong>156</strong></td>
<td><strong>0,24</strong></td>
<td><strong>90-120</strong></td>
<td>1.4</td>
</tr>
<tr>
<td>6248</td>
<td>SSE (slow)</td>
<td>11</td>
<td>~4-5</td>
<td>&lt;40</td>
<td>&lt; 0.05</td>
</tr>
<tr>
<td><strong>6532</strong></td>
<td><strong>LSE2</strong></td>
<td><strong>135</strong></td>
<td><strong>0,3</strong></td>
<td><strong>90-110</strong></td>
<td>1.2</td>
</tr>
<tr>
<td>7631</td>
<td>SSE (slow)</td>
<td>2</td>
<td>~4-5</td>
<td>&lt;40</td>
<td>&lt; 0.05</td>
</tr>
<tr>
<td>7709</td>
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<td>7</td>
<td>~4-5</td>
<td>&lt;40</td>
<td>&lt; 0.05</td>
</tr>
<tr>
<td>7998</td>
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<td>12</td>
<td>~4-5</td>
<td>&lt;40</td>
<td>&lt; 0.05</td>
</tr>
<tr>
<td><strong>8151</strong></td>
<td><strong>LSE3</strong></td>
<td><strong>146</strong></td>
<td><strong>0,3</strong></td>
<td><strong>50-70</strong></td>
<td>1.3</td>
</tr>
<tr>
<td>9376</td>
<td>SSE (very slow)</td>
<td>&lt; 1</td>
<td>~15</td>
<td>&lt;40</td>
<td>&lt; 0.05</td>
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<tr>
<td><strong>9722</strong></td>
<td><strong>LSE4</strong></td>
<td><strong>160</strong></td>
<td><strong>0,3</strong></td>
<td><strong>80-100</strong></td>
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<tr>
<td>10971</td>
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<td>8</td>
<td>4,3</td>
<td>&lt;40</td>
<td>&lt;0.07</td>
</tr>
<tr>
<td>11434</td>
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<td>&lt; 1</td>
<td>~5</td>
<td>&lt;40</td>
<td>&lt;0.05</td>
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<tr>
<td><strong>11725</strong></td>
<td><strong>LSE5</strong></td>
<td><strong>185</strong></td>
<td><strong>0,3-0,4</strong></td>
<td><strong>90-120</strong></td>
<td>1.6</td>
</tr>
</tbody>
</table>
Supplementary Movie S1. Spatio-temporal evolution of AE activity over the fault surface during the experiment. The AE plotted in each movie frame shows past 25 seconds of AEs with time color-encoded and circle sizes corresponding to AE magnitudes. The contour plot shows the density of events accumulating within each loading phase (P1-P5, see e.g. Figure FF1) preceding the LSE (the contour plot is “reset” after each LSE).

animation-Q95-large-w25s1.25-outlines.mp4

Supplementary Movie S2. Spatio-temporal evolution of AE activity over the fault surface framing the onset of CSE at T=3414s. The AE plotted in each movie frame shows past 10 seconds of AEs with time color-encoded and circle sizes corresponding to AE magnitudes. The contour plot shows the density of events accumulating since the occurrence of CSE, i.e. it represents the damage accumulation following the nucleation of CSE.

animation-CSE1-Q95-w10s0.25-accum.mp4

Supplementary Movie S3. Spatio-temporal evolution of AE activity over the fault surface framing the onset of CSE at T=3673s. The AE plotted in each movie frame shows past 10 seconds of AEs with time color-encoded and circle sizes corresponding to AE magnitudes. The contour plot shows the density of events accumulating since the occurrence of CSE, i.e. it represents the damage accumulation following the nucleation of CSE.

animation-CSE2-Q95-w10s0.25-accum.mp4

Supplementary Movie S4. Spatio-temporal evolution of AE activity over the fault surface framing the onset of SSE at T=3963 s. The AE plotted in each movie frame shows past 10 seconds of AEs with time color-encoded and circle sizes corresponding to AE magnitudes. The contour plot shows the density of events accumulating since the occurrence of SSE, i.e. it represents the damage accumulation following the nucleation of SSE.

animation-SSE1-Q95-w10s0.25-accum.mp4