The effect of shear strain and shear localization on fault healing

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Abstract

The seismic cycle of repeated earthquake failure requires that faults regain frictional strength during the inter-seismic phase, when the fault is locked or undergoing quasi-static creep. Fault healing plays a central role in determining earthquake stress drop, recurrence interval, elastic radiation frequency and other source parameters. In particular, the longer a fault remains quasi-stationary, the stronger it becomes and the larger the potential stress drop can be for the next event. Here we address the role of shear strain and strain localization on fault healing and healing rate. We performed slide-hold-slide friction experiments on quartz gouge in the double-direct shear configuration for shear strain up to 25 and hold times from 10 to 1000 s. The results show that both healing and healing rate increase non-linearly with increasing shear strain. Frictional healing scales with volumetric strain within the laboratory fault zone. Using the volumetric strain upon reshear as a proxy for strain localization, we demonstrate that the capacity of a fault to heal is directly proportional to shear band width and degree of strain localization. The more the deformation is localized, the higher are the healing and healing rate, and thus, the fault strength. Our data provide a framework for understanding variations in fault strength over the seismic cycle and the role of brecciation and strain localization on spatiotemporal variations in fault strength.

Keywords: Laboratory experiments, Fault healing, Friction, Geomechanics, Earthquake dynamics.

1. Introduction

During an earthquake, faults weaken as they slip and release elastic energy (Scholz, 2019). As slip slows and ultimately ceases, faults regain frictional strength in a phenomenon often referred to as frictional healing. The shear stress necessary to initiate a subsequent earthquake depends on the time, stress state, and thermochemical conditions of frictional healing (Beeler
et al., 1994; Dieterich, 1972, 1978; Frye & Marone, 2002; Karner et al., 1997; Karner & Marone, 2001; Scholz & Engelder, 1976). The longer a fault remains quasi-stationary, the stronger it becomes and the larger is the potential stress drop for the next event (Hampel & Hetzel, 2012; Hillers et al., 2009; Marone et al., 1995; McClaskey et al., 2012).

Fault healing is a crucial parameter in the earthquake cycle, influencing earthquake size, recurrence interval, and elastic radiation frequency (e.g., McClaskey et al., 2012; Scholz et al., 1986). Frictional healing takes place at the atomic scale via mechanical and chemical processes occurring at highly stressed asperities and it can also involve cementation and lithification processes. Frictional contact junctions strengthen logarithmically with time via stress corrosion, indentation-creep and contact welding (Bowden & Tabor, 1964; Dieterich & Kilgore, 1994; Li et al., 2011; Scholz & Engelder, 1976). Under higher temperature and/or in presence of fluid, chemical process such as mineral precipitation (Olsen et al., 1998), recrystallization (Muhuri et al., 2003) and pressure solution (Hickman & Evans, 1991, 1992, 1995; Niemeijer et al., 2008; Scuderi et al., 2014; Yasuhara et al., 2003, 2005) enhance fault healing.

