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Exploring fault preparation and earthquake nucleation from the laboratory

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1 Introduction

The initiation of **unstable fault slip** leading to earthquakes involves intricate physical processes and interactions. Investigations at both field and laboratory scales have highlighted the existence of **spatio-temporal variations in seismic or aseismic observations** near the epicenter of a major seismic event[1,2].

These variations are often associated with the **preparatory phase of major earthquakes** and are believed to involve processes resulting from **progressive localization of deformation,** around the eventual rupture zone, that **accelerates leading up to failure**. However, the time and spatial scales of this behavior are not well understood due to **our lack of understanding into the physical mechanisms within the preparatory zones**.

2 Material and methods

We perform a triaxial test on a sample of **Berea sandstone**. **16 piezo-electric transducers** (PZTs) are used **passively** to detect **acoustic emissions** (AEs) and **actively** to construct a **P-wave velocity model**. **Distributed strain sensing** (DSS) with **optical fibers** is employed to measure axial and circumferential strain (Fig. 1).
We conduct simulations using **H-MEC**[3], which is a 2D fully coupled and continuum based seismo-hydro-mechanical poro-visco-elasto-plastic numerical modeling code (Fig. 2). We track the **dissipation of mechanical energy**, which is related to **irreversible processes** consuming strain energy: $\boldsymbol{D = \sigma'_{ij} \cdot \dot{\varepsilon}'_{ij}}$.

