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1 **Fault rock heterogeneity can produce fault weakness and reduce fault stability**

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11

12 **Abstract**

13 Geological heterogeneity is abundant in crustal fault zones; however, its role in controlling the
14 mechanical behaviour of faults is poorly constrained. Here, we present laboratory friction experiments
15 on laterally heterogeneous faults, with patches of strong, rate-weakening quartz gouge and weak, rate-
16 strengthening clay gouge. The experiments show that the heterogeneity leads to a significant reduction
17 in strength and frictional stability in comparison to compositionally identical faults with homogeneously
18 mixed gouges. We identify a combination of weakening effects, including smearing of the weak clay;
19 differential compaction of the two gouges redistributing normal stress; and shear localization producing
20 stress concentrations in the strong quartz patches. The results demonstrate that geological heterogeneity
21 and its evolution can have pronounced effects on fault strength and stability and, by extension, on the
22 occurrence of slow-slip transients versus earthquake ruptures and the characteristics of the resulting
23 events, and should be further studied in lab experiments and earthquake source modelling.

24

25

1 **Introduction**

2 Many large crustal faults have been shown to be frictionally weak¹⁻⁶ when compared to
3 laboratory measurements of quasi-static fault friction. The coefficient of friction $\mu = \tau/\overline{\sigma}_n$, where τ is
4 the shear stress during slip and $\overline{\sigma}_n$ is the effective normal stress, of most geological materials is typically
5 measured in the laboratory to be between 0.6-0.85 at slow slip speeds, independent of rock type⁷, with
6 the exception of a few weak minerals, predominantly phyllosilicates^{7,8}. Possible explanations for weak
7 faults in nature, where the apparent μ at which faults operate is often less than 0.5, include localization
8 of weak minerals along structural foliations⁹⁻¹³, dynamic weakening during seismic slip¹⁴, and elevated
9 pore fluid pressure interpreted as lower friction coefficients^{15,16}. As well as being apparently weak,
10 many crustal faults also exhibit a spectrum of slip behaviour, with earthquake slip and aseismic creep
11 often occurring on the same fault^{17,18} and slow slip phenomena being prevalent at all crustal depths¹⁹.
12 While the apparent weakness of faults and spectrum of slip behaviour can be attributed to the effects of
13 spatially varying and temporally evolving confinement, temperature, and pore fluid pressure, it is clear
14 that heterogeneity in fault zone rocks (Fig. 1a) can also play an important^{20,21}, if not dominant, role.

15 Geological investigations have shown that heterogeneity in fault zone rocks occurs over many
16 different scales, from submillimetre-scale structural foliations^{9,10}, centimetre- to meter-scale blocks
17 within a shear zone mélangé²², hundreds-of-meters scale where lenses of damaged protolith can be
18 entrapped within the core of wide (km-scale) fault zones^{23,24} (e.g. Fig. 1a), to tens-of-kilometers scale
19 variations in rock types^{10,25}. The role of large-scale fault rock heterogeneity has been highlighted in a
20 number of studies; for example, it has been suggested that heterogeneities such as seamounts can act as
21 earthquake nucleation sites and control the seismogenic behaviour of subduction zone megathrust
22 faults^{26,27}. However, the importance of small-scale fault rock heterogeneity in controlling fault slip
23 behaviour, average fault strength, and fault stability is still uncertain.

24 Here, the effect of fault rock heterogeneity on fault strength and slip behaviour is investigated
25 by a series of laboratory friction experiments on simulated laterally heterogeneous faults. The faults
26 consist of different sized patches of strong, rate-weakening quartz, and weak, rate-strengthening clay
27 fault gouges. Until now, the majority of experimental investigations have been performed using

