Lab earthquakes in rock gouge: dynamic triggering and rapid weakening

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Summary paragraph:

Large and destructive earthquakes on mature faults in the Earth’s crust occur as slip in a layer of fine granular material – fault gouge - produced by comminution during sliding (Scholtz, 2019). Frictional resistance of the fault is one of the main factors controlling earthquake nucleation, dynamic propagation, and arrest, and hence the destructive ground shaking of earthquakes (Kanamori and Brodsky, 2004; Scholtz, 2019). The response of the gouge layer to slip has mostly been studied in experiments with uniform slip imposed in relatively small samples. Here, we present laboratory experiments that feature spontaneously developing sequences of dynamic ruptures in fine fault gouge as found in cores of mature faults (Scholtz, 2019). The ruptures are resolved in space and time by recently developed high-speed diagnostics. The experimental findings reveal highly complex slip processes and dynamic triggering of earthquake nucleation by transient seismic waves, consistent with observations of instantaneous dynamic triggering in natural faults (Gomberg and Johnson, *Nature*, 2005; Antonioli et al., 2006; Tape et al., 2013). The dynamic triggering is enabled by pronounced rapid frictional weakening consistent with flash heating (Rice, 2006; Beeler et al., 2008; Goldsby and Tullis, 2011; Tullis, 2015) which results in small nucleation sizes; significant re-strengthening occurs upon slip slow-down. Both weakening and healing occur over slip scales of tens of microns in the rock gouge, values much smaller than in most experiments but consistent with theories of flash heating. Our results indicate that dynamic triggering may be promoted by rapid, enhanced weakening of fault gouge, which would otherwise behave as a barrier to dynamic rupture. This provides experimental support to the concept that dynamic weakening may enable rupture to break through stable, creeping fault regions (Noda and Lapusta, 2013), that would not be expected to host large dynamic ruptures.
Introduction

Characterizing the evolution of dynamic slip processes and rock friction during fault slip in the Earth’s crust is a fundamental step to enhance our understanding of earthquake physics, as friction controls key aspects of earthquakes, including nucleation, shear stress drop and magnitude (Kanamori and Brodsky, 2004; Scholtz, 2019), and as a result how damaging they can be. In the last forty years, we have come a long way from the notion of friction coefficient as a single number characterizing an interface (Byerlee, 1978). Frictional strength is required to weaken for earthquakes to nucleate and propagate, as indicated by theoretical and numerical studies, but how friction evolves and what variables control its evolution are topics of current research (Dieterich, 2007; Ben-David et al., 2010; Goldsby and Tullis, 2011; Di Toro et al., 2011; Ikari et al., 2011; Brown and Fialko, 2012; Scuderi et al., 2014; Collettini et al., 2019).

Earthquakes propagate along localized zones in thin layers of gouge, the fine-grain rock powder present in natural faults that results from wear along the slipping surfaces (e.g., Chester and Chester, 1998; Reches and Lockner, 2010, Scholtz, 2019). Laboratory experiments on gouge and several types of bare rock have shown that frictional instabilities depend on the rate of slip and its history, as described by the rate-and-state friction laws (Dieterich, 2007); these laws adequately describe friction at aseismic slip rates of 1 to 100s of μm s⁻¹ (Marone, 1998). At seismic slip rates of ~ 1 m s⁻¹, several friction weakening mechanisms have been proposed, including flash heating, shear melting, thermal pressurization of pore fluids, and elastohydrodynamic, nanoparticle, or silica gel lubrication (Tsutsumi and Shimamoto, 1998; Goldsby and Tullis, 2002; Di Toro et al., 2004; Brodsky and Kanamori, 2004 Rice, 2006; Di
In this study, we document rapid and dramatic friction changes over short slip distances along rock gouge interfaces in laboratory experiments mimicking earthquake sequences in mature faults. These changes result in earthquake triggering by seismic stress waves as observed on natural faults (Hill and Prejean, 2015). An increasing body of evidence indicates that earthquakes can be triggered by dynamic stress changes (Das and Scholtz, 1981; Harris, 1998; Freed, 2005; Gomberg et al., 2004; Steacy et al., 2005; Gomberg and Johnson, *Nature*, 2005; Antonioli et al., 2006; Velasco et al., *Nature Geoscience*, 2008; Tape et al., 2013; Cattania et al., 2017; Sleep 2019 JGR, Li et al., GRL, 2019). Many observations, however, refer to remote triggering of earthquakes occurring with a distinct delay with respect to the primary event and on a different fault, often making the causal link not straightforward. Our experiments provide clear evidence of dynamic triggering occurring on the same timescales as the stress perturbation, allowing for clear connection to be drawn. Furthermore, a plausible explanation of our findings is that dynamic triggering is enabled by rapid, dynamic weakening of fault gouge which otherwise would serve as a barrier to dynamic rupture, lending experimental support to the idea that dynamic weakening can help rupture break through stable, creeping rupture segments (Noda and Lapusta, 2013).
Laboratory earthquakes along gouge interfaces

To better understand the evolution of friction in natural faults and to study earthquake triggering by transient stress transfer, we produce and analyze sequences of laboratory earthquakes along rock gouge interfaces (Fig. 1). The sequences of spontaneously propagating dynamic ruptures are produced in our laboratory setup developed to mimic the main features of faults in the Earth’s crust (see section “Laboratory earthquakes along rock gouge interfaces” in Methods). Dynamic ruptures in rock gouge are produced by employing a hybrid configuration featuring a quartz gouge fault embedded along the interface of a polymeric specimen, made of Homalite-100. The combination of quartz gouge and Homalite allows us to retain the advantage of producing dynamic ruptures offered by smaller instability lengthscales due to bulk Homalite properties (Rubino et al., 2017) while permitting us to study a realistic fault rheology (Supplementary Information). This is an important advantage as it allows us to observe well-developed ruptures within a specimen size of tens of centimeters instead of meters, as would be required for rocks (Dieterich, 1981; Okubo and Dieterich, 1984; Beeler, 2012; McLaskey and Kilgore, 2013; McLaskey et al., 2014) (Supplementary Information). We employ fine-grained quartz powder (5 microns in diameter, see Methods), to simulate fine gouge along the principal slipping zones of mature faults (Chester et al., 2005, 2006; Rice, 2006). Previous versions of this setup featuring dynamic ruptures along Homalite interfaces, without gouge, have been successfully used to investigate a number of fundamental issues in earthquake physics, including sub-Rayleigh to supershear transition, rupture directionality due to bimaterial effect, pulse-like to crack-like transition, and the possibility that thrust faults might open (Xia et al., 2004; 2005; Lu et al., 2007; Gabuchian et al., 2017; Rubino et al., 2017; Rubino et al. 2020, Rosakis et al 2020).
Our dynamic imaging technique clearly captures the complex full-field behavior of ruptures propagating through the gouge interface (Figs. 1b and 1c), while simultaneously tracking the slip history of rupture sequences (Figs. 2a and 2b), and the friction evolution along the fault (Fig. 2c). These measurements are enabled by our recent advances in quantifying the full-field behavior of ruptures and the evolution of dynamic friction (Rubino et al., 2017; Gori et al., 2018; Rubino et al., 2019; Rubino et al., 2020; Rosakis et al., 2020; Tal et al., 2020). The technique, based on digital image correlation (DIC) (Sutton et al., 2009) coupled with ultrahigh-speed photography (Methods), produces maps of displacements, particle velocities and stresses with a temporal resolution of 0.5 – 1 µs (Rubino et al., 2019). Friction evolution, obtained as the ratio of shear to normal stress, is tracked alongside slip and slip rate at every point along the interface within the imaged field of view (Rubino et al., 2017). In the experiments presented here, two rupture sequences are initiated by means of small bursts induced by two NiCr wires placed across the fault (Fig. 1a). The initial pre-load level is $P = 14$ MPa, and the fault inclination angle is $\alpha = 29^\circ$. After the first sequence of ruptures has propagated and arrested, the prestress is reset to the same level and a new rupture is initiated by triggering another wire (Extended Data Fig. 1 and Methods section).