In the laboratory, fault healing has been studied in so-called slide-hold-slide experiments where fault motion is interrupted for specific waiting times to simulate the interseismic period of the seismic cycle. This type of experiment can be performed on bare rock surfaces or simulated fault gouge. Using such experiments, previous studies showed that fault healing depends on the hold time (Dieterich, 1972, 1978; Scholz & Engelder, 1976), the normal stress (Dieterich & Linker, 1992; Linker & Dieterich, 1992; Richardson & Marone, 1999), the shear stress (Karner & Marone, 1998; Nakatani & Mochizuki, 1996), the loading rate (Marone, 1998a), the fault slip rate (Bedford et al., 2023), the temperature (Karner et al., 1997; Olsen et al., 1998; Yasuhara et al., 2005), fault zone minerology (Carpenter et al., 2016; Saffer & Marone, 2003; Seyler et al., 2023) and the presence of water (Bos et al., 2000; Dieterich &
Conrad, 1984; Frye & Marone, 2002; Niemeijer et al., 2008; Scuderi et al., 2014). Typically, slide-hold-slide experiments are performed after sufficient shear displacement has accumulated to produce steady-state friction conditions, which involves factors such as development of a stable shear fabric and particle size distribution (Logan et al., 1992; Marone, 1998a). The role of shear fabric on Coulomb strength and friction is well known (Collettini et al., 2009; Faulkner et al., 2003; Scholz, 2019), however there are relatively few laboratory studies that have documented the role of shear strain on fault healing (Dieterich, 1981; Richardson & Marone, 1999). Existing works show that healing increases with shear displacement, and particularly at small displacement (< 5 mm) when the shear fabric is evolving. For natural faults, depending on the boundary conditions, and the maturity in terms of fabric evolution, faults can exhibit different fabric patterns. Indeed, shear deformation on natural fault can be accommodated on different structures going from ultra-localized shear zones having submillimetre scale thickness (e.g., pseudotachylite; Di Toro et al., 2005) to distributed interconnecting shear zones of pluri-metric scale (Collettini et al., 2019; Fagereng & Beall, 2021; Kirkpatrick et al., 2021; Montési & Zuber, 2002; Morgan & Boettcher, 1999), or even thick large distributed ductile shear zones at greater depth (e.g., mylonite; Lapworth, 1885). The localized and distributed shear deformation can overprint (Behr & Platt, 2011; Marchesini et al., 2019; Prando et al., 2020; Wehrens et al., 2016) revealing complex fault history.

Existing laboratory studies document how fault gouge shear fabric evolves with shear displacement (Beeler et al., 1996; Gu & Wong, 1994; Haines et al., 2013; Logan et al., 1992; Mandl et al., 1977; Marone, 1998a; Scuderi et al., 2017; Yund et al., 1990). At low shear displacement, shear deformation is initially pervasive. When the fault starts to yield, Riedel shears begin to form and develop with increasing displacement. At higher displacement, the Riedel shear bands are omnipresent and connect to form boundary parallel zones (so called Y-
or B-shears). With increasing shear displacement and strain, shear deformation within fault
gouge transitions from distributed to localized (Logan et al., 1992). This transition is
accompanied by changes in fault stability. For distributed deformation, faults are usually
velocity strengthening and are, therefore, intrinsically stable. However, when shear
deformation localizes, frictional sliding evolves toward velocity weakening and potentially
unstable behaviour (Bedford & Faulkner, 2021; Beeler et al., 1996; Marone, 1998a; Noël et
al., 2023; Scuderi et al., 2017, 2020; Urata et al., 2017). The transition to velocity weakening
with increasing shear displacement and shear strain is well known, however there are
relatively few laboratory studies that have measured the corresponding changes in friction
parameters and attempted to identify the physico-chemical processes of fault healing.

The purpose of this paper is to report on laboratory slide-hold-slide experiments designed
to measure variations in fault healing with shear strain for simulated fault gouge composed of
quartz powder. We study shear displacements up to 26 mm (shear strain up to 25) to
characterize the evolution of fault healing with increasing shear strain. Our data constitute the
first systematic study of fault frictional healing evolution with increasing cumulative slip and
provide new insight on fault strength evolution during the interseismic phase.

2. Material and methods

The experiments were performed using a biaxial deformation apparatus (BRAVA,
Collettini et al., 2014), in a double-direct shear (DDS) configuration (Fig. S1 in
supplementary materials). This arrangement allows for independent control of normal and
shear forces on the laboratory faults. We measured forces using load cells mounted close to
the sample with a resolution of 0.03 kN. Normal and shear displacement were measured by
Linear Variable Differential Transformers (LVDTs) attached directly on the loading pistons
with a resolution of 0.01 μm. In the DDS configuration, a central forcing block was moved
vertically (shear direction) between two stationary side blocks. The shear deformation in the
gouge layers was ensured by grooves (0.8-mm height and 2-mm spacing), at the surfaces of
each forcing block, oriented perpendicular to the shear direction. Lateral extrusion
(perpendicular to shear direction) was avoided by metal guide plates attached on the side of
the stationary blocks and thin stretchable rubber around the layers.

