The role of heterogeneity in fault zone weakening and stability

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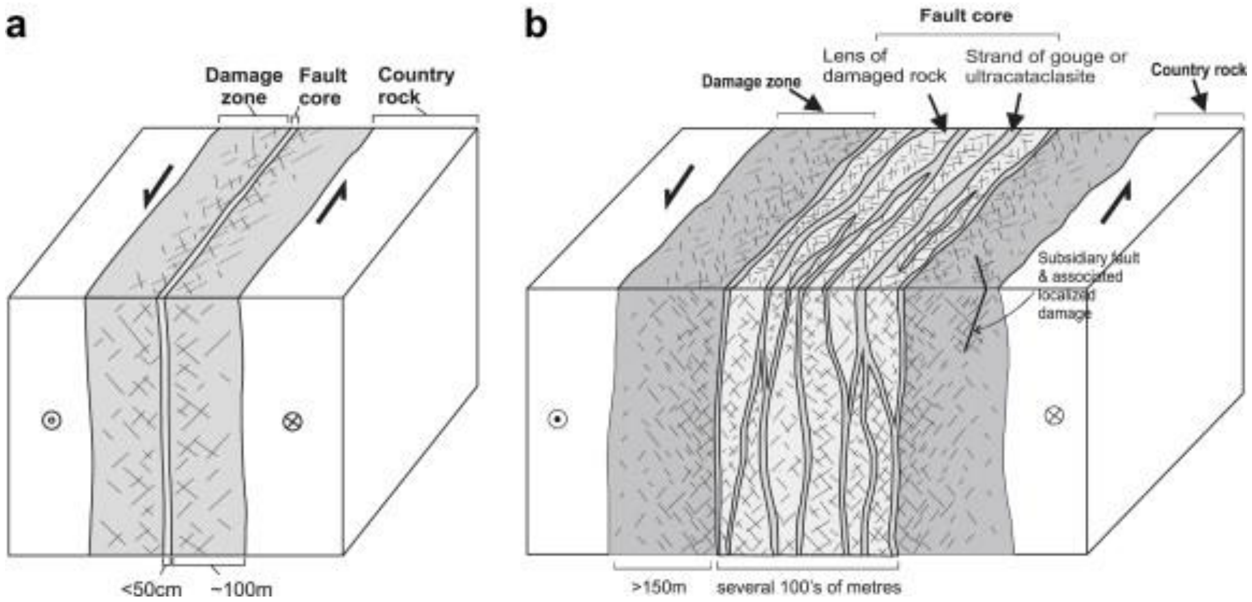
Fault zone structure



Mitchell and Faulkner (2009), J. Struct. Geol.

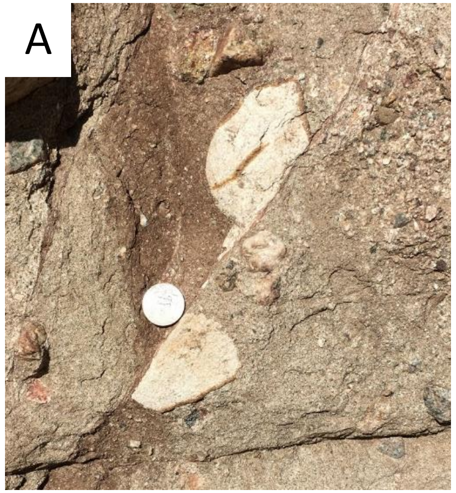
Brittle fault zones are typically envisaged to consist of a fault core, where the majority slip is accommodated, surrounded by a zone of fractured country rock. The fault core is comprised of high-strain gouge material formed from the progressive wear of the country rock and can form either one strand or consist of multiple strands of gouge material that anastomose around lenses of more competent rock (e.g. Mitchell and Faulkner, 2009).

In the latter case it is clear that fault zones can have highly complex heterogeneous structures, consisting of materials with variable physical and mechanical properties.