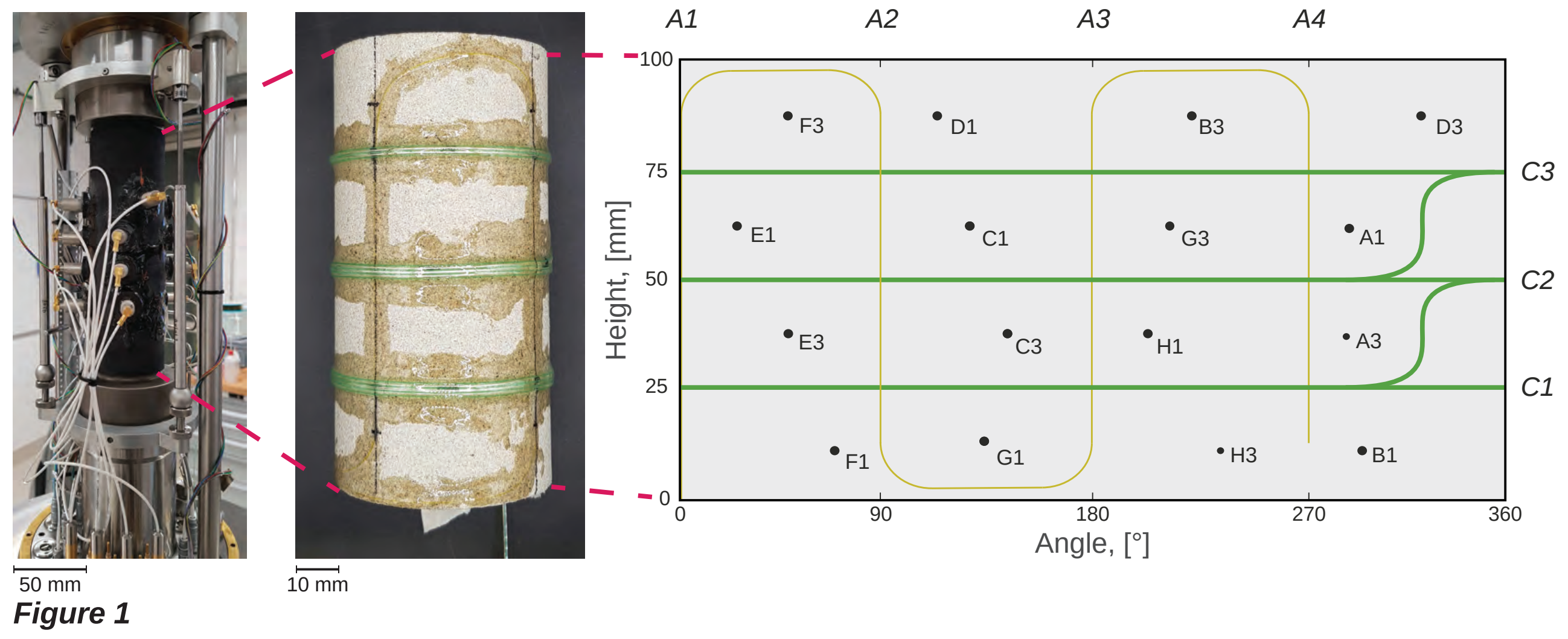

Figure 1

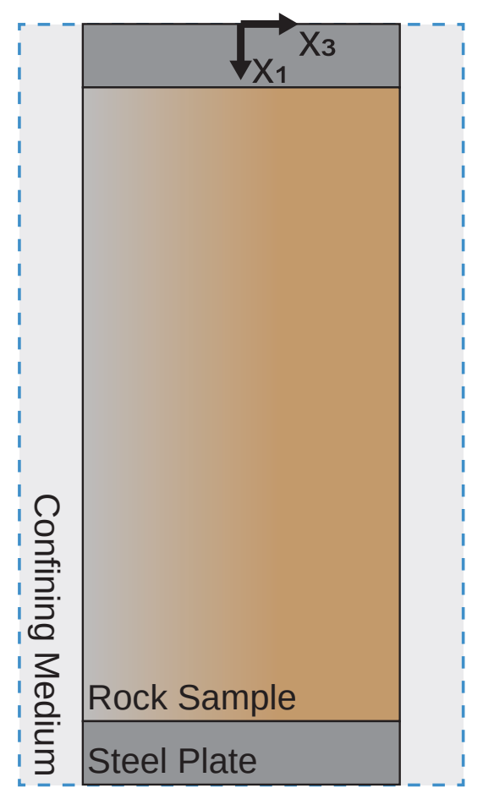

Figure 2

The following **protocol** is used:

- a **confining pressure** (blue line, Fig. 3) of **20 MPa** is applied to the sample and is kept constant,
- **differential stress** (red line, Fig. 3) is increased with a **constant piston displacement rate** (0.33 µm/s) until the **failure of the sample** is reached with associated major stress drop.

