The Role of Grain Size and Effective Normal Stress on Localization and the Frictional Stability of Simulated Quartz Gouge

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Abstract For earthquakes to occur on tectonic faults deformation localizes onto discrete slip surfaces within the gouge material of the fault core. Here, we investigate how localization is promoted in quartz gouge, a material known to exhibit unstable stick-slip behavior, by assessing the role of grain size and effective normal stress (\(\sigma_n\)) on microstructural evolution and frictional behavior. We observe stable sliding, slow-slip instability, and stick-slip with increasing displacement. We find that initially fine-grained gouge and high \(\sigma_n\) promote unstable stick-slip behavior, whereas slow-slip is more prevalent at low \(\sigma_n\). Microstructural analyses of the sheared gouges show that stick-slip behavior occurs after localization of deformation on to discrete Y-shears, which undergo a significant cataclastic grain size reduction relative to the bulk of the gouge, a process enhanced by high \(\sigma_n\). Our results show that localization and instability are promoted by high effective normal stress and small grain size.

Plain Language Summary Understanding the frictional properties of the abraded fine powder (gouge) sandwiched into a tectonic fault is key to understanding the nature of fault slip. The majority of fault slip, whether it occurs in abrupt earthquake events, slow slip transients or via continuous aseismic creep, is accommodated by shearing of this powdery gouge rather than rock-on-rock friction. In this study, we perform friction experiments on quartz gouge to investigate what properties of the gouge promote the occurrence of stick-slip events, the laboratory equivalent of an earthquake. We find that in order for stick-slip to occur the deformation must localize on to discrete planes within the gouge itself. This process of localization is promoted by fine-grained gouge and a high normal stress (how much the fault is pushed together by rock on either side), as in order to localize efficiently the material within the discrete planes undergoes a significant grain size reduction via mechanical grinding, a process that is enhanced under high normal stress.

1. Introduction

In recent decades, much focus has been placed on understanding the internal structure of large-displacement tectonic fault zones and how it relates to the mechanical, hydraulic and seismic properties of the fault. Typically, brittle fault zones consist of a narrow (<1 m) fault core, or wider region comprising multiple fault cores, surrounded by a damage zone of fractured country rock (Chester & Logan, 1986; Chester et al., 1993; Faulkner et al., 2003, 2010; Mitchell & Faulkner, 2009; Sibson, 2003). The fault core, where the majority of slip occurs, consists of high-strain gouge material formed by progressive frictional wear of the country rock. Strain within the fault core can be distributed throughout the gouge layer (e.g., Faulkner et al., 2003; Rutter et al., 1986) or localized onto discrete slip surfaces within the layer itself (e.g., Chester et al., 1993; Chester & Logan, 1986). Laboratory experiments have shown that shear localization within the gouge is a prerequisite for unstable stick-slip behavior (Gu & Wong, 1994; Leclère et al., 2016; Logan et al., 1992; Scuderi et al., 2013, 2017). Understanding the properties of fault gouge that promote localization and stick-slip behavior is, therefore, important for gaining insights into the earthquake behavior of large seismogenic faults.

Many laboratory investigations into the frictional behavior of fault gouge at slow slip speeds (<1 mm/s) have focused on the stability of frictional sliding using a rate-and-state framework (Dieterich, 1979; Marone, 1998; Ruina, 1983). It has been shown that minerals which strengthen when slip velocity is increased, such as most clay minerals, exhibit stable sliding (Collettini et al., 2019; Ikari et al., 2009; Morrow et al., 2017; Saffer & Marone, 2003), whereas those that weaken with increasing velocity, such as quartz, undergo...
stick-slip sliding (Gu & Wong, 1994; Leeman et al., 2016; Scuderi et al., 2017). As well as rate-weakening behavior, the stiffness of the loading system is important in determining whether stick-slip sliding occurs (Leeman et al., 2015, 2016). The stiffness dictates how the system unloads with slip; if the fault weakens with slip more rapidly than the system unloads, then acceleration occurs, resulting in unstable sliding. Systems which are more compliant (i.e., less stiff) promote stick-slip behavior (Leeman et al., 2015).

