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Mechanical and Microstructural Characterization of Groningen-type Natural and Simulated Fault Gouges

Job Arts[1] (j.p.b.arts@uu.nl), André Niemeijer[1], Martyn Drury[1], Ernst Willingshofer[1], Liviu Matenco[1]
[1]Utrecht University

Introduction

Gas production from the Groningen gas field causes compaction and induced seismicity within the reservoir and overlying/underlying lithologies. Recent studies of earthquake localization have shown that seismicity dominantly occurs on complex normal fault systems that cut lithologies of contrasting frictional proporties (Fig. 1a &b). However, little is known about the effects of fault heterogeneity on the mechanical strength and stability of Groningen-type faults. Modelling of induced fault rupture to quantitatively assess seismic hazards requires such knowledge.

This study aims at understanding how material mixing in fault gouges affects the mechanical strength and stability of faults that juxtapose contrasting lithologies including Ten Boer claystone (TB) and Slochteren Sandstone (SS). Friction experiments were performed on both homogeneous and heterogenous simulated gouge mixtures, in a rotary shear configuration (Fig 3). The mechanical data provides key information on the frictional strength and stability of fault gouge mixtures.

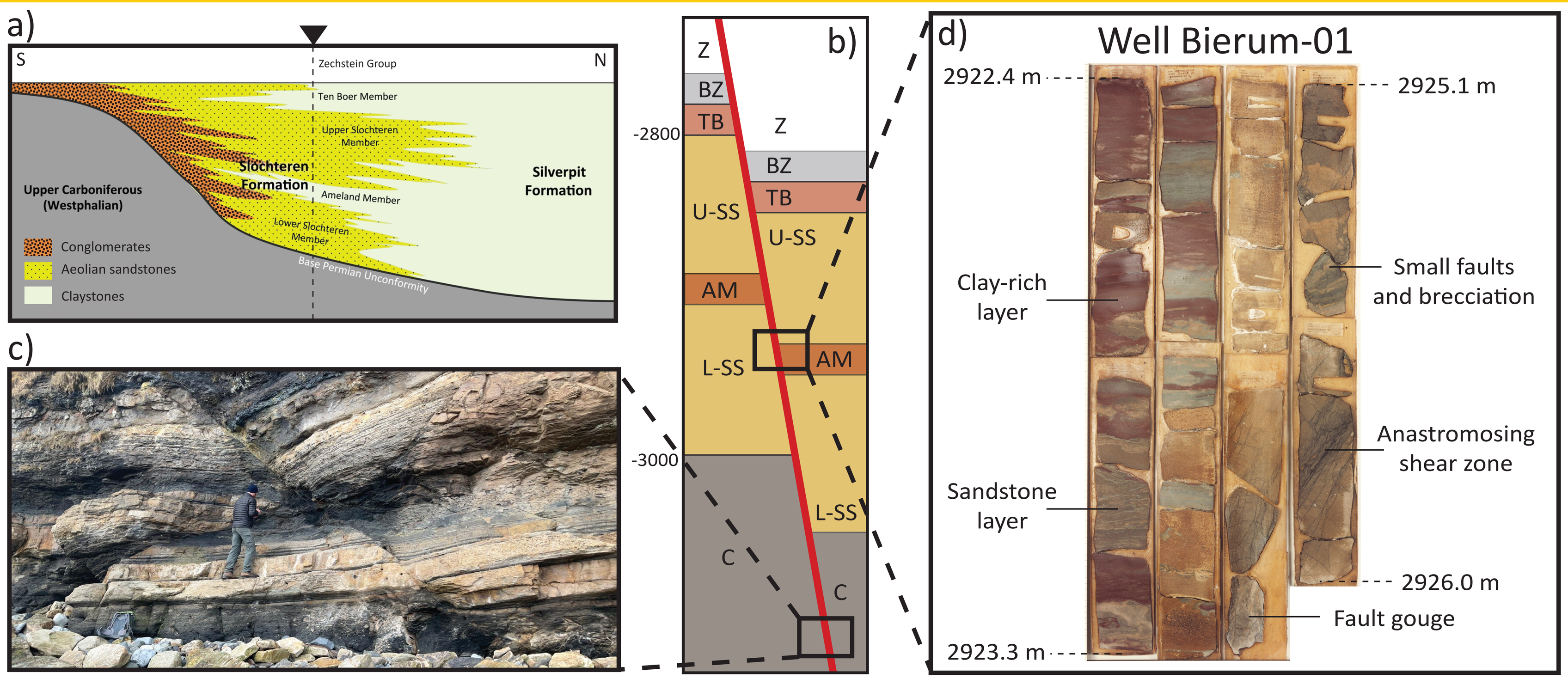