Our experiments were performed using simulated fault gouge obtained by grinding
Fontainebleau sandstone (a pure quartz sandstone) and sieving the particles to ensure an initial
grain size lower than 63 μm. Laser granulometry analysis shows that the gouge median grain
size is 15.8 μm (for more details see Noël et al., 2023). The gouge layers were built using a
precision level jig to obtain a uniform and reproducible initial layer thickness of 3 mm over
the sample holder to obtain a 50 × 50 mm fault surface. Additionally, two experiments were
performed with an initial thickness of 8 mm, allowing to measure healing behaviour at lower
shear strain. Prior to each experiment, the gouge samples were dried in an oven at 60°C for at
least 10 hours and cooled down to room temperature for 2 hours. Then, the experiments were
performed under room temperature (∼ 22°C) and humidity conditions (∼ 70%) (Table S1 in
supplementary materials).

After placing the sample into the deformation apparatus, the normal stress ($\sigma_n$) was
increased slowly to 20 MPa and the sample was allowed to compact to a quasi-steady state
(typically for about an hour). We held the normal stress at 20 MPa throughout the
experiments using a fast-acting servo-control mechanism. The shear stress was then increased
by moving the vertical piston downward at 1 μm/s up to 5 kN (= 1 MPa), after which the load
point velocity was set to 5 μm/s. After 1.4 mm of shear displacement (Fig. 1), which
corresponds to a macroscopic shear strain of 0.82, we performed slide-hold-slide (SHS) tests
with 0.2 mm of shear displacement between each hold period. Then, for shear displacements
of 5 to 10 mm, the shear displacement between each hold was raised to 0.5 mm. Finally, from
10 to 26 mm of shear displacement, we imposed 2.5 mm of shear displacement between each hold. We varied the hold time between experiments (from 10 to 1000 s), but used a constant value during each experiment so that we could assess variations in healing as a function of shear strain. During the experiments, mechanical data were recorded at 10 Hz using a 16-bit analogue to digital system. In some tests we also measured elastic wave speed of the fault zone using piezo-electric sensors mounted within the DDS arrangement following the method described in Tinti et al. (2016) (see supplementary materials).

We report mechanical data for one gouge layer of the DDS configuration. The normal stress was computed as the ratio of the normal force $F_n$ to the sample contact area ($\sigma_n = F_n/A$, where $A = 25 \text{ cm}^2$). The shear stress is the ratio of half of the measured shear force $F_s$ for DDS to the sample contact area ($\tau = 0.5 F_s/A$). We derive friction $\mu$ from the ratio of shear stress to normal stress ($\mu = \tau/\sigma_n$) assuming that the Coulomb cohesion parameter is zero. Compaction and dilation were computed as half of the normal piston displacement, corrected from the geometrical thinning considering a rectangular model (Kaproth & Marone, 2014). The macroscopic shear strain was computed by summing the ratio of shear displacement increments divided by the instantaneous corrected layer thickness.

For each SHS test, we computed frictional healing $\Delta \mu_s$, creep relaxation $\Delta \mu_c$, and the friction variation needed to overcome the healed fault $\Delta \mu_b = \Delta \mu + \Delta \mu_c$ (left insert on Fig. 1). From the evolution of the frictional healing as a function of hold time, the frictional healing rate $\beta$ was retrieved as:

$$\Delta \mu = \beta \log_{10}(1 + t_{\text{hold}}/t_c)$$  \hspace{1cm} (1)$$

where $t_{\text{hold}}$ is the hold time and $t_c$ is a regularization term that corresponds to negligible healing (here assumed to be 1 s). Assuming a constant frictional contact area, we computed the volumetric strain by the ratio of the normal displacement (corrected from geometrical...
thinning) with the sample instantaneous layer thickness (right insert on Fig. 1). The variation
of volumetric strain during the hold $\Delta \varepsilon_{\text{vol}}^{\text{hold}}$, and from the onset of shearing to the peak friction
$\Delta \varepsilon_{\text{vol}}^{\text{reshear}}$, was then computed. Note that during hold periods and from the onset of shearing to
the peak friction, the geometrical thinning is null or negligible (i.e., fault zone shear
displacement is negligible), allowing for accurate measurements of volumetric strain. We
adopt the convention that positive volumetric strain indicates compaction and negative
variation indicates dilation.