Fault zone heterogeneity

In natural fault zones heterogeneity occurs over many different scales. From faulting of centimeter-scale geological features such as clasts and foliations (images A and B below), to wide fault zones consisting of strands of different lithologies that are each tens-of-meters in width (as shown in image C, a section through the Carboneras Fault Zone), to the plate interface-scale where kilometer sized asperities/patches have been suggested to act as potential nucleation sites for megathrust earthquakes in subduction zones (e.g. Bilek and Lay, 2002; image D).

A



Punchbowl, California

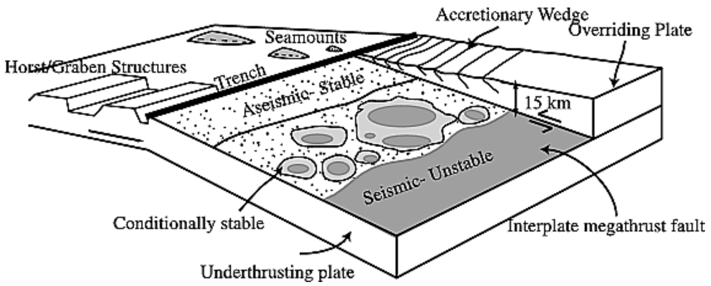
B

Alpine Schist, NZ

C

Carboneras Fault, SE Spain

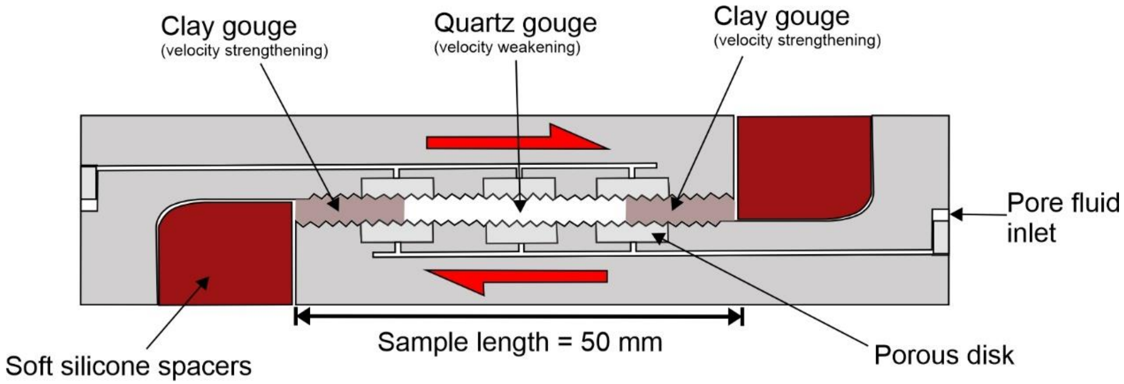
D

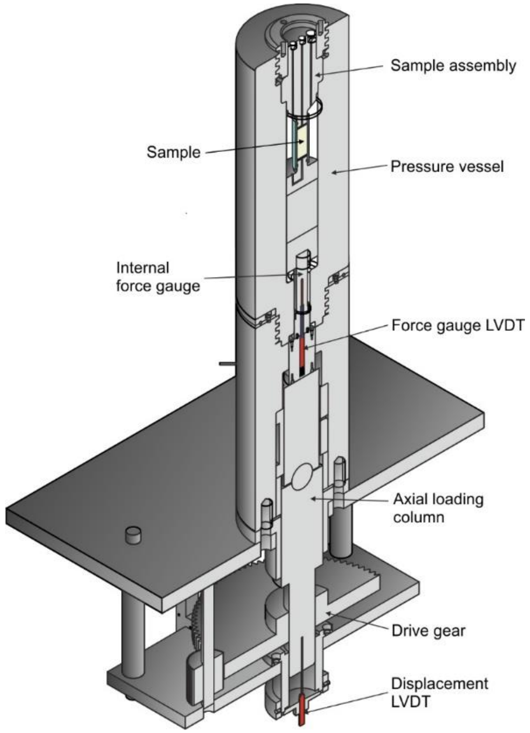


Bilek and Lay (2002)
Geophys. Res. Letters

centimeter-scale — 10's of meter-scale — kilometer-scale →

Methods: How does heterogeneity affect fault strength?