1 mixtures of different fault gouge materials with varying frictional properties, where the materials are
2 homogeneously mixed together^{28–31}; intact wafers of natural gouge have also been used^{9,10}. In this work,
3 experiments are performed on both homogeneously mixed and spatially heterogeneous gouge layers
4 consisting of quartz, frictionally strong and rate-weakening, and kaolinite clay powder, frictionally
5 weak and rate-strengthening. The fault gouge layers (50 mm long, 20 mm wide, with a thickness of ~1
6 mm at the onset of shear, after initial pressurization) are sheared in a direct shear arrangement (Fig. 1b,
7 see also Supplementary Fig. 1) within a triaxial deformation apparatus (see Methods). The
8 heterogeneous gouge layers are constructed by placing different sized patches of fine-grained quartz
9 and clay powder (both <5 μm grain size) adjacent to each other in a symmetrical pattern, with a central
10 quartz patch being bound by two clay patches (Fig. 1b). This symmetrical arrangement ensures that no
11 misalignment between the direct shear forcing blocks would occur as a result of any differential
12 compaction between the different materials; furthermore, the amount of gouge material used (measured
13 by weight prior to the experiment) was calculated so that the thickness of the quartz and clay gouges
14 were the same after initial pressurization and a small amount of shear (Supplementary Fig. 2). The
15 normal stress is applied by the confining pressure (P_c) in the triaxial apparatus, held constant at 60 MPa
16 for all tests in this study, and the pore fluid pressure (P_f) within the gouge is servo-controlled at a
17 constant value of 20 MPa, resulting in the effective normal stress $\bar{\sigma}_n = 40$ MPa ($\bar{\sigma}_n = P_c - P_f$). The
18 gouge layers are sheared up to a maximum displacement of 8.5 mm (shear strain ≈ 10 , given the final
19 layer thickness of ~0.85 mm). Monitoring the evolution of shear stress while applying velocity steps
20 from 0.3 to 3 $\mu\text{m}\cdot\text{s}^{-1}$ and back allows the experiments to quantify the rate-and-state friction parameters
21 that determine the stability of fault slip³². These sliding velocities are sufficiently slow, given the gouge
22 permeability, to ensure that pore pressure transients do not build up within the gouge layer during
23 shearing³³. The sizes of the strong yet unstable quartz and weak but stable clay patches are varied to
24 investigate the role of different scales of heterogeneity on the magnitude and stability of fault friction.

25 **Results**

26 The experimental results indicate pronounced differences between the behaviour of laterally
27 heterogeneous faults compared to the laterally homogeneous faults with mixed gouge (Figure 1). All

1 experiments are characterized by an initially rapid increase in shear stress during the loading phase,
2 before the samples clearly yield - i.e., shear inelastically - after approximately 1 mm of displacement.
3 After that, the friction coefficient μ of the homogeneously mixed gouge layers remains relatively
4 constant (Fig. 1d), with rate-and-state effects consistent with results from previous experimental
5 studies²⁹⁻³¹. In contrast, the heterogeneous gouge layers all show ubiquitous weakening (Fig. 1c), with
6 μ evolving towards the value of the weaker clay phase. To ensure that the observed weakening was not
7 caused by the arrangement of the different gouge patches in the experiments, tests were performed
8 where the symmetry of the heterogeneous layers was reversed (i.e., a central clay patch bound by two
9 quartz patches). These tests also exhibit similar weakening (Supplementary Fig. 3) suggesting that it is
10 the heterogeneity itself, not the arrangement of the different materials, that causes the weakening. Stable
11 sliding is observed for all homogeneously mixed faults and the majority of heterogeneous faults.
12 However, when the quartz patch in the heterogeneous layers comprises $\geq 80\%$ of the total sliding area,
13 unstable stick-slip sliding emerges, typically triggered by up-steps in the sliding velocity (Fig. 1c).

14 The observed weakening of the heterogeneous faults is greater than can be explained by the
15 observed smearing of the clay patches. Microstructural analysis of a heterogeneous layer recovered at
16 the end of an experiment (Fig. 2a) shows smearing of clay into localized boundary Y-shears that
17 propagate into the quartz patch. With progressive smearing and localization of the clay phase (Fig. 2b),
18 the strength of the layer overall is expected to decrease as a greater proportion of the slipping surface
19 can be located within the weak clay phase³⁴. As the frictional strength of the endmember gouge
20 compositions is known (i.e. 100% quartz and 100% clay in Fig. 1c), the predicted weakening due to
21 smearing can be calculated (Fig. 2c) by assuming that the overall strength is determined by the strength
22 of the two gouges acting in series, based on their relative proportions (the arithmetic mean of μ , based
23 on the proportions of clay and quartz within the layer). The predicted weakening, associated with the
24 relative increase of the clay patches is considerably less than the observed weakening in the experiments
25 (Fig. 2c), suggesting that clay smearing alone is not responsible for the progressive weakening of
26 heterogeneous faults.

