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1 Highlights

2 **The effect of stress barriers on unconventional-singularity-driven frictional rupture**

3 Barnaby Fryer, Mathias Lebihain, Corentin Noël, Federica Paglialunga, François Passelègue

- 4 • Stress barriers promote rupture arrest by decreasing energy flux to the crack tip
- 5 • Long-tailed frictional weakening must be included in LEFM to predict crack arrest
- 6 • This long-tailed weakening depends on the in-situ stress conditions
- 7 • Fault preconditioning is experimentally demonstrated to contain dynamic events

8 The effect of stress barriers on unconventional-singularity-driven
9 frictional rupture

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14 France

15 **Abstract**

Whether or not energy dissipation is localized in the vicinity of the rupture tip, and whether any distal energy dissipation far from the crack tip has a significant influence on rupture dynamics are key questions in the description of frictional ruptures, in particular regarding the application of Linear Elastic Fracture Mechanics (LEFM) to earthquakes. These questions are investigated experimentally using a 40-cm-long experimental frictional interface. Three independent pistons apply a normal load with a fourth piston applying a shear load, enabling the application of a heterogeneous stress state and stress barriers. After loading the frictional interface to a near-critical state, subsequent unloading of one normal-load piston leads to dynamic ruptures which propagate into the heterogeneous stress fields. The ruptures in these experiments are found to be driven by unconventional singularities, characterised by an ever-increasing breakdown work with slip, and as a result do not conform to the assumptions of LEFM. As these experimental stress barriers inhibit slip, they therefore also reduce the breakdown work occurring outside of the cohesive zone. It is shown that this distal weakening, far from the crack tip, must be considered for the accurate prediction of rupture arrest length. These experiments are performed in the context of a proposed stimulation technique for Enhanced Geothermal Systems (EGSs). It has previously been suggested, through theoretical arguments, that stress barriers could be induced through the manipulation of pore pressure such that there is reduced seismic hazard during the shear stimulation of EGSs. This stimulation technique, known as preconditioning, is demonstrated here to reduce the mechanical energy flux to the crack tip, G , while also increasing the fracture energy, G_c . Preconditioning is shown to be capable of arresting seismic rupture and reducing co-seismic slip, slip velocity, and seismic moment at preconditioning stresses which are reasonably achievable in the field. Due to the fully-coupled nature of seismic rupture and fault slip, preconditioning also reduces distal weakening and its contribution to the propagation of induced seismic ruptures. In a similar vein, heterogeneous pore pressure fields associated with some seismic swarms can be used to explain changes in stress drop within the swarm without recourse to material or total-stress heterogeneity.

16 **Keywords:** Frictional ruptures, Stress barriers, Rupture dynamics, Unconventional singularity,
17 Preconditioning

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18 1. Introduction

19 The injection of fluid into the subsurface has been associated with induced seismicity on a
20 significant number of occasions. These injection operations have had a variety of purposes, such
21 as fluid disposal/storage, improved hydrocarbon recovery (e.g., Raleigh et al. (1976)), and reser-
22 voir stimulation (e.g., Bao and Eaton (2016)). In the case of reservoir stimulation for Enhanced
23 Geothermal Systems (EGSs), the mechanical stimulation of a fault or fracture zone is, in the-
24 ory, achieved through the induced shear dilation of the targeted discontinuity (e.g., Lee and Cho
25 (2002)). The shearing itself is induced through the increase in pore pressure associated with fluid
26 injection, which acts to reduce the fault's effective normal stress and initiate shear failure. Ideally,
27 this process occurs aseismically, such that seismic waves are not radiated. However, as injection
28 continues, the rupture front bounding the stimulated region grows, potentially surpassing the area
29 of increased pore pressure if the fault is critically stressed (Garagash and Germanovich, 2012;
30 Bhattacharya and Viesca, 2019; Cebry and McLaskey, 2021). Eventually, this rupture front may
31 reach a critical length, known as the nucleation length (Ida, 1972; Okubo and Dieterich, 1984;
32 Campillo and Ionescu, 1997; Uenishi and Rice, 2003), and begin accelerating, resulting in the
33 dynamic rupture of the fault and the radiation of potentially-damaging seismic waves. The un-
34 derstanding of how to achieve shear dilation in an aseismic manner while avoiding the dynamic
35 rupture of the fault is an obstacle for the global development of EGSs, and a number of field-scale
36 EGS projects have been impeded or halted due to the seismicity they have induced (e.g., Basel,
37 Switzerland (Häring et al., 2008); Pohang, South Korea (Kim et al., 2018)).

38 The success or failure of an EGS operation is strongly dependent on the state of stress in the
39 subsurface. This is because the state of stress not only influences the susceptibility of a given fault
40 to shear dilation (e.g., Lee and Cho (2002)), but also affects the nucleation length (Okubo and
41 Dieterich, 1984), rupture velocity (Ben-David et al., 2010), slip velocity (Okubo and Dieterich,
42 1984), rupture halting (Husseini et al., 1975), and radiated seismic energy (Scholz, 1968) of
43 earthquakes. In particular, recent experimental and theoretical studies have highlighted that the
44 rupture length, i.e., the size of the earthquake that will eventually be induced, is contingent
45 upon the stress distribution along the fault (Bayart et al., 2016; Galis et al., 2017). Indeed,
46 rupture arrest is described by the flux of total potential energy per unit extension of the crack
47 tip (commonly termed G) and the dissipated energy related to the unit extension of the crack
48 tip (commonly termed G_c or fracture energy); both of these terms depend on the stress state. It
49 is generally assumed that weakening is localized near the crack tip, such that, while slip may
50 continue, there is no further weakening once slip has reached a critical slip distance, allowing
51 the stress and strain fields around the crack tip to be described by a conventional singularity.
52 However, recently, instances of continued power-law weakening beyond this critical slip distance
53 have been observed experimentally, resulting in unconventional singular stress and strain fields
54 (Paglialunga et al., 2024). This raises the question as to whether or not the energy release rate
55 and, therefore rupture arrest, are truly governed exclusively by near-tip weakening (Garagash,
56 2021; Brener and Bouchbinder, 2021b; Kammer et al., 2024). It is further unclear what effect, if
57 any, stress barriers and the stress state in general have on distal weakening and if a reduction in
58 distal weakening promotes rupture arrest.

59 Engineering operations are capable of influencing the state of stress in the Earth's crust. For
60 example, fluid production was first connected to land subsidence nearly a century ago (Pratt and
61 Johnson, 1926), and fluid injection was linked to seismicity in the 1960's and 1970's (Raleigh
62 et al., 1976). Concurrently, in the oil and gas industry, operators began actively manipulating
63 the *in-situ* stress with hydraulic fracturing operations, first employed in the 1940's (Clark, 1949),

64 which rely on the reduction of the minimum principal effective stress through the increase of
65 fluid pressure (Hubbert and Willis, 1957). Later, operators began recognizing that the *in-situ*
66 stress could be manipulated prior to initiating a hydraulic fracture for that fracture’s eventual
67 benefit (Shuck, 1977).

68 Similarly, the mining industry has been employing a de-stressing technique referred to as
69 preconditioning since the 1950’s (Roux et al., 1957). In this operation, a rock face is artificially
70 fractured in order to relieve stress and reduce the occurrence and severity of rockbursts. Still in
71 its relative infancy, the EGS industry has not sufficiently developed methods to reduce the hazard
72 of induced seismic events related to stimulation operations. However, the potential to direct
73 and inhibit stimulation treatments by manipulating pore pressure has been recognized for two
74 decades already (Baria et al., 2004), and methodologies to inhibit the occurrence of large seismic
75 events such as cyclic stimulation/fatigue hydraulic fracturing (Zimmermann et al., 2010; Zang
76 et al., 2013; Hofmann et al., 2019; Noël et al., 2019), control theory (Stefanou and Tzortzopoulos,
77 2022), fracture caging (Frash et al., 2021), and preconditioning (Fryer et al., 2020, 2023; Jalali
78 et al., 2023) have been suggested, developed, and, in the case of cyclic stimulation, even deployed
79 at the field scale.

80 Here, using the effective stress principle, the preconditioning of an EGS through the de-
81 velopment of stress barriers (Fryer et al., 2023) is demonstrated experimentally using a biaxial
82 apparatus. In practice these stress barriers are proposed to be achieved through an extended (but
83 short compared to the background stressing rate) period of production, reducing pore pressure
84 and increasing effective stress, prior to a comparatively-shorter period of injection, stimulating
85 the fault by inducing slip, Figure 1(a-c). Here, this procedure will be simulated in dry conditions
86 with changes in total normal stress, Figure 1(d,e). It is shown that preconditioning has the ca-
87 pability to halt nucleated dynamic ruptures, reducing the hazard associated with fluid injection
88 into a fault. Preconditioning achieves this moderation in hazard through the abatement of energy
89 available to the propagating rupture via a diminished stress drop and the increase in the energy
90 required to continue dynamic propagation via an increased fracture energy; in accordance with
91 previous findings and predictions (Husseini et al., 1975; Freund, 1990; Kammer et al., 2015;
92 Bayart et al., 2016; Galis et al., 2017; Bayart et al., 2018; Gvirtzman and Fineberg, 2021; Cebry
93 et al., 2022; Fryer et al., 2023; Barras et al., 2023). Further, it will be shown that distal weaken-
94 ing, far from the crack tip, exhibits a first-order control on rupture arrest and is also reduced by
95 preconditioning and stress barriers in general.

96 2. Methods

97 2.1. Experimental Setup

98 The biaxial apparatus, CrackDyn, located at Géoazur in Valbonne, France, was used to per-
99 form experiments on two polymethylmethacrylate (PMMA) rectangular-prism blocks (40×10
100 $\times 1$ cm and $45 \times 10 \times 1.8$ cm), yielding a fault length, L , of 40 cm and a fault width of 1 cm,
101 Figure 1(f). The position of any point along the sample is given by its horizontal, x , and vertical,
102 y , coordinates. The apparatus engages with the sample blocks via three independent vertical pis-
103 tons, responsible for applying normal forces, and one horizontal piston, responsible for applying
104 a shearing force. The pistons are driven with two ENERPAC P141 hydraulic pumps and transmit
105 load to the sample blocks via steel sample holders. The sample holders transmitting the normal
106 stress to the fault system are discontinuous, allowing for a heterogeneous normal load to be ap-
107 plied along the fault length, Figure 1f. The force applied by each piston is recorded at 500 Hz by

108 a Scaime K13 load cell located in between it and the sample holder. Thirteen 350-Ohm strain-
 109 gauge rosettes (39 total strain gauges), recording at 2 MHz, are glued at 3 mm from the simulated
 110 fault interface. The strain gauges' signals are amplified by a factor of 100 by Elsys SGA-2 MK2
 111 amplifiers. Twenty Brüel & Kjær type 8309 accelerometers are glued either horizontally or verti-
 112 cally at approximately 1 cm from the simulated fault interface and record at 2 MHz with a cutoff
 113 frequency of 54 kHz. Finally, three high-intensity light sources emit light which traverses the
 114 sample to arrive at a Phantom TMX 6410 high-speed camera. The light is cross-polarized with
 115 two linear polarizing filters. During the experiments, the camera was triggered using a piezo-
 116 electric sensor and recorded frames at 500 kHz (1.7 μ sec exposure time with a 1280 \times 32 pixel
 117 resolution across the fault length, i.e., 350 μ m per pixel). The high-speed camera and the use of
 118 polarized light with a birefringent material allow for the use of photoelasticity, which enables the
 119 tracking any propagating dynamic ruptures (Rosakis et al., 1999; Nielsen et al., 2010; Schubnel
 120 et al., 2011; Latour et al., 2013; Gounon et al., 2022; Paglialunga et al., 2023). The piezoelectric
 121 sensor signal used for the camera triggering was split between the recording computers and used
 122 to synchronize the different recording systems. The data treatment is addressed in the appendix
 123 A.