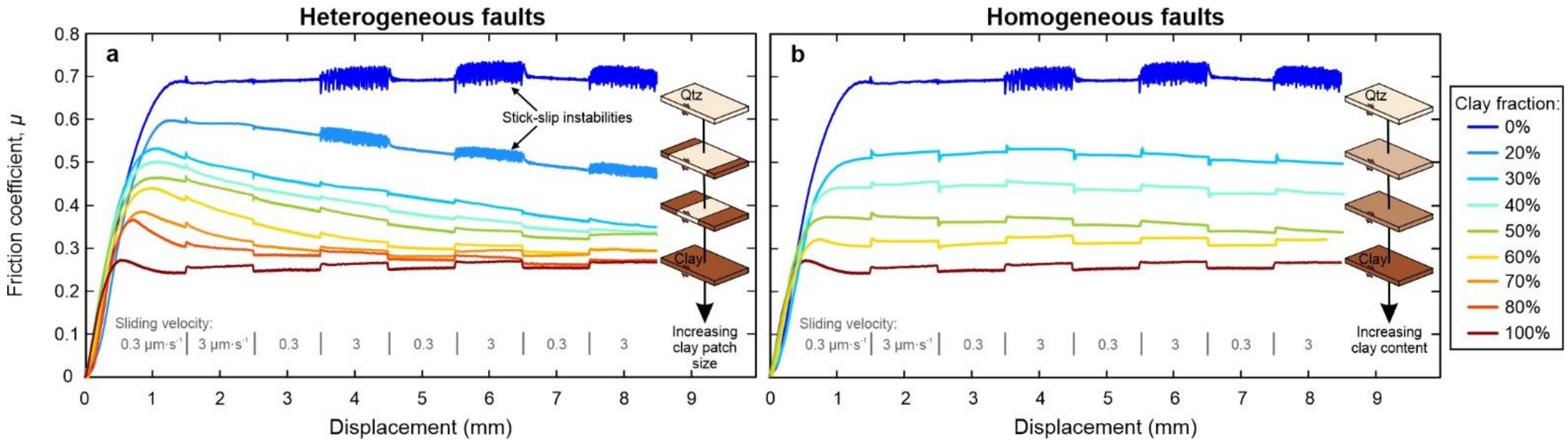


In this study we experimentally investigate the role of heterogeneity on fault strength and stability using a direct-shear arrangement. This is done by placing patches of different fault gouge material adjacent to each other to create a fault layer with a simple heterogeneous structure. The direct-shear assembly is then placed within a triaxial deformation apparatus where the layer is sheared and the frictional properties are measured.

Two different types of fault gouge material are used to create the heterogeneous fault layers: (i) a rate-weakening quartz gouge (5 µm average grain size), and (ii) a rate-strengthening clay gouge (80% kaolinite). The relative size of the clay-quartz patches is varied to investigate how the scale of heterogeneity controls bulk fault behaviour.

The gouge materials are arranged in a symmetrical pattern to negate any effects of differential compaction.

Results: Frictional strength evolution



Experimental conditions:

Confining pressure = 60 MPa

Pore-fluid pressure = 20 MPa

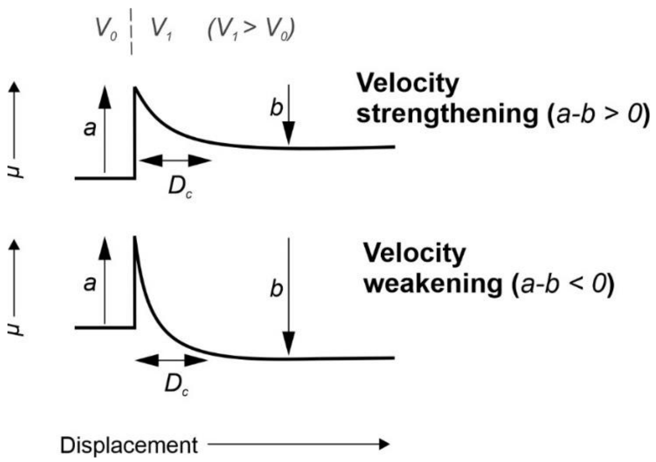
Effective normal stress = 40 MPa

Velocity steps of 0.3 to 3 μm·s^{-1} and back are applied throughout the experiment so that the rate-and state friction parameters can be analysed.