3. Results

The mechanical data of shear stress vs. shear displacements are very consistent between
experiments (Fig. 1). First, the friction increases quasi linearly with shear displacement. After
a shear displacement of ~ 1 mm, the rate of strengthening decreases and friction reaches a
quasi-steady-state value of $0.610 \pm 0.008$ after ~ 5 mm of shear displacement. Our
experiments typically show a small degree of strain weakening throughout the rest of the
experiment, with final friction values of $0.591 \pm 0.005$ at 25.5 mm of shear displacement.

All the slide-hold-slide sequences show a typical behaviour (insert in Fig. 1). Before the
initiation of the hold, friction is quasi-constant. Then, during the hold phase friction drops
logarithmically over time. After the hold phase, when the gouge is resheared, friction
increases rapidly and reaches a peak. In our experiments, peak friction was always higher than
the initial value, indicating positive values of frictional healing. After the peak, friction decays
with increasing shear displacement (typically over 100 to 150 $\mu$m) and regains the initial
quasi-constant value. Upon reshear, the gouge first dilates rapidly up to peak friction. The
dilation rate is then reduced after the peak while friction decays (insert in Fig. 1). Finally,
fault zone compaction occurs during additional shearing at the quasi-constant friction value.
For the SHS tests, $\Delta \mu$ depends on hold time, shear displacement and macroscopic shear strain (Figs. 2a and b). Longer hold times lead to larger $\Delta \mu$. Indeed, the fault gouge healing shows a large increase over the first 5 mm of shear displacement (and macroscopic shear strain ~3), followed by a slower but continuous increase during additional shear (Fig. 2a). Interestingly, the healing rate $\beta$ also shows a fast increase during the first 5 mm of shear displacement (macroscopic shear strain ~3), followed by a slower increase from 5 to 20 mm of shear displacement (macroscopic shear strain from 3 to 13) to finally reach a plateau at around 20 mm of shear displacement (macroscopic shear strain ~13) (Fig. 2c).

The volumetric strain during hold periods $\Delta \varepsilon_{\text{vol}}^{\text{hold}}$, i.e., compaction, increases with the hold time (Fig. 3) and varies systematically with macroscopic shear strain (Fig. 3a). Fault zone compaction (i.e., positive values of $\Delta \varepsilon_{\text{vol}}^{\text{hold}}$) during healing increases linearly with logarithm of hold time (Fig. 3b), consistent with frictional healing. But the variations in this parameter with shear strain are more complex. It first decreases with shear strain (Fig. 3a) to a minimum value and then increases with additional shear strain. The initial reduction, for shear strains < 3, is associated with net layer compaction and attainment of steady state frictional strength. Note that the magnitude of layer compaction for a given hold time first decreases with increasing shear strain. This is consistent with progressive shear localization because, during shearing, dilation should mainly occur within the shear bands as other areas –so called spectator regions– are relatively inactive and therefore we expect that compaction will be focused primarily within the shear bands. Spectator regions around the shear bands do not dilate and thus compaction there is negligible. Once shear localization has reached a steady state, and shear band thickness reaches a steady state, volumetric strain during holds increases with shear strain because layer thickness continues to decreases via geometric thinning. The minimum values of $\Delta \varepsilon_{\text{vol}}^{\text{hold}}$ occur at shear strains of $3.9 \pm 0.48$ and $2.0 \pm 0.42$ for the two tested initial thicknesses; of 3 and 8 mm, respectively.
We also measured the volumetric strain from the onset of shearing at the end of the hold period to the peak friction $\Delta \varepsilon_{\text{vol}}^{\text{resh}}$ (Fig. 3c). The fault zone dilates during this time and the amount of dilation increases with the logarithm of hold time (Fig. 3d). The magnitude of healing-induced fault dilation decreases with shear strain initially and then reaches a steady state (Fig. 3c). The decrease of dilation with shear strain shows similar variation as the compaction healing (Fig. 3c). Indeed, for all of our tests, $\Delta \varepsilon_{\text{vol}}^{\text{resh}}$ first increased in magnitude up to shear strains of $3.4 \pm 0.4$, after which the values stabilized and the rate of change is much slower.