**Dynamic triggering of laboratory ruptures in rock gouge**

We find that slip in the rock gouge proceeds through sequence of dynamic, laboratory earthquake events triggered by dynamic rupture nearby. The first sequence of events within our observation window starts with a supershear rupture entering the portion of the fault with the gouge layer and losing steam shortly after (Figs. 1b and 2a, bottom; Extended Data Fig. 2 and
Supplementary Video 1), suggesting that the gouge layer may act as a barrier to the propagating dynamic rupture. As the rupture is weakened it leaves residual, ongoing slip in its wake (with slip rates on the order of 0.2 - 0.3 ms) (Fig. 1b). At the same time, it is clear that slip continues outside the observation window, as the arrest of the rest of the rupture upon reaching a barrier can be only gradual, with the healing fronts propagating at best with the wave speeds (Madariaga, 1976; ??). As a manifestation of that, the next attempt to rupture the gouge layer comes from the trailing-Rayleigh rupture feature which typically follows the supershear rupture tip and often amplifies the fault slip (Ref e.g. Lu et al., 2010; Rubino et al., 2020), identified by the characteristic pattern of the fault-parallel particle velocity and shear stress (Extended Data Fig. 3). This rupture also loses steam shortly after entering the portion of the interface with rock gouge, consistent with the interpretation of gouge acting as a barrier to the advancing rupture. As with the previous rupture, residual, heterogeneous slip is left in its wake. This ongoing slip results in an accelerating front 9 µs later (Figs. 1b and 2a), with slip rates up to 1 m/s.

Another prominent dynamic rupture emerges in the gouge ($t = 87.6 \mu$s in Figs. 1b and 2a), as evidenced by the temporal evolution of the fault-parallel particle velocity (Extended Data Fig. 3 and Supplementary Video 1). The dynamic rupture starts at the location where the prior rupture partially arrested (around $x_1 \sim 12$ mm), creating stress concentration. This laboratory rupture has moment magnitude of about $M_w = -6.7$ (Supplementary Information). It initially grows bilaterally, then propagates to the right and finally arrests within the imaged window. Note that in the inter-event time between the main rupture events described so far, there is ongoing slower slip occurring (Fig. 1b), characterized by several (with two successful) attempts to grow into large-scale dynamic ruptures (Supplementary Video 1). Dynamic ruptures may be favored by
localization processes that enable shearing thin layers and activate flash heating weakening mechanism. The transition from slower slip to fully dynamic events is then promoted by dynamic stress changes associated with stress waves travelling through the bulk and interacting with the pre-existing state of stress developed during the prior rupture arrest (Supplementary Information). Note that this triggering occurs over a timescale of microseconds, on the same order of magnitude as the stress transient and of the characteristic rupture timescales, similar to the observation of instantaneous dynamic triggering in earthquake sequences in nature (e.g. Antonioli et al., 2006; Tape et al., 2013).

Further, the initiation of faster slip of the dynamically triggered events occurs on a length scale of less than 10 mm. The nucleation size is affected by the shear modulus of the bulk material, which is about 20 times larger for rocks than Homalite. Hence the corresponding dynamic nucleation size for a case of rock gouge within rock bulk would be about 20 times larger, or less than 0.2 m. This is much less than quasi-static nucleation sizes of about 1 m observed in rock experiments in large samples (McLaskey et al., 2014), indicating that dynamic nucleation sizes are much smaller than quasi-static ones, consistent with numerical simulations (Kaneko and Lapusta, 2008).

The second rupture sequence features a similar succession of events with the supershear and sub-Rayleigh portions of the incoming rupture running out of steam shortly after entering the gouge layer, within the first ~ 15 mm of the imaging window, and leaving residual, ongoing slower slip in the wake (Fig. 1c and Supplementary Video 2). Remarkably, we find that two additional laboratory earthquake ruptures are dynamically triggered within the field of view (Figs. 1c and...
 Extended Data Figs. 4 and 5), with magnitudes $M_w = -6.16$ and $M_w = -6.23$, respectively (Supplementary Information). The temporal evolution of the particle velocity shows the first of these two ruptures growing from approximately the same location where the prior slip penetrated along the interface (Fig. 2b) at time $t = 40.8 \, \mu s$ (Fig. 2b, blue curves, Extended Data Fig. 4). The slip-rate profile along the interface captures the nucleation phase of the dynamically triggered rupture (Fig. 3a, dashed blue curves), and its further propagation as a slip pulse (Fig. 3a, solid blue curves). The second dynamically triggered rupture (Fig. 2b, magenta curves) nucleates at $t = 81.8 \, \mu s$, as indicated by the slip rate profile along the interface (Fig. 3a, magenta solid curves). The time sequence of the fault-parallel particle velocity shows the rupture nucleating and propagating bilaterally (Figs. 3a and 3b; Extended Data Fig. 5). Analysis of the rupture arrival times indicates that both dynamically triggered ruptures propagate at supershear speeds (Extended Data Fig. 2b; Supplementary Information). Most importantly, the shear stress full-field maps and their traces along the interface clearly describe the profound stress changes associated with each of these two dynamically triggered ruptures (Figs. 3c-3d and 3e-3d, respectively, and Extended Data Fig. 6).