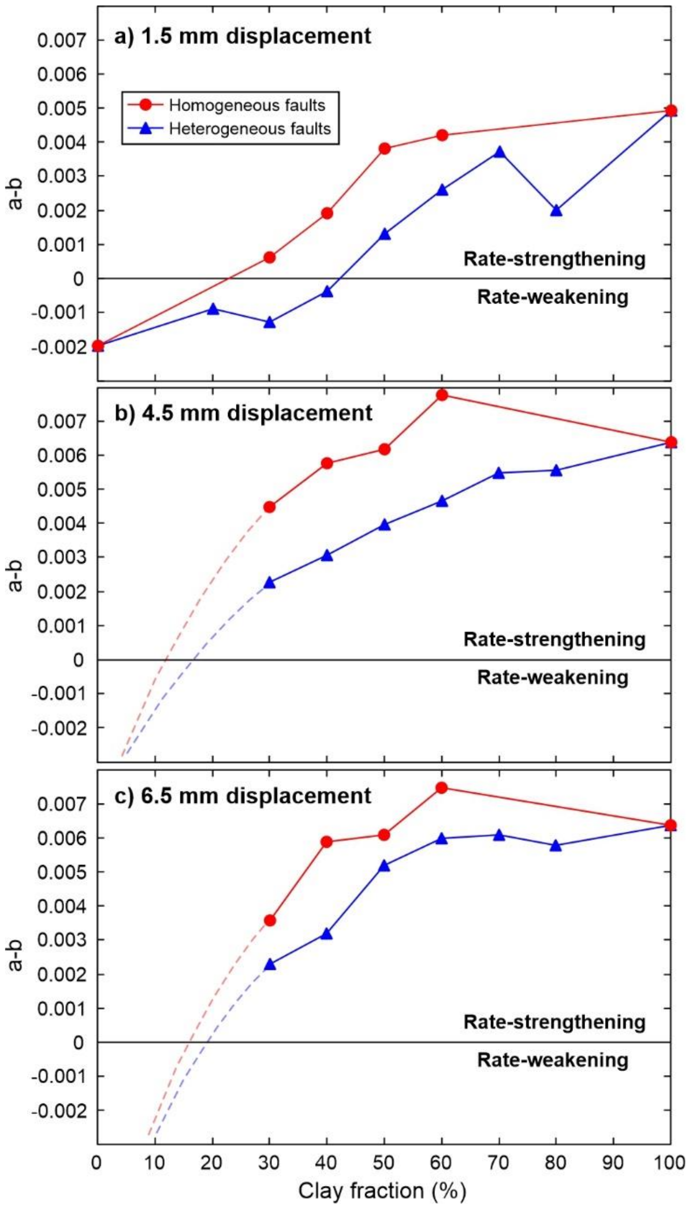
The **heterogeneous gouge layers all show ubiquitous post-yield weakening** (Fig. A), with μ evolving strongly towards the value of the weaker clay phase as displacement is accumulated. In contrast, homogeneously equivalent gouge layers (i.e. where the quartz and clay gouges are mixed together) show minimal post-yield evolution with μ remaining relatively constant as displacement is accumulated (Fig. B).

Stable sliding is observed for all homogeneously mixed faults and the majority of heterogeneous faults. However when the quartz patch in the heterogeneous layers comprises ≥80% of the total sliding area the emergence of unstable stick-slip sliding occurs, typically triggered by up-steps in the sliding velocity (Fig. A).