1 An additional cause of the weakening could be differential compaction between the different
2 gouge materials resulting in a redistribution of normal stress (see Supplementary Information for full
3 discussion of this effect). The volumetric strain data from the endmember quartz and clay gouge
4 experiments show that the quartz gouge experiences a greater layer thickness reduction of about 20 μm
5 than the clay gouge during slip (Supplementary Fig. 2). In the heterogeneous layer experiments this
6 would result in an increase of normal stress on the weaker clay patches leading to a progressive
7 reduction in shear resistance, as observed in our experiments. The magnitude of this effect is dependent
8 on the bulk (K) and shear (G) moduli³⁵, which are poorly constrained for the gouge materials in this
9 study. Using plausible values for the moduli (Supplementary Information) indicates that this differential
10 compaction effect could potentially explain a large component of the weakening we observe in our
11 experiments (Fig. 2d).

12 The velocity steps from Figure 1c-d are used to calculate the evolution in the rate-and-state
13 friction^{36–38} parameter ($a - b$), which determines the frictional stability of the fault^{39–41}. When ($a - b$) >
14 0, the sliding behaviour is rate-strengthening, suppressing instabilities and promoting stable sliding,
15 whereas when ($a - b$) < 0, the sliding behaviour is rate-weakening which promotes unstable slip
16 behaviour and the occurrence of stick-slips in the laboratory. The values of ($a - b$) are consistently
17 lower (i.e., less rate-strengthening) in the heterogeneous faults throughout the experiments (Figure 3a-
18 c). This finding indicates that the heterogeneous faults are closer to the potentially unstable, rate-
19 weakening regime than their homogeneous counterparts.

20 For the homogeneous faults with the pure quartz gouge and the heterogeneous faults where the
21 quartz patch comprises $\geq 80\%$ of the total sliding area, only the first velocity step can be used to
22 determine the rate dependence due to the occurrence of stick-slip instabilities triggered by subsequent
23 velocity steps. However, this initial velocity step at 1.5 mm displacement does show negative values of
24 ($a - b$) associated with rate-weakening behaviour (Fig. 3a), which is consistent with the occurrence of
25 stick-slip instabilities later in the experiment. All of the calculated rate-and state friction data are
26 presented in Supplementary Table 1.

27

1 **Discussion**

2 Our experiments show that laterally heterogeneous fault gouge layers weaken significantly in
3 comparison to homogeneous layers, pointing to heterogeneity-induced weakening effects. We
4 hypothesize that the weakening occurs due to a combination of mechanisms, all of which can affect
5 natural faults. The mechanical smearing of the weak phase with slip can reduce the overall shear
6 resistance as shear is likely to localize within the weak phase³⁴, although this mechanism by itself can
7 explain only part of the observed weakening (Fig. 2c, see also Supplementary Fig. 4). Another
8 contributing mechanism can be differential compaction of the weak and strong phases during shear
9 (Supplementary Fig. 2) which would result in a redistribution of normal stress along the shearing layer,
10 with the weaker phase supporting higher normal stresses (see Supplementary Information for further
11 discussion of this effect). The differential compaction can produce significant weakening effects (Fig.
12 2d) but it is poorly constrained, with the conclusions based on end-member tests of pure quartz and clay
13 samples under constant normal stress, highlighting the need to better capture and characterize the
14 compaction/dilation effects in gouge experiments. Finally, additional weakening can be due to shear
15 occurring in the weaker clay gouge that produces stress concentrations along localized Y-shear bands
16 that propagate through the stronger quartz patches leading to enhanced weakening. Similar shear stress
17 concentrations have also been suggested to promote slip events in strong, rate-weakening gouge patches
18 in recent low normal stress experiments on decimeter-scale heterogeneous faults⁴². Due to difficulty
19 keeping the gouge layer intact during recovery at the end of our experiments, we were unable to acquire
20 detailed microstructural images of the tips of the propagating shear bands to look for evidence of
21 shear/damage zones in the quartz patch. We do, however, observe R_1 Riedel shears in the quartz patch
22 (Fig. 2a) which may help facilitate weakening by connecting the smeared clay on opposite sides of the
23 layer.

24 Competency contrasts between strong and weak materials in shear zone mélanges have been
25 suggested previously to be important in controlling the average fault strength and rheology⁴³, with only
26 a small amount of well-connected weak material needed to reduce fault strength when structural
27 foliations are well developed⁹. In our experiments, if the gouge layers could be taken to greater shear