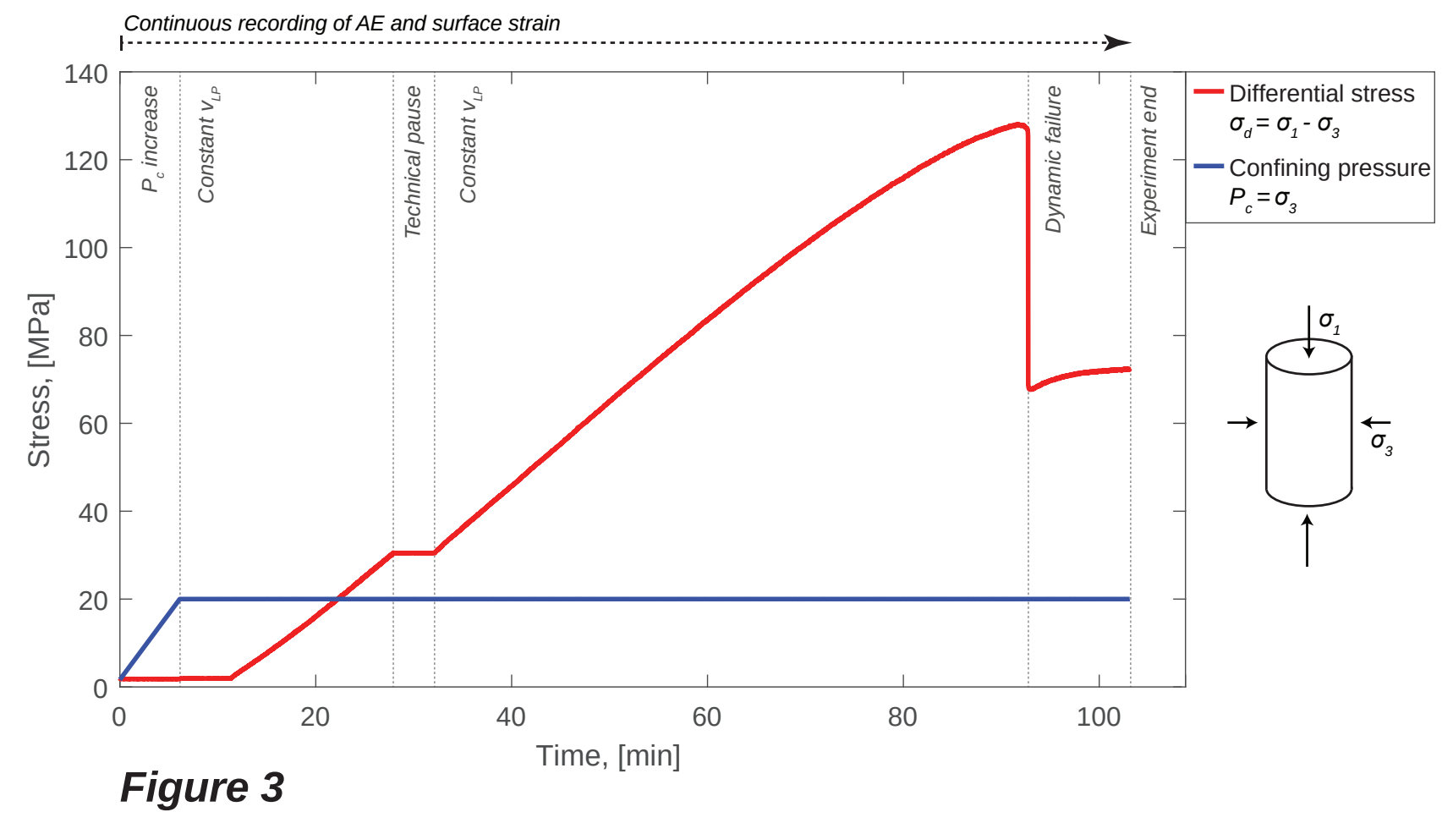

Figure 3

3 Laboratory Results

We observe the formation of **two clusters of AEs at the top and bottom of the sample** (Fig. 4) during approximately the entire test. Shortly (<5 min) before the macrofracture nucleation, the **AEs localize** on one side of the bottom half of the sample. Then, the macrofracture nucleates and propagates upwards.

The last interpolated DSS measurement of circumferential strain (Fig. 5) shows **deformation localization spatially correlating with the last cluster of AEs** that anticipated the nucleation of the macrofracture.

By repeatedly pulsing from each PZT sensor, we construct P-wave velocity models and investigate their **spatial variations** (Fig. 6). **Central regions** of the sample experience a **stronger velocity decrease** significantly earlier than the macrofracture nucleation. However, **no seismic activity** is detetced there before failure (Fig. 4).

