Mechanical and Microstructural Characterization of Spatially Heterogeneous Groningen-type Simulated Fault Gouges

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1. Introduction

Gas production from the Groningen gas field causes compaction and induced seismicity on complex normal fault systems that cut lithologies of contrasting frictional properties (sandstones vs claystones; Fig. 1b & c). Little is known about the effects of along-fault heterogeneity on the mechanical strength and stability of faults. Such knowledge is required to model induced fault rupture and to quantitatively assess seismic hazards.

Aims of this study:
Quantifying the effects of along-fault heterogeneity on the frictional behaviour of faults in the Groningen gas field.

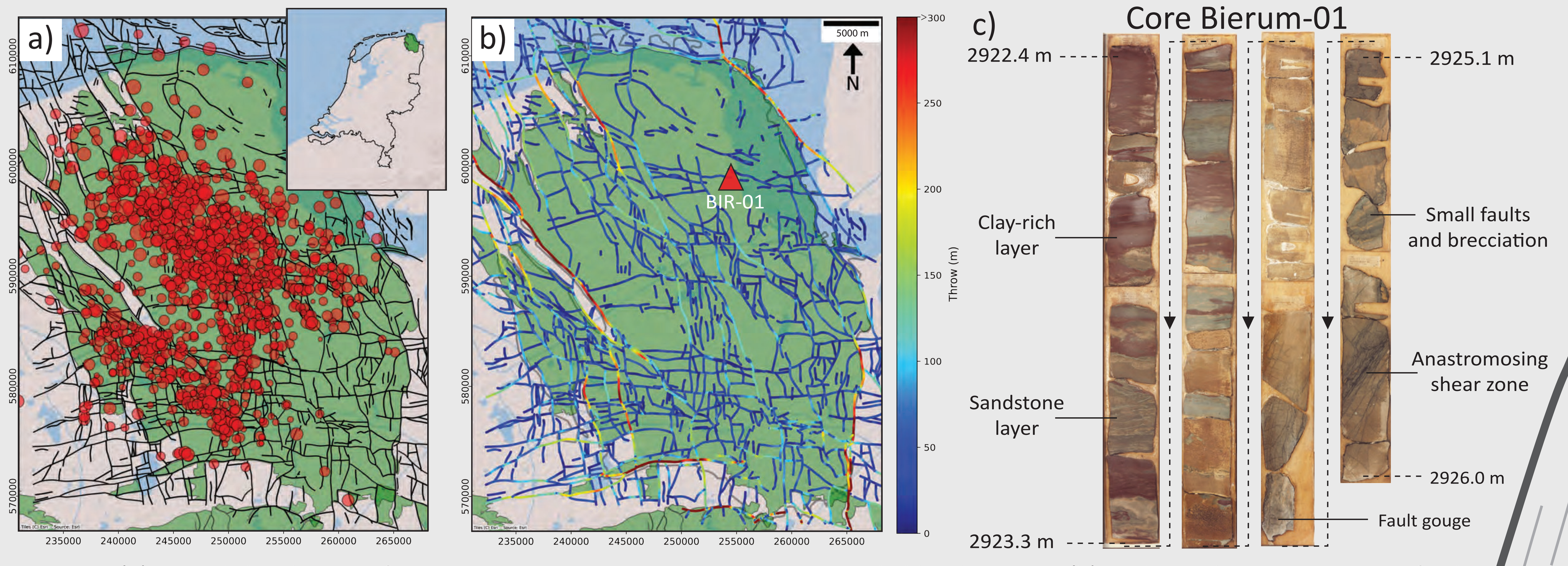
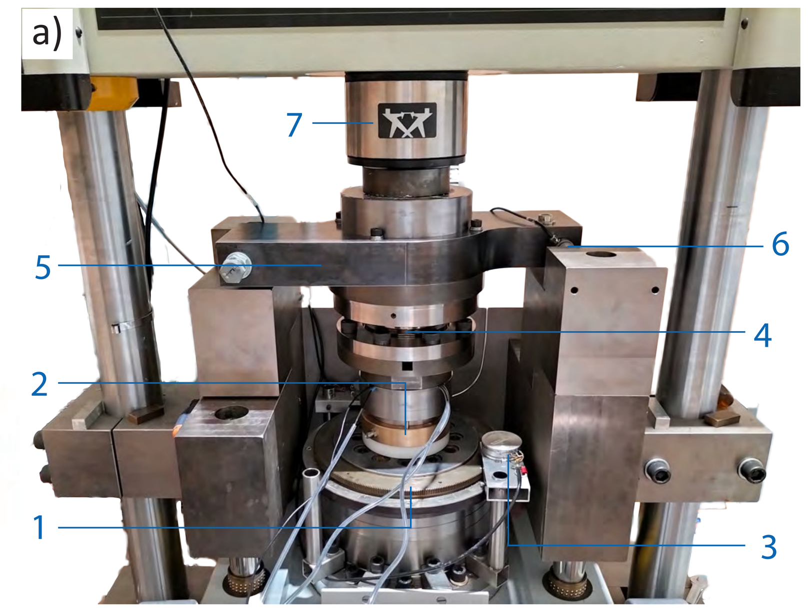