1 displacements, the clay smearing we observe along the edges of the quartz patch (Fig. 2a) would
2 ultimately form a through-going layer of interconnected weak material after a few centimetres of slip.
3 Previous work has shown that such through-going layers can lead to a reduction in the frictional strength
4 at slow slip velocities¹¹ and also increase the efficiency of dynamic weakening at seismic slip velocities
5 (1 m/s)⁴⁴. Although weak phase smearing would, to some extent, homogenize the fault in the overall
6 direction of shear, heterogeneity would likely always be prevalent in natural faults, particularly
7 perpendicular to the slip direction and also at scales larger than investigated in this study, as observed
8 in natural fault zones^{25,45}. Our results show that the average frictional strength of laterally heterogeneous
9 faults is not just an average of the respective friction properties (Fig. 2c), and that competency contrasts
10 can substantially reduce the fault strength, even when structural foliations are in their infancy and
11 unconnected (Fig. 2a). They also highlight the need to investigate further how different types of fault
12 heterogeneity, including fault-parallel and fault-normal heterogeneity, and its evolution, affect the
13 frictional behaviour of faults.

14 Contrasting material properties within fault zones have also been suggested to give rise to
15 mixed fault slip behaviour⁴⁶ and exert an important control on earthquake rupture dynamics^{47,48}.
16 Heterogeneities are also thought to strongly influence the sliding behaviour of other types of frictional
17 interface, such as at the base of glaciers⁴⁹. Our experiments show that heterogeneity produces an overall
18 reduction in stability when compared to homogeneous faults (Fig. 3). It should be noted that a sufficient
19 amount of rate-weakening material is still required to promote unstable slip. In our experiments, when
20 the proportion of the rate-weakening material is $\leq 70\%$, the heterogeneous faults are stable overall, with
21 positive ($a - b$) values, although the values are closer to zero (and hence rate-neutral behaviour) than
22 those of their homogeneous counterparts (Fig. 3); however the behaviour remains rate-strengthening,
23 instabilities do not initiate and aseismic slip prevails. Only when the strong rate-weakening patch
24 comprises $\geq 80\%$ of the layer do stick-slip instabilities occur (Fig. 1c). As shown previously in
25 experimental studies on rate-weakening quartz gouges, microstructural evolution and deformation
26 localization into discrete shear bands is a prerequisite for unstable stick-slip behaviour⁵⁰⁻⁵². Therefore,
27 in the heterogeneous faults, slip behaviour would be dictated by the competing processes of fault

1 stabilization via deformation in weak rate-strengthening materials, versus destabilization caused by
2 localization within the strong rate-weakening patches. When the strong rate-weakening patches are
3 large enough for their internal structure to evolve independently, stick-slip instability may occur.

4 The role of heterogeneity is summarized in Figure 4, where, for a given clay-quartz mixture,
5 heterogeneous faults are weaker and less stable relative to their homogeneous equivalents. Although it
6 is often invoked that large-scale heterogeneities are responsible for the spectrum of slip behaviour
7 observed on natural faults^{17,18}, the results presented here highlight the potential of small-scale
8 heterogeneities, which are also abundant in natural fault zones^{9,10,22}, to exert a significant control on
9 fault zone strength and stability. There are similarities between the slip behaviour we observe in our
10 small-scale heterogeneous experiments and how large-scale heterogeneities are thought to control the
11 behaviour of natural faults. For example, decreasing the size of the rate-weakening patch makes the
12 response more stable in both our experiments and numerical modelling⁵³, as can be intuitively expected
13 and consistent with stability studies of rate-and-state faults that slip instability can only result from large
14 enough rate-weakening patches³⁹. At the same time, small-scale fault zone heterogeneity would more
15 readily evolve with shear, and hence may depend on the fault maturity, healing processes, and spatio-
16 temporal history of fault slip.

17 To summarize, we show that, by introducing a simple heterogeneous structure into a fault zone,
18 the fault strength is substantially reduced and the stability of the experimental fault is overall decreased
19 in comparison to compositionally identical but homogeneously mixed gouges. Our data, along with the
20 abundance and complexity of heterogeneity that occurs over many different scales in nature^{9,10,22–25},
21 suggest that interactions between heterogeneously distributed materials with different frictional
22 properties likely exerts an important control over the mechanical strength and influences whether
23 tectonic faults experience aseismic or earthquake slip. The smaller the scale of heterogeneity, the more
24 likely it is to be intractable in modelling earthquake source processes and hence ignored. These
25 considerations, together with our findings, necessitate further laboratory experiments and modelling to
26 study the effects and evolution of fault rock heterogeneity within complex fault zones, to enable the

1 quantification and inclusion of the smaller-scale heterogeneity effects into larger-scale constitutive laws
2 for modelling fault processes of societal interest, such as nucleation of natural and induced earthquakes.