124 2.2. *Experimental Approach*

125 The sample is loaded in steps, Figure 1(d,e), by increasing the normal stress and shear stress
 126 applied at the pistons in increments of 30 bar. After initial loading, the normal stresses applied
 127 by all three vertical pistons are equivalent and set to either 60, 90, or 120 bar nominal normal
 128 stress, σ^0 , i.e., as read on the pump's analogue gauge in the hydraulic pressure lines. The shear
 129 stress is set to a value just below the shear stress required to initiate a dynamic event, in this
 130 case corresponding to 100, 145, or 190 bar nominal shear stress. The volume at the shear pump
 131 was then maintained constant for the rest of the experiment. At this stage the sample fault is
 132 considered to be loaded and representative of a tectonically-loaded natural fault, Figure 1a. If the
 133 sample is to be preconditioned, the normal stress applied by all three vertical pistons is increased
 134 by a nominal normal stress of $\Delta\sigma^p$, such that $\frac{\Delta\sigma^p}{\sigma^0}$ is equivalent to approximately 0.08, 0.16, or
 135 0.24, Figure 1(b,d). In practice, if the normal total stress on a fault is given by a lithostatic
 136 gradient of 23 $\frac{\text{MPa}}{\text{km}}$ and the pore pressure by a hydrostatic gradient of 10 $\frac{\text{MPa}}{\text{km}}$, these values of $\frac{\Delta\sigma^p}{\sigma^0}$
 137 correspond to producing fluid from the fault such that the effective hydrostatic gradient on the
 138 fault is reduced to approximately 9, 8, or 7 $\frac{\text{MPa}}{\text{km}}$. At each normal stress a base case is also tested
 139 twice whereby the stress is not preconditioned and $\frac{\Delta\sigma^p}{\sigma^0} = 0$, serving as reference. Injection is
 140 then simulated by reducing the stress applied by the right-hand-side vertical piston (closest to
 141 the horizontal piston), leaving the other two vertical pistons applying the preconditioned stress,
 142 Figure 1(d-f). The unloading generally results in an audible acoustic event, after which the shear
 143 and then normal stresses are unloaded and the sample reset.

144 3. **Experimental Results**

145 The local stress recorded by the strain gauge rosettes show that the stress profiles are highly
 146 reproducible between experiments, Figure 2. The strain gauges show that preconditioning in-
 147 creases the normal stress, σ_{yy} , with smaller changes to shear stress, σ_{xy} . Strain gauge measure-
 148 ments were further able to provide stress profiles just before and just after the nucleation of the
 149 principal dynamic event associated with each experiment, Figure 2.

150 The stress-induced birefringence of the PMMA samples allows for photoelasticity measure-
 151 ments, which provide a second independent method to track the propagating ruptures. When

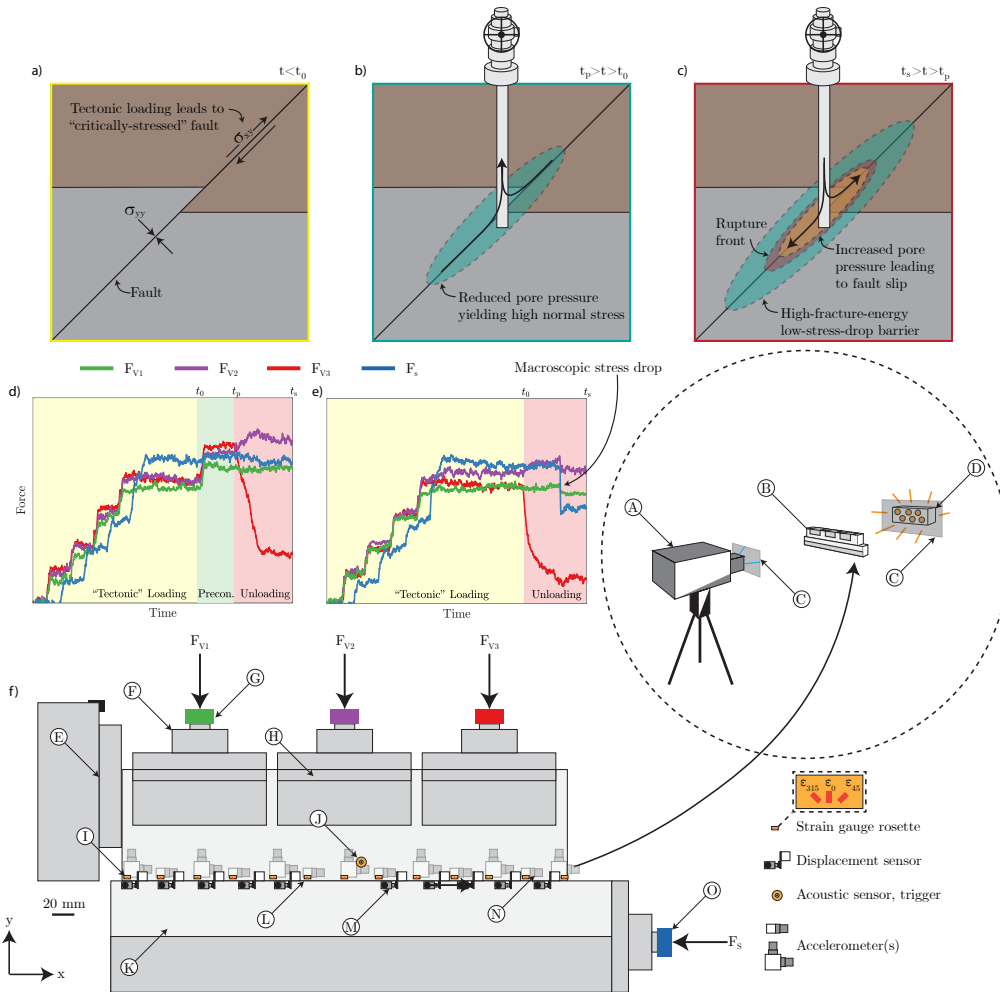


Figure 1: An overview of preconditioning and the experimental procedure. (a-c) illustrates preconditioning as it could be applied at the field scale, with the process simulated in the laboratory here under dry conditions. (a) Tectonic loading results in a critically-stressed fault at depth. (b) A well is drilled into the fault. Fluid is produced from the fault, reducing the pore pressure and increasing the effective normal stress. (c) Fluid is injected into the fault on a time scale significantly shorter than the production phase in (b). The increased pore pressure locally reduces the effective stress and initiates slip. This slipping or rupture front may outpace the fluid pressure front, but will encounter the low-pore-pressure region, which acts as a fracture-energy and reduced-shear-stress-drop barrier (Fryer et al., 2023). In the context of this figure, t is time, t_0 is the start of operations, t_p is the time when fluid production stops, and t_s is the time of shut-in. (d,e) The stress profiles of two example experiments, illustrating the left-most vertical load (green), central vertical load (purple), right-most vertical load (red), and shear load (blue). Initially, the normal and shear loads are increased, simulating tectonic loading (a). If preconditioning is applied (b,d), the vertical loads are increased. In the case preconditioning is not applied, this step is skipped (e). The right-most vertical load is then reduced, simulating fluid injection. This results in the nucleation of a dynamic rupture. Note the macroscopic stress drop present in the non-preconditioned case (e). This macroscopic stress drop is not present in the preconditioned case (d) and is the first piece of evidence suggesting that the preconditioned case halted rupture propagation, containing the event, whereas the non-preconditioned case ruptured the entire experimental fault, reaching the sample edges and resulting in reduced stiffness and extra slip (e.g., Kilgore et al. (2017)). (f) The experimental setup with the inset showing the camera setup. (A) high-speed camera, (B) biaxial setup, (C) linear polarizer, (D) light source, (E) stopper, (F) load cell, (G) vertical piston, (H) sample holder, (I) strain gauge rosette, (J) acoustic sensor (trigger), (K) PMMA sample, (L) sample-sample interface, (M) displacement sensor (only in Supplementary Material), (N) accelerometer, and (O) horizontal piston.

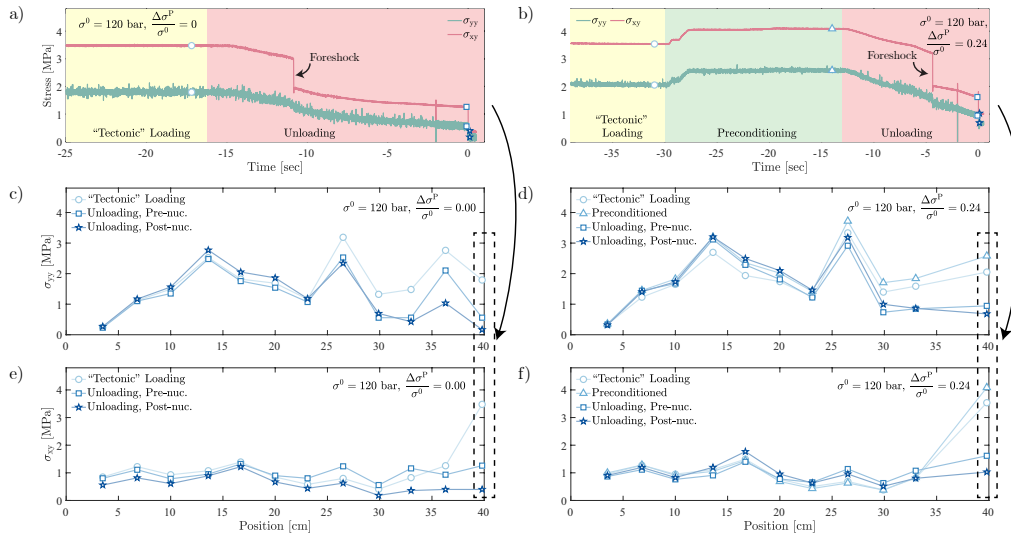


Figure 2: Stress profiles deduced from strain gauge measurements for two experiments performed at a nominal normal stress of 120 bar. (a,c,e) No preconditioning is performed. (b,d,f) A preconditioning of 30 bar is applied. (a,b) The stress profile in time found from one strain gauge located at a position near the sample edge ($x = 40$ cm), in the area where the sample is unloaded. The initial normal (green) and shear (red) stresses, representative of the *in-situ* stress resulting from tectonic loading have a yellow background. The unloading phase has a red background. In (b) the preconditioning phase has a green background. Note both experiments have a foreshock during the unloading phase which is contained on one side of the sample. The normal (c,d) and shear (e,f) stress profiles across the entire surface of the sample, using all working strain gauges at specific moments: after "tectonic" loading (circle), after preconditioning (triangle), during unloading but prior to the dynamic event (square), and after the dynamic event (star). Markers represent values found from the strain gauges. Lines are linear interpolations. Note the similarities in the initial stress profiles (circles) between the two cases. Additionally, note the stress increase in (d,f) related to preconditioning (triangles). Finally, note the reduced shear stress in (e) after the event across the entirety of the sample (stars). The shear stress is increased in the preconditioned case (f). The case without preconditioning resulted in the rupturing of the entire sample; the preconditioned case had a contained event.