One further mode of fault slip that occurs both in nature and experiments is slow-slip (Bürgmann, 2018). Slow-slip events (SSEs) occur when slip rate increases above the driving rate but is prevented from accelerating to typical earthquake slip rates (between 1 and 10 m/s). The reasons for the occurrence of SSEs are widely debated but have been suggested to be related to frictional transitions with increasing velocity and slip (Ikari et al., 2013), dilatancy hardening (Segall et al., 2010), constrained nucleation due to some combination of system properties (Dal Zilio et al., 2020; Leeman et al., 2016; Rubin, 2011), or a heterogeneous distribution of structural and frictional properties (Avouac, 2015; Barnes et al., 2020; Thomas et al., 2014). Temporal changes in fault slip behavior also occur, with SSEs sometimes preceding large earthquakes (Kato et al., 2012; Radiguet et al., 2016). In experiments, slow-slip is seen with increasing displacement, as the frictional properties evolve (Scuderi et al., 2017), or as the stiffness of the system is tuned to favor a slip mode between stable sliding and stick-slip instability (Leeman et al., 2015, 2016; Scuderi et al., 2016).

There have been many previous experimental studies on quartz-feldspathic gouges, including at hydrothermal conditions where the kinetics of dissolution-precipitation processes strongly affects the frictional behavior (Giger et al., 2008; Kanagawa et al., 2000). At low temperatures, quartz gouges typically show a transition from rate-strengthening to rate-weakening behavior and from stable to stick-slip sliding with fault slip (Biegel et al., 1989; Leeman et al., 2016; Scuderi et al., 2017). This is associated with the development of shear localization in the gouge as strain is accumulated (Scuderi et al., 2017). However, in experiments where frictional wear also occurs (i.e., when rock forcing blocks are used), re-stabilization of the gouge at high shear strains (γ > 15) has been observed as more material is incorporated into the layer (Wong et al., 1992), causing the frictional behavior to transition back to rate-strengthening (Beeler et al., 1996) and stable sliding (Gu & Wong, 1994; Wong et al., 1992). Therefore, the frictional evolution and stability of gouge layers can be controlled by both internal processes, such as localization in the layer, and external processes, such as incorporation of new material via wear of the country rock (or forcing blocks in experiments).

Here, we investigate the internal evolution of simulated quartz gouges by analyzing the effect of initial grain size and effective normal stress (σn) on localization and sliding behavior. It has been shown previously that within localized shear bands the grain size is significantly reduced compared to the bulk of the gouge (Marone & Scholz, 1989; Scuderi et al., 2017; Smith et al., 2015), suggesting that grain size must be an important parameter in controlling localization behavior. However, to our knowledge, the role of grain size in determining the onset of localization and unstable behavior has not previously been determined. We therefore perform a suite of experiments on simulated quartz gouges with three different initial grain sizes and document their microstructural evolution with slip behavior. Experiments are performed under controlled effective normal stress conditions of up to 120 MPa, which are representative of stresses that brittle faults experience in the crust, and also significantly higher than most previous low temperature experimental studies on quartz friction (e.g., Leeman et al., 2016; Scuderi et al., 2017).

2. Materials and Methods

2.1. Starting Materials

The starting materials are quartz powders from the US Silica MIN-U-SIL range (99.5% SiO2). These powders were chosen to simulate fault gouge as their fine grain size promotes a transition from stable to unstable frictional sliding within shear strains that can be achieved in our experimental setup. We test the frictional properties of three different size fractions of quartz powder, which we herein refer to as 5, 15 and 30 µm quartz gouge, respectively. These sizes are actually the maximum grain sizes of the different powders, the median grain sizes D(50) are 1.9, 4.3, and 8.5 µm, respectively (Table S1). The grain size distributions were provided by the manufacturer and are shown in Figure S1.
2.2. Experimental Apparatus and Procedure