**Evolution of dynamic friction in rock gouge**

To understand the evolution of the frictional strength in quartz gauge, we monitor the friction coefficient (and the slip rate) vs. slip at two locations on the fault (marked in Fig. 2a and 2b) for each sequence (Figs. 4a-d and Figs. 4e-h, respectively; similar plots showing time histories at the same locations are given in Extended Data Fig. 7). During both sequences, friction displays a rate-strengthening behavior with the arrival of the first supershear rupture (see the Supplementary Information for a detailed description). Conversely, when the trailing sub-
Rayleigh rupture arrives, friction initially increases to (please give value) but subsequently drops by $\Delta f = 0.22$ and $\Delta f = 0.35$ (Figs. 4a and 4e) after only about 10 \( \mu m \) of slip. Despite this pronounced dynamic weakening, the rupture still loses steam and nearly arrests, indicating that the gouge layer serves as a velocity-strengthening barrier unless dynamic weakening is activated. Such behavior has been shown in numerical models to potentially allow dynamic rupture of otherwise stable, velocity-strengthening fault regions that tend to creep in the interseismic period (Noda and Lapusta, 2013). Our experiments show that the amounts of slip – 0.01 mm - needed for pronounced dynamic weakening in the presence of ongoing rupture in fine fault gouge are much smaller than slips of the order of 10 mm needed for transition from velocity-strengthening to moderately velocity-weakening friction in slow friction sliding experiments (Marone, 1998; Scuderi et al., 2017; Masuda et al., 2019).

Similarly striking dynamic friction weakening is exhibited during the propagation of the dynamically triggered events. For example, during the second sequence, the second dynamically triggered rupture shows an initial marked strengthening, followed by an even more prominent weakening that results in the decrease of the friction coefficient by $\Delta f = 0.64$, and then substantial restrengthening of $\Delta f = 0.27$ (Figs. 4f and 4h). The initial increase in friction is consistent with the direct effect of the standard rate-and-state friction laws (Dieterich, 2007). However, the observed pronounced weakening cannot be solely due to the mild weakening described by standard rate-and-state laws. Instead, we find that our measurements of rapid friction weakening are consistent with the flash heating weakening mechanism (Rice, 2006; Beeler et al., 2008; Goldsby and Tullis, 2011; Tullis, 2015; Rubino 2017). During flash heating, the micron-scale tips of contacting asperities heat up and weaken, resulting in a significant drop
in frictional strength with a significant, $1/V$ dependence on slip velocity $V$. Because of the local and transient nature of the process, frictional strength is quickly recovered when slip rate subsides. Note that dynamic weakening in our experiments occurs over slip scales of the order of 1-10 µm. This is consistent with the physics and theories of flash heating (e.g., Rice, 2006) that indicate that the weakening should occur over scales comparable to the asperity/contact sizes.

Several other weakening mechanisms resulting in pronounced drops in frictional strength have been proposed, including nanoparticle lubrication, silica gel lubrication, and shear melting (Tsutsumi and Shimamoto, 1998; Goldsby and Tullis, 2002; Di Toro et al., 2004; Di Toro et al., 2011; Brown and Fialko 2012; Nakamura et al., 2012; Motohashi et al., 2019). However, these mechanisms produce persistent weakening in fault strength, which is inconsistent with the rapid healing observed in our experiments. Recently, a mechanism based on the presence of amorphous nanopowder and involving particulate flow and intraparticle plasticity has been surmised to explain weakening and re-strengthening (Rowe et al., 2019). However, for this mechanism, as for others mentioned above, weakening requires a large amount of slip and re-strengthening occurs over a timescale of seconds after slip has ended (Rowe et al., 2019). Other weakening mechanisms commonly used to explain fault weakening, in the presence of fluid, are thermal pressurization of pore fluids (Rice, 2006) and elastodynamic lubrication of faults (Brodsky and Kanamori, 2004) but these mechanism cannot be operating here as they require the presence of fluids and our experiments are performed on dry gouge.
Conclusions

To summarize, the sequences of laboratory earthquakes propagating along quartz gouge-filled interfaces presented here exhibit dynamic triggering of ruptures. Transient seismic waves propagating in the bulk result in the triggering of secondary focal mechanisms, consistent with observational studies of instantaneous dynamic triggering (Antonioli et al., 2006; Tape et al., 2013). In our observations, slip ruptures never completely arrest. Rather slower slip events linger on the interface until localization processes lead to the activation of dynamic weakening by flash heating. Overall, these slower and faster slip manifestations appear as a cascading of events, similarly to the observations of earthquake triggering by cascade of foreshock (Ellsworth and Bulut, 2018; Yoon et al., 2018). The observation of spontaneous nucleation and propagation of dynamic ruptures in rock gouge and the local visualization and dynamic measurement of friction is a unique feature of this setup, as traditional experiments either impose a controlled slip rate history or, when ruptures are spontaneous, cannot be imaged at such a level of detail, while friction and other relevant quantities cannot be measured directly on the fault. Our experiments highlight the complexity of rupture phenomena on interfaces with rock gouge. These complexities can also arise in a more general context of stress heterogeneities on the interface and can influence the radiation frequency of a wide range of earthquake rupture events. Our measurements of friction evolution during the two rupture sequences in quartz gouge are characterized by dramatic changes, exhibiting high peak resistance, due to rate-and-state friction behavior, followed by low resistance consistent with the flash heating weakening mechanism. Our findings suggest that dynamic triggering and pronounced weakening may dominate slip processes in earthquakes of all sizes, including microseismicity (Lui and Lapusta, 2016). Most
Importantly, our results show that dynamic triggering may be favored by dynamic weakening of fault gouge, which would otherwise present a barrier to dynamic rupture propagation. These observations offer experimental support to the hypothesis that dynamic weakening mechanisms may allow ruptures to expand through stable, creeping fault regions (Noda and Lapusta, 2013), with important implication for the assessment of the earthquake hazard, as fault segments previously though to slip stably may indeed host large earthquakes.

**METHODS**

**Preparation of the rock gouge interface embedded in the polymer sample**

The laboratory setup simulates earthquakes by dynamic ruptures propagating along a quartz gouge interface embedded between two plates of a polymer, Homalite-100, loaded in compression and shear (Fig. 1). Two quadrilateral plates of size 200 mm x 200 mm x 10 mm are CNC cut out of a Homalite-100 sheet. The mating faces are then polished to a near-optical grade finish and bead-blasted with abrasive glass beads with diameter in the range 104-211 µm (Lu et al., 2010; Mello et al., 2010; Rubino et al., 2019). The quartz gouge interface is produced by employing a fine-ground quartz powder commercially available (MIN-U-SIL 5, US Silica), that has 99.5% content of SiO$_2$, and 96% of the grains equal or less then 5 µm in size. A 1 mm-deep channel is milled along a portion of each mating half of the Homalite specimen (colored in brown in Fig. 1a). The channel is 60 mm x 9 mm, with the wall thickness being 0.5 mm on each side. The channel contains the rock gouge material during preloading and prevents it from spilling over during rupture propagation. A fine mist of glue is deposited at the bottom of each channel, and then each half of the specimen is pressed against quartz gouge, under room-humidity, laid on a flat working surface. The deposit of glue allows the gouge particle to adhere
to the bottom of the channel and avoids creating a slip plane there, while at the same time it does not interfere with the gouge particles through the thickness of the gouge layer. The thin layer of gouge particles glued at the bottom of each of the channels manufactured in Homalite ensures that shear failure takes place within the gouge thickness, rather than along the gouge-polymer interface. The excess gouge is subsequently removed by passing a razor blade over the interface, ensuring that the packed gouge is flush with the lateral walls of the channel. The two mating halves are then placed into contact and into the specimen holder, which in turn is positioned in the loading frame. The lateral surfaces are thoroughly cleaned to prepare them for optical imaging. Using this manufacturing protocol ensures that the shear stresses measured in the polymer are, by traction continuity, those experienced by the gouge layer and allows us to measure the frictional behavior of rock gouge.