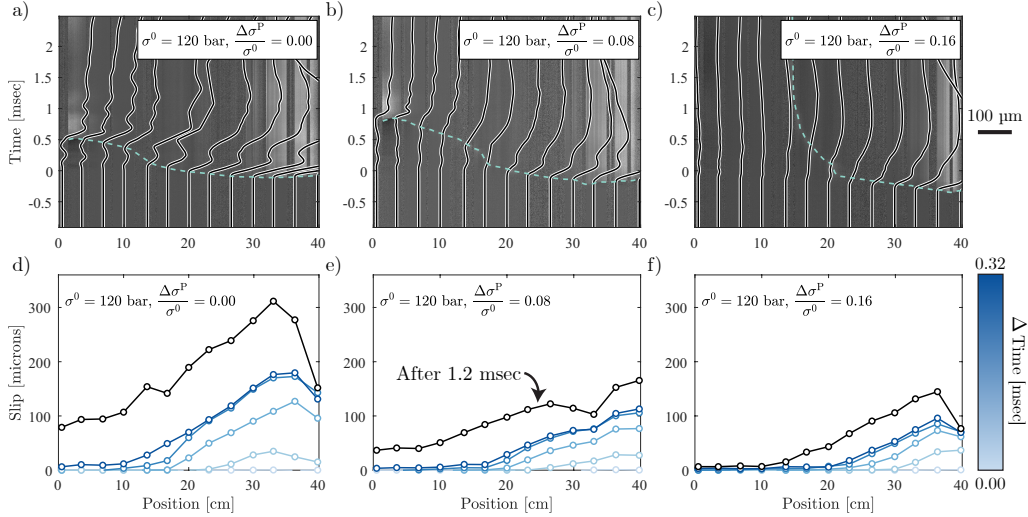


Figure 3: Three experiments are shown, all performed at a nominal normal stress of 120 bar. (a,d) No preconditioning is performed. (b,c,e,f) Preconditioning is performed up to a nominal normal stress of (b,e) 130 and (c,f) 140 bar. (a-c) The videogram profiles illustrate the progression of the rupture fronts and are overlain by the local displacement recorded by the horizontally-oriented accelerometers (black lines). The displacements are zeroed to the location of the sensor and deviation from this position indicates local displacement. The scale for the displacement is found on the right. The rupture front is traced with a dotted line. Note that certain spatial bands where the grey-scale remains uniform on the videograms correspond to areas where light was not able to pass through the sample at the height of the fault. This is due to it being blocked by a sensor. (d-f) The slip profiles as calculated from the accelerometers positioned along the fault interface. An initial time, here denoted by the color bar as 0.00 microseconds, is chosen just before slip initiates. Then, four additional evenly-spaced times are taken starting from this moment at 0.08, 0.16, 0.24, and 0.32 microseconds. The “final” slip profile after 1.2 microseconds is shown in black. The positions of the accelerometers are denoted by white circles, with linear interpolation between these points.

152 these measurements are taken in combination with the slip profiles, computed from the ac-
 153 celerometers, the rupture fronts of the dynamic events can be traced, Figure 3(a-c). Measure-
 154 ments of slip were used to build slip profiles across the fault interface, Figure 3(d-f). The slip
 155 profiles show that the larger the magnitude of the preconditioning, the smaller the total cumu-
 156 lative slip and slip velocities are. Note finally that the characteristic rise times (slip durations)
 157 computed by the accelerometers are similar to the characteristic source durations (the time re-
 158 quired for the rupture to traverse the sample) observed on the videograms, meaning that these
 159 ruptures exhibit crack-like, as opposed to pulse-like, behaviour.

160 Preconditioning results in halted and/or slowed rupture and reduced slip, slip velocity, stress
 161 drop, and moment magnitude, Figures 3 and 4. The videogram measurements were manually
 162 traced, allowing for the creation of rupture profiles for the dynamic events associated with each
 163 experiment, Figure 4(a-c). In all cases where preconditioning was not applied, the rupture was
 164 able to traverse the entire interface, highlighting that, while the stress state along the interface is
 165 heterogeneous (all ruptures experienced deceleration at approximately $x = 15$ cm, presumably
 166 associated with a higher normal stress at this position, Figure 2(c,d)), on the whole the tested
 167 conditions can be considered representative of a critically-stressed fault. However, with the
 168 exception of one experiment ($\sigma^0 = 120$ bar; $\frac{\Delta\sigma^P}{\sigma^0} = 0.08$), preconditioning was able to halt the
 169 dynamically-propagating rupture before it reached the sample edges at all tested nominal normal

170 stresses ($\sigma^0 = 60, 90, \text{ and } 120 \text{ bar}$) and all tested levels of preconditioning ($\frac{\Delta\sigma^p}{\sigma^0} = 0.08, 0.16,$
171 0.24). This result is further confirmed by the slip profiles, Figure 4(d-f). Generally, although
172 the results are influenced by whether or not the rupture reaches the free boundary at the sample
173 edges (Kilgore et al., 2017), preconditioning results in reduced total slip behind the crack tip
174 and reduced slip velocity, Figure 4(d-i). In fact, the accelerometers provide a near-continuous
175 measure of slip along the interface that can be used to estimate the seismic moment, M_0 , of each
176 event as $M_0 = \mu A_s D$ (Aki, 1966), where μ is the dynamic shear modulus, D is the slip, and A_s
177 the area of the ruptured region along the interface. Without preconditioning, experiments with
178 nominal normal stresses of 60, 90, and 120 bar yield average seismic moments of 416, 940, and
179 1608 N·m, respectively. With a preconditioning of $\frac{\Delta\sigma^p}{\sigma^0} = 0.24$, experiments with nominal normal
180 stresses of 60, 90, and 120 bar yield seismic moments of 86, 474, and 495 N·m, respectively,
181 corresponding to a 50 to 79% reduction in seismic moment due to preconditioning. Finally,
182 strain gauge measurements from before and after the passing of the rupture front allow for the
183 calculation of a continuous stress drop profile, Figure 4(j-l). Preconditioning results in smaller
184 stress drops behind the rupture front, as well as negative stress drops (increases in shear stress)
185 in the cases that it is able to halt the propagating rupture. The stress drop profile, $\Delta\sigma_{xy}(x)$, will
186 later be seen to be of importance for the energy flux reaching the crack tip of the propagating
187 rupture.

188 4. Discussion

189 4.1. Fault preconditioning for reduced hazard during EGS stimulation

190 During crack propagation, the mechanical energy release rate, or the flux of total potential
191 energy per unit extension of a crack's tip, G , is equivalent to the dissipated energy related to that
192 same unit extension, which is known as the fracture energy, G_c , such that (Griffith, 1921; Freund,
193 1990),

$$G = G_c. \quad (1)$$

194 The arrest of a dynamically-propagating shear crack can occur due to an increase in G_c or a
195 reduction in G , such that G falls below G_c (Husseini et al. (1975); Rice (1980), page 594; Freund
196 (1990), Eqn. 7.4.27; Kammer et al. (2015); Bayart et al. (2016)).

197 In this context, fault preconditioning results in a reduction in the energy available to a propa-
198 gating rupture and in a fracture energy barrier (Fryer et al., 2023). These predictions are based on
199 and in agreement with Linear Elastic Fracture Mechanics (LEFM) theory (Husseini et al., 1975;
200 Rice, 1980; Freund, 1990; Kammer et al., 2015; Bayart et al., 2016; Galis et al., 2017; Bayart
201 et al., 2018; Gvirtzman and Fineberg, 2021; Cebry et al., 2022; Paglialunga et al., 2022). Here,
202 the possible effects of preconditioning have been explored experimentally, demonstrating gener-
203 eral agreement with previously-made predictions. In particular, preconditioning has been shown
204 to be capable of slowing and/or halting a dynamically propagating rupture as well as reducing
205 the slip and slip velocity behind the dynamically-propagating crack tip, resulting in a smaller
206 seismic moment for nucleated events. This effect of preconditioning on rupture propagation can
207 be principally the result of (i) the increase in the energy required to continue crack propagation
208 (the fracture energy, G_c), (ii) the reduction of the mechanical energy flux at the crack tip (G), or
209 (iii) a combination of both.

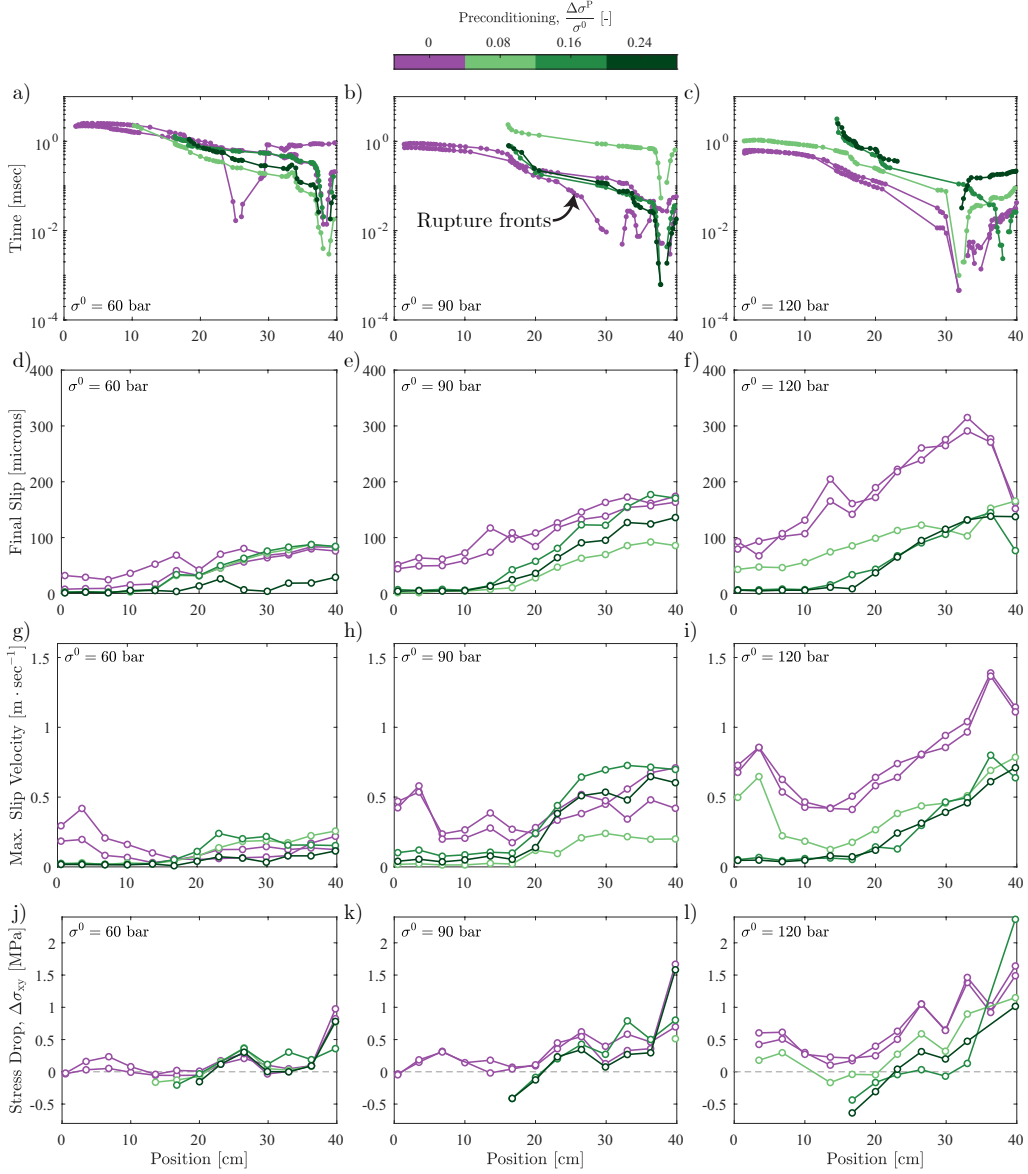


Figure 4: (a-c) The crack tip progression for each experiment, manually picked from videograms. Dots represent manually-picked points; linear interpolation is used between these points. (d-f) The total (maximum) slip calculated from the accelerometers, calculated up to 1.5 msec after the trigger. (g-i) The maximum slip velocity up to 1.5 msec after the trigger. For (d-i), white dots represent the locations of accelerometers; linear interpolation is used between these locations. (j-l) The stress drop resulting from the dynamic event calculated using the strain gauges. White dots represent the locations of strain gauge rosettes; linear interpolation is used between these locations. Stress drops are only plotted for positions behind the crack tip; however note that the strain gauge at 0.5 cm was not working for the experiments at 120 bar. Experiments are performed at (a,d,g,j) 60, (b,e,h,k) 90, and (c,f,i,l) 120 bar nominal normal stress. For all plots, the color bar indicates the amount of preconditioning used in each experiment.