The gouges are deformed at ambient temperature in a direct-shear arrangement (Figure 1a) within a triaxial deformation apparatus (see Faulkner & Armitage, 2013). A gouge layer, measured by weight to give an initial thickness of 1.5 mm, is placed between the steel direct-shear forcing blocks and soft silicone spacers are positioned at each end to allow displacement to be accommodated without supporting any load (Figure 1a). The sliding area (36 × 20 mm) on the forcing blocks contains grooves perpendicular to the shear direction (200 µm deep with a 400 µm spacing) to ensure that deformation occurs within the gouge layer and not between the forcing blocks and the edges of the layer. Once assembled the direct-shear assembly is wrapped by a low friction PTFE sleeve (0.25 mm thickness) and inserted into a 3 mm thick PVC jacket. The PTFE sleeve minimizes friction between the forcing blocks and the jacket in the vicinity of the layer.

Figure 1. (a) Schematic diagram of the direct-shear arrangement used in the experiments (platen diameter is 20 mm). (b) Mechanical data from the friction experiments on the 5 µm, (c) 15 µm, and (d) 30 µm grain size quartz gouges sheared under different effective normal stresses. All experiments reach steady-state sliding after approximately 1.5 mm displacement, before the emergence of SSEs and/or stick-slip instabilities after approximately 3.5 mm in some tests (see main text). Insets (i)–(iv) show close-ups of the different styles of unstable sliding (discussed in main text). Stops 1–3 show where some repeat tests were stopped early and the samples recovered for microstructural analysis (see Figure 2). SSE, slow slip event.
is placed between the platens of the sample assembly and inserted into the pressure vessel of the triaxial rig. Normal stress is applied by the confining pressure ($P_c$), and pore-fluid pressure ($P_f$) is introduced to the sample through three porous disks on each forcing block, spaced to ensure pore-fluid pressure is evenly distributed (Figure 1a). Deionized water was used as the pore fluid and held at a constant pressure of 20 MPa for all experiments in this study. The gouge is sheared by the axial piston of the triaxial apparatus at a constant displacement rate of 1 µm/s throughout the experiments. The evolution of shear stress is monitored by an internal force gauge, with a measurement resolution better than 0.05 kN, while the effective normal stress ($\sigma_n = P_c - P_f$) is held constant by servo-controlled pumps, with a resolution better than 0.1 MPa, on both the confining and pore pressure systems. Experimental data were logged at a frequency of 1 Hz.

The frictional response of the different quartz gouges was tested over a range of $\sigma_n$, from 40 to 120 MPa (e.g., when $\sigma_n = 120$ MPa, $P_c = 140$ MPa, and $P_f = 20$ MPa). The maximum displacement that can be achieved with this setup is 6 mm (16.7% of the total layer length of 36 mm), which equates to a shear strain ($\gamma$) of ~7, given the final layer thickness of ~0.85 mm and once the elastic distortion of the loading system has been accounted for (machine stiffness = 90 kN/mm). As outlined in the results section, some of the coarser grained gouge samples sheared at low $\sigma_n$ (≤80 MPa) did not exhibit unstable stick-slip behavior after this amount of strain. Therefore to test whether these gouges would experience stick-slip if more strain was accumulated, another set of longer direct-shear forcing blocks (sliding area = 50 × 20 mm) were used that allow a maximum displacement of 8.5 mm ($\gamma = 10$). However these longer forcing blocks could not be used when $\sigma_n$ ≥ 100 MPa, as the larger sliding area requires greater axial loads to be applied, which can cause the blocks themselves to experience inelastic deformation and bend during loading.