Figure 1: (a) Spatial distribution of seismic events in the Groningen area, recorded by the KNMI. (b) Faults in the Groningen gas field coloured by fault throw (www.nam.nl). (c) Example of lithological heterogeneity along core sections of the Bierum-01 well (www.nlog.nl).

2. Methods

Friction experiments were performed in a rotary shear configuration to accomodate large displacements.

Experimental conditions:
- Velocity steps: 10-30-100-300-1000-300-100-30-10 μm/s
- σ_n = 5.0 MPa
- Temperature = 20°C
- Pore fluid: DI-water



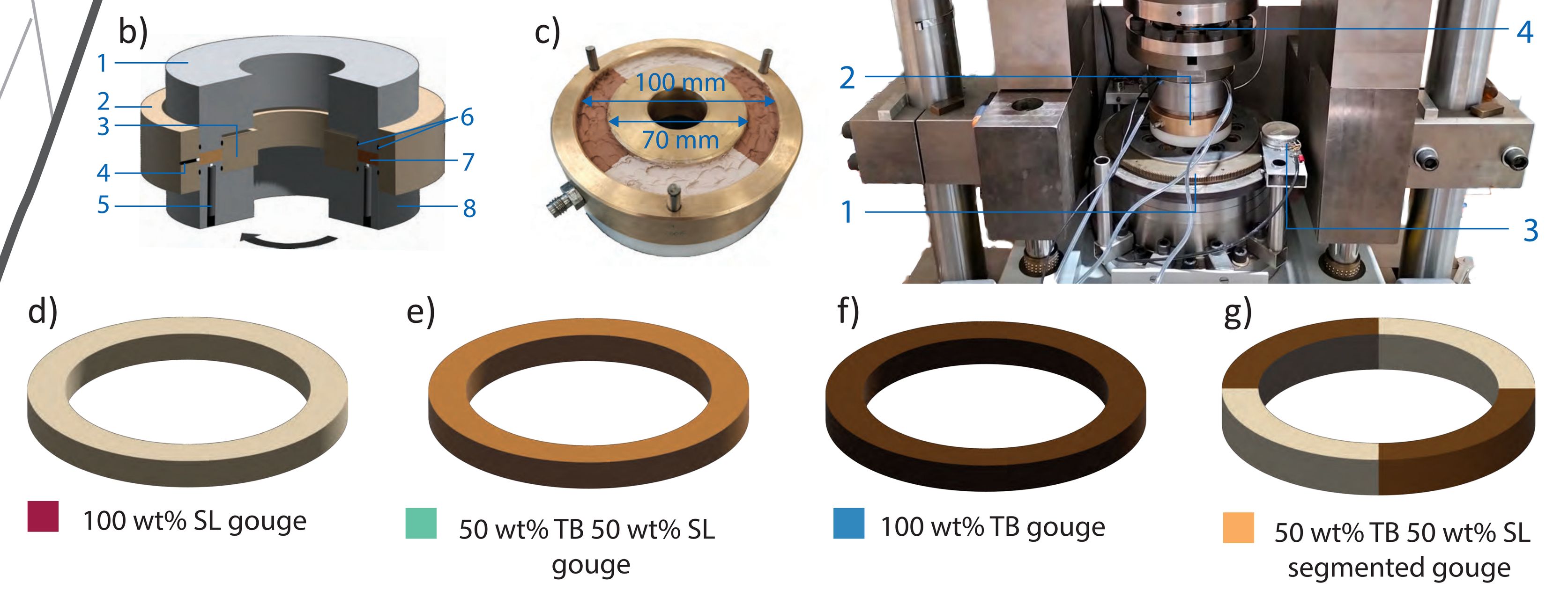


Figure 2: (a) Rotary shear apparatus at Utrecht University: 1) Rotary table, 2) sample assembly, 3) Potentiometer, 4) inline HBM torque sensor, 5) crosshead, 6) load washer (torque), 7) Instron load cell (axial load). (b) Sample assembly: 1) upper piston, 2) outer ring, 3) inner ring, 4) fluid port, 5) pressure transducer, 6) O-rings, 7) sample material, 8) lower, rotating piston. (c) Sample assembly with segmented gouge sample. Simulated fault gouges derived from the Groningen stratigraphy: (d) Slochteren sandstone, (e) a homogeneous mixture of Sochteren sandstone and Ten Boer claystone (50:50 wt%), (f) Ten Boer claystone, and (g) a segmented sample of Slochteren sandstone and Ten Boer claystone.