210 *4.1.1. Influence of fault preconditioning on G_c*

211 The dependence of G_c on normal stress was examined through two calibration experiments,
 212 both exhibiting complete ruptures. The determination of G_c began with the calculation of the
 213 breakdown work, w_b , (Tinti et al., 2005; Brener and Bouchbinder, 2021b,a),

$$w_b(D) = \int_0^D (\sigma_{xy}(\delta) - \sigma_{xy}(D)) d\delta, \quad (2)$$

214 where $d\delta$ is an increment of slip. Note that the definition of breakdown work here is slightly
 215 modified from that introduced by Tinti et al. (2005) to follow Brener and Bouchbinder (2021b,a);
 216 Paglialunga et al. (2022, 2024), and is precisely the definition of fracture energy in Abercrombie
 217 and Rice (2005), stemming from Palmer and Rice (1973). The breakdown work was determined
 218 for multiple events at various strain gauge rosettes.

219 Initially, once the rupture tip first passes a specific location along the fault and slip initiates,
 220 breakdown work scales as $w_b \propto D^2$ (Tinti et al., 2005; Brener and Bouchbinder, 2021b); however,
 221 this phase is generally not seen here to due the frequency response of the accelerometers. At
 222 larger values of slip, the relationship between w_b and D undergoes a change, such that $w_b \propto D^m$,
 223 where m is a fitting parameter. The slip which corresponds to this change in dependence is known
 224 as the critical slip distance, D_c , and corresponds to a cross-over slip scale. Within the framework
 225 of LEFM, weakening is localized in an infinitesimal region near the crack tip, so that no further
 226 weakening occurs when $D \geq D_c$. This results in $w_b \propto D^0$ and corresponds to a singularity
 227 order, ξ , of -0.50 (e.g., Svetlizky et al. (2020); Shlomai et al. (2021); Brener and Bouchbinder
 228 (2021b)). The breakdown work achieved at $D = D_c$ is equivalent to the fracture energy, such that
 229 $G_c = w_b(D = D_c)$.

230 In these experiments, breakdown work is generally a continuously-increasing function of slip
 231 even when $D \geq D_c$, and can be fit as $w_b(D \geq D_c) = AD^m$, Figure 5b and appendix B, where A is
 232 a fitting parameter. There is therefore a cross-over behaviour occurring at $D = D_c$ from a small-
 233 slip behaviour where $w_b \propto D^2$ to a large-slip behaviour where $w_b \propto D^m$, as described by previous
 234 authors (Viesca and Garagash, 2015; Brantut and Viesca, 2017; Brener and Bouchbinder, 2021b;
 235 Paglialunga et al., 2024). The latter results in unconventional singularity orders in stress and
 236 strain, $\xi = \frac{m-1}{2-m}$, ranging between -0.52 and -0.18 , with mean and median values of -0.28
 237 and -0.24 , respectively, appendix B. Such values depart from the ‘‘conventional’’ -0.5 value of
 238 LEFM and are close to the value -0.25 expected for flash heating (Brantut and Viesca, 2017;
 239 Brener and Bouchbinder, 2021b; Paglialunga et al., 2024) and thermal pressurization (Viesca
 240 and Garagash, 2015). In order to further confirm the presence of these unconventional singular-
 241 ity orders, the stress perturbations associated with passing rupture tips were fit to the ruptures’
 242 singular fields using both the unconventional singularity orders found from the trend between w_b
 243 and D and the conventional singularity order of $\xi = -0.50$ (Irwin (1957); Freund (1990), Eqn
 244 4.3.23; Paglialunga et al. (2024), Eqns 7-9), appendix B. The use of unconventional singular-
 245 ity orders generally resulted in superior fits, Figure 5a, thereby providing further evidence for
 246 the unconventional nature of these singularities. These experimental results are a demonstration
 247 of the numerical prediction by Lambert and Lapusta (2020) that breakdown energy is ‘‘neither a
 248 constant material property nor uniquely defined by the amount of slip attained during the rupture’’
 249 and builds upon previous discussions by, for example, Abercrombie and Rice (2005); Kammer
 250 et al. (2024) who considered the scale dependence of earthquake rupture.

251 The fitting of the singular field with the conventional singularity order of $\xi = -0.50$ further
 252 allows for the calculation of G_c^{LEFM} (e.g., Svetlizky et al. (2020)). This value of G_c^{LEFM} and the

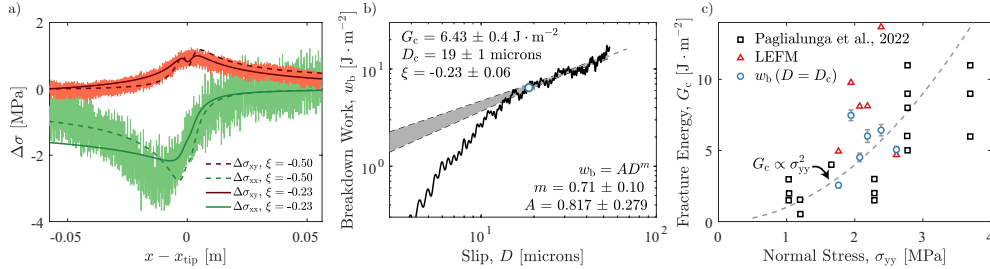


Figure 5: a) An example of the fitting (dark and dashed lines) of $K_{II}^{(\xi)}$ to the stress change seen by one strain gauge rosette (light lines, green for σ_{xx} and red for σ_{xy}) as the rupture front passes it. The dashed lines are fit as a conventional singularity with $\xi = -0.5$; the dark lines are fit as an unconventional singularity with $\xi = -0.23$. These data are from a calibration experiment and are filtered at 100 kHz. b) From the same experiment, the breakdown work plotted as a function of slip. After the trend between w_b and D turns over, becoming approximately linear in log-log space, it is fit as $w_b = AD^m$. The beginning of this trend corresponds to $D = D_c$ and $w_b(D = D_c) = G_c$ and is marked with a blue point. Further, the singularity order can then be calculated as $\xi = \frac{m-1}{2-m}$. The cross over in scaling at $D = D_c$ has been described by Viesca and Garagash (2015); Brantut and Viesca (2017); Brener and Bouchbinder (2021b); Paglialunga et al. (2024). c) The fracture energy, G_c , versus normal stress, σ_{yy} , based on calibration experiments performed for this study using either LEFM fits (triangles) or the change in trend between breakdown work and slip (circles). Data taken from Paglialunga et al. (2022) are also plotted (squares).

253 value of G_c found from the trend between w_b and D allow for the calibration of G_c 's dependence
 254 on normal stress, Figure 5c and appendix C. G_c 's dependence on normal stress has been pre-
 255 viously demonstrated (Okubo and Dieterich, 1981, 1984; Bayart et al., 2016, 2018; Paglialunga
 256 et al., 2022), and the results here are in agreement with previous findings, Figure 5(c). Therefore,
 257 the increase in normal stress associated with pore pressure preconditioning is predicted to cause
 258 in an increase in fracture energy, resulting in a fracture energy barrier. These fracture energy
 259 barriers represent *local* impediments to propagation and have been previously shown to be capa-
 260 ble of halting dynamically-propagating ruptures (Husseini et al., 1975; Bayart et al., 2016, 2018;
 261 Gvirtsman and Fineberg, 2021). It should be noted, however, that, for the normal stresses inves-
 262 tigated here, G_c varies only from approximately 5 to 10 $\frac{J}{m^2}$, depending on whether the LEFM or
 263 breakdown-work-derived values are used. As will be demonstrated later, these results imply that
 264 fracture energy barriers do not exert the primary control on rupture arrest in these scenarios.

265 4.1.2. Influence of fault preconditioning on the energy flux, G

266 Complementary to this effect on the fracture energy, fault preconditioning is also expected to
 267 reduce the energy flux to the crack tip. In the case of rupture arrest during mode-II propagation
 268 in plane stress conditions (in the framework of LEFM - these equations are undefined for uncon-
 269 ventional singularities), $\lim_{v \rightarrow 0} G = G^{\text{stat}}(a) = \frac{(K_{II}^{\text{stat}}(a))^2}{E}$ (Freund (1990), Eqn. 5.3.10). The quantity
 270 $K_{II}^{\text{stat}}(a)$, the static mode-II stress intensity factor, can then be calculated explicitly as (Tada et al.
 271 (2000), Eqn. 8.3; Kammer et al. (2015); Bayart et al. (2016)),

$$272 K_{II}^{\text{stat}}(a) = \frac{2}{\sqrt{\pi a}} \int_0^a \frac{\Delta\sigma_{xy}(s) F\left(\frac{s}{a}\right)}{\sqrt{1 - \left(\frac{s}{a}\right)^2}} ds, \quad (3)$$

272 where $F\left(\frac{s}{a}\right) = 1 + 0.297\left(1 - \left(\frac{s}{a}\right)^{\frac{5}{4}}\right)$, a is the crack length, and ds is an increment of crack length.
 273 In the frameworks of LEFM and cohesive zone models, the residual friction is often treated as a

274 local property of the interface (e.g., Bayart et al. (2016); Ke et al. (2018)), such that the residual
 275 shear stress can be predicted based on the known normal stress prior to the rupture. This enables
 276 the calculation of first K_{II}^{stat} and then G^{stat} from the initial loading conditions. In the case of
 277 conventional singularities, this approach provides values of G^{stat} which show excellent agreement
 278 with observed rupture arrest when compared to G_c (e.g., Bayart et al. (2016, 2018); Ke et al.
 279 (2018)). However, in the case of the unconventional singularities observed here, the calculation
 280 of $\Delta\sigma_{xy}$ is less clear. Behind the observed rupture arrest length, in an analogous fashion to LEFM,
 281 the measured stress drops (which, unlike for conventional-singularity-driven ruptures, include
 282 long-tailed weakening) might be taken after the shear stress achieves a relatively constant value.
 283 In front of the observed rupture arrest length, and again as in LEFM (e.g., Bayart et al. (2016); Ke
 284 et al. (2018)), an attempt might be made to predict the residual shear stress were the crack to pass
 285 a given location. The challenge arises from the fact that shear cracks driven by unconventional
 286 singularities do not present locally-constant values of residual friction. Consequently, variations
 287 in stress drop, slip, and rupture length are all interdependent, as observed in elastodynamics
 288 (e.g., Madariaga (2015)). Nevertheless, to adhere to a procedure typical of LEFM, an attempt
 289 was made to characterize the “residual” friction of the fault ahead of the observed rupture arrest
 290 length, and thereby predict the residual shear stress and stress drop that would result after the
 291 passing of a rupture front. This involved determining the “residual” friction of all complete
 292 ruptures, taking the median of this ensemble, and using this value to predict the stress drop
 293 that would have occurred for the contained ruptures were they to outgrow the location of their
 294 actual arrest. This residual friction profile therefore varies spatially and is assumed to be a local
 295 property of the interface.