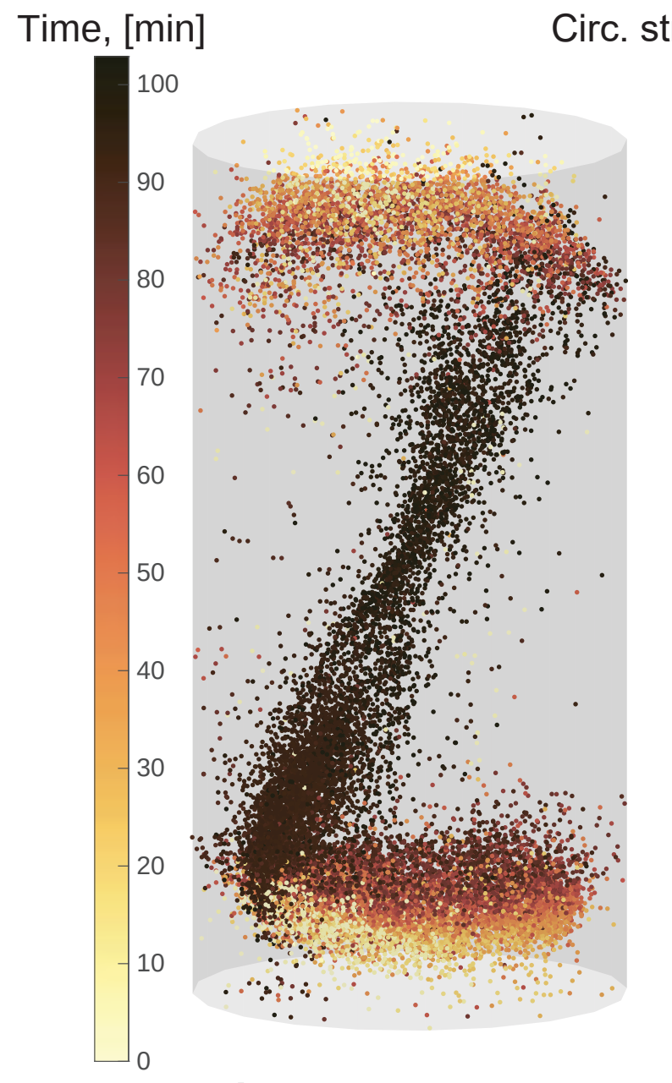

Figure 4

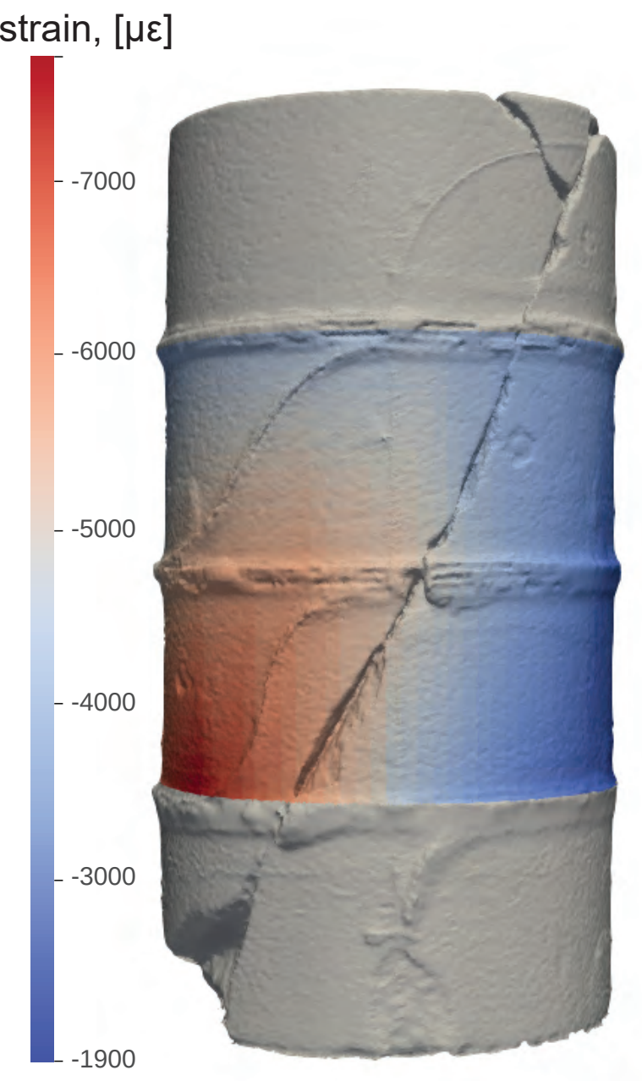

Figure 5

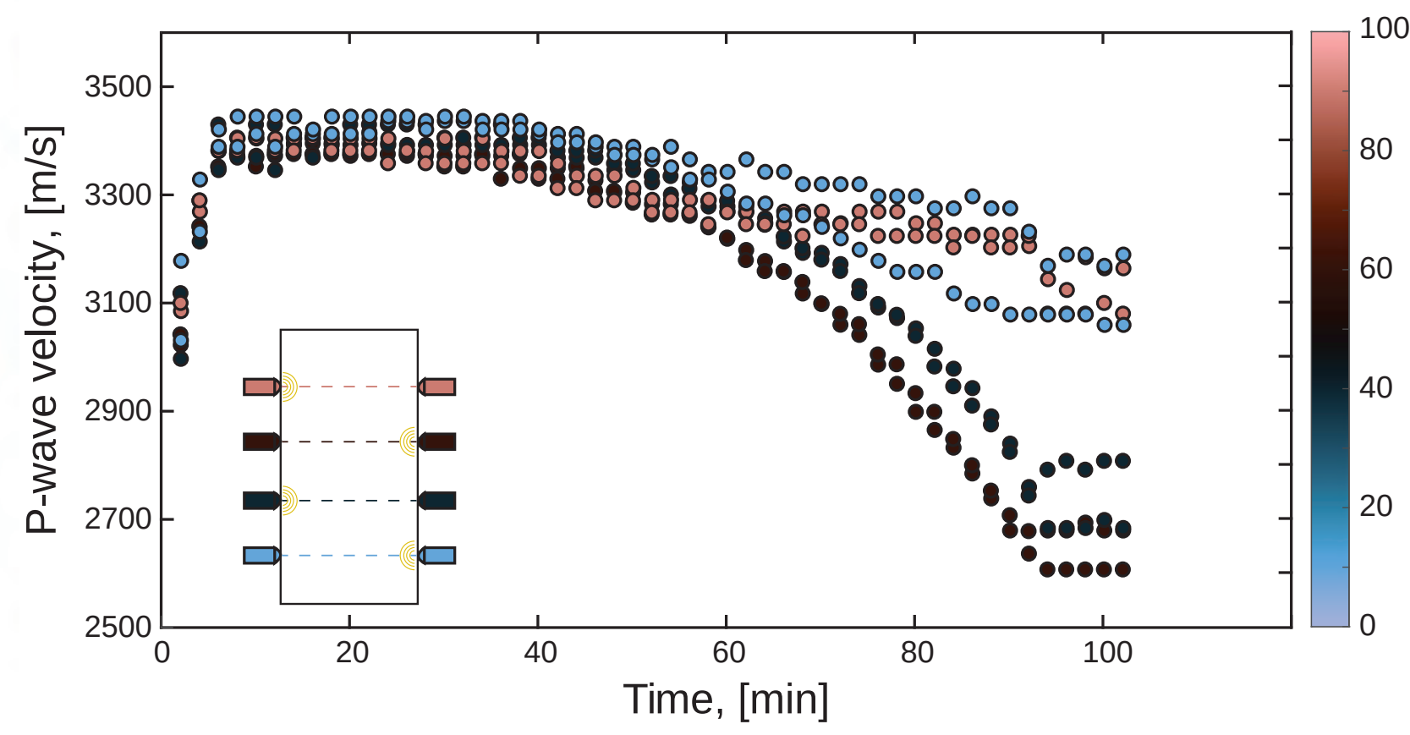

Figure 6

4 Numerical Results

We build a binary mask that isolate regions of the sample with **high dissipative levels** (Fig. 7) to track **irreversible deformation** in the sample. The simulations reveal **three distinct stages of preparatory processes:**

1) highly dissipative fronts propagate towards the middle of the sample correlating with the observed **AE locations** (Fig. 7, left)
2) dissipative regions are individuated in the middle of the sample and could be linked to the discernible **decrease of the P-wave velocities** (Fig. 7, middle)
3) a system of **conjugate bands** form, coalesce into a single band that grows from the center towards the sample surface and is interpreted to be due to the **preparation of a weak plane** (Fig.7, right).