3

4 **Methods**

5 *Experimental Procedure*

6 The gouge layers are deformed in a direct-shear arrangement (Supplementary Fig. 1) within a
7 triaxial deformation apparatus⁵⁴. The layers (~1.3 mm initial thickness prior to pressurization), prepared
8 in either heterogeneous patches or as a homogeneous quartz-clay mixture, are placed between the direct-
9 shear forcing blocks and soft silicone spacers are positioned at each end so that displacement can be
10 accommodated without supporting any load (Supplementary Fig. 1). To discourage boundary shear at
11 the edges of the gouge layer, the sliding area (50 × 20 mm) on the forcing blocks contains grooves cut
12 perpendicular to the sliding direction (200 μm deep with 400 μm spacing). Once the gouge layer is
13 constructed, the direct-shear arrangement is surrounded by a low-friction polytetrafluoroethylene
14 (PTFE) sleeve (0.25 mm thickness) to minimize jacket friction in the vicinity of the layer, before being
15 placed into a soft, 3 mm thick, PVC jacket (Nalgene 180 clear tubing). The jacketed direct-shear
16 arrangement is then placed in between the platens of the sample assembly which is inserted into the
17 pressure vessel of the triaxial apparatus. In this geometry, the normal stress (σ_n) is applied to the gouge
18 layer by the confining pressure. The pore-fluid pressure is introduced to the layer through three porous
19 disks, embedded in each direct-shear forcing block, which are positioned to ensure an even distribution
20 of pore fluid throughout the layer. Deionized water is used as the pore fluid. Both the confining and
21 pore-fluid pressures are held constant throughout the experiments by servo-controlled pumps on each
22 pressure system, with a resolution better than 0.01 MPa. Linear variable differential transformers
23 (LVDTs) are attached to the pistons of the servo-control pumps, meaning that the volume of fluid
24 expelled from the sample as it compacts during shearing can be monitored as the pressure is held
25 constant. We therefore use the pore pressure pump as a pore volumometer to track the evolution of layer
26 thickness during our experiments (Supplementary Fig. 2); we assume that sliding area remains constant

1 and that all volumetric strain is accommodated by a change in layer thickness. The gouge layers are
2 sheared by the axial piston of the triaxial apparatus and velocity steps are imposed to calculate the rate-
3 and-state friction parameters. The evolution of shear stress is monitored by an internal force gauge
4 within the axial piston, with a measurement resolution of better than 0.05 kN.

5

6 **Data Availability**

7 The associated experimental data files for this research can be accessed in National Geoscience Data
8 Center (NGDC) via the following link:

9 <https://webapps.bgs.ac.uk/services/ngdc/accessions/index.html#item164865>

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- 13

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5

6 **Author contributions**

7 J.D.B and D.R.F developed the main ideas. J.D.B performed the experiments, ran microstructural
8 analyses and produced the initial manuscript. All authors contributed to interpreting the results and
9 editing the manuscript.