2.3. Microstructural Analysis

Upon removal from the deformation apparatus the gouge is recovered for post-mortem analysis. Before removal from the jacket the length of the direct-shear assembly is measured and is found to be consistent with the shortening values measured by the loading column, suggesting there is negligible effect of any backsliding caused by elastic relaxation of the silicone spacers or PVC jacket which could disturb the microstructure. The jacket is then carefully cut off the assembly and the direct-shear forcing blocks are separated to reveal the sheared gouge layer. Although initially loose powders, by the end of the experiment the gouges have enough cohesion to form a wafer that can be prepared for microstructural analysis. These wafers are carefully lifted off the experimental assembly and left to dry in a desiccator for 24 h before being vacuum impregnated with low viscosity epoxy resin. The samples are then cut perpendicular to the shear plane and parallel to the transport direction, before this surface is re-impregnated with resin and polished for SEM analyses. Backscatter electron images (BSE) were acquired using a Philips XL30 tungsten filament SEM and a JEOL JSM-6500F FE-SEM using an accelerating voltage of 20 kV and a beam current of 3 nA at a working distance of 13 mm. To investigate the progressive microstructural evolution of the gouge layers, repeat tests were performed and stopped at different displacements, the samples were then prepared for microstructural analysis. These displacements were chosen to correspond to just after yielding of the gouge layer and the onset of stick-slip sliding (see Section 3.2).

As well as BSE imaging, some of the localized slip surfaces within the gouge were analyzed using secondary electron (SE) imaging. As outlined in the results section, the quartz gouge ultimately localizes deformation onto fault-parallel boundary Y-shear planes. Upon disassembly at the end of an experiment, the gouge layers often separate along these localized slip surfaces. Therefore, to analyze these surfaces in more detail, some samples were not impregnated with epoxy resin, rather the gouge layers were prepared for SE imaging by adhering them to a glass slide before gold coating the surface. SE images were collected using a JSM-7001F Schottky Emission SEM using an acceleration voltage of 10 kV at a working distance of 10 mm.

3. Results

3.1. Mechanical Data

The mechanical data for the different grain size gouges are presented in Figures 1b–1d. All tests show initial elastic loading followed by yielding and the initiation of steady-state sliding after ~1–1.5 mm of load point displacement. Steady-state sliding continues until, in some tests, the emergence of instabilities occurs.
Instabilities occur either as fast dynamic stick-slip events, accompanied by audible energy radiation, or as slower silent stress drops (with durations >1 s), which we herein refer to as SSEs. The emergence of instabilities, and the type of instability (i.e., stick-slip, SSE or a mixture of both), is dependent on both the initial grain size of the gouge and $\sigma_n$.

For the 5 µm gouge, the onset of instability initiates after about 3–4 mm displacement, independent of $\sigma_n$ (Figure 1b). For tests where $\sigma_n \geq 60$ MPa the majority of instabilities are audible stick-slips, although some small SSEs (~0.5 MPa magnitude) occur at the transition between stable and unstable sliding (Figure 1b, inset (i)). When $\sigma_n = 40$ MPa, there is a prolonged period of SSE’s (Figure 1b, inset (ii)), although the instabilities transition into audible stick-slips after ~5 mm of displacement. The magnitude of the stress drops during stick-slip increases with $\sigma_n$, from ~1 to 1.5 MPa at $\sigma_n = 40$ MPa, to 7–8 MPa at $\sigma_n = 100$ MPa, above which the magnitude no longer increases. Note, however, that the relative magnitude of the stress drops appears to be largely independent of $\sigma_n$ (~6–10% of the steady-state shear stress).

For the 15 µm gouge, when $\sigma_n \geq 80$ MPa, the transition from stable to unstable sliding occurs at ~3–4 mm displacement (Figure 1c), similar to the 5 µm gouge. At lower $\sigma_n$, more displacement is required to initiate unstable sliding (~5 mm when $\sigma_n = 60$ MPa, and ~7.5 mm when $\sigma_n = 40$ MPa), thus the longer direct-shear forcing blocks were used for these tests (see Section 2). Again, at the lowest effective normal stress of 40 MPa, the majority of instabilities are SSEs, with complex long-period modulation and transient amplitude variations of the stress drops also observed (Figure 1c, inset (iii)). When $\sigma_n \geq 60$ MPa the majority of instabilities are audible stick-slips with the magnitude of the stress drop increasing with $\sigma_n$.

The 30 µm gouge is predominantly stable under the range of test conditions, with only the experiments at 100 and 120 MPa effective normal stress experiencing instabilities after ~4.5 mm displacement (Figure 1d). These instabilities are a mixture of SSEs and audible stick-slips with complex long-period amplitude modulation (Figure 1d, inset (iv)). All other 30 µm experiments ($\sigma_n \leq 80$ MPa) exhibited stable steady-state sliding for the entirety of the experiment, even when the longer direct-shear forcing blocks were used to achieve greater displacements.