Controlled rupture initiation procedure
The applied load $P$ and inclination angle $\alpha$ control the level of applied normal and shear prestress, $\sigma_0 = P \cos^2 \alpha$ and $\tau_0 = P \sin \alpha \cos \alpha$, respectively. The specimen is loaded quasi-statically to $P = 14.3$ MPa, then a dynamic rupture is initiated in Homalite by the rapid discharge of a NiCr wire placed across the interface (W1 in Extended Data Fig. 1). Under these loading conditions, a supershear rupture, followed by a trailing-Rayleigh signature, is produced along a purely Homalite interface (Xia et al., 2004; Rosakis et al., 2007; Lu et al., 2010; Rubino et al., 2010), and it is the only rupture controlled using this experimental procedure. The other ruptures observed during the sequence are associated to the coupling between stress waves traveling in the medium and the frictional behavior of quartz gouge. After the first sequence of dynamic
events, the load is increased again to $P = 14.4$ MPa, and a new rupture is initiated from a second NiCr wire (W2 in Extended Data Fig. 1).

**Full-field imaging technique**

The full-field behavior of laboratory earthquakes is captured using digital image correlation (DIC) (Sutton et al., 2009) coupled with the ultrahigh-speed digital photography, tailored to capture dynamic ruptures (Rubino et al., 2017; Rubino et al., 2019; Rosakis et al., 2020). In order to provide a characteristic texture for image correlation, a region of interest is covered with a random speckle pattern over a white coating. The sequence of images deformed by the propagating ruptures is captured by an ultrahigh-speed camera (Shimadzu HPV-X) at 1 million frames/sec, and is processed with image matching algorithms to produce the evolving sequence of full-field displacements, velocities, and stresses. The field of view employed in this study is 47 x 29.4 mm$^2$ and is positioned entirely over the portion of the interface enriched with rock gouge, i.e. it does not contain any portion of the Homalite interface. Displacements fields are obtained employing the commercial software VIC-2D (Correlated Solutions Inc.), with a subset size of 51x51 pixels$^2$ and a step size of 1 pixels, using the “Fill-Boundary” algorithm to treat interface discontinuity. The first image in each sequence is taken as the reference configuration for the digital correlation. To denoise the displacement obtained from DIC, the fields are filtered using the NL-mean filter (Buades et al., 2008; Rubino et al., 2015; Rubino et al. 2019) and are subsequently processed using the “symmetry-adjustment” procedure described in Rubino et al. 2019, where the fault-parallel and fault-normal displacements are enforced to be anti-symmetric and symmetric, respectively. The particle velocities and strain changes are computed from the displacements by time and space differentiation (Rubino et al., 2019). Slip is computed by the
difference of displacements at pixels immediately above and below the interface, and slip rate is
its time derivative. Stress changes are computed from strain changes using the effective linear
elastic properties of Homalite-100, with Poisson’s ratio and Young’s modulus \( \nu = 0.35 \) and
\( E_d = 5.3 \) MPa, respectively (Sing and Parameswaran, 2003; Rubino et al., 2019). Since
Homalite-100 is a viscoelastic material, we use the high-strain rate properties to compute the
dynamic stress changes (Rubino et al., 2019). The total stresses are obtained by adding the
prestress levels \( \tau_0 \) and \( \sigma_0 \) to the dynamic stress change (Rubino et al., 2019). The prestresses \( \tau_0 \)
and \( \sigma_0 \) are those computed using the measured \( P \) before each sequence (Extended Data Fig. 1).
The stress fields obtained by numerous previous photoelastic measurements and the repeatability
of the tests indicate that the assumption of uniform prestress levels is reasonable. We note that
there may be some mild stress heterogeneities along the interface with deviations from \( \tau_0 \) and \( \sigma_0 \),
which would result in slightly different total stresses. The total shear stress given in Fig. 3c-3f
and obtained under the assumption of constant prestress, help visualize the level of stress
experienced by the fault, but our observations focus on the measured stress changes (Extended
Data Figs. 3 and 6), not on the total stress levels. Friction is computed by the ratio of shear and
normal stress, averaged one pixel above and below the interface (Rubino et al., 2017). Note that
friction may be affected by shear stress inhomogeneities. However, here we focus on friction
changes and our observations of significant friction variations do not depend on the assumption
of constant prestress.

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Author contributions

All authors contributed to developing the main ideas, interpreting the results, and producing the manuscript. V.R. performed the measurements and analyzed the data.
References