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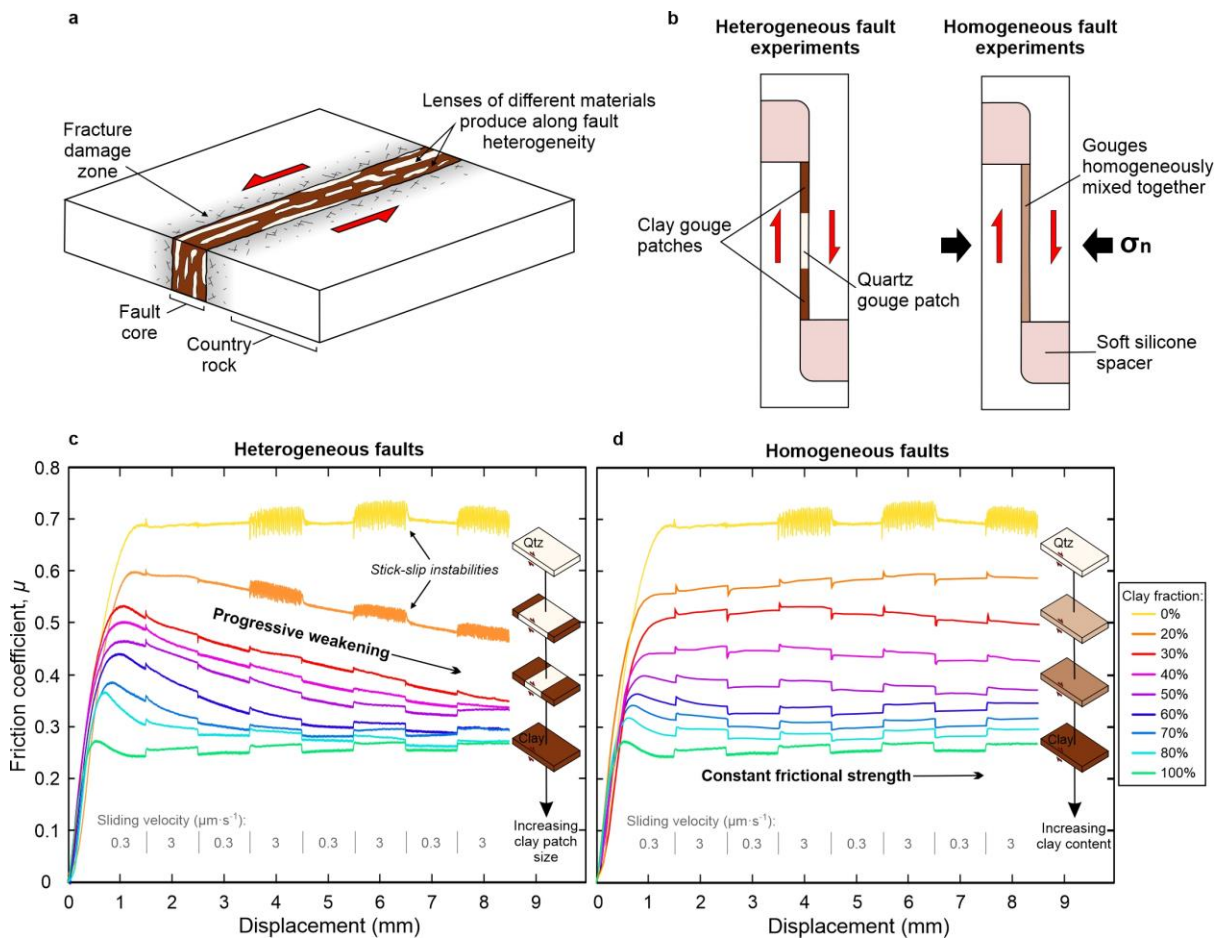
11 **Competing interests**

12 The authors declare no competing interests.

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1

2 **Figure 1| Mechanical behaviour of laterally heterogeneous vs. homogeneously mixed clay-quartz**

3 **fault gouge layers. a,** Schematic diagram of a typical natural fault zone showing how lenses of different

4 materials trapped within the fault core produces a heterogeneous structure. **b,** Simplified diagrams of

5 the experimental setup for the heterogenous fault experiments, where quartz and clay gouges are

6 separated into adjacent patches, and homogenous fault experiments where the two gouges are

7 homogeneously mixed together. **c,** Evolution of the friction coefficient (μ) with displacement for the

8 heterogeneous experimental faults and, **d,** the homogeneous experimental faults. Heterogeneous faults

9 show ubiquitous post-yield weakening with increasing displacement, in contrast to homogeneous faults

10 where μ remains relatively constant once the layer has yielded after approximately 1 mm of slip. For

11 pure quartz and heterogeneous faults where the quartz patch comprises $\geq 80\%$ of the total fault area,

12 stick-slip instabilities occur, triggered by up-steps in the sliding velocity.