To summarize, both healing and healing rate increase with net shear strain. While the healing rate seems to reach a plateau after a shear strain $\sim 13$, frictional healing continues to increase with shear strain for the entire range we studied. The variations of healing with shear strain are similar to those of volumetric strain. In particular, $\Delta \varepsilon_{\text{vol}}^{\text{resh}}$ seems to follow the same logarithmical increase with shear strain as fault healing.
Figure 1: Mechanical data for five complete experiments (friction as a function of shear displacement) obtained on quartz gouge having initial thickness of 3 mm. Experiments with hold time from 10 to 1000 s are shown. The insets show zooms of friction and volumetric strain as a function of time for a 100 s SHS test (black dashed rectangle). Left inset shows $\Delta \mu$, $\Delta \mu_c$ and $\Delta \mu_b$. Right inset shows volumetric strain during the hold and reshear, $\Delta \varepsilon_{\text{vol}}^{\text{hold}}$ and $\Delta \varepsilon_{\text{vol}}^{\text{reshear}}$. 
Figure 2: Healing, $\Delta \mu$, data obtained from experiments on quartz gouge with initial thickness of 3 mm and hold times varying from 10 to 1000 s. a) Healing as a function of the macroscopic shear strain. Data from quartz gouge with initial thickness of 3 and 8 mm are presented with the full and open symbols respectively. b) Healing as a function of the hold time for samples of initial thickness of 3 mm. The colour bar represents the macroscopic shear strain. The lines show healing rate $\beta$ obtained as the best fit of the healing data using Equation 1. c) Healing rate $\beta$ as a function of the macroscopic shear strain. The vertical error bars show 95% confidence limits. The horizontal error represents the deviation of shear strain from one experiment to another. The separated data of healing as a function of hold time for the different tested macroscopic shear strain and their fit are presented in the supplementary materials Fig. S9. Additional data plots can be found in the supplementary materials Figs. S2-S8.
Figure 3: a) Volumetric strain variation during hold, $\Delta \varepsilon_{\text{vol}}^{\text{hold}}$, as a function of macroscopic shear strain. b) Volumetric strain variation during hold as a function of hold time. c) Volumetric shear strain variation during reshear (from the end of hold to the peak friction), $\Delta \varepsilon_{\text{vol}}^{\text{reshear}}$, as a function of the macroscopic shear strain. The insert shows a zoom of the data (blue dashed rectangle). d) Volumetric strain variation upon reshear as a function of hold time. For panel a) and c), the colour of the symbols is the hold time. For panel b) and d), the colour is the macroscopic shear strain. Data from quartz gouge having initial thickness of 3 and 8 mm are presented with the full and open symbols, respectively. Note that positive volumetric strain variations indicate compaction and negative variation indicates dilation.