### 3.2. Microstructural Evolution

The microstructural evolution through the transition from stable to unstable sliding was investigated by performing repeat tests on the 15 µm gouge (where $\sigma_n = 80$ MPa) and stopping after different amounts of displacement (labeled on Figure 1c). After yielding and the initiation of steady-state sliding (Stop 1 on Figure 1c) pervasive $R_1$ Riedel shears cross-cut the gouge layer with ~0.4 mm spacing between each shear band (Figures 2a and 2b), corresponding to the spacing of the grooves on the direct-shear forcing blocks. As displacement continues toward the transition between stable and unstable sliding (Stop 2 in Figure 1c), $R_1$ Riedel shears become less prominent and incipient B-shears are observed (B-shears are finite localized zones parallel to the shear direction) (Figures 2c and 2d). It is difficult to ascertain whether $R_1$ Riedel shears actually become less prominent or whether they become too difficult to distinguish at higher strains due to poor contrast between the $R_1$ Riedel shears and the bulk of the gouge as the monomineralic quartz becomes more comminuted. We are confident that the incipient B-shears in Figure 2b are real shear bands and not unloading features as, by the end of the experiment (Stop 3 on Figure 1c), after multiple stick-slip instabilities have occurred, these B-shears along the boundaries of the gouge layer become the prominent microstructural feature (Figures 2e and 2f). Within the B-shears, the gouge is highly comminuted and the grain size is significantly reduced relative to the bulk of the gouge outside the localized band. Deformation within these B-shears is also further localized onto discrete planes (Y-shears) hosted within the main shear bands (inset of Figure 2f). The thickness of the B-shears for the 15 µm gouge is ~30–40 µm, whereas for the 5 µm gouge deformed under the same $\sigma_n$ the B-shears are less prominent (Figure S2) with a thickness of ~4–6 µm. However, it should be noted that the absolute thickness cannot be constrained as some of the layer may have broken off upon removal from the direct-shear assembly at the end of the experiment. For the 30 µm gouge deformed under an effective normal stress of 120 MPa (where instabilities occurred), B-shears with thicknesses >100 µm are observed at the end of the experiment (Figure S2), suggesting that wider localized zones form in coarser grained gouges. A schematic summary of the microstructural evolution of...
quartz gouge layers, from predominantly R1 Riedel shears at yield, to predominantly B-shears containing localized Y-shear planes at the end of the experiment, is shown in Figure 2g.

As shown in the BSE images, the deformation within the B-shears can be localized onto discrete Y-shear planes (inset of Figure 2f). Occasionally, upon removal from the direct-shear assembly at the end of the experiment, the gouge layer separates along these discrete planes revealing a surface with striations running parallel to the shear direction. To analyze further, these surfaces were imaged using SE (see Section 2). The surfaces were also analyzed to look for any microstructural features, such as frictional melt that has been observed in many bare surface experiments (e.g., Harbord et al., 2017; Hayward et al., 2016; Passelègue et al., 2016), that might explain why the peak-strength between stick-slip events reaches greater levels than the steady-state strength (Figure 1b, inset (i)). The SE images reveal the striated surfaces in more detail (Figure 3a), with no evidence of frictional melt observed on the surfaces. Instead the images highlight the highly comminuted and very fine grain size of the gouge that comprises these planes (Figures 3b and 3c), with the majority of the grains on the order of 50–500 nm in diameter with an angular morphology (Figure 3c).