3. Results: Mechanical data

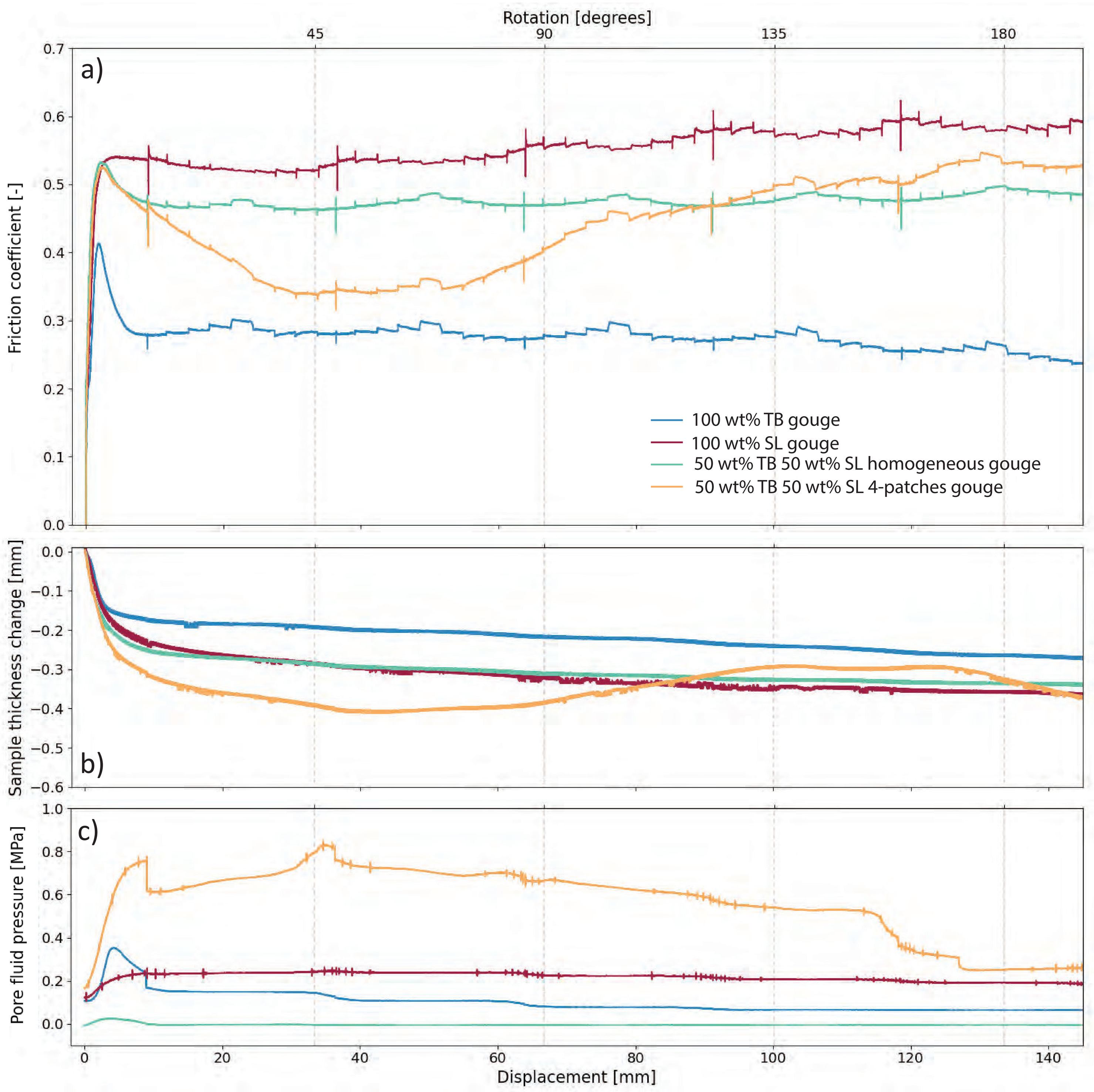


Figure 3: (a) Friction coefficient as function of mean displacement for simulated gouges: Ten Boer claystone gouge (blue), Slochteren sandstone gouge (red), 50:50 wt% homogeneous mixture (green) and 50:50 wt% segmented gouge (yellow). Note the evolution in friction coefficient for the segmented gouge. Friction coefficients are corrected