Figure 1: Laboratorv earthquake sequences in rock gouge exhibiting dynamic triggering and dramatic friction variations. (a) Laboratory configuration: the specimen features a layer of quartz rock gouge along the interface of two Homalite plates. A channel is manufactured along a portion of the interface on both mating sides of the Homalite plates (colored in brown). The inset shows a cross section of the channel with rock gouge. Two embedded wires allow initiation of two distinct rupture sequences in the same sample, accumulating slip over repeated events, and allow studying rupture evolution along the gouge layer. Maps of the slip rate time histories along the interface for the (b) first and (c) second rupture sequences, respectively. The maps show the complexity of the rupture behavior along the gouge interfaces, including the four main dynamic events in each rupture sequence described in the text and shown in Fig. 2. The slip rate spatiotemporal maps also reveal residual, ongoing slip in the inter-event time, rather than complete rupture arrest and quiescence. (d) Slip distribution of the Tohoku-Oki earthquake.
Figure 2: Slip history for the two rupture sequences featuring dynamically triggered events. (a) Incremental slip vs. position along the interface for the four events of the first sequence of ruptures (from bottom to top): an arresting supershear rupture; its trailing-Rayleigh signature; a weak supershear pulse, and an event dynamically triggered 9 µs later (Fig. 1d). (b) Incremental slip vs. position along the interface for the four events of the second sequence of ruptures (from bottom to top): an arresting supershear rupture; its trailing-Rayleigh signature; and two events dynamically triggered 9 µs and 10 µs after pre-slip is detected on the interface, with the nucleation occurring within the field of view (Extended Data Figs. 3 and 4). Insets show the fault-parallel particle velocity at time frames corresponding to the events described by the slip vs. position curves. The black vertical dashed lines indicate the location for which the friction vs. slip evolution is given in Fig. 4. (c) Friction vs. time and vs. distance along the interface. The friction coefficient before ruptures arrival $f_0 = \sigma_0/\tau_0 = 0.55$ is represented in black, while the red regions indicate the friction coefficient increase associated with the direct effect and the blue region the pronounced weakening due to flash heating. Two planes, at $x_1 = 5$ mm and $x_1 = 40$ mm, intersect the friction surface and provide the friction time history at those two locations.
Figure 3: Evolution and characteristics of the two dynamically triggered ruptures in the second sequence of ruptures. (a) Distribution of slip rate along the fault for several time instances revealing the pulse-like and supershear nature of the first triggered rupture and nucleation of the second triggered rupture. (b) Full-field distribution of the fault-parallel particle velocity right after the nucleation of the first triggered event, highlighting the propagation of the dynamically triggered rupture. (c-d) Distribution of shear stress along the interface and (e-f), full-field maps of the shear stress for the two dynamically triggered ruptures indicating the pronounced shear stress changes that lead to dynamic triggering.
Figure 4: Rate-and-state friction features and pronounced dynamic weakening during dynamic events within the rock gouge. (a-b, e-f) Friction vs. slip and (c-d, g-h) slip rate vs. slip for the two rupture sequences, for selected locations along the interface, indicating dramatic evolution of friction both among and within dynamic events. The friction evolution in both sequences is characterized by a marked increase associated with the direct effect of rate-and-state friction followed by weakening, with the second sequence of events displaying, within micrometers of slip, a remarkable pronounced dynamic weakening consistent with flash heating. Note that, in both sequences, the first supershear ruptures are arrested, potentially due to initially rate-strengthening gouge friction. These unexpected findings indicate that strengthening-to-weakening friction evolution and pronounced dynamic weakening in fine fault gouge consistent with mature faults may occur over slip distances much smaller than previously thought.
Supplementary Discussion

1. Theoretical estimates of the nucleation size

The nucleation length scale on a fault governed by rate-and-state friction can be estimated using the following relation (Rubin and Ampuero, 2005):

\[ h^* = \frac{1}{\pi} \frac{\mu}{(1 - \nu)(b - a)^2} \frac{D_{RS}}{\sigma} \]

where \( \mu \) is the shear modulus, \( D_{RS} \) is the characteristic length scale of rate and state, \( \sigma \) is the normal stress and \( a \) and \( b \) are rate-and-state parameters, valid for \( 0.5 < a/b < 1 \). This theoretical prediction provides an order of magnitude estimate, useful to design our experiments. Assuming \((b - a) = 0.005, b = 0.02 \) and \( D_{RS} = 1 \mu m \), the rate and state properties of Homalite-100 (Lu 2009), computing the (quasi-static) shear modulus of Homalite from the low-strain-rate Young’s modulus 2.17 GPa (Sing and Paramesawaran, 2003) and Poisson’s ratio \( \nu = 0.35 \), and taking \( \sigma = 10 \) MPa, yields a nucleation size \( h^*_{\text{Homalite}} = 31.5 \) mm. Having nucleation sizes on the order of tens of millimeters enables us to produce dynamic ruptures within small laboratory specimens, even for relatively low confinements, which is an important advantage due to the versatility of this configuration. Conversely, assuming a shear modulus representative of rocks (e.g. \( \mu = 44 \) GPa for bare quartz, Ref: Wang, Mao, Jiang, & Duffy, 2015, Phys Chem Minerals) and keeping the rate-and-state parameters the same gives \( h^*_{\text{rock}} = 1.72 \) m. Although the actual values of the rate and state parameters \( a \) and \( b \) are likely to be slightly different, the term \( b/(b - a)^2 \) will still be on the same order of magnitude. On the other hand, assuming \( D_{RS} = 1 \mu m \) is consistent with previous laboratory measurements (Marone and Kilgore, 1993; Scuderi et al., 2017). Hence, employing a rock sample would result in nucleation length scales on the order of 1 meter, consistent with the large sample size used in experimental setups using natural rocks (Dieterich, 1981; Okubo and Dieterich, 1984; Beeler, 2012; McLaskey et al., 2014; McLaskey 2019). This explains the use of
a hybrid configuration featuring a specimen made of a polymer, controlling the nucleation length scale, and a layer of rock gouge embedded along the interface to control the frictional properties.

2. Dynamic triggering

How slip is initiated on faults in the Earth’s crust is an open question in earthquake seismology. The most common mechanism of earthquake triggering is associated with local static stress changes (Stein et al., Science, 1994; Harris et al., Nature, 1995). A growing body of evidence indicates that earthquakes can also be triggered by dynamic stresses transferred by propagating seismic waves (Das and Scholtz, 1981; Harris, 1998; Freed, 2005; Steacy et al., 2005; Gomberg et al., Nature, 2004; Gomberg and Johnson, Nature, 2005; Velasco et al., Nature Geoscience, 2008; Rubinstein et al., 2011; Cattania et al., 2017; Sleep 2019 JGR, Li et al., GRL, 2019). Field observations indicate that the faults are critically stressed and in a state of incipient failure (Zoback and Zoback, 2002). As a consequence earthquakes can be triggered by small stress changes associated with other, remote, earthquakes usually with a delay, known as clock advance (Hill and Prejean, 2015). Dynamic triggering can also occur on the same fault system (Antonioli et al., 2006) and be instantaneous (Antonioli et al., 2006; Tape et al., 2013). Other sources of transient stresses that can trigger remotely earthquakes include fluid injection and withdrawal (McGarr et al., 2002), magmatic intrusions (Hill et al., 2002; Manga and Brodsky, 2006; Savage and Clark, 1982), and solid Earth tides (Cochran et al., 2004; Thomas et al., 2009; 2012), as well as other mechanisms (Hill and Prejean, 2015). At the same time, failure may result from the concomitant reduction in fault strength associated with the nonlinear frictional response to small variations in stress (Dieterich, 1979, Johnson and Jia, 2005), and subcritical crack growth (Atkinson, 1984), as well as with fluid pore pressure increase (Lockner and Beeler, 2002). While field observations and
numerical simulations help to understand the complexity of these phenomena in natural settings, laboratory experiments based on a simpler, idealized scenario allow clear conclusions to be drawn.