4. Discussion

4.1. Healing evolution with shear strain, volumetric strain and localization

The development of fault zone shear fabric with increasing shear displacement has been the subject of many experimental studies (Bedford & Faulkner, 2021; Beeler et al., 1996; Haines et al., 2013; Logan et al., 1992; Marone, 1998a; Scuderi et al., 2017; Yund et al.,...
For felsic fault gouge, increasing shear displacement and strain cause a transition from distributed to localized deformations, see e.g., Figure 6 of Logan et al. (1992). When the gouge reaches its peak strength, Riedel shear planes (oblique shear bands oriented at about 15° from the macroscopic shear direction) develop and become pervasive with increasing strain. Incipient boundary shear planes (parallel to the shearing direction) then develop at shear strain of ~3-10. With additional shear strain, shear tends to localize into Y-shear planes (Bedford & Faulkner, 2021; Scuderi et al., 2017). For the quartz gouge studied in this work and under the same experimental conditions, Noël et al. (2023) showed similar microstructure development with an evolution from distributed to localized (first Riedel and then boundary planes) deformation with increasing shear strain (see their Figure 10 and 11, for additional information). This transition from distributed to localized deformation also goes along with a transition from velocity strengthening to velocity weakening behaviour (Beeler et al., 1996; Marone, 1998a; Noël et al., 2023).

We observed that the macroscopic shear strain has also a drastic influence on the healing and the healing rate of the simulated quartz gouge (Fig. 2). In addition, fault gouge healing properties are accompanied by variations of volumetric strain during both hold and reshear (Fig. 3). Previous experimental studies showed that upon shearing, or upon an increase in shear velocity, simulated and natural fault gouge experience dilation (Beeler & Tullis, 1997; Marone, 1998a; Marone et al., 1990; Marone & Scholz, 1989; Segall & Rice, 1995). The absolute dilation depends on the normal stress (Samuelson et al., 2009), the shear stress (Karner & Marone, 1998; Nakatani & Mochizuki, 1996), the loading rate (Marone, 1998b), the fault composition (Carpenter et al., 2016), the time of stationary contact (Carpenter et al., 2016; Morrow & Byerlee, 1989; Niemeijer et al., 2008), and the shear displacement (Dieterich, 1981; Richardson & Marone, 1999).
Our experiments were performed on the same initial material and under the same stress conditions; thus, the volumetric strain variations can be used to assess the degree of shear localization within the gouge layer. In particular, we use the dilation upon reshear, $\Delta \varepsilon_{\text{vol}}^{\text{reshear}}$, as a proxy for strain localization (Marone & Kilgore, 1993; Rathbun & Marone, 2010). We posit that from the onset of shear to the peak shear stress, dilation takes place solely in the volume of the gouge that accommodates shear strain. As $\Delta \varepsilon_{\text{vol}}^{\text{reshear}}$ increases (and becomes closer to 0) with increasing shear strain (that is, the dilation upon reshear is smaller and smaller with increasing shear strain), we can infer that the degree of shear localization increases with the macroscopic shear strain. Interestingly, for a constant hold time, the variations in frictional healing as a function of shear strain are linearly proportional to the dilation upon reshear (Fig. 4a). If we normalize $\Delta \varepsilon_{\text{vol}}^{\text{reshear}}$ by the logarithm of the hold time (which is equivalent to plotting as a function of the healing rate $\beta$), it allows us to remove the general trend of the variation of volumetric strain with hold time (Fig. 3). This indicates that the datapoints group together and suggests that healing increases quasi-linearly with $\Delta \varepsilon_{\text{vol}}^{\text{reshear}} / \log(1 + t_{\text{hold}}/t_c)$ (Fig. 4b). This implies that the capacity of a fault to heal, as well as its healing rate, are directly proportional to the volume involved in the shear deformation. The more the deformation is localized, the higher are the healing and healing rate, and thus, the fault strength.