for average pore fluid pressures as shown in (c). (b) Shear-induced sample thickness change as function of displacement.

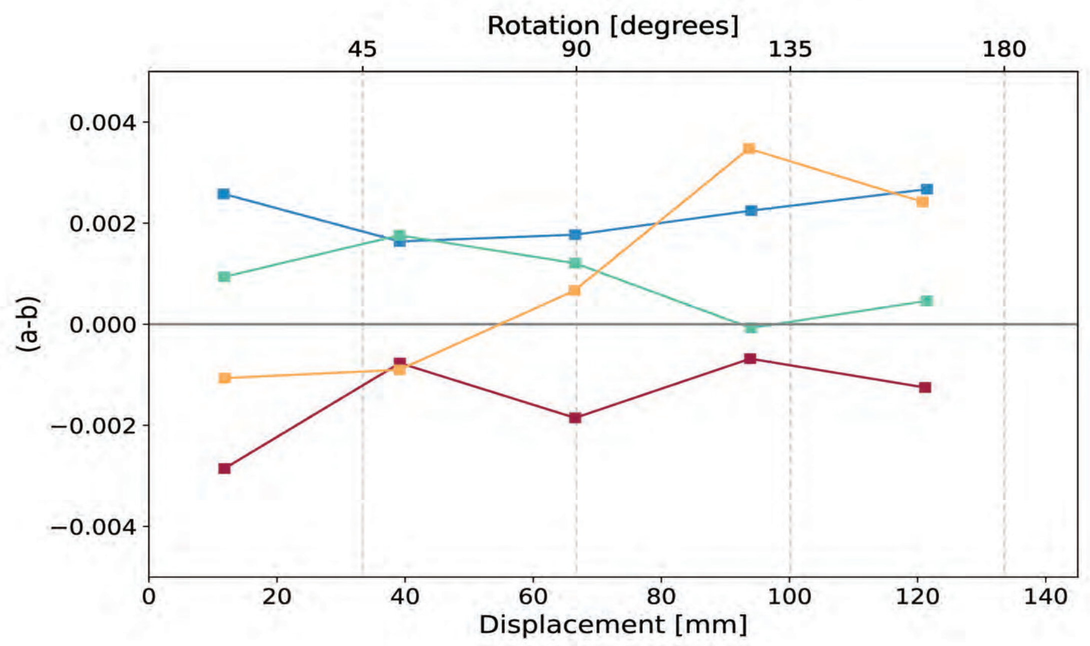


Figure 4: Rate sensitive friction parameter (a-b) plotted against mean displacement.

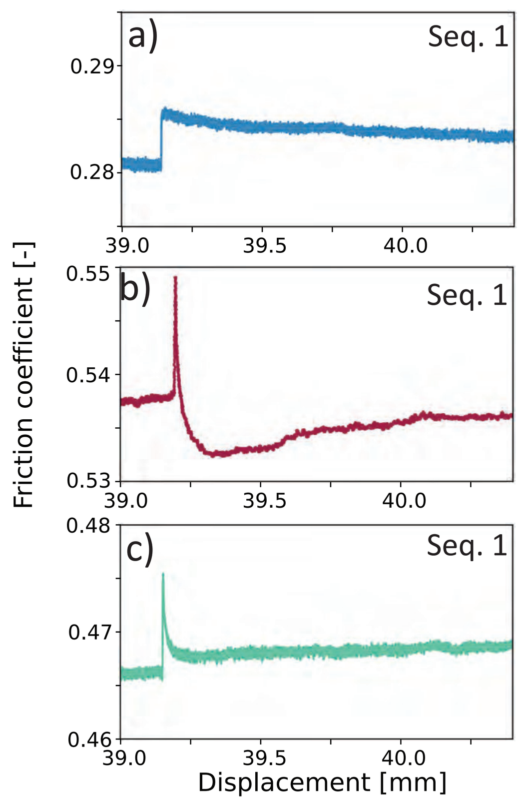


Figure 5: Frictional responce of homogeneous gouges to velocity up-step (10-30 μm/s) during vs-sequence 1.