296 This approach enables the estimation of G^{stat} , representative of the mechanical energy flux to
 297 the crack tip. G^{stat} is reduced during the preconditioning experiments, Figure 6(a-c), reflecting
 298 the reduction in energy flux when preconditioning is applied and occurring due to reduction in
 299 stress drop available to propagate the crack, Figure 4(j-l). This stress drop reduction, in turn, is
 300 due to the increase in the “residual” shear stress, appendix D. Due to the preconditioning phase,
 301 the normal stress distribution prior to rupture nucleation is increased from its *in-situ* value, while
 302 the shear stress distribution remains approximately unchanged, Figure 2(d,f). As the “residual”
 303 shear stress depends directly on the normal stress, this implies that the drop in shear stress avail-
 304 able has been reduced by preconditioning. Indeed, preconditioning and stress barriers in general
 305 (i.e., local decreases in shear stress and/or local increases in normal stress) can even result in a
 306 negative stress drop, whereby shear stress is actually increased by the passing rupture, removing
 307 energy from the propagating crack tip, Figures 4(j-l). In fact, whether or not a stress drop is pre-
 308 dicted to be negative or positive has been suggested numerous times as a criterion for dynamic
 309 rupture propagation (Garagash and Germanovich, 2012; Cebry et al., 2022), and is inherent in
 310 the LEFM framework (Freund (1990), Eqn 7.4.27; Bayart et al. (2016, 2018); Ke et al. (2018))
 311 as a negative stress drop leads to a sharp decrease in energy release rate, see Figure 6(a-c). These
 312 stress drop barriers represent *global* impediments to rupture propagation as the stress drop across
 313 the entire interface of the slipping fault must be taken in to consideration. These experimental
 314 results highlight that pore pressure changes realistically achievable with pore pressure precondi-
 315 tioning (i.e., tens of percent of the normal stress) lead to relatively large changes in G^{stat} when
 316 compared to the potential changes in fracture energy, in conditions relevant for laboratory experi-
 317 ments (up to two orders of magnitude for G^{stat} compared to approximately a factor of four for
 318 G_c). Indeed, at $x = 15$ cm, a common position for rupture arrest, G_c is predicted to be increased
 319 by a factor of approximately two due to preconditioning, see appendix C. Conversely, at this
 320 position G^{stat} is increased by a factor of 10 and 100 for experiments at a nominal normal stress

321 of 90 and 120 bar, respectively. There is limited apparent effect for experiments performed at a
 322 nominal normal stress of 60 bar. Hence, the primary mechanism leading to the arrest of a rupture
 323 related to fault or reservoir preconditioning is the reduction of energy flux to the crack tip.

324 4.2. Influence of barrier size on rupture arrest

325 Our results demonstrated that fault preconditioning can halt potential seismic rupture prop-
 326 agation due to the reduction of the energy flux to the crack tip. However, several studies have
 327 shed light on ruptures skipping over spatially-limited barriers (Das and Aki, 1977; Cebry et al.,
 328 2023). The focus here has been principally placed on testing different magnitudes of pore pres-
 329 sure preconditioning, with $\frac{\Delta\sigma^p}{\sigma^0} = 0.08, 0.16, 0.24$. However, as previously highlighted (Fryer
 330 et al., 2023), the extent of this barrier is also of significance. If the period of production leading
 331 to preconditioning is too short, the stress barrier may be large in magnitude, but will be small in
 332 extent. It is therefore possible that dynamically-propagating ruptures will be able to overcome
 333 these barriers and continue propagating. To illustrate this, preconditioning was only applied to
 334 one of the pistons (both central- and periphery-only preconditioning were tested, affecting ap-
 335 proximately one third of the fault length), with the result compared to the base case where the
 336 entire sample interface is preconditioned, Figure 7. As can be seen, the ruptures in these cases
 337 are liable to skip past the barrier for low values of $\frac{\Delta\sigma^p}{\sigma^0}$, highlighting the significance of achiev-
 338 ing pore-pressure decreases which are not just large in magnitude, but also in extent. Stress
 339 drops behind the crack tip recorded 1 msec after the trigger were also used to reconstruct the
 340 $\frac{G^{\text{stat}}}{G_c}$ profiles of these events. Generally, good but imperfect agreement is achieved with theory as
 341 the case with preconditioning applied to only the left-most piston never achieves values of G^{stat}
 342 significantly lower than G_c and is the only case presented in which the rupture is not arrested,
 343 Figure 7a. Note further that the rupture renucleates beyond the preconditioning stress in the case
 344 that preconditioning is only applied to the middle piston, Figure 7b.

345 4.3. Can the effect of fault preconditioning on rupture length be predicted?

346 Following Barras et al. (2023), their equation 31, the arrest length, \bar{L}_{arr} , of a crack-like rup-
 347 ture encountering a stress barrier can be predicted in the framework of LEFM for the case of
 348 homogeneous loading and constant residual friction by,

$$\bar{L}_{\text{arr}} = -\frac{\bar{x}_b \bar{\tau}_0}{\bar{\tau}_b}, \quad (4)$$

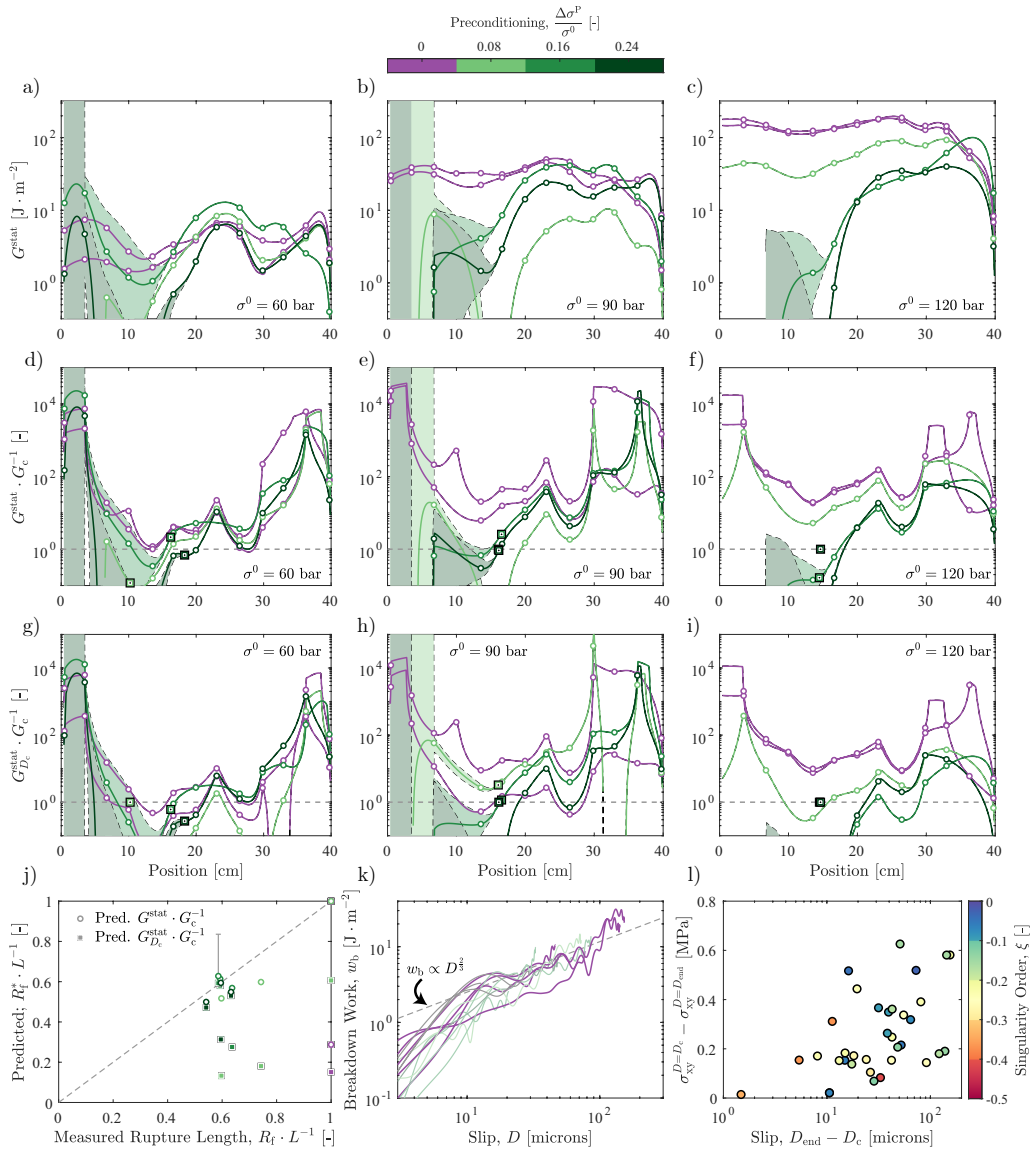
349 where $\bar{x}_b = \frac{x_b}{H}$ is the position of the barrier normalized by the damage zone, H , and $\bar{\tau}_0$ and $\bar{\tau}_b$ are
 350 the dimensionless stress parameters outside and within the barrier,

$$\bar{\tau}_0 = \frac{\frac{\sigma_{xy}^0}{\sigma_{yy}^0} - f_r}{f_p - f_r}, \quad \bar{\tau}_b = \frac{\frac{\sigma_{xy}^b}{\sigma_{yy}^b} - f_r}{f_p - f_r}, \quad (5)$$

351 resulting in, for the dimensional form of arrest length,

$$L_{\text{arr}} = x_b \frac{\sigma_{xy}^0 - f_r \sigma_{yy}^0}{\sigma_{xy}^b - f_r \sigma_{yy}^b}. \quad (6)$$

352 Here, σ_{xy}^0 and σ_{yy}^0 are the shear and normal stresses in the zone outside the barrier, and σ_{xy}^b and
 353 σ_{yy}^b are the shear and normal stresses within the barrier, respectively. f_p and f_r are the peak and



354 residual friction coefficients, respectively. This equation represents a simplified approach with
355 its use of unrealistic homogeneous stress values, see Figure 2. However, it may still provide
356 a first-order estimate of the arrest length of the rupture. Considering that two out of the three
357 pistons maintain their preconditioned load during the unloading of the third piston, the barrier
358 position can be taken as one-third of the sample length, or approximately 13 cm. In the case
359 that the nominal normal load is 120 bar, the shear stress can be taken as approximately 1.2 MPa,
360 Figure 2(e,f). The normal load is more heterogeneous. At the moment of nucleation, in the case
361 that $\sigma^0 = 120$ bar, the normal stress is approximately 0.8 MPa in the unloaded zone and 1.6 MPa
362 in the barrier region. Finally, the measured residual friction is heterogeneous across the sample
363 interface, but to a first order might be taken as 0.5. Crudely, this yields an arrest length estimate
364 of 26 cm which is in agreement with the measured rupture lengths for the preconditioned cases,
365 Figure 4(a-c). It should be emphasized, however, that there is a large degree of arbitrariness in
366 this calculation, which inherently does not consider the large degree of heterogeneity along the
367 sample interface, despite the tested material's synthetic nature and the highly-controlled labo-
368 ratory environment. Indeed, for the experiments performed at a nominal normal stress of 120
369 bar without preconditioning, the normal stress in the barrier region is only marginally lower,
370 Figure 2, yet this small discrepancy in normal stress is sufficient to enable complete rupturing
371 in all cases which are not preconditioned. It is difficult to see how such fine margins could be
372 accurately captured by an approach which does not incorporate heterogeneity. More success
373 may be had applying this approach to either larger-scale or more extreme cases, where the stress
374 conditions are not on the border between halting or encouraging rupture propagation.