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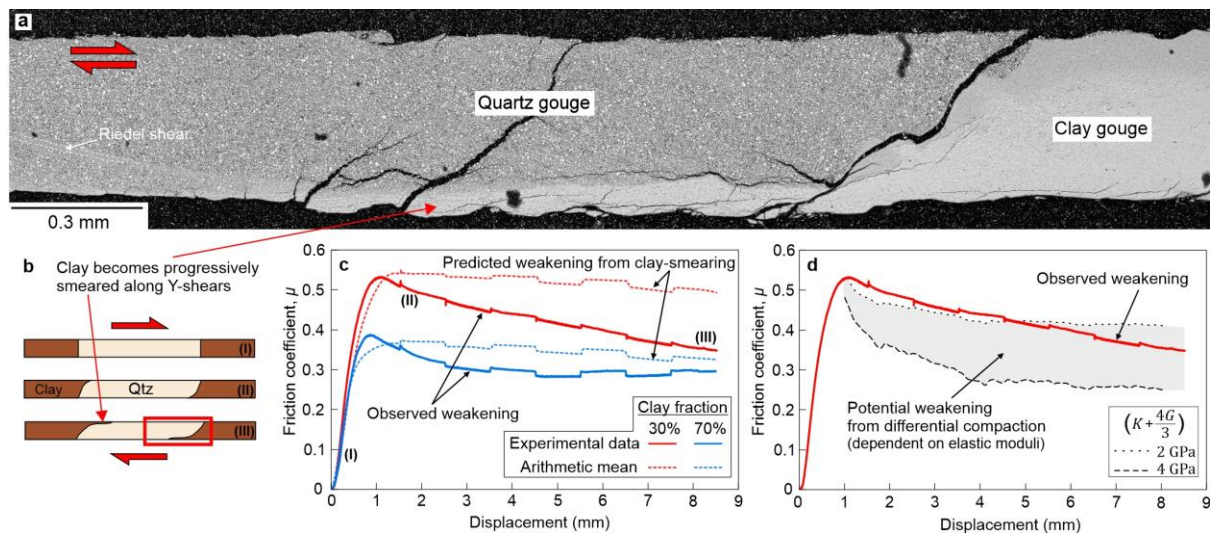
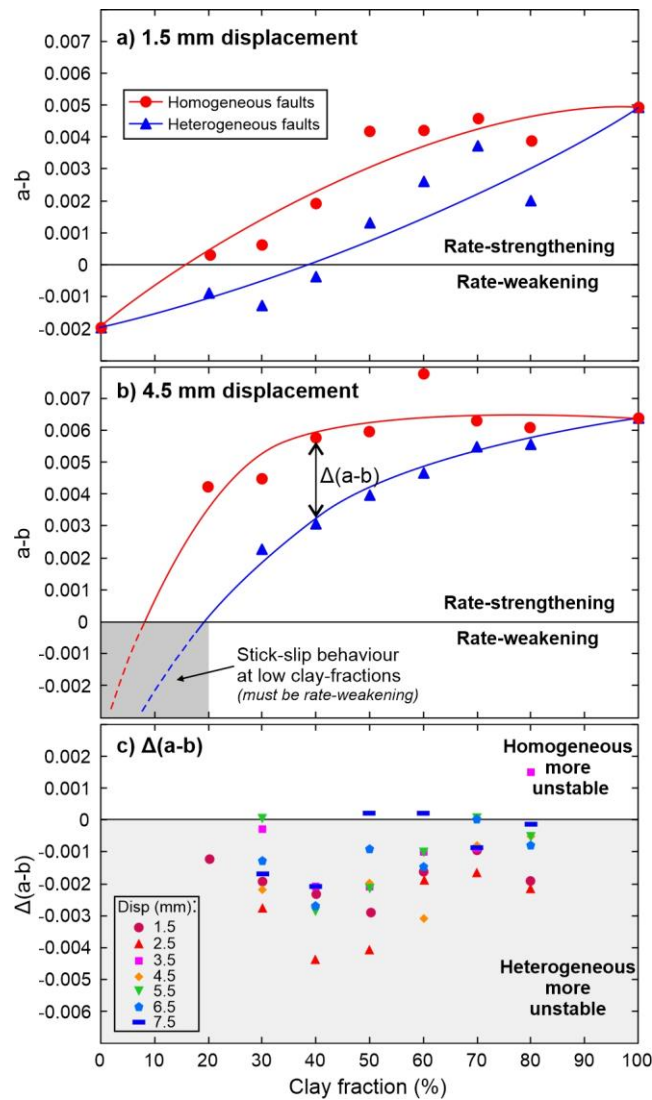
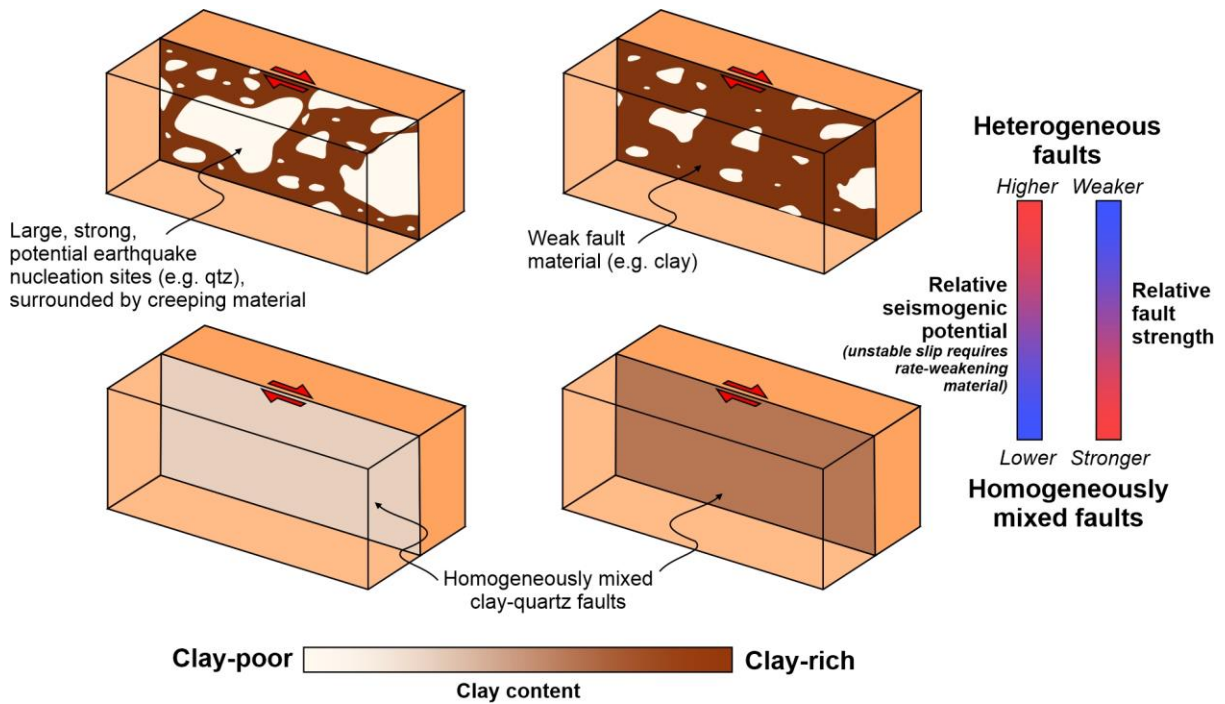