Results: Rate and state data



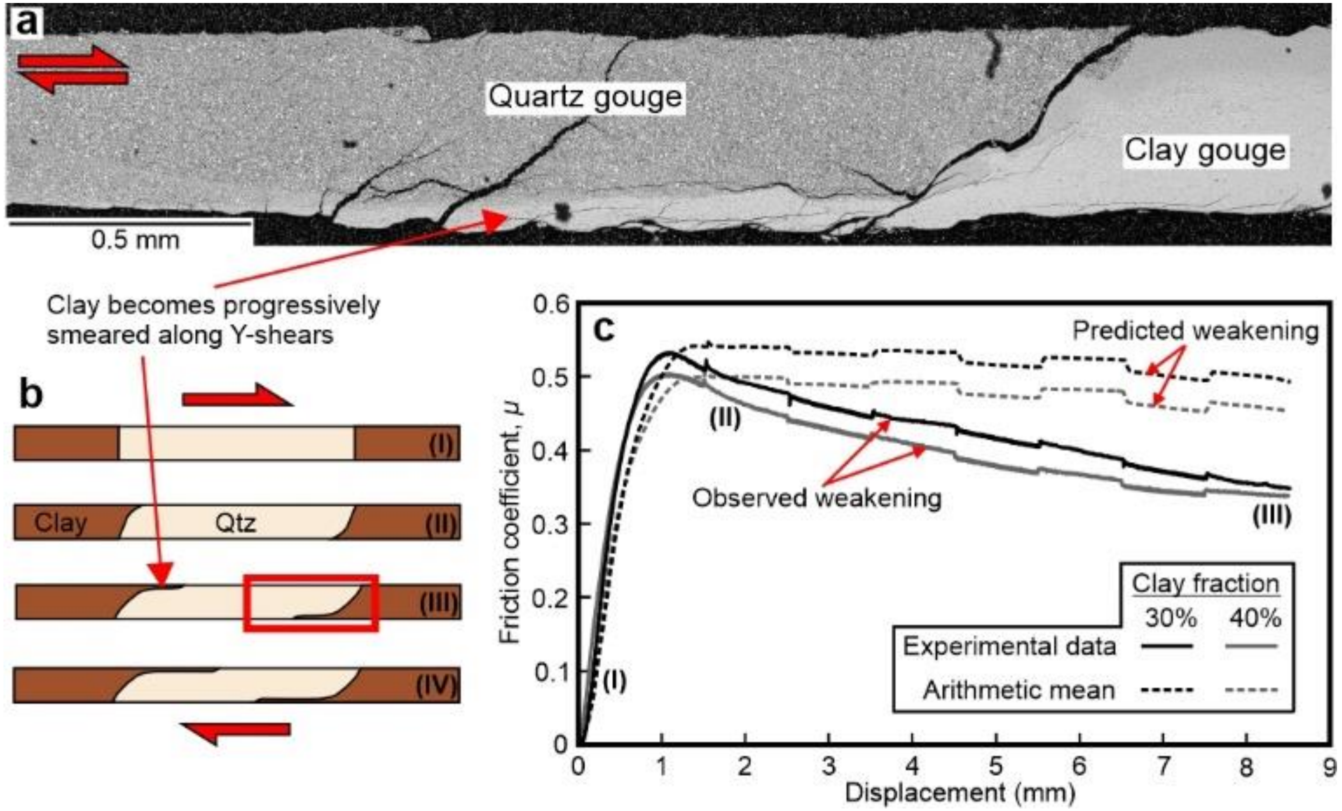
The velocity steps are used to calculate the evolution in the rate-and-state friction parameter a-b, which determines the frictional stability of the fault. When a-b>0 the sliding behaviour is rate-strengthening, suppressing instabilities and promoting stable sliding, whereas when a-b<0 the sliding behaviour is rate-weakening which promotes unstable slip behaviour and the occurrence of stick-slips in the laboratory.



The figure (right) shows how a-b evolves with increasing amounts of displacement as a function of clay fraction for both heterogeneous and homogeneous faults. The results show that a-b is consistently less in heterogeneous faults throughout the experiment, indicating that <u>heterogeneous faults are more unstable than their homogeneous equivalents</u>.

For the pure quartz gouge and the heterogeneous faults where the quartz patch comprises ≥80% of the total sliding area, only the first velocity step can be processed due to the occurrence of stick-slip instabilities triggered by subsequent velocity steps later in the experiment. However this initial velocity step at 1.5 mm displacement does show negative a-b values associated with rate-weakening behaviour, which is consistent with the occurrence of stick-slip instabilities later in the experiment (see figure on previous slide).