Figure 1: (a) Schematic overview of the Rotliegend group in the Groningen field (after De Jager & Visser, 2017). (b) Schematic overview of a normal fault cutting the stratigraphy of the Groningen field and the underlying/overlighing lithologies and examples of heterogeneity in (c) Carboniferous outcrops displaying lithological heterogeneity at Howich Bay, Northern UK and in (d) core sections of the Bierum-01 well (www.nlog.nl).

Methods

Friction experiments were performed on homogeneous and spatially heterogeneous simulated fault gouges (Fig. 2). Spatial heterogeneity was defined by horizontal layering (sandwich) and vertical segementation. Experiments were performed in a rotary shear configuration (Fig3.) to accomodate large shear-displacements. A specially designed piston with a pressure transducer installed in the vicinity of the simulated fault gouge allowed to measure the local build-up of the pore fluid pressure at nucleation velocities. After an initial shearing-phase at 10 µm/s, five sequences of velocity steps were performed to obtain the velocity-dependence of friction. Experimental conditions:

- σ_n = 5.0 MPa
- Velocity steps: 10-30-100-300-1000-300-100-30-10 µm/s
- Room temperature
- "Drained" conditions

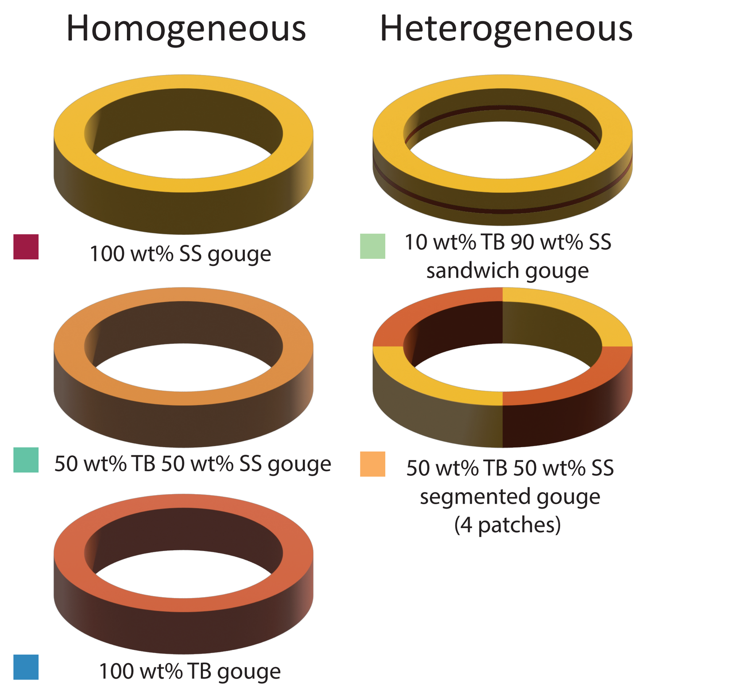

Figure 2: Simulated fault gouge compositions and initial distributions. SS = Slochteren sandstone gouge, TB = Ten Boer claystone gouge.