4. Discussion

4.1. The Role of Grain Size and Normal Stress on Frictional Stability

The mechanical results in Figure 1 show that the onset of unstable sliding in quartz gouge is promoted by a fine initial grain size and high $\sigma_n$. This is highlighted by comparing the behavior of the $5 \mu m$ gouge, which exhibited unstable sliding over the entire range of $\sigma_n$, to the $30 \mu m$ gouge, which only underwent unstable
sliding at $\bar{\sigma}_n \geq 100$ MPa. However, we hypothesize that if the gouge layers could be taken to greater shear strains, beyond those permitted by our experimental setup, then the 30 µm gouge would also exhibit unstable sliding over the entire effective normal stress range of this study. This is supported by the high-strain gouge experiments of Beeler et al. (1996) who observed increasingly rate-weakening behavior in granite gouge up to displacements of 40 mm (equivalent to $\gamma \approx 40$ in their setup). The requirement for greater shear strain when deforming at low $\bar{\sigma}_n$ can be seen in the mechanical data for the 15 µm gouge (mid-size fraction tested in this study), where at $\bar{\sigma}_n \leq 60$ MPa, greater displacements are required to initiate unstable sliding than samples deformed above this value (Figure 1c).

The transition into stick-slip behavior is associated with the occurrence of SSEs. Similar slow stress drops have been observed previously in experiments at the transition between stable and unstable sliding (Leeman et al., 2016; Scuderi et al., 2016) and in nature SSEs sometimes precede large earthquakes (e.g., Kato et al., 2012; Radiguet et al., 2016). The transitional region is also associated with complex long-period modulation and transient amplitude variations of the stress drops (Figure 1, insets (iii) and (iv)), which have been observed previously in experiments (Leeman et al., 2016; Scuderi et al., 2016) and are predicted by theory (Gu et al., 1984). This transitional behavior of SSEs and chaotic sliding is more prolonged at low $\bar{\sigma}_n$, whereas at high $\bar{\sigma}_n$ the sliding behavior evolves more efficiently into repetitive stick-slips (Figure 1b, inset (i)). These findings therefore suggest that SSEs in nature may be promoted by low $\bar{\sigma}_n$, which is supported by evidence of SSEs occurring on natural faults when the pore-fluid pressure approaches lithostatic pressure (Kodaira et al., 2004; Warren-Smith et al., 2019), from induced SSEs caused by fluid injection (Duboeuf et al., 2017; Guglielmi et al., 2015) and from theoretical predictions of SSEs at low $\bar{\sigma}_n$ (Liu & Rice, 2007).

The early onset and efficient transition into unstable stick-slip sliding at high $\bar{\sigma}_n$ also promoted by a fine initial grain size, is a reflection of microstructural evolution of the gouge and its ability to localize deformation into discrete shear bands within the layer. The microstructural images in Figure 2 show that the onset of unstable sliding is associated with the development of localized Y-shear planes within B-shear zones in the gouge. Previous studies have shown similar evolution in gouge microstructure during the transition from stable to unstable sliding (Gu & Wong, 1994; Logan et al., 1992; Scuderi et al., 2017), although it should be noted that the ratio between the stiffness of the loading system and the critical rheological stiffness of the gouge ultimately determines whether stable, slow- or stick-slip occurs on these localized features (Scuderi et al., 2017; Tinti et al., 2016). The grain size within the localized B-shears is significantly reduced in comparison to the bulk of the gouge in the layer (Figures 2e, 2f, and 3), suggesting that grain size reduction helps facilitate localization and promote stick-slip sliding. The deformation is further localized within these B-shears onto discrete Y-shear planes (Figures 2e, 2f, and 3), which likely host the stick-slip ruptures that occur in the experiments. The process of grain size reduction and comminution will be more enhanced at high $\bar{\sigma}_n$ and the reduced grain size within the localized B-shears will be achieved more efficiently if the gouge already has an initially fine grain size, evidenced by the narrower B-shears that occur at finer grain
sizes (Figure S2). Therefore, the mechanical data in Figure 1, where the onset of stick-slip is achieved at lower shear displacements for fine grain gouges and at high $\bar{\sigma}_n$, is a result of the gouge being able to localize more easily under these conditions.