Previous experimental studies have shown that gouge is required to observe dynamic triggering (Johnson and Jian, 2005; Johnson et al., 2008, 2012; van der Elst et al., 2012), and that experiments on bare rock faces or other materials do not display dynamic triggering. While bare rock surfaces exhibit predominantly velocity weakening behavior, simulated fault gouge initially displays velocity strengthening and then, at increasing levels of slip, velocity weakening behavior, similar to the displacement dependent behavior exhibited by natural faults (Dieterich, 1981; Tullis, 1988; Marone et al., 1990; Marone et al., 1992; Marone and Kilgore, 1993; Scott et al., 1994; Beeler et al. 1996; Marone, 1998; Goldsby and Tullis, 2002; Di Toro et al., 2011; Rowe et al., 2019). This complex behavior exhibited by gouge may be responsible of dynamic triggering (Johnson and Jian, 2005; Johnson et al., 2008, 2012; van der Elst et al., 2012). Perturbation of only few microstrains may result in triggered fault slip (Johnson et al., 2008; van der Elst and Brodsky, 2010; Johnson et al., 2012; Johnson et al., 2016). While these studies were able to show the behavior of multiple stick slip events, they were not able to study in details the dynamics of individual events. In this study, we focus on the behavior of individual dynamic ruptures spontaneously evolving along gouge interfaces and on instantaneous dynamic triggering, by monitoring the full-field displacements, velocities, and stresses of propagating ruptures using our recently developed ultrahigh-speed imaging technique (Rubino et al., 2019).

In our experiments, we find evidence of dynamic triggering, due to transient stressing, as an active mechanism to nucleate ruptures on a rock gouge fault. During both sequences of laboratory
earthquakes, the partial arrest of the supershear and sub-Rayleigh ruptures result in a shear stress concentration, leaving the rock gouge fault close to failure and prone to dynamic triggering. Stress waves emitted by ruptures propagating along a portion of the simulated fault, trigger laboratory earthquakes along a different portion of the same fault, as described below and in the main text. This is different from remote triggering, where seismic waves emitted from an earthquake on one fault trigger earthquakes on a distinct fault system. However, the mechanism responsible for triggering is similar, in that transient stresses interact with a pre-existing stress structure resulting in rupture nucleation.

The rupture initiated in Homalite by the NiCr wire propagates bilaterally; while the right-traveling portion of this rupture enters the field of view and the gouge layer, the left-travelling portion, not captured by our field of view, keeps propagating along the portion of the interface left of the initiation site (Fig. 1a), continuously emitting stress waves, and resulting in dynamically triggering a new rupture in the gouge layer, whose state of stress has been altered by the previous arrested ruptures.

First sequence

During the first sequence of ruptures, there is a shear stress concentration in the region $x_1 \sim 10 - 36$ mm at $t = 87.6 \mu$s, with an overstress of $\Delta \tau \sim 4$ MPa (Extended Data Fig. 3), associated to the arrest of the sub-Rayleigh rupture. The stress level indicates that the interface is in a critical state, i.e. near to failure, and so it is susceptible to be triggered by dynamic waves traveling in the medium. Indeed, the time evolution of the fault-parallel particle velocity shows the dynamic triggering and subsequent propagation of a dynamic rupture (Extended Data Fig. 3 and...
Supplementary Video 1). Another rupture enters the field of view at time $t = 65.6 \mu s$ (Fig. 2a), exhibiting a supershear pulse-like behavior. The nucleation of this rupture is also likely due to dynamic triggering occurring in the gouge layer, just outside the field of view, or to shear stress concentration developing at the edge of the gouge pocket with the passage of the first two ruptures. However, since rupture re-nucleation occurs just outside the field of view, the evidence for dynamic triggering is not as clear in this case. The slip accumulation associated to this rupture is also rather modest (Fig. 2a).

**Second sequence**

Similarly, during the second sequence of ruptures, as the incoming sub-Rayleigh rupture arrests, it develops a stress concentration with an over-stress of $\Delta \tau \sim 4$ MPa, as revealed by a plot of the full-field shear stress at a time shortly preceding the nucleation of the dynamically triggered event (Extended Data Fig. 6, $t = 38.8 \mu s$). Once the dynamically triggered rupture propagates, it produces a marked shear stress drop, as indicated by a snapshot of the shear stress profile along the interface and by the full-field shear stress at a time ($t = 49.8 \mu s$) during the early stages of rupture propagation (Figs. 3c and 3d). When this first dynamically triggered rupture is arrested, in turn it produces a shear stress concentration (with an over-stress also on the order of 4 MPa), which leaves the fault close to failure and prone to dynamic triggering by stress waves. At the same time, slower slip processes continue on the interface. However, the stress concentration persists until $t = 81.8 \mu s$ when another rupture re-nucleates (Extended Data Fig. 6 and Supplementary Video 2) from approximately the same location where the previous dynamically triggered rupture arrested, and drops the stress by $\Delta \tau \sim 7.5$ MPa (Figs. 3e and 3f). The incremental slip time history indicates that there is an early attempt of nucleation of this rupture at $t = 71.8 \mu s$, which does not result in
much accumulated slip, as reflected by almost overlapping curves (Fig. 2b), and the slip rate only shows a brief transient (Supplementary Video 2).

The strains required for triggering may be rather small (<10^{-8}) (van der Elst and Brodsky, 2010), and therefore may not be detected experimentally by our technique, as they are below the noise threshold. However, such deformations induce significant slip (~20-50 µm, Fig. 2) and slip rates (up to ~ 10 m/s, Figs. 4c, 4d, 4g, 4h; Extended Data Figs. 7c, 7d, 7g, 7h). Note that the propagation of the rupture is consistent with the spatial distribution of the shear stress concentrations. The accumulated slip on the interface reveals that dynamic triggering of ruptures occur approximately in the same location where previous ruptures arrested (Figs. 2), consistent with the hypothesis that dynamic triggering takes place as a result of the fault being in a critical state, due to stress concentration associated to rupture arrest. The dynamically triggered ruptures observed here propagates at supershear speeds, as deduced by the rupture arrival times along the interface (Extended Data Fig. 2).

3. Computation of the laboratory earthquakes magnitude

The moment magnitude of our laboratory earthquake ruptures is computed using the following relation (Kanamori and Brodsky, 2004):

$$M_w = \frac{\log_{10} M_0}{1.5} - 6.07$$

where $M_0$ is the seismic moment, expressed in N m. The seismic moment is given by (Kanamori and Brodsky, 2004): $M_0 = \mu \delta S$, with $\mu$ the shear modulus, $\delta$ the average slip and $S$ the ruptured surface. In these calculations, we consider the shear modulus of bare quartz $\mu = 44$ GPa (Wang et
al., 2015) in order to estimate what would by the magnitude of an earthquake fully occurring in a rock medium. Note that since the shear modulus is a property of the bulk rather than the interface, to interpret our experiments we also use the shear modulus of the polymer. For completeness, we report below the magnitude obtained using both the shear modulus of rock and Homalite-100. The ruptured surface is given by the rectangular area $S = L_{rup} h$, where the rupture length $L_{rup}$ is deduced by the extension of the slip curves of Fig. 2, and $h$ is the gouge width, associated with the specimen thickness. Since the specimen thickness is 10 mm and the gouge walls are 0.5 mm each, $h = 9$ mm. The average slip $\bar{\delta}$ is computed as the average of slip over the rupture length $L_{rup}$. For the dynamically triggered rupture during the first sequence, $L_{rup} = 27.6$ mm and $\bar{\delta} = 9.5$ $\mu$m yield $M_0 = 0.10$ Nm and $M_w = -6.7$. The two dynamically triggered ruptures during the second sequence have $L_{rup} = 69.1$ mm and $L_{rup} = 53.1$ mm, respectively. Since these two ruptures extend outside the field of view, their size is estimated by measuring half the rupture length, which falls entirely within the field of view and multiplying by two. The average slips associated to these ruptures are: $\bar{\delta} = 26.9$ $\mu$m and $\bar{\delta} = 27.4$ $\mu$m, respectively. These parameters lead to $M_0 = 0.74$ Nm and $M_w = -6.16$ for the first, and to $M_0 = 0.58$ Nm and $M_w = -6.23$ for the second dynamically triggered ruptures, respectively. Using the dynamic shear modulus of Homalite-100, $\mu_d = 1.96$ GPa, the moment magnitudes for the three laboratory earthquake ruptures considered above are: $M_w = -7.63$, $M_w = -7.06$, $M_w = -7.13$, respectively.