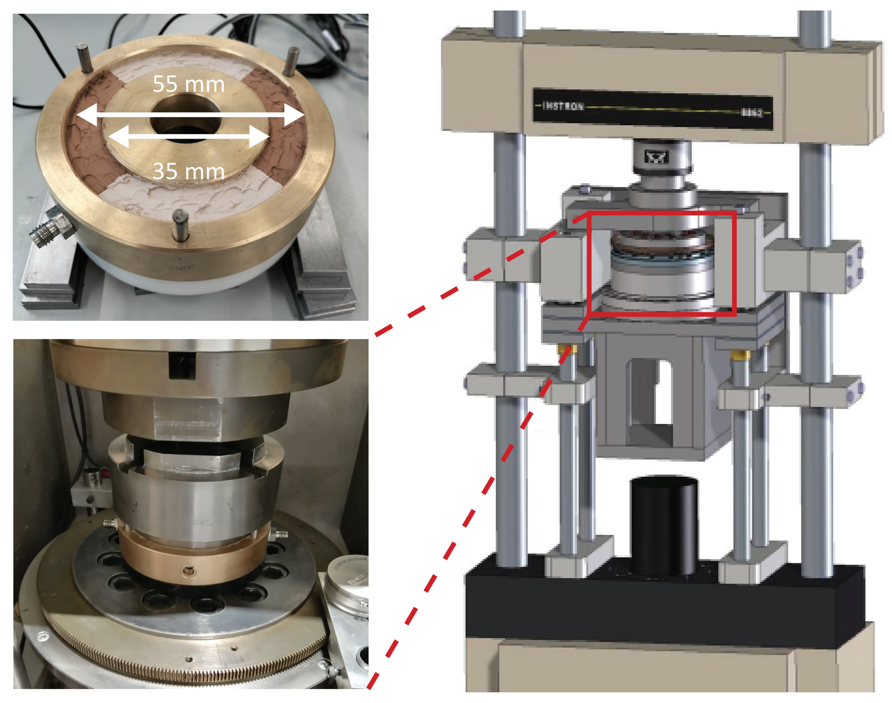

Figure 3: Rotary shear configuration and sample assembly at the HPT laboratory. Four pressure transducers are installed in the lower piston to measure local pore fluid pressures.