### 4.2. Implications for Fault Zone Evolution

In our experiments, the microstructural evolution of the gouge layer is internal, such that any changes to the structure (i.e., localization in to shear bands) are a result of changes in the properties of the gouge itself, in this case cataclastic grain size reduction during shearing, as no material was added to the layer from external sources. However, in nature the incorporation of new gouge material into the fault core via frictional wear of the country rock can be an important process (Hirose et al., 2012; Scholz, 1987), producing wide fault zones (e.g., Faulkner et al., 2003) and potentially stabilizing the fault (Wong et al., 1992). Despite this, the existence of narrow gouge layers in some high displacement fault zones, such as the Punchbowl Fault in California (Chester & Logan, 1986), suggests that frictional wear does not always play a significant role in fault evolution. This is particularly likely for faults hosted in strong quartzo-feldspathic rocks, as the formation of the fault (i.e., a plane of weakness) results in a significant mechanical strength contrast between the host rock and the main fault zone (Faulkner et al., 2008), meaning that further deformation will be preferentially accommodated by the fault as continued frictional wear of the host rock becomes unfavorable, notwithstanding any thermal effects or fault roughness. In this case, any evolution of the fault zone structure will likely be internal, like in our experiments, or by alteration from circulating hydrothermal fluids.

The SE images in Figure 3 show a lack of melt on the surfaces of the Y-shear planes, and instead highly comminuted nanograins are present. Previous work using TEM analyses has shown that some amorphous material can form at the boundaries of these nanograins (see supplementary material of Scuderi et al., 2017), however, this is not a prominent feature of high-strain zones (De Paola et al., 2015; Scuderi et al., 2017). The lack of melt or any other features that may lead to enhanced re-strengthening between stick-slip events suggests that less energy is dissipated on these localized slip planes in comparison to bare-surface friction experiments, where melt is commonly observed under similar normal stresses (e.g., Habord et al., 2017; Hayward et al., 2016; Passelègue et al., 2016). This could be due to aqueous pore fluids in our experiments dissipating heat more efficiently than dry bare surface experiments, or because gouges are granular materials and the localized Y-shears have a finite thickness meaning some of the slip is accommodated away from the localized slip plane during rupture. The formation of wider localized zones with increasing gouge grain size (Figure S2), and production of new surface area associated with grain-size reduction within these zones, may therefore have important implications for the energy balance during earthquake rupture (e.g., Chester et al., 2005). The development of nanograins within the fault core can also have important implications for evolution of fault zone behavior and structure. For example in carbonate-hosted faults it has been suggested the formation of nanograins within localized shear bands can influence fault rheology and promote a switch to viscous grain-size sensitive deformation mechanisms at coseismic slip rates (Demurtas et al., 2019; De Paola et al., 2015; Pozzi et al., 2019). The increased surface area of the gouge caused by mechanical grain size reduction will strongly promote chemical processes in the fault zone such as hydrothermal alteration (Bruhn et al., 1994; Callahan et al., 2019), grain growth (Sammis & Ben-Zion, 2008) and lithification (Angevine et al., 1982; Karner et al., 1997; Tenthorey & Cox, 2006), which can significantly change the mechanical evolution of the fault, as shown by experiments under hydrothermal conditions (Giger et al., 2008; Kanagawa et al., 2000). However, regardless of any subsequent evolution in fault zone properties caused by the development of nanograins, which may not be preserved over the timescales of earthquake recurrence, our results show that grain size reduction is an important process in facilitating localization that is required to promote unstable stick-slip behavior.

### 5. Conclusions

Our results show that localization within gouge layers is important for unstable stick-slip behavior to occur and is promoted by a fine-grained starting material and high $\bar{\sigma}_n$. The grain size of the material in the localized B-shear bands within the gouge layer is significantly reduced by mechanical crushing and cataclasis during shearing. This process is facilitated more efficiently at high $\bar{\sigma}_n$ and when the starting material has...
a fine initial grain size. The transition from stable to unstable sliding in quartz gouge is associated with complex amplitude modulation of the stress drops and the occurrence of SSEs, which are more prominent at low \(\sigma_n\). These findings are important for understanding how fault zones evolve in nature and to identify the properties of fault materials that may lead to unstable seismic slip.

Data Availability Statement

The data reported in the figures can be accessed in National Geoscience Data Center (NGDC) data repository: https://webapps.bgs.ac.uk/services/ngdc/accessions/index.html#item137431.

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