375 Conversely, the approach of Section 4.1.2 integrates the heterogeneity present along the fault
376 into its prediction of rupture halting and has been successful in this regard (e.g., Bayart et al.

Figure 6 (*preceding page*): While Equation 3 can be used in the prediction of rupture arrest length using the full stress drop, the stress drop at $D = D_c$ does not provide satisfactory predictions. Therefore, in order to describe shear crack growth when driven by unconventional singularities for which energy dissipation is not exclusively located at the crack tip, continued weakening after $D = D_c$ must be incorporated; the consideration of energy dissipation localized in the vicinity of the rupture tip without the inclusion of tail processes is not sufficient. (a-c) The profiles of G^{stat} for each experiment. G^{stat} is based on a combination of the measured stress drop behind the ultimate crack tip arrest length and the predicted stress drop ahead of the ultimate observed crack tip arrest length. The prediction ahead of the ultimate crack tip arrest length is based on the median of the ensemble of residual friction values calculated from experiments without preconditioning, as these experiments exhibited complete ruptures, appendix D. The uncertainty bounds are based on the first and third quartile of the same ensemble of residual friction values. (d-f) The evolution of $\frac{G_c^{\text{stat}}}{G_c}$ for each experiment. G_c profiles are calculated based on the measured normal stress and the trend shown in Figure 5c. (g-i) The evolution of $\frac{G_{D_c}^{\text{stat}}}{G_c}$ based on the profiles of $G_{D_c}^{\text{stat}}$ built using the stress drop at $D = D_c$. Note that for certain strain gauges it was not possible to accurately pick D_c . At these strain gauges the full stress drop was used, such that $\frac{G_{D_c}^{\text{stat}}}{G_c}$ is overestimated. The friction profile used to predict stress drops ahead of the rupture tip was also built using the stress drop at $D = D_c$. (d-i) The position at which the rupture was arrested, based on the videograms, is shown with a square. Where possible the square is placed on the relevant $\frac{G_c^{\text{stat}}}{G_c}$ curve; otherwise it is placed at $\frac{G_c^{\text{stat}}}{G_c} = 1$. j) The predicted rupture length versus the measured rupture length for the cases that the energy flux is calculated using the full stress drop, G^{stat} , and the stress drop at $D = D_c$, $G_{D_c}^{\text{stat}}$. k) The breakdown work development with slip for all experiments based on a strain gauge rosette located outside the approximate point of nucleation (rosette located at $x = 29.9$ cm). Emphasis is placed on complete ruptures, with preconditioned experiments in a faded color. The ruptures from calibration experiments at the same rosette are shown in faded grey. The breakdown work for all calibration experiments can be found in the appendix B. l) The difference in residual shear stress at $D = D_c$ compared to when $D = D_{\text{end}}$ versus the slip occurring after $D = D_c$. D_{end} is the final value of slip. The color bar shows the inverted value of ξ , the singularity order of the rupture at the location of the strain gauge. Experiments performed at (a,d,g) 60, (b,e,h) 90, and (c,f,i) 120 bar nominal normal stress. (a-k) The color bar indicates the amount of preconditioning used in each experiment.

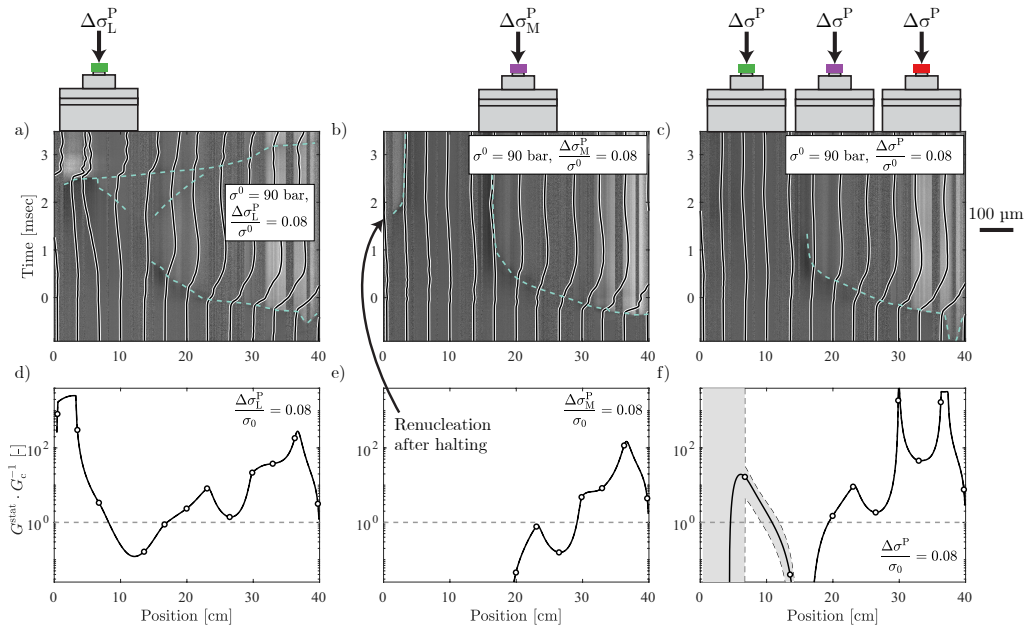


Figure 7: Three separate experiments, all performed at a nominal normal stress of 90 bar and a preconditioning stress of 7 bar. Unloading is performed only by the right-hand side piston. (a-c) The videogram illustrates the progression of the rupture front and is overlain by the local displacement recorded by the horizontally-oriented accelerometers (black lines). The scale for the displacement found from the accelerometers is found on the right. The rupture front is traced with a dotted teal line. Note that certain spatial bands where the grey-scale remains uniform on the videograms correspond to areas where light was not able to pass through the sample at the height of the fault. This is due to it being blocked by a sensor. (d-f) The ratio of G^{stat} to G_c calculated 1 msec after the trigger. As the ratio falls below one the rupture is predicted to halt. White dots mark the locations of strain gauge rosettes. (a,d) Preconditioning is only applied by the left-most piston. The rupture is initially slowed before accelerating again after approximately 2.5 msec. (b,e) Preconditioning is only applied to middle piston. The rupture is halted but is then able to jump past the barrier and reinitiate on the left-hand side of the sample. (c,f) Preconditioning is applied to all three pistons. The rupture is halted and does not reinitiate. Note that rupture halting is predicted in (f) despite the large values of $\frac{G^{\text{stat}}}{G_c}$ predicted on the left-hand side of the sample.

377 (2016, 2018); Ke et al. (2018)). However, unlike the predictions by Barras et al. (2023) and
 378 others (e.g., Kammer et al. (2015)), these approaches require the characterization of the residual
 379 friction (and therefore residual shear stress) along the entirety of the fault, and generally assume
 380 that the residual friction is a local interface property. This poses a problem for the case of un-
 381 conventional singularities, where a steady-state residual friction is not reached and the amount
 382 of weakening and residual shear stress depend on the amount of slip, Figure 6(k,l). Interestingly,
 383 by considering the full stress drop in Equation 3, the calculation of G^{stat} yields satisfactory pre-
 384 dictions of rupture arrest length when compared to G_c , Figure 6(d-f,j). Unfortunately, due to the
 385 continued weakening, the *a priori* predictions of these full stress drops is not obvious, with slip,
 386 rupture length, and stress drop being fully coupled.

387 One alternative possibility is to assume that the energy dissipation relevant for driving the
 388 rupture is exclusively located at the crack tip, in the process zone. If this were to be the case,
 389 it might be possible to characterize the interface's residual friction at $D = D_c$ such that *a priori*
 390 predictions could be performed. To test this assumption, the stress drop up to $D = D_c$ was used
 391 in Equation 3 to ultimately calculate the tip-localized static energy flux, $G_{D_c}^{\text{stat}}$. $G_{D_c}^{\text{stat}}$ is always less
 392 than or equal to G^{stat} due to continued long-tail weakening which occurs when $D > D_c$ (Lambert
 393 and Lapusta, 2020; Brener and Bouchbinder, 2021b,a; Paglialonga et al., 2022, 2024). Values of
 394 $G_{D_c}^{\text{stat}}$ were compared to G_c to predict crack arrest, Figure 6(g-i). This methodology under predicts
 395 ultimate crack length, Figure 6(j), implying that $G_{D_c}^{\text{stat}}$ is an under-prediction of the energy driving
 396 rupture propagation. The continued weakening occurring when $D > D_c$, Figure 6(k,l), which
 397 is not localized at the crack tip, therefore plays a significant role in the propagation of ruptures
 398 driven by unconventional singularities. Further, as this continued weakening must be considered
 399 when calculating the energy flux driving the crack tip, the characterization of a residual friction
 400 to be used in the *a priori* prediction of stress drop is difficult or even impossible for these ruptures
 401 as a true residual friction is not achieved even after $D \gg D_c$. Several weakening mechanisms are
 402 expected to induce long-tailed weakening (i.e. unconventional singularity orders), such as thermal
 403 pressurization (Viesca and Garagash, 2015), flash heating (Brantut and Viesca, 2017), and melt
 404 lubrication of the full fault interface (Di Toro et al., 2011). Therefore, long-tailed weaken-
 405 ing may be a common phenomenon for natural earthquakes. Nevertheless, it cannot be excluded
 406 that the residual friction might reach a steady-state value after a large amount of slip such that an
 407 equilibrium between the heat production and the heat dissipation within the fault zone has been
 408 achieved (although this seems unlikely for thermal pressurization considering the relatively long
 409 time scale of fluid diffusion). If this steady state residual friction is attained, the singularity is
 410 expected to become conventional, allowing for predictions using LEFM. However, steady state
 411 will require large amounts of slip (>10 meters (Di Toro et al., 2011), likely corresponding to a
 412 large moment-magnitude, $M_w > 7$, earthquake), resulting in cohesive zones on the order of kilo-
 413 meters (considering slip velocities on the order of meters per second and rupture velocities of
 414 many hundreds of meters per second). These large sections the fault which do not achieve suffi-
 415 cient slip will not reach a steady state friction. This steady state is further unlikely to be achieved
 416 in the context of induced seismicity and smaller magnitude events as thermal slip equilibrium
 417 distances depend inversely on normal stress (Di Toro et al., 2011).