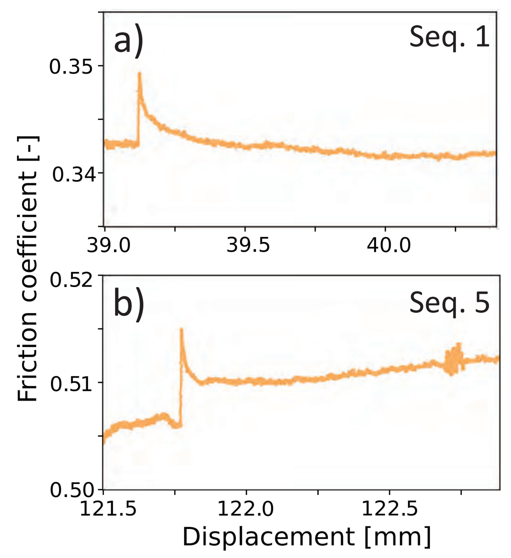


Figure 6: Frictional responce of segmented gouges to velocity up-step (10-30 μm/s) during VS-sequence 1 (a) and VS-sequence 2 (b).

4. Results: Microstructural data

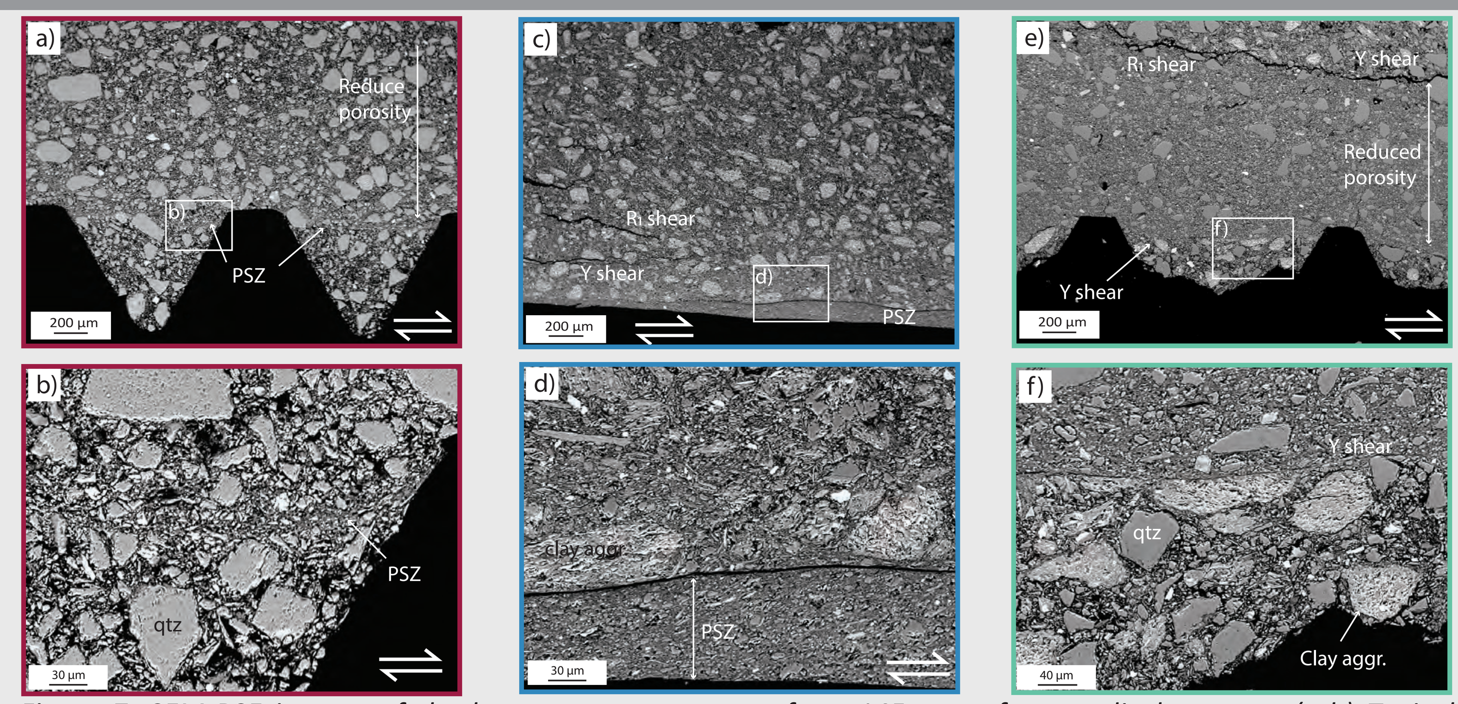


Figure 7: SEM-BSE images of the homogeneous gouges after ~145 mm of mean displacement. (a-b) Typical microstructures in Slochteren sandstone