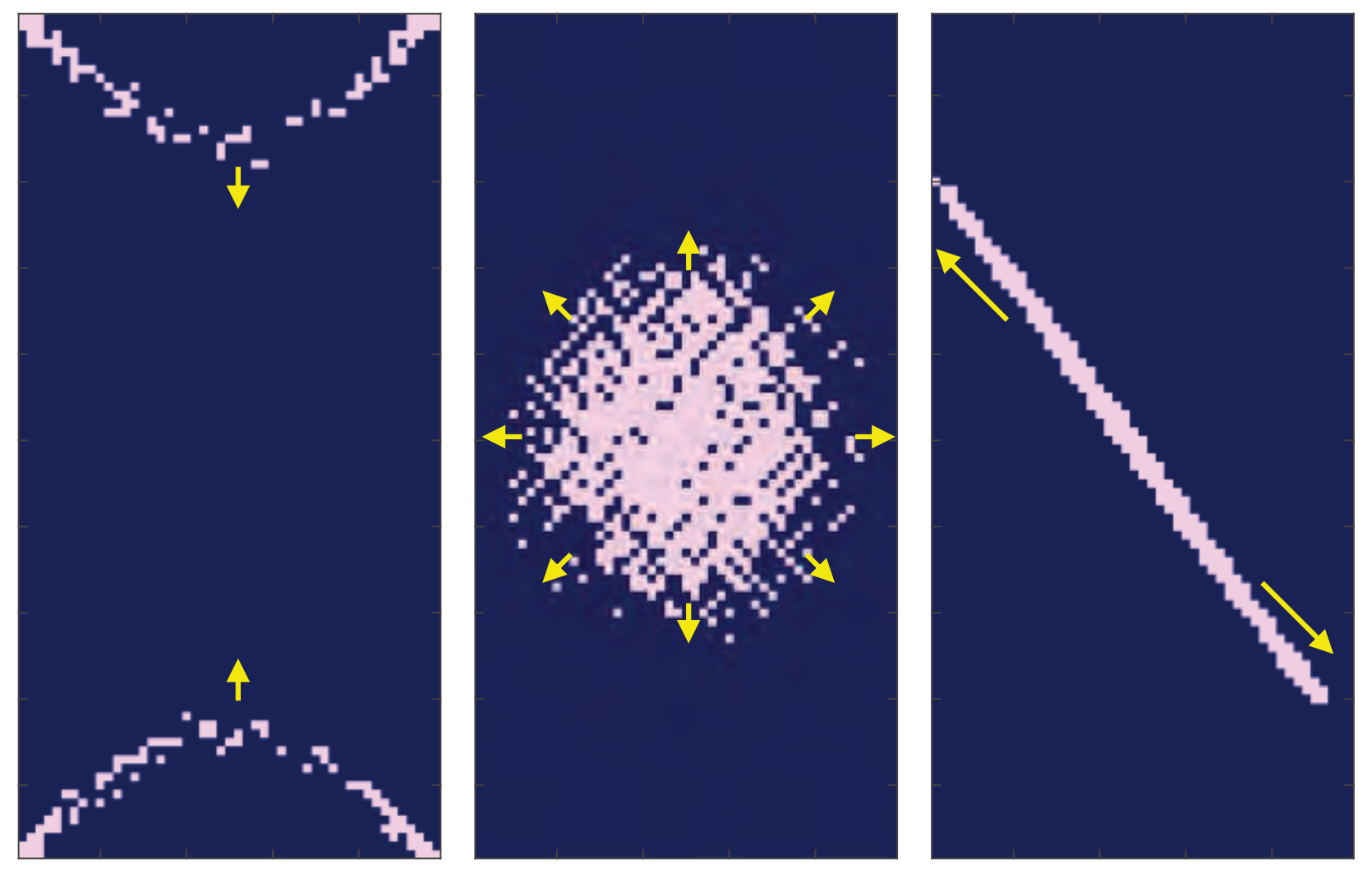

Figure 7

5 Discussion

The **mean volumetric strain rate and AE rate temporally correlate** and are both indicative for a **preparatory process** prior to the sample failure (Fig. 8, top). The increased seismic activity could be caused by the **localization of deformation**.

The **simulated dissipation** also shows an **abrupt increase** prior to failure (Fig. 8, bottom). The cause of this increase might be related to a **preparatory process** also responsible for the **acceleration** of the volumetric strain and AE rates. The model appears to capture this **accelerated behavior**.