418 In order for fracture mechanics to one day provide *a priori* predictions of rupture arrest for
 419 unconventional singularities, it must account for this continued weakening (Brener and Bouch-
 420 binder, 2021b,a). Ideally, an equation of motion describing the propagation of the ruptures should
 421 be developed to replace the edge-localized Equation 1 for unconventional-singularity-driven rup-
 422 tures. It may be that, in the case of rupture arrest, this equation of motion will lend itself to cases

423 where G_c can be neglected, potentially leading rupture propagation domains, such as a stress-
424 drop-dominated domain, analogous to the zero-toughness asymptotic solutions for fluid-driven
425 mode-I fractures (Savitski and Detournay, 2002). At any rate, it has been shown here that stress
426 barriers not only affect the LEFM-defined parameters G_c and G , they also further reduce the
427 breakdown work by reducing the slip and weakening (stress drop) occurring outside of the co-
428 hesive zone, thereby further reducing the energy flux propagating to the crack tip beyond what
429 can be predicted by LEFM. Indeed, the events with the smallest amount of additional weaken-
430 ing when $D > D_c$ are those with the largest stress barriers. This additional, distal weakening
431 has been shown to be significant for the accurate calculation of the energy flux to the crack tip.
432 These results are even more relevant for induced seismicity, since shear ruptures propagating in
433 the presence of fluids are inherently expected to be driven by unconventional singularities (i.e.,
434 even without the activation of thermal weakening, as for instance in the case of mode-I frac-
435 tures), due to the diffusion of the fluid pressure along the fault and in the surrounding medium
436 (Garagash et al., 2011).

437 4.4. Natural stress barriers and earthquake swarms

438 Heterogeneous pore pressure fields associated with some seismic swarms can induce stress
439 barriers which can be used to explain changes in stress drop within the swarm without recourse
440 to material or total-stress heterogeneity. Earthquake swarms are common in areas of volcanism
441 and geothermal activity and occur such that the number and magnitude of earthquakes fluctuate
442 in time whilst not presenting a distinct, larger-magnitude main shock (Mogi, 1963). Swarms
443 have been previously suggested to be related to heterogeneous material properties and stress
444 distributions (Mogi, 1963), with evidence from laboratory (Scholz, 1968) and earthquake moni-
445 toring (Ross et al., 2020) studies. For example, the 2016-2019 earthquake swarm near Cahuilla,
446 California is thought to have been due to fluid influx and to be located along a fault with per-
447 meability barriers (Ross et al., 2020). In fact, before the occurrence of a moment magnitude,
448 M_w , 4.4 earthquake, the swarm was seen to migrate in space and time, exhibiting progressively
449 lower stress drops (Ross et al., 2020). While the influence of mechanical properties is likely in
450 this case (Ross et al., 2020), for a constant shear stress (on the time scale of the fluid diffusion),
451 a lower fluid pressure will result in an increased effective normal stress and, therefore, an in-
452 creased “residual” shear stress, resulting in an ultimately lower stress drop, as has been shown
453 in this work. Since the fluid source in this M_w 4.4 earthquake’s case was thought to be coming
454 from a point source (a broken seal connected to a deeper reservoir) (Ross et al., 2020), the earth-
455 quakes occurring farther from the point source were likely occurring in and/or propagating into
456 zones of lower fluid pressure and therefore higher residual shear stress, offering an additional
457 explanation for trends in stress drop seen for this swarm. It should be further noted that, as with
458 injection-induced seismicity, fluid-driven earthquake swarms can be expected to be characterised
459 by unconventional-singularity-driven ruptures due to their reliance on fluid pressure, making the
460 results presented here particularly applicable.

461 5. Conclusion and Outlook

462 Preconditioning has been demonstrated experimentally, with stress changes that correspond
463 to pore pressure changes which are reasonably achievable in the field. Preconditioning consis-
464 tently results in rupture arrest at stress changes which correspond to pore pressure reductions of
465 $2 \frac{\text{MPa}}{\text{km}}$. All tested magnitudes of preconditioning (1, 2, and $3 \frac{\text{MPa}}{\text{km}}$) result in reduced co-seismic

466 slip, slip velocity, stress drop, and seismic moment. However, these experiments were performed
467 on analogue material at laboratory scales and stresses. Meso-scale testing could be pursued to
468 test the influence of these limitations.

469 The experimental ruptures investigated here were driven by unconventional singularities,
470 such that breakdown work continuously increased with slip. LEFM requires scale separation
471 between edge-localized dissipation and linear elastic driving energy. The breakdown work in-
472 creasing with slip breaks this scale separation as the energy dissipation is not exclusively local-
473 ized near the crack tip (Brener and Bouchbinder, 2021b,a; Paglialunga et al., 2022, 2024). This
474 makes the *a priori* use of a constant residual frictional coefficient to predict rupture arrest unten-
475 able. In order to precisely predict rupture arrest the full evolution of shear stress with slip must
476 be considered, and an equation of motion for unconventional-singularity-driven ruptures should
477 be developed. Here, ruptures which propagated into stress barriers were characterised by less
478 slip and less weakening (stress drop) behind the crack tip. This means that stress barriers arrest
479 ruptures by not just increasing the “residual” shear stress reached in the cohesive zone of the
480 passing crack tip, they also reduce the long-tailed weakening occurring farther behind the crack
481 tip by inhibiting slip and rupture advance. In summary, stress barriers increase fracture energy,
482 reduce energy flux to the crack tip resulting from cohesive-zone weakening, and reduce energy
483 flux to the crack tip resulting from distal, long-tailed weakening. All three of these effects aid
484 in the arrest of the rupture and explain not only why preconditioning has the ability to reduce
485 seismic hazard but also why natural fluid-driven earthquake swarms might exhibit lower stress
486 drops away from the fluid source.

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497 tional licence

498 Data availability

499 The data collected for this work and used in the analyses is publicly available (Fryer et al.,
500 2024).

501 Appendix A. Tracking the rupture

502 Strain gauge data are filtered with a 6-th order low-pass Butterworth filter at 28 kHz, except
503 for the fitting of the singular field where the filter is set to 100 kHz. The strain, ϵ_i , measured on

504 each strain gauge, i , is calculated as,

$$\epsilon_i = \frac{-4V_i}{V_{\text{ex}} \left(G_f G_{\text{amp}} \left(1 + \frac{2V_i}{V_{\text{ex}} G_{\text{amp}}} \right) \right)}, \quad (\text{A.1})$$

505 where V_i is the voltage measured by the i -th strain gauge, V_{ex} the excitation voltage, G_f the gauge
 506 factor, and G_{amp} the amplification gain. Depending on the orientation of the strain gauge from
 507 the vertical direction in degrees, these strains are referred to as ϵ_{315} , ϵ_0 , and ϵ_{45} . These strains are
 508 then used to calculate the strain tensor at the location of the strain gauge rosette as,

$$\epsilon_{xx} = \epsilon_{315} + \epsilon_{45} - \epsilon_0, \quad \epsilon_{yy} = \epsilon_0, \quad \epsilon_{xy} = \frac{\epsilon_{45} - \epsilon_{315}}{2}. \quad (\text{A.2})$$

509 The stress tensor was then calculated using Hooke's Law in plane stress, considering the strain
 510 rate dependence of the Young's Modulus of PMMA. A static Young's Modulus of 3.3 GPa and
 511 a dynamic Young's Modulus of 5.7 GPa were employed. Poisson's ratio was taken as 0.33,
 512 appropriate for PMMA. The static Young's Modulus was used to find all loading-phase stresses.
 513 The dynamic Young's Modulus was used to calculate the dynamic stress drop, following Bayart
 514 et al. (2016, 2018).

515 For each frame, the grayscale image recorded by the camera is taken as a 1280 x 32 matrix
 516 where the value ranges from zero (black) to a maximum value (white). The average grayscale
 517 map of the first 20 frames serve as a reference. All the future frames are compared to this
 518 reference in order to track stress changes along the interface and, therefore, track the rupture
 519 front position (e.g., Nielsen et al. (2010); Schubnel et al. (2011)).

520 The data from the accelerometers is converted from mV into $\frac{\text{m}}{\text{sec}^2}$ using the calibration pro-
 521 vided by Brüel & Kjær. These accelerations are integrated twice in time to find both the velocity
 522 and displacement (e.g., Schubnel et al. (2011)). These data are unfiltered and multiplied by two,
 523 considering they represent movement on only one of the two similarly-sized blocks.

524 Appendix B. Characterizing dynamic rupture

525 To further confirm the presence of the unconventional singularity orders, the stress pertur-
 526 bation associated with a passing rupture can be described as (Irwin (1957); Freund (1990), Eqn
 527 4.3.23; Paglialunga et al. (2024), Eqns 7-9),

$$\begin{aligned} \Delta\sigma_{xx}(r, \theta) &= \frac{4(\xi + 1) K_{\text{II}}^{(\xi)}}{\hat{D} \sqrt{2\pi}} \left[\alpha_s (1 + 2\alpha_d^2 - \alpha_s^2) r_d^\xi \sin(\xi\theta_d) - \alpha_s (1 + \alpha_s^2) r_s^\xi \sin(\xi\theta_s) \right], \\ \sigma_{xy}(r, \theta) &= \sigma_{xy}^{\text{min}} + \frac{2(\xi + 1) K_{\text{II}}^{(\xi)}}{\hat{D} \sqrt{2\pi}} \left[4\alpha_s \alpha_d r_d^\xi \cos(\xi\theta_d) - (1 + \alpha_s^2)^2 r_d^\xi \cos(\xi\theta_s) \right], \\ \Delta\sigma_{yy}(r, \theta) &= \frac{4(\xi + 1) \alpha_s (1 + \alpha_s^2) K_{\text{II}}^{(\xi)}}{\hat{D} \sqrt{2\pi}} \left[r_d^\xi \sin(\xi\theta_d) - r_s^\xi \sin(\xi\theta_s) \right], \quad (\text{B.1}) \end{aligned}$$

528 where r and θ are polar coordinates centered on a steadily-moving crack tip, $K_{\text{II}}^{(\xi)}$ is the instan-
 529 tantaneous mode-II stress intensity factor, $\hat{D} = 4\alpha_d \alpha_s - (1 + \alpha_s^2)^2$ is the Rayleigh function (Freund
 530 (1990), Eqn 4.3.8), and $\alpha_d = \sqrt{1 - (v/C_d)^2}$ and $\alpha_s = \sqrt{1 - (v/C_s)^2}$ are velocity factors (Fre-
 531 und (1990), Eqn 4.3.12), where v is the rupture velocity and C_d and C_s are the P- and S-wave

Table B.1: Results of the fitting procedure used to find G_c described in the text. The ID contains the nominal normal stress of the calibration experiment, the event number, and the strain gauge rosette number. σ_{yy} is the local normal stress measured by the strain gauges, v the local rupture velocity found from the videograms, l is the cohesive zone size and is found by choosing D_c on the plot of w_b vs. D (see main text for plot and Paglialunga et al. (2024), for example) and finding the time required to achieve this D_c since the passing of the rupture front. This time is multiplied by v (assumed constant) to yield l . The error in l is found based on the error in D_c (which affects the time to achieve D_c) and an assumed error of $10 \frac{\text{m}}{\text{sec}}$ in v . Note that the uncertainty in l can be considered to be larger than the error presented here due to the sensitivity of l to other parameters. $G_c (D = D_c)$, D_c , and ξ are found from the plot of breakdown work versus slip.