Under the conditions of our experiments, at room temperature, we can assume that fault healing is primarily mechanical and due to particle reorganization and compaction, each of which increase the grain coordination number and fault zone density. In addition, highly stressed contact junctions increase in real contact area and/or quality (Bowden & Tabor, 1964; Dieterich & Kilgore, 1994; Scholz & Engelder, 1976). Thus, an important question is that of why localized deformation enhances healing compared to distributed deformation? Past experiments showed a correlation between compaction and frictional healing (Frye &
Marone, 2002; Richardson & Marone, 1999). Indeed, enhanced compaction caused by normal stress vibration increases fault gouge frictional healing (Richardson & Marone, 1999). Here, compaction of the localized zone during holds may also be the main mechanism involved in healing. Indeed, for localized deformation (i.e., at large macroscopic strain), the shear strain within the gouge layer is heterogeneous, with high shear strain in the localized shear band and low shear strain in the surrounding (Frye & Marone, 2002; Sleep et al., 2000). During a hold phase, compaction occurs mainly in the volume of gouge that is involved in the previous shearing that is, in shear bands. Indeed, spectator regions of the gouge (areas that are not involved in shearing) do not dilate upon reshear and therefore remain quasi static during shearing. At large shear strain, the deformation is localized and only a small volume needs to be re-organized, an efficient grain packing may occur rapidly, leading to efficient healing. On the contrary, for distributed deformations (i.e., at low macroscopic shear strain), the shear strain is relatively homogeneous within the gouge layer. Therefore, during holds, many particles are involved in compaction processes. Such large reorganization implies non-static conditions (i.e., when a grain is moved it also moves the surrounding ones) potentially delaying healing mechanisms. This observation is supported by the compaction during hold $\Delta v_{\text{vol}}^{\text{hold}}$ (Fig. 3a). The first decrease of $\Delta v_{\text{vol}}^{\text{hold}}$ (at shear strain between 0 and 3) shows the transition from distributed to localized shear deformation. Then, when deformation is localized (at shear strain $> 3$), the increase in $\Delta v_{\text{vol}}^{\text{hold}}$ must emerge from: i) gouge thinning at equivalent microstructural shear state (as volumetric strain is computed by the ratio of the normal displacement to the instantaneous layer thickness), and ii) compaction enhancement within the localized shear bands, due to high grain reduction, favouring healing (Marone & Kilgore, 1993). As expected, and also observed by Noël et al. (2023) on the same quartz gouge and under the same experimental boundary conditions, at large shear strain, high grain reduction can be observed in the Riedel shear bands developed in the gouge (Fig. 5a).
Additionally, a higher grain size reduction can also be observed in the boundary shear planes (Fig. 5b), indicating that at large strain, the majority of the deformation is accommodated through boundary shear planes (see also Noël et al. (2023) Figure 10).

Figure 4: a) Healing, $\Delta \mu$, as a function of the volumetric shear strain variation during reshear (from the end of hold to the peak friction), $\Delta \varepsilon_{\text{vol}}^\text{reshear}$, a proxy for shear strain localization. The lines show the best fit of the data for each hold time (indicated on the lines). The full lines are for the experiments with initial gouge thickness of 3 mm. The dashed lines are for the experiments with initial gouge thickness of 8 mm. b) Healing as a function of the shear strain variation during reshear normalized by the hold time. Data from quartz gouge having initial thickness of 3 and 8 mm are presented. The legend and the colour bar are valid for both plots. Note that the first hold is not represented as it is often of scale (see Fig. 3).

4.2. Relationship between healing rate, $\beta$, and rate-and-state evolution parameter, $b$

In this section, we try to make a link between the healing rate, $\beta$, that is a parameter measured under quasi-static conditions, and the evolution parameter of the rate-and-state, $b$, a parameter commonly measured during velocity step experiments. Indeed, both parameters are linked to the population of asperities involved in the sliding surface, or volume. In the case of bare rock surface, healing has been shown, historically, to be directly linked to the real
contact area, and thus the asperity size that increases with the logarithm of time (Bowden & Tabor, 1964; Dieterich & Kilgore, 1994; Frye & Marone, 2002; Marone & Saffer, 2015; Rabinowicz, 1951; Scholz & Engelder, 1976). Recently, nanoscale chemical bond formation at the fault interface has also been suggested as an additional mechanism for fault healing (Bedford et al., 2023; Bhattacharya et al., 2022; Li et al., 2011; Thom et al., 2018). The healing rate, $\beta$, thus depends on the growth rate and the quality change of asperity contact junctions. For gouge samples, similar observation show that the contact area involved in the healing processes depends on shear localization and shear fabric development (see paragraph 4.1, Fig. 4). Under dynamic conditions, and when sliding at a steady-state and at constant velocity, the average life time of contacting asperity is constant (Dieterich, 1979). When the fault is subject to a change in sliding velocity ($V$) the population of contacts is renewed over a characteristic slip distance (Rabinowicz, 1951). In the rate-and-state framework (Dieterich, 1978; Ruina, 1983), the variation of steady-state sliding friction due to a velocity change is proportional to the difference between a direct effect, $a$, and an evolution effect, $b$: $\frac{\partial \mu_{ss}}{\partial \ln V} = (a - b)$.