gouge, (c-d) Ten Boer claystone gouge microstructures, and (e-f) microstructures of homogeneously mixed gouge (50:50 wt% TB/SL).

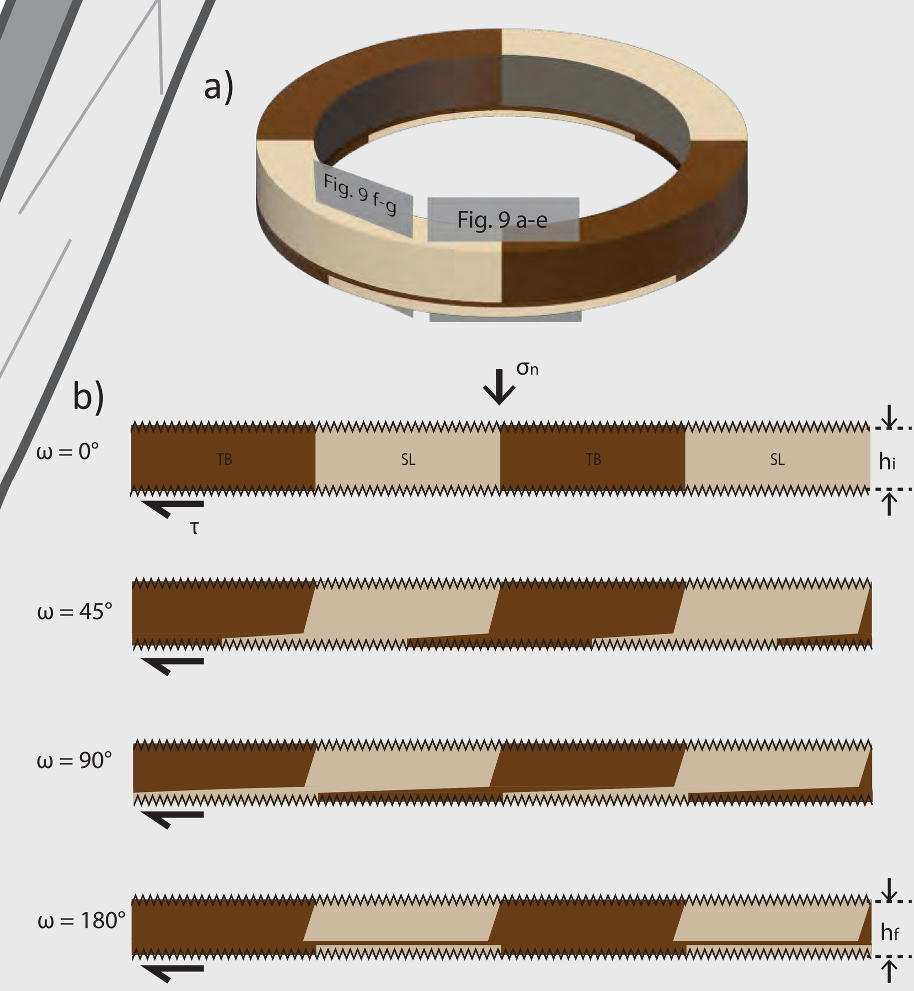


Figure 8: (a) Gouge distribution of segmented sample after ~180 degrees of rotation. Locations of micrographs (Fig. 9) are indicated. (b) Schematic overview of the incremental evolution of the segmented gouge sample.