4. Evolution of dynamic friction in quartz gouge

The evolution of dynamic friction in quartz gouge is tracked at all points along the interface within the field of view. Two locations (marked in Fig. 2) are selected to show salient features of the friction evolution with slip, for each of the two rupture sequences: $x_1 = 8$ mm and $x_1 = 18$ mm
for the first sequence (Figs. 4a and 4b, respectively) and \( x_1 = 5 \text{ mm} \) and \( x_1 = 40 \text{ mm} \) for the second sequence (Figs. 4e and 4f, respectively). The friction time histories are given at the same locations in Extended Data Fig. 7.

**First sequence**

Let us start analyzing the friction evolution during the first sequence of ruptures at \( x_1 = 8 \text{ mm} \). This location emphasizes the effect of the initial supershear and sub-Rayleigh ruptures but does not show as much the effect of the dynamically triggered event (Fig. 2a). As the supershear rupture arrives at \( x_1 = 8 \text{ mm} \), friction increases with increasing slip rate, exhibiting typical rate-strengthening behavior (Figs. 4a and 4b). When the sub-Rayleigh rupture comes, friction first increases, as expected from the direct effect of rate-and-state friction, but then weakens as the slip rate increases up to a peak of 2.5 m/s, resulting in a drop of \( \Delta f = 0.22 \), until finally it partly recovers when the slip rate diminishes (Figs. 4a and 4b). The weak supershear pulse coming next faces a rate-strengthening behavior, while the following dynamically triggered event results in modest weakening \( (\Delta f = 0.077) \) at this location. By contrast, the friction evolution at the other location, \( x_1 = 18 \text{ mm} \), shows more prominently the effect of the dynamically triggered rupture with a pronounced strengthening and subsequent weakening, resulting in a frictional drop of \( \Delta f = 0.41 \) (Figs. 4b and 4d).

**Second sequence**

The second sequence of events exhibits more dramatic changes in friction (Figs. 4e-4h and Extended Data Figs. 7e-7h), indicating the evolution of friction with accumulating slip. The two locations chosen, \( x_1 = 5 \text{ mm} \) and \( x_1 = 40 \text{ mm} \) (Fig. 2b), emphasize the friction evolution
associated to each of the two dynamically triggered ruptures (Figs. 4e and 4g and Figs. 4f and 4h, respectively). The arrival of the supershear and trailing-Rayleigh ruptures at $x_1 = 5$ mm, produces a similar evolution of friction to the one observed during the first sequence, with rate-strengthening behavior associated to the supershear rupture, increase in friction due to the direct effect during the sub-Rayleigh rupture, and subsequent pronounced weakening resulting in a friction change of $\Delta f = 0.35$ (Figs. 4e and 4g). When this rupture arrests it results in shear stress concentrations ($t = 38 \mu s$ in Extended Data Fig. 6), reflected as an increase in friction coefficient. At the arrival of the dynamically triggered rupture, friction displays a marked drop of $\Delta f = 0.58$, following the direct effect, and then healing as the rupture arrests (Figs. 4e and 4g). Friction evolution at the location closer to the initiation of the second dynamically triggered rupture ($x_1 = 40$ mm) shows a pronounced increase followed by a marked reduction by $\Delta f = 0.64$, the most significant friction change measured in our experiments, and ends with re-healing. Note that there is an initial attempt of dynamic triggering with slip rates on the order of 1 m/s and resulting in an increase of the friction coefficient (Figs. 4f and 4h and Extended Data Fig. 7f and 7h). This rupture arrests shortly after and gives way to the main rupture which reaches a peak slip rate of 6 m/s. Note that the dynamic weakening observed for rock gouge interfaces is more pronounced that that observed for Homalite interfaces (Rubino et al., 2017), even at much lower levels of slip rate, consistent with previous experimental observations on rock gouge (Goldsby and Tullis, 2011).

Interestingly, in both sequences the second dynamically triggered ruptures induce a more marked direct effect, as well as a more pronounced weakening behavior, compared to the previous ruptures in each sequence, resulting in severe changes in the friction coefficient. This complex behavior is condensed in the spatiotemporal plot of Fig. 2c (and additionally in Extended Data Fig. 8 and
Supplementary Video 3), showing friction time histories at all locations along the interface. In this three-dimensional representation of the frictional behavior, providing friction time histories at nearly-continuous locations along the interface, the significant increase in shear resistance due to the direct effect is clearly visible in the regions colored in red (particularly for the two dynamically triggered ruptures) and the subsequent weakening is highlighted by the blue regions.

To summarize, in both rupture sequences we see pronounced weakening in fine fault gouge occurring over 10 μm (or 0.01 mm) of slip, which is much smaller than that required to transition from velocity-strengthening to moderately velocity weakening friction in slow friction sliding experiments, which is on the order of 10 mm (Marone, 1998). This suggests that in the experiments presented here, quartz gouge is characterized by a velocity-strengthening behavior (in a rate-and-state sense) up until the interface slides fast enough to activate dynamic weakening in the form of flash heating. Our findings also indicate that, in the absence of flash heating, fault gouge would act as a barrier to dynamic rupture propagation, with its stable, velocity-strengthening behavior. One important consequence of this is that the presence of dynamic weakening (as flash heating or any other form such as thermal pressurization) may result in ruptures breaking through stable, creeping fault segments (Noda and Lapusta, 2013), that otherwise would not be thought to host large earthquakes, with significant implications for earthquake hazard assessments.
Extended Data Fig. 1: Specimen loading time history. The specimen is compressed in the axial direction by a load $P$, which results in a resolved normal and shear stresses on the interface inclined at an angle $\alpha$, given by $\sigma_0 = P \cos^2\alpha$ and $\tau_0 = P \sin \alpha \cos \alpha$, respectively. The load is quasi-statically increased up to $P = 14.3$ MPa, then the first sequence of ruptures is triggered by the discharge of a NiCr wire placed across the interface, denoted as W1 in the inset. After the first sequence of recorded events, and additional slip occurring after the end of recording, the load drops to $P = 13.3$ MPa. The far-field loading is subsequently increased to $P = 14.4$ MPa and the second sequence of events is triggered by the discharge of a second wire, denoted as W2 in the inset. The total load drop of the far-field loading is $\Delta P = 7.5$ MPa. Note that the total load drop is partly due to the second recorded sequence of ruptures and partly to additional slip occurring after the end of recording and associated to reflections subsequently propagating through the interface.
Extended Data Fig. 2: Maps of the slip rate time history at each point along the interface. 