Results

Frictional strength

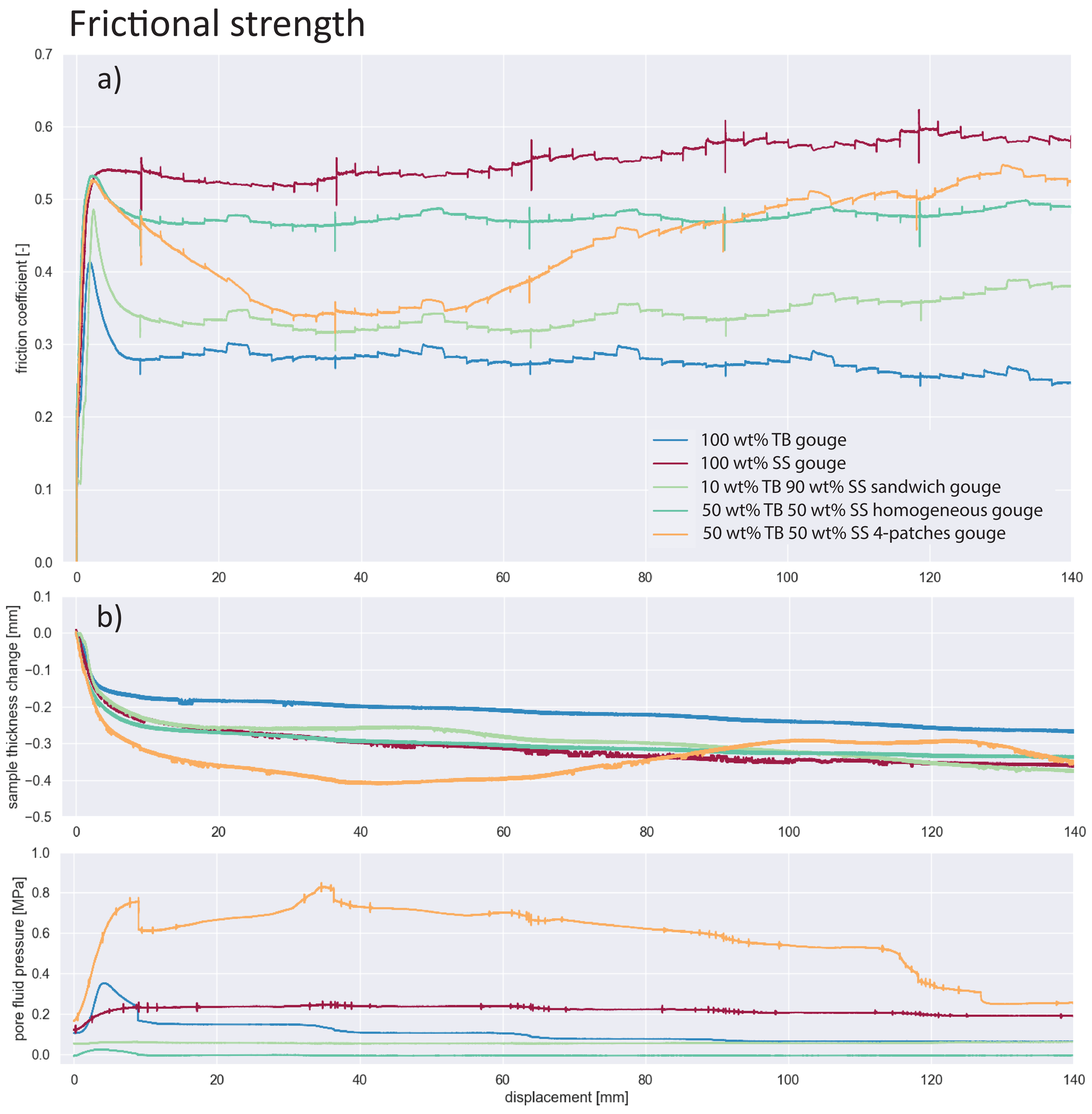

Figure 4: (a) Friction coefficient vs mean shear displacement for spatially homogeneous and heterogeneous samples and corresponding (b) Sample thickness change and (c) mean pore fluid pressures (average of pore fluid pressures measured by four pressure transducers in the lower piston).

Frictional stability

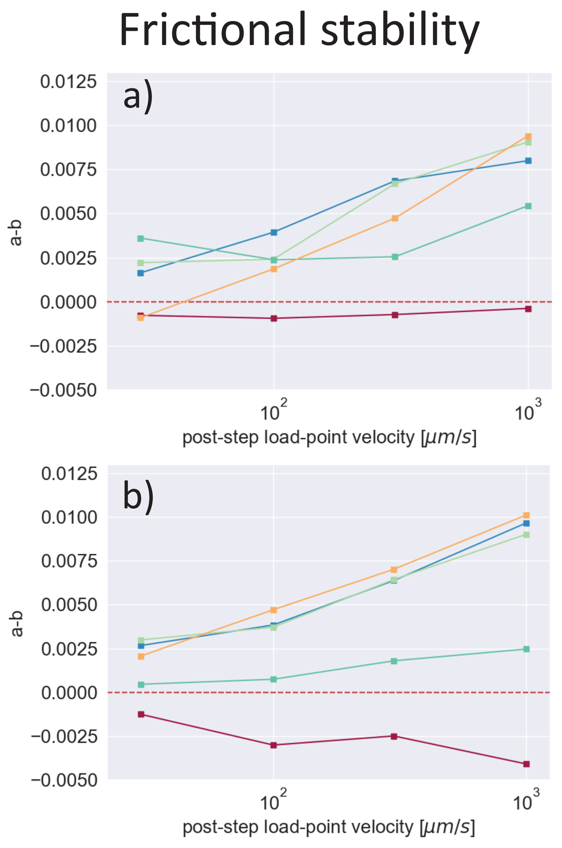

Figure 5: Rate sensitive friction parameter (a-b) for (a) velocity stepping sequence 2 and (b) velocity stepping sequence 5.

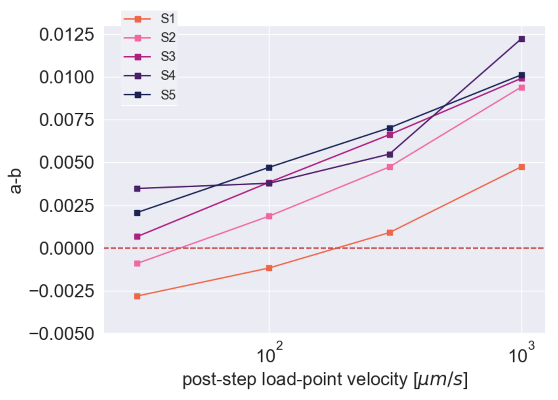

Figure 6: Rate sensitive friction parameter (a-b) for the segmented sample (50 wt% TB, 50 wt% SS; four patches perpendicular to shear direction).