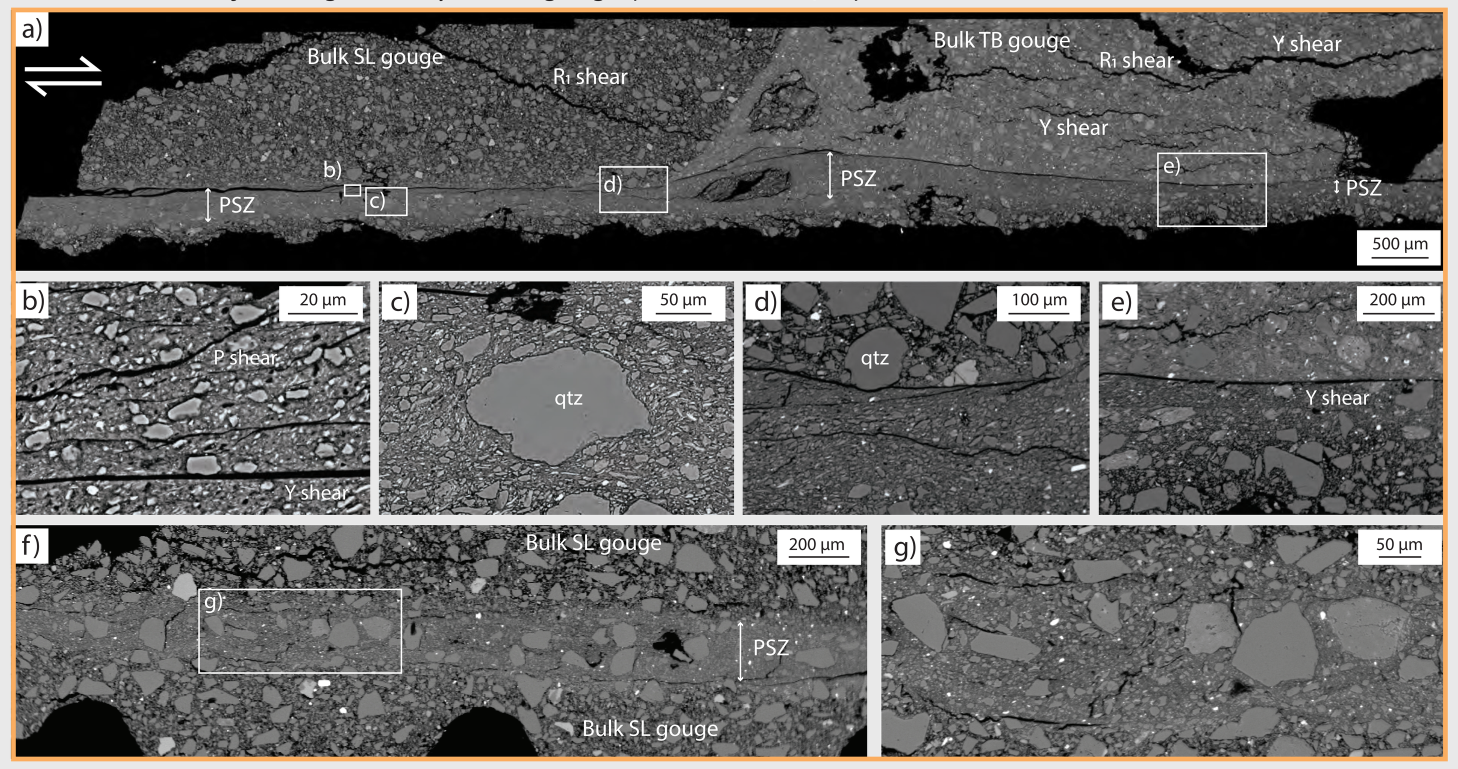


Figure 9: SEM-BSE images of segmented gouge (r290) after ~145 mm of mean shear-displacement. (a) Section at interface between SL gouge and TB gouge . (b-e) Images at higher magnification showing microstructures related to the principal slip zone (PSZ). (f) Section within the SL domain showing a high abundance of quartz grains within the clay smear. (g) Locally, quartz grains within the PSZ are in contact and continuous Y-shears are absent.

5. Take home messages

- The evolution in friction coefficient of segmented gouges is characterized by:
  - A phase of displacement-weakening attributed to clay-smear development.
  - Subsequent displacement-strengthening caused by lithology mixing and quartz incorporation into the clay-smear.
- Frictional stability of segmented gouges is initially dominated by the Slochteren sandstone gouge segments, displaying velocity weakening behaviour.
- With increasing displacement, clay-smear development causes a shift towards more stable behaviour.
- Transients in pore fluid pressure are enhanced by along-fault heterogeneity in porosity and permeability.