**a**, First rupture sequence. The map allows tracking the speed of the individual ruptures identified: the trailing-Rayleigh rupture ($V_r = 0.94 \text{ km/s}$), a supershear pulse ($V_r = 1.98 \text{ km/s}$), and the dynamically triggered rupture, nucleating around $x_1 = 15 \text{ mm}$, and propagating at supershear speeds bilaterally (at $V_r = 1.73 \text{ km/s}$ and $V_r = 1.43 \text{ km/s}$, leftward and rightward, respectively).

Similarly, this map allows tracking the speed of the identified ruptures: the trailing-Rayleigh rupture ($V_r = 1.13 \text{ km/s}$), the first dynamically triggered supershear pulse ($V_r = 2.59 \text{ km/s}$, then slowing down at $V_r = 1.63 \text{ km/s}$) nucleated at $x_1 = 3 \text{ mm}$, and the second dynamically triggered rupture, nucleated around $x_1 = 40 \text{ mm}$, and propagating at supershear speeds bilaterally (at $V_r = 2.50 \text{ km/s}$ and $V_r = 1.36 \text{ km/s}$, leftward and rightward, respectively). Rupture arrival is identified by the fault-parallel velocity exceeding 0.5 m/s. Note that the rupture speed regime along the gouge interface depends on the Homalite-100 wave speeds, as the wave propagate through the bulk of the parent material. The shear and pressure wave speed of Homalite-100 are $c_{s,\text{HSR}} = 1.3 \text{ km/s}$ and $c_{p,\text{HSR}} = 2.6 \text{ km/s}$, respectively.
Extended Data Fig. 3: Snapshots of the fault-parallel velocity and shear stress change fields during the first ruptures sequence. The full-field maps show the arrival of the sub-Rayleigh rupture ($t = 44.6 \mu s$) and the nucleation ($t = 87.6 \mu s$ and $88.6 \mu s$) and propagation ($t = 92.6$ and $84.6 \mu s$) of a supershear pulse-like rupture. The supershear pulse is dynamically triggered and nucleates in the region where the sub-Rayleigh rupture arrested and concentrated stress. Note that the shear stress maps denote the stress change with respect to the pre-stressed state at the beginning of the first sequence.
Extended Data Fig. 4: Fault-parallel velocity maps showing dynamic triggering of a first rupture during the second sequence. The snapshots show a rupture nucleating at $x_1 = 3 \text{ mm} \ (t = 41.8 \mu s)$ and its subsequent growth and propagation ($t = 43.8 - 62.8 \mu s$). Nucleation occurs in the region where a previous sub-Rayleigh rupture arrested and concentrated stresses (see Extended Data Fig. 5, $t = 38.8 \mu s$) by dynamic stress transfer. The rupture propagates as a pulse, first increasing in intensity and then arresting at around $x_1 = 40 \text{ mm} \ (t = 67.8 \mu s)$. 
Extended Data Fig. 5: Fault-parallel velocity maps showing dynamic triggering of a second rupture during the second sequence. The snapshots show a rupture nucleating at $x_1 \sim 40 \text{ mm} \ (t = 81.8 \mu \text{s})$ at the location where the previous rupture arrested, producing a concentration in shear stress. The rupture initially propagates bilaterally ($t = 83.8 - 87.8 \mu \text{s}$). After an initial crack-like phase, the rupture develops into two pulses. The weaker rupture traveling to the left eventually stops, while the rupture propagating to the right leaves the field of view as a strong pulse.
Extended Data Fig. 6: Maps of the shear stress change during the second ruptures sequence. The snapshots show the arresting sub-Rayleigh rupture ($t = 26.8$ and $28.8 \, \mu s$), leaving a shear stress concentration in the wake ($t = 38.8 \, \mu s$), which prepares the ground for dynamic waves to trigger a new rupture. This dynamically triggered rupture, in turn, also concentrates stress when it arrests further down the interface at $x_1 \sim 40 \, \text{mm}$, and makes conditions favorable for a second rupture to be dynamically triggered ($t = 83.8 \, \mu s$). The second dynamically triggered rupture subsequently propagates as a supershear pulse, with a characteristic shear Mach cone formation ($t = 87.8$ and $89.9 \, \mu s$). The shear stress maps denote the stress change with respect to the pre-stressed state at the beginning of the first sequence.
Extended Data Fig. 7: Friction and slip rate time histories for the two rupture sequences in rock gouge. a, b, Friction vs. time, and c, d, slip rate vs. time for the first ruptures sequence at \( x_1 = 8 \) mm and \( x_1 = 18 \) mm along the interface, respectively. e, f, Friction vs. slip, and g, h, slip rate vs. time for the second ruptures sequence at \( x_1 = 5 \) mm and \( x_1 = 40 \) mm along the interface, respectively. Like the friction evolution with slip (Fig. 4), the friction time histories shown here are characterized by the first sequence displaying a marked increase due to the direct effect of rate-and-state friction followed by weakening, and by the second sequence also displaying the direct effect and a more pronounced weakening consistent with the flash heating mechanism. As noted in Fig. 4, in both sequences the first supershear ruptures are arrested and only display rate-strengthening behavior, whereas the trailing-Rayleigh signatures and subsequent dynamically triggered ruptures induce substantial weakening. This is an unexpected finding as the transition from weakening to strengthening behavior occurs with slips on the order of \( \sim 10 \) µm, whereas it was previously thought to occur on slip scales on the order of \( 10 \) mm.
Extended Data Fig. 8: Friction time histories along the interface for the two sequences of laboratory earthquakes. (a) First and (b) second sequence of ruptures (same as in Fig. 1e). This figure presents the two cases next to each other for comparison. The friction coefficient before ruptures arrival $f_0 = \tau_0/\sigma_0 = 0.55$ is represented in black, while the red regions indicate the friction coefficient increase associated with the direct effect and the blue region the pronounced weakening due to flash heating. Planes intersecting the friction surface are shown at the two locations analyzed in Fig. 4 and Extended Data Fig. 7. The planes are at $x_1 = 8$ mm and $x_1 = 18$ mm, and at $x_1 = 5$ mm and $x_1 = 40$ mm, for the first and second sequences, respectively.