Microstructures

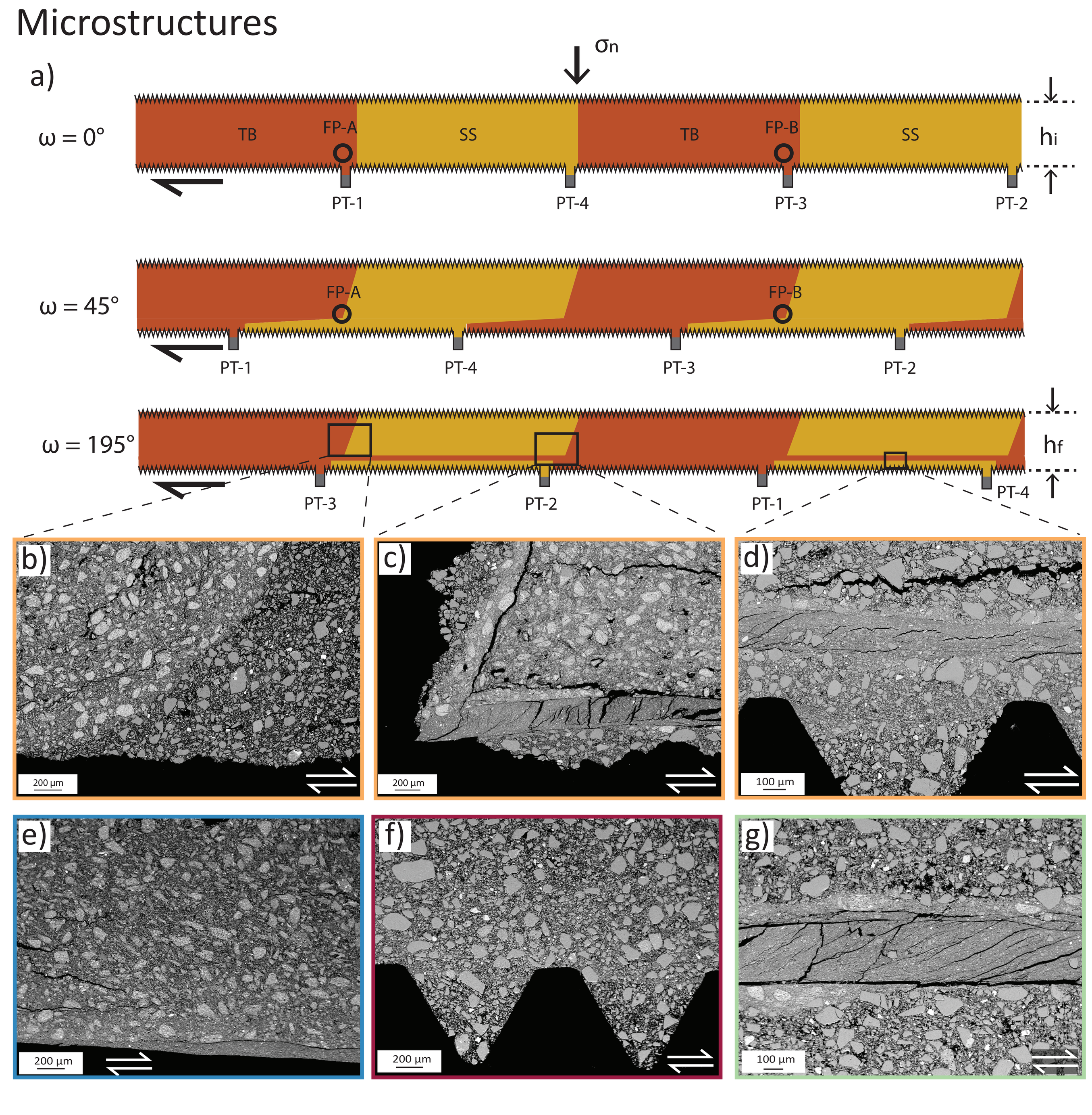

Figure 7: (a) Schemetic overview of fault gouge distribution as function of angular rotation for the segmented sample (50 wt% TB, 50 wt% SS; four patches perpendicular to shear direction). (b,c and d) SEM-BSE images of the segmented sample (locations are indicated on the schematic overview). SEM-BSE images of (e) 100% TB gouge, (f) 100% SS gouge, and (g) 10 wt% TB/90 wt% SS sandwich gouge.

Key findings

- Spatial heterogneity significantly affects the frictional strength and stability of simulated gouges of mechanically contrasting lithologies.
- The evolution in frictional strength of segmented gouges is characterized by:
  - A phase of shear-weakening attributed to clay smear weakening.
  - Subsequent shear strengthening, likely caused by lithology mixing and thinning of the clay smear.
- Frictional stability of segmented gouges is initially dominated by the Slochteren Sandstone gouge segments, displaying velocity weakening behaviour.
- With increasing shear-displacement, clay-smear development causes a shift towards more stable behaviour.
- Transients in pore fluid pressure are enhanced by fault-perpendicular heterogeneity in porosity and permeability.

References

De Jager, J., & Visser, C. (2017). Geology of the Groningen field – an overview. Netherlands Journal of Geosciences, 96(5), S3-S15. doi:10.1017/njg.2017.22