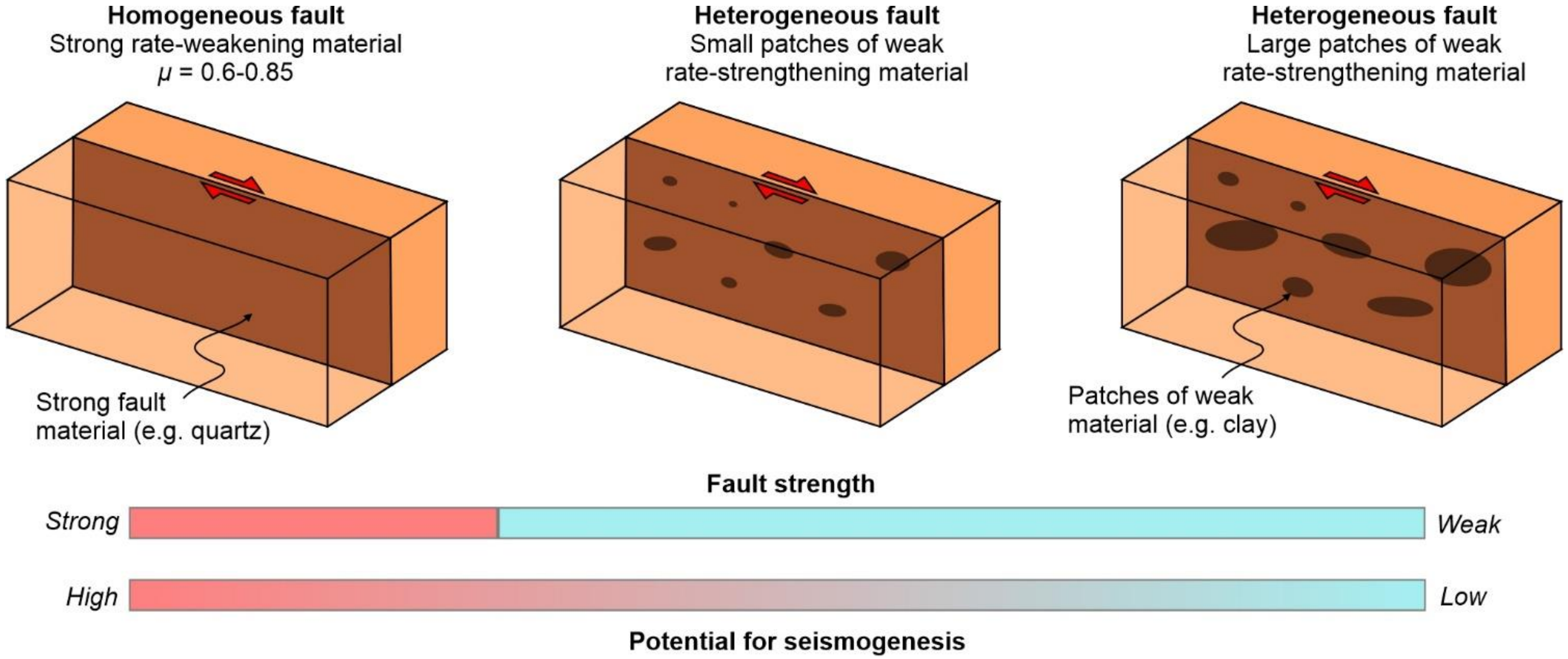
Results: Microstructure and predicted weakening



Microstructural analysis of a heterogeneous layer recovered at the end of an experiment (Fig. A) shows smearing of clay into localized boundary Y-shears that propagate into the quartz patch. With progressive smearing and localization of the clay phase (Fig. B), the strength of the layer overall is expected to decrease as a greater proportion of slip can be accommodated by the weak phase. This predicted weakening is calculated by assuming the overall strength of the layer is determined by the strength of the two gouges acting in series, based on their relative proportions (i.e. the arithmetic mean of μ, based on the relative proportions of clay and quartz within the layer). As shear progresses, the length of the clay patches increases by the amount of displacement on the fault as clay is localized along the Y-shears (Fig. B). However, the predicted weakening is considerably less than the observed weakening in the experiments (Fig. C).