ID	σ_{yy} [MPa]	v [$\frac{\text{m}}{\text{sec}}$]	$G_c (\xi = -\frac{1}{2})$ [$\frac{\text{J}}{\text{m}^2}$]	l [cm]	D_c [μm]	$G_c (D = D_c)$ [$\frac{\text{J}}{\text{m}^2}$]	ξ [-]
200/1/11	1.95	214	9.77	1.2 ± 0.2	16 ± 3	7.47 ± 0.38	-0.24 ± 0.03
200/2/10	1.76	281	4.94	0.6 ± 0.2	9 ± 5	2.55 ± 0.18	-0.52 ± 0.04
200/2/11	2.07	178	8.10	1.3 ± 0.1	12 ± 1	4.51 ± 0.30	-0.24 ± 0.04
200/3/7	2.61	145	4.69	4.2 ± 0.3	19 ± 0	5.06 ± 0.22	-0.18 ± 0.25
200/3/11	2.19	159	8.12	1.6 ± 0.4	15 ± 5	6.01 ± 0.45	-0.27 ± 0.06
300/4/5	2.39	26	13.68	2.3 ± 1.0	19 ± 1	6.43 ± 0.40	-0.23 ± 0.06

532 velocities, respectively. σ_{yy} is positive in compression. The polar coordinates are corrected
533 for distortion as $\theta_d = \arctan(\alpha_d \tan(\theta))$, $\theta_s = \arctan(\alpha_s \tan(\theta))$, $r_d = r \sqrt{1 - (v \sin(\theta) / C_d)^2}$, and
534 $r_s = r \sqrt{1 - (v \sin(\theta) / C_s)^2}$ (Freund (1990), Eqn 4.3.12). σ_{xy}^{\min} is the minimum value of shear
535 stress achieved after the passing of the rupture. By fitting all three stress components to Equa-
536 tion B.1, $K_{II}^{(\xi)}$ can be found for each location along the fault with reliable strain gauge measure-
537 ments. The singularity order, ξ , is -0.5 for conventional-singularity-driven shear cracks, which
538 reduces Equation B.1 to the classical equations (Freund (1990), Eqn 4.3.23). Here, $K_{II}^{(\xi)}$ was fit
539 with both $\xi = -0.5$ and the value of ξ found from the fitting of the trend between breakdown
540 work to slip. The use of unconventional singularity orders generally resulted in superior fits,
541 thereby providing further evidence for the unconventional nature of these singularities. Note that
542 this inversion requires a constant rupture velocity. The variation in rupture velocities during these
543 experiments may lead to error in the inversion.

544 The fits performed assuming a conventional singularity order (i.e., $\xi = -0.5$) were used to
545 provide a point of comparison for the values of G_c found considering the trend between w_b and
546 D . Following LEFM, G , which depends on the velocity of propagation, can be related to the
547 dynamic mode-II stress intensity factor, $K_{II}^{(\xi=-0.5)}$, as (Freund (1990), Eqn 5.3.10; Bayart et al.
548 (2016)),

$$G(v) = \frac{\alpha(1-v^2)}{E} f_{II}(v) [K_{II}^{(\xi=-0.5)}(a, v)]^2, \quad (\text{B.2})$$

549 where $\alpha = 1$ in plane stress conditions, a is the crack length, and $f_{II}(v)$ is a decreasing function
550 of velocity equivalent to (Freund (1990), Eqn 5.3.11),

$$f_{II}(v) = \frac{\alpha_s v^2}{\hat{D}(1-v)C_s^2}, \quad (\text{B.3})$$

551 having the property $\lim_{v \rightarrow 0} f_{II}(v) = 1$ (Freund (1990), page 234). Considering then that during
552 dynamic rupture propagation $G = G_c$, the fit performed using Equation B.1 assuming $\xi = -0.5$,
553 allows for the calculation of G_c . This value of G_c and the value of G_c found from the trend
554 between w_b and D allow for the calibration of G_c 's dependence on normal stress, Table B.1.

555 Appendix C. Dependence of the fracture energy G_c on normal stress

556 G_c depends on both the stress drop and the critical slip distance (Rice (1980), Chapter 5;
557 Ohnaka (2003)) and therefore approximately quadratically with normal stress. Locally, both
558 peak and residual shear stress vary linearly with normal stress, due to changes in real contact
559 area (Bayart et al., 2016), with real contact area depending (sub-)linearly on normal stress (Bow-
560 den and Tabor, 1938; Archard, 1957). D_c can be estimated to vary linearly with normal stress
561 assuming a constant rupture velocity and purely slip weakening behaviour (Ida, 1972; Palmer
562 and Rice, 1973; Rice, 1980), with D_c 's dependence on normal stress shown experimentally for
563 PMMA (Paglialunga et al., 2022) and granite (Passelègue et al., 2016). Considering that fracture
564 energy is estimated as $G_c = D_c (\sigma_{yy}) \sigma_{yy} \frac{f_p - f_r}{2}$ (e.g., Ida (1972); Palmer and Rice (1973); Rice
565 (1980), Chapter 6; Okubo and Dieterich (1981, 1984)) in the linear slip weakening case, where
566 f_p and f_r are the peak and residual friction coefficients, respectively, the result is that fracture
567 energy is predicted to vary approximately quadratically with normal stress. This dependence
568 could be even stronger as $f_p - f_r$ is also considered to scale with normal stress (Passelègue et al.,
569 2016), for example through the activation of dynamic weakening mechanisms, such as flash
570 heating (e.g., Brantut and Viesca (2017)), where residual friction is greatly reduced. It should
571 be noted that K_{II}^{stat} also depends linearly on stress drop, implying a quadratic dependence of G^{stat}
572 on normal stress in an LEFM framework. The activation of thermal weakening mechanisms at
573 higher normal stresses, leading to long-tailed weakening, can be expected to further strengthen
574 this dependence and may lead to a scale dependence in the relative importance of G^{stat} and G_c at
575 higher normal stresses and longer rupture lengths. The measured normal stress and empirically-
576 estimated fracture energy profiles are displayed in Figure C.8.

577 Appendix D. Residual shear stress

578 In these experiments, the residual shear stress is not a constant, nor a material property,
579 Figure D.9. As described in the main text, normal stress barriers result in an increase in residual
580 shear stress due to their ability to impede frictional rupture, thereby reducing distal weakening.
581 Further, in a frictional setting the residual shear stress is generally thought as dependent on
582 normal stress. As normal stress barriers represent zones of increased normal stress, the residual
583 shear stress can be expected to be larger in these cases.

584 In order to predict the stress drop ahead of the ultimate crack length (i.e., in zones where
585 the rupture did not pass and stress drop could therefore not be measured), the residual friction
586 of the samples was characterized. This was done by taking the residual friction of all six non-
587 preconditioned experiments as these experiments exhibited complete ruptures. The median and
588 first and third quartile values of this ensemble, Figure D.10, were then used in combination with
589 the measured normal and shear stresses to predict the stress drops of unruptured zones in the
590 calculation of Equation 3. Note the edges of the sample exhibit large errors in residual friction
591 due to the low values of normal stress present in these locations. Generally these areas are
592 insignificant for rupture arrest prediction, as ruptures arrest typically between 10 and 20 cm.

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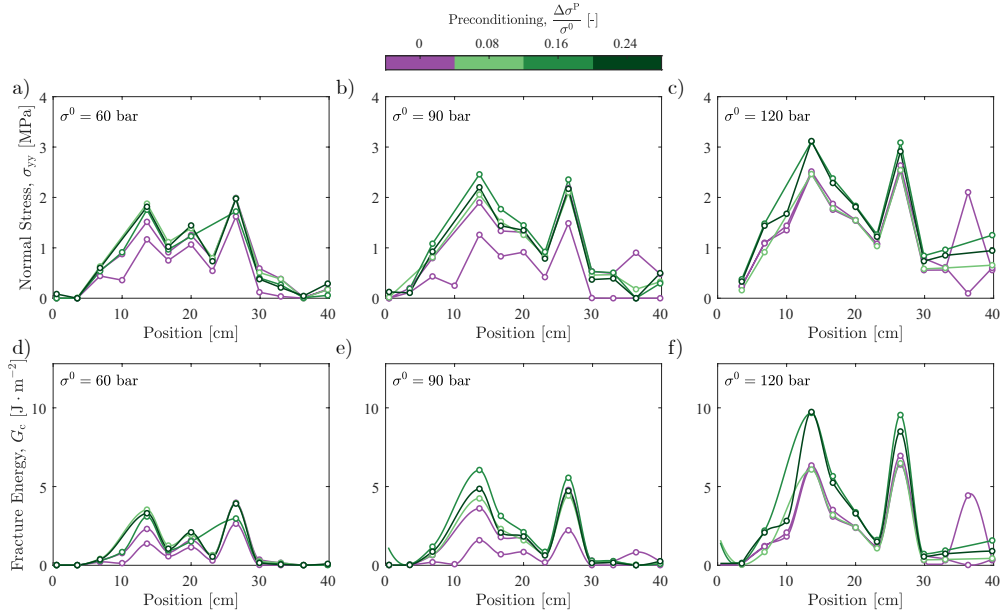


Figure C.8: (a-c) The normal stress measured by the strain gauges just before nucleation, found using the static Young's Modulus and limited to a minimum value of zero. (d-f) The predicted value of $G_c = \sigma_{yy}^2 + 0.001$ (with σ_{yy} in MPa) just before nucleation across the entire laboratory fault considering the measured normal stress. Experiments performed at (a,d) 60, (b,e) 90, and (c,f) 120 bar nominal normal stress. The color bar indicates the amount of preconditioning used in each experiment.

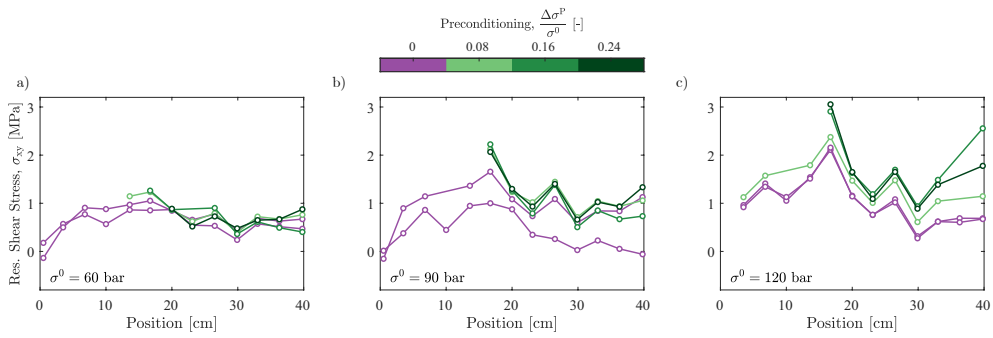


Figure D.9: The measured residual shear stress of each experiment, taken only for locations behind the arrested crack tip. Results for (a) 60, (b) 90, and (c) 120 bar nominal normal stress. The color bar indicates the amount of preconditioning used in each experiment.

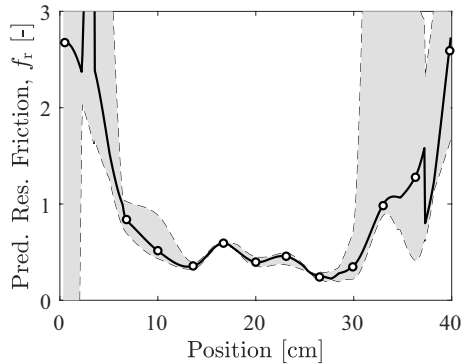


Figure D.10: The residual friction calculated based on all 6 non-preconditioned experiments, with estimated error shown as grey shading. The error and value of the residual friction are based on the first, second, and third quartile values of residual friction for the ensemble of experiments.

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