Figure 2| Microstructural evolution and potential causes of weakening in the heterogeneous fault gouge layers. **a**, Backscatter electron image of the interface between a clay-quartz patch recovered at the end of an experiment. The clay phase becomes smeared along a boundary Y-shear plane that propagates into the quartz patch. Since it is difficult to keep the gouge layer intact upon removal from the direct shear assembly at the end of the experiment, the full extent of the localized shear band was not recovered. **b**, Schematic diagram showing the evolution of the fault gouge layers with progressive smearing of the clay phase along localized Y-boundary shears (red box shows the location of the micrograph in **a**). **c**, Observed weakening versus predicted weakening due to clay smearing for heterogeneous layers comprised of 30 and 70% clay fractions. The predicted weakening is calculated using the arithmetic mean of the friction coefficients of the endmember quartz and clay gouges and by assuming that the length of the clay patches increases by the amount of displacement on the fault as clay is smeared along localized Y-shear planes. The observed weakening is considerably greater than the predicted weakening. The labels (I), (II) and (III) correspond to the structural evolution in **b**. **d**, The potential weakening effect from differential compaction between the clay and quartz gouge patches. This effect is dependent on the bulk (K) and shear (G) moduli of the gouge, which are poorly constrained (see Supplementary Information for full discussion). The differential compaction could account for a large component of the weakening in the heterogeneous fault experiments.



1

2 **Figure 3| Evolution of the stability-controlling rate-and-state friction parameter ($a - b$) as a**
 3 **function of clay content for the spatially heterogeneous and homogeneously mixed clay-quartz**
 4 **fault gouge layers. The ($a - b$) values are compared after a. 1.5 mm and b. 4.5 mm displacements, with**
 5 **the heterogeneous faults having consistently lower values than the homogeneous faults. c. The**
 6 **difference in ($a - b$) between the heterogeneous and homogeneous faults, $\Delta(a-b)$, is shown for all**
 7 **velocity steps across the entire displacement range, with the majority of values being negative,**
 8 **highlighting that the heterogeneous faults are less stable than their homogeneous counterparts. Note**
 9 **that, for displacements larger than 1.5 mm, the ($a - b$) values cannot be calculated for the homogeneous**
 10 **quartz fault (i.e., 0% clay fraction) or the heterogeneous fault with a 20% clay fraction, as stick-slip**
 11 **instabilities were triggered by the velocity steps.**



1

2 **Figure 4| Schematic fault model showing the effect of heterogeneity on fault strength and stability.**

3 For a given clay-quartz composition, the introduction of heterogeneity (i.e. the separation of clay and

4 quartz into patches) leads to a reduction in fault strength relative to a homogeneously equivalent fault

5 and also a decrease in stability, increasing the likelihood of seismogenesis on the fault.