In the case of long hold times, it is clear that the healing rate $\beta$ scales with the friction parameter $b$ (Beeler et al., 1994). However, only rare experimental studies have compared healing or healing rate data with rate-and-state parameters retrieved from velocity step experiments (Marone, 1998a; Marone & Saffer, 2015). Interestingly, Noël et al., 2023, performed velocity step experiments on the same simulated quartz gouge and under the same experimental conditions. They demonstrate that the rate-and-state parameter ($a-b$) evolves with shear displacement, and that this evolution emerges from the increase of the evolution parameter, $b$, while $a$ remains constant. The increase of $b$ with shear displacement was inferred to emerge from shear strain localization. The comparison of the healing rate, $\beta$, with the evolution parameter $b$, shows the same evolution with the macroscopic shear strain (Fig. 4).
In addition to their similar evolution, their absolute values are very close. Note that past studies (Beeler et al., 1994; Marone & Saffer, 2015) found a better similarity between $\beta$ and $b$ when $b$ is inverted using the ageing law (Dieterich, 1978) rather than the slip law (Ruina, 1983). In Fig. 5, the plotted $b$ values were obtained by inverting laboratory data using the slip law, but the inversion using the ageing law gives equivalent values. This implies that, under the tested conditions, the micromechanisms involved in both parameters could be equivalent, and that this mechanism depends on strain localization. In our experiments, the healing mechanisms that are influenced by shear strain localization are primarily mechanical, and due to particle comminution, reorganization and compaction, which increase the local shear band density and volumetric grain contacts.
Figure 5: a) and b) Post-mortem micrograph acquired after a velocity step experiment on the same material and under the same experimental boundary condition for a macroscopic strain of 20.5 showing a large view with the Riedel shear planes (a) and a zoom on a boundary shear plane showing high grain...
reduction (b). c) Healing rate, $\beta$, obtained from slide-hold-slide experiments (this study) and evolution effect, $b$, obtained from velocity step experiments (Noël et al., 2023) as a function of macroscopic shear strain for quartz gouge made of Fontainebleau sandstone with initial thickness of 3 mm. The velocity steps were inverted using Ruina (slip) law (Ruina, 1983). Note that the data inverted from Dieterich (ageing) law are equivalent. The symbols represent different upstep velocity from 30 to 300 $\mu$m/s and are compared to $\beta$ obtained here at a sliding velocity of 3 $\mu$m/s. d) Schematics showing the principal microstructural states experienced by the gouge with increasing shear strain. For a more complete view of the quartz gouge microstructural development with increasing shear strain see Bedford & Faulkner (2021); Marone & Scholz, (1989); Scuderi et al. (2017).

5. Conclusion

We conducted biaxial experiments on simulated quartz gouge, at 20 MPa of normal stress, and up to high macroscopic shear strain (> 26) to measure the influence of shear strain and localization on fault healing. The results show that both healing and healing rate increase non-linearly with increasing macroscopic shear strain. This increase is accompanied with volumetric strain variations within the simulated gouge sample. Using the volumetric strain variations upon reshear as a proxy for strain localization, we demonstrate that the capacity of a fault to heal is directly proportional to the volume involved in the shear deformation. The more the deformation is localized, the higher are the healing and healing rate, and thus, the fault strength. This result implies that fault strength can be highly influenced by strain localization and that natural fault strength vary over time and space.

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Data availability
Raw data can be found at https://zenodo.org/record/8297726.

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