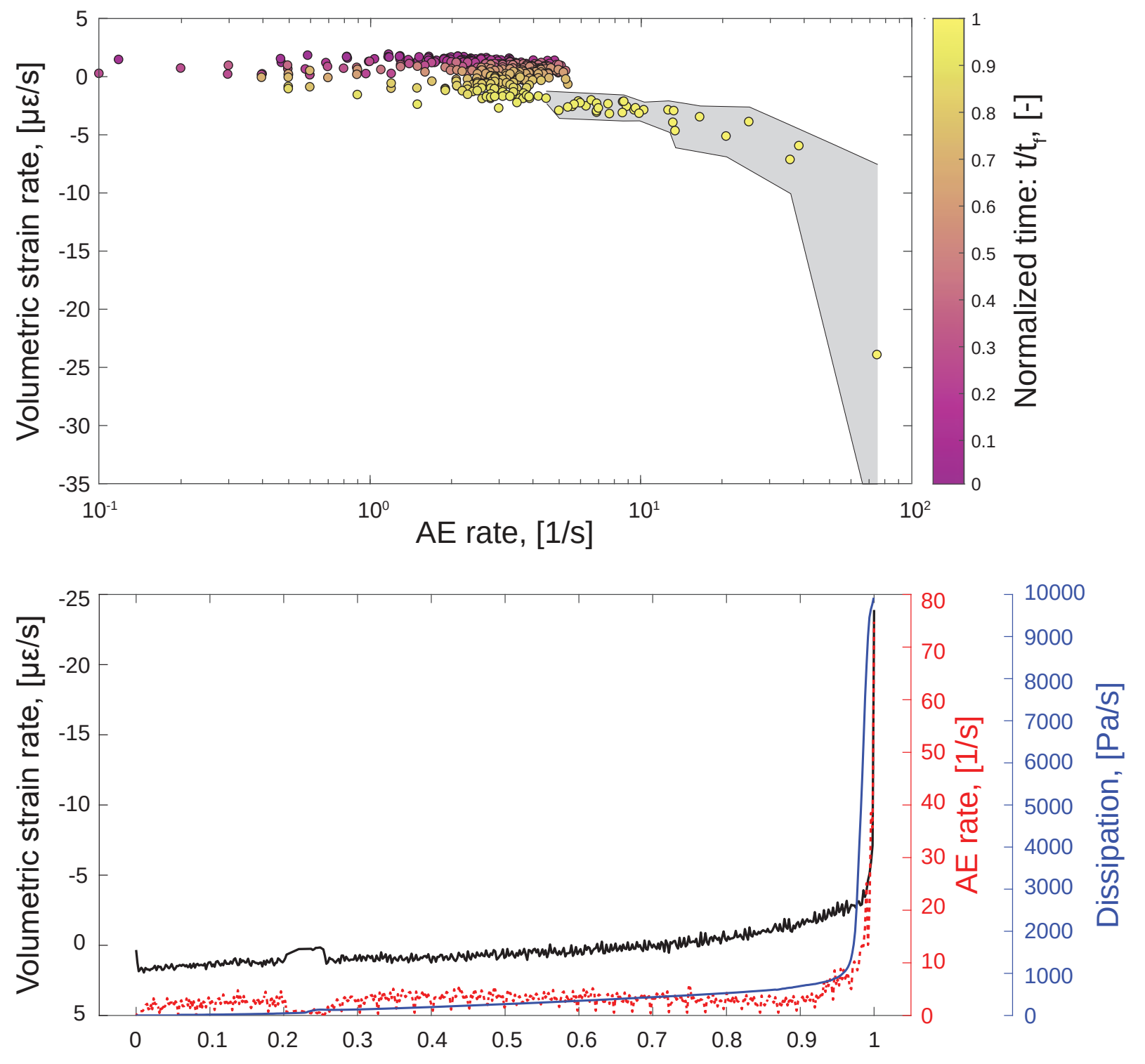

Figure 8

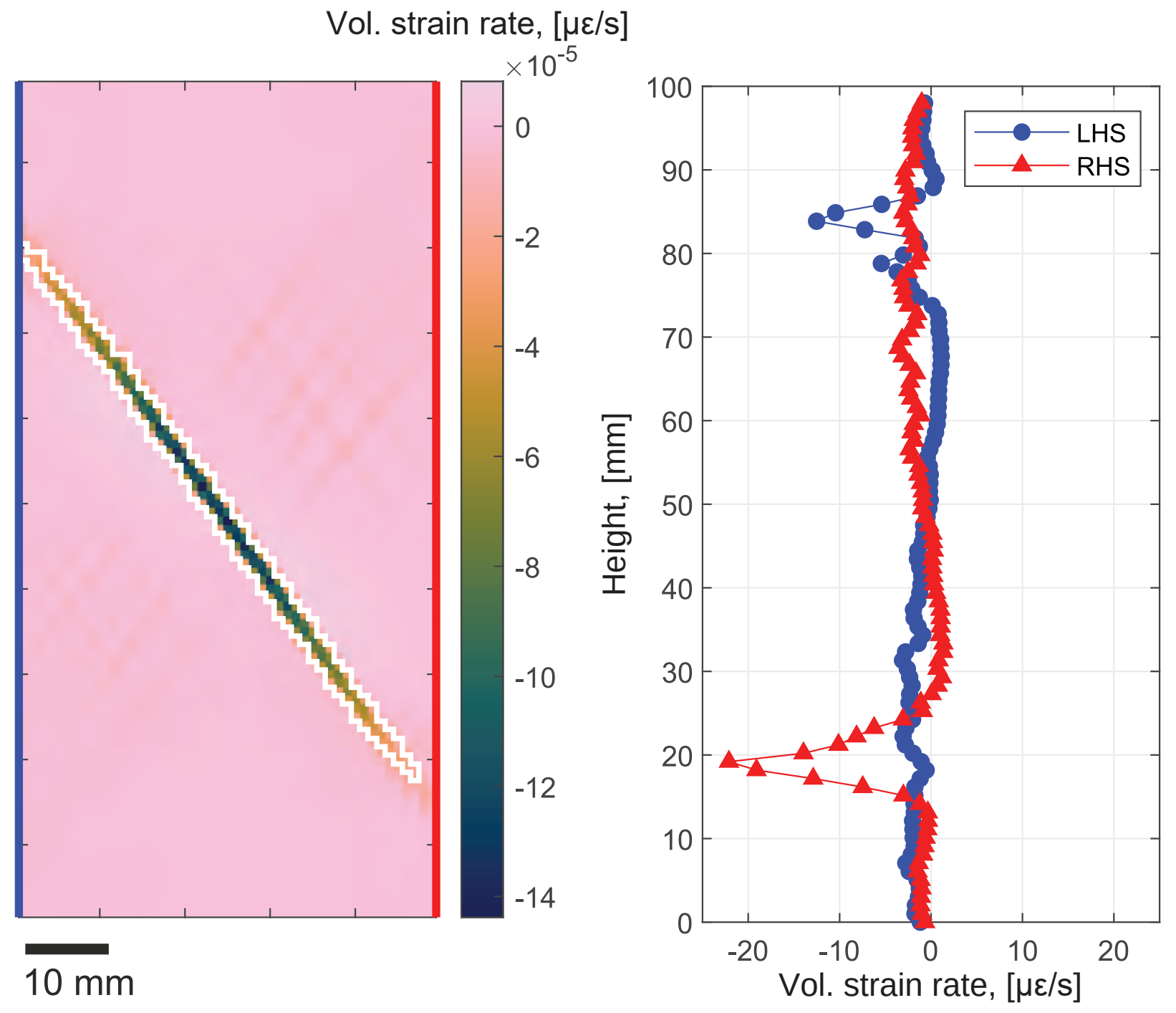

Figure 9

Volumetric strain rate localization is also observed **numerically** (Fig. 9) and spatio-temporally correlates with the laboratory observations. This process is observed as soon as the weak plane **approaches the sample surface** and **interacts** with it.

Due to our choice of using H-MEC in a **quasi-static** manner, our numerical results are deemed reliable only **up to the onset of fracture nucleation**; dynamic propagation is not currently considered in this investigation.

6 Conclusions

This study investigated both **aseismic and seismic preparatory processes linked to strain localization** preceding rock failure. **By combining laboratory measurements and numerical simulations**, we were able to capture a large variations of processes leading up to the nucleation of the shear fracture. **Developing models that capture a range of behaviors** at various scales, including the laboratory, is a necessary step **to properly upscale research efforts** to the reservoir and field scales.

References

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