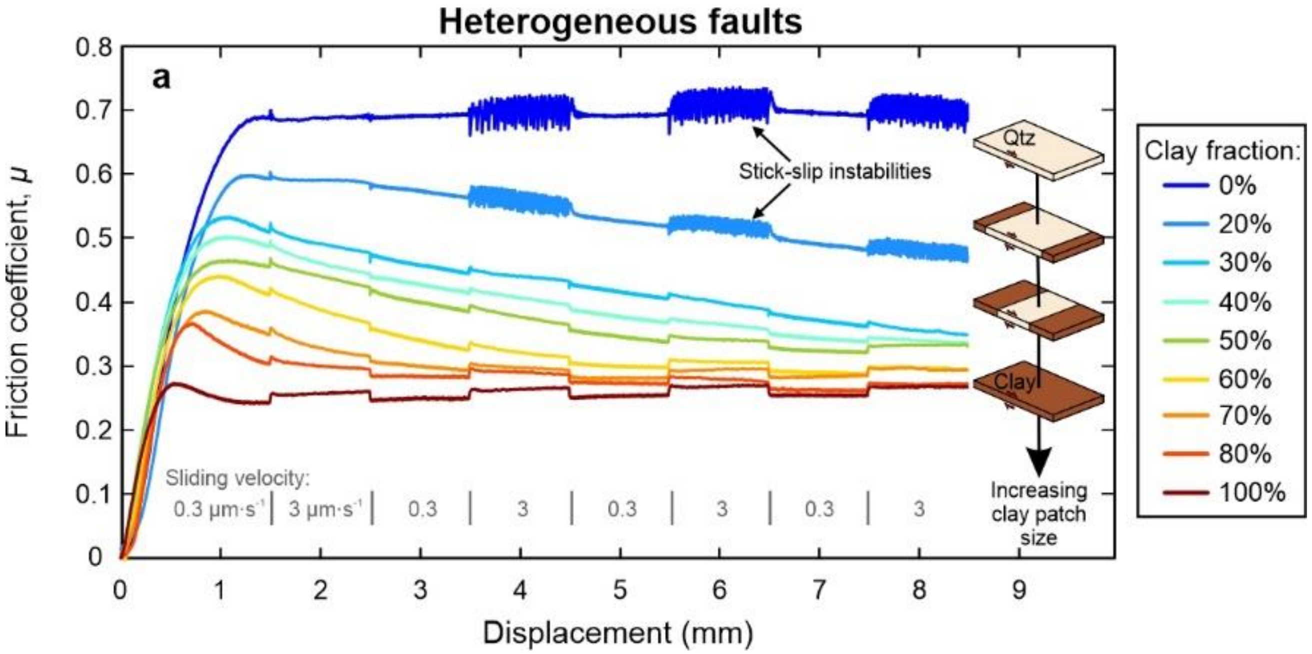
We postulate that the <u>additional weakening results from stress concentrations produced by localization of the weak phase along Y-shear bands</u>. The bulk strength of heterogeneous faults is not just an average of the respective material properties.

Influence of heterogeneity on fault behaviour



The experimental results presented here suggest that heterogeneity produces weak faults, even when the proportion of weak material within the fault core is low. However the relative size of strong and weak patches exerts an important control on the overall fault slip behaviour. When the strong patch comprises <80% of the total fault area then deformation of the weak phase dominates and the fault slips in a stable aseismic fashion. However when the fault comprises ≥80% of the total fault area then unstable stick-slip sliding occurs.

Summary/conclusions



Fault zone heterogeneity leads to fault weakening.

Stress concentrations produced by preferential weak-phase localization lead to enhanced weakening and shear at an overall low stress.

Heterogeneous faults are more unstable than their homogeneous equivalents.

The interplay between the scale of heterogeneity and fault structure will likely control the seismogenic potential of the fault.