# Modelling precursory laboratory seismicity using a roughness-based rate- and state-dependent friction model

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# Abstract

We investigate experimental results from a direct shear friction apparatus, where a fault was formed by pressing mature, worn surfaces of two polymethyl methacrylate (PMMA) samples on top of each other in a dry environment. The fault was sheared until macroscopic stick-slip frictional failure occurred. Before the macro-failure small precursory seismicity nucleated from regions that also experienced aseismic slow slip. These precursory events did not cascade-up into gross fault rupture and arrested locally. Reasons as to why ruptures arrested are investigated using a 1-D rate and state friction (RSF) model. Surface profilometry of the fault surface taken \textit{a posteriori} revealed wear in the form of a bimodal Gaussian distribution of surface height. In our model, this unique distribution of surface roughness is determined to be a proxy for the heterogeneous spatial description of the critical slip distance  $D_{c}$ . We assume that smooth (polished) sections of fault exhibited lower  $D_{c}$  than rougher sections of the bimodal Gaussian roughness profile. We used a quasi-dynamic RSF model that determined localized seismicity initiated at the smooth sections. Source properties: average slip delta, seismic moment  $M_{0}$ , stress drop  $D_{c}$  we discuss and fracture energy  $C^{1}$ , were determined for each event. We compare the numerically modeled source properties to experimental source characteristics inferred from seismological estimates using an array of acoustic emission sensors from a concerted study. We discuss similarities, discrepancies and assumptions between these two independent models (kinematic and dynamic) used to study earthquakes for the first time in the laboratory.

# Modelling precursory laboratory seismicity using a roughness-based rate- and state-dependent friction model

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9 Key Points:

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10	• Rate and state friction (RSF) models were developed from roughness measurements
11	of a friction experiment that displayed properties of wear
12	• Simulations showed that smooth sections nucleated events that ruptured and were
13	arrested by local roughened sections representing barriers
14	• Source properties of the RSF ruptures were compared to independently measured
15	kinematic estimates from a concerted study for the first time

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#### 16 Abstract

We investigate experimental results from a direct shear friction apparatus, where a fault 17 was formed by pressing mature, worn surfaces of two polymethyl methacrylate (PMMA) 18 samples on top of each other in a dry environment. The fault was sheared until macro-19 scopic stick-slip frictional failure occurred. Before the macro-failure small precursory seis-20 micity nucleated from regions that also experienced aseismic slow slip. These precursory 21 events did not cascade-up into gross fault rupture and arrested locally. Reasons as to why 22 ruptures arrested are investigated using a 1-D rate and state friction (RSF) model. Sur-23 face profilometry of the fault surface taken a posteriori revealed wear in the form of a bi-24 modal Gaussian distribution of surface height. In our model, this unique distribution of 25 surface roughness is determined to be a proxy for the heterogeneous spatial description 26 of the critical slip distance  $D_c$ . We assume that smooth (polished) sections of fault ex-27 hibited lower  $D_c$  than rougher sections of the bimodal Gaussian roughness profile. We used 28 a quasi-dynamic RSF model that determined localized seismicity initiated at the smooth 29 sections. Source properties: average slip  $\delta$ , seismic moment  $M_0$ , stress drop  $\Delta \tau$  and frac-30 ture energy  $G^{'}$ , were determined for each event. We compare the numerically modeled source 31 properties to experimental source characteristics inferred from seismological estimates us-32 ing an array of acoustic emission sensors from a concerted study. We discuss similarities, 33 discrepancies and assumptions between these two independent models (kinematic and dy-34 namic) used to study earthquakes for the first time in the laboratory. 35

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#### Plain Language Summary

Recent seismic observations show that faults experience a range of slip patterns spanning many scales in both space and time. Understanding how slip accumulates on complex fault systems can lead to a better understanding of regions that are more prone and susceptible to large events.

We studied a scaled version of a frictional fault laboratory. This fault also showed complex slip behavior. We notice that scaled versions of earthquakes occurred in larger regions that were also slipping more slowly. This behavior has also been observed in nature but we are not certain as to why exactly. We linked this behavior to a mathematical model that describes friction on faults. To add complexity, we used the experimental roughness measured along the interface, which might explain the complicated slip patterns. Using the roughness, we found that the model produced earthquakes patterns and general be-

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haviors that matched many experimental measurements taken independently. We found
that complexity formed by fault roughness can produce a wide range of slip behaviors that
are also observed in natural systems at many scales. Understanding how roughness evolves
over a fault's lifetime will be important for moving forward earthquake science.

#### 52 1 Introduction

Growing amounts of seismologic observations capture an ever larger diversity in slip 53 behavior along natural faults. Over recent years seismologists have reported the occur-54 rence of slow earthquakes (Ide et al., 2007; Beroza & Ide, 2011) and it is now commonly 55 accepted that slip happens over different length and time scales (Peng & Gomberg, 2010). 56 Slow earthquakes themselves have been observed to have a wide range of slip behaviors 57 and radiation patterns. Due to the close spatial proximity of slow earthquakes to massive 58 megathrust earthquakes, connecting the physical impact of these slow processes imposes 59 on regions of the fault that is historically susceptible to fast sliding on large scales. Hav-60 ing insight in these connections is critical to developing a better understanding of the en-61 tire earthquake cycle (Obara, 2011; Obara & Kato, 2016). 62

It is believed that slow and fast earthquakes share a common slip mechanism (Obara 63 & Kato, 2016). Slow slip is also believed to occur in the nucleation phase associated with 64 the onset of frictional instability (also known as the premonitory or preslip phase). The 65 preslip phase has sometimes been identified in the onset of the mainshock seismogram (Iio, 66 1995; Ellsworth & Beroza, 1995). Detection of a nucleation phase at regional scales (kms) 67 using the onset of seismograms is difficult since it resides at the lower thresholds of seis-68 mologic capabilities (Tullis, 1996). Recent improvements in geodetic measurements (GPS, 69 InSAR) have been able to lower the detectable threshold and identify this phase over long 70 time scales (months to years) and length scales (kms) (e.g. Brodsky & Lay, 2014; Ruiz 71 et al., 2014; Socquet et al., 2017). The nucleation phase and associated premonitory slip 72 is well observed in laboratory experiments on frictional faults (Dieterich, 1978; Ohnaka 73 & Shen, 1999; Nielsen et al., 2010; Latour et al., 2013; McLaskey & Kilgore, 2013; P. A. Sel-74 vadurai & Glaser, 2015a) but remains debated as to whether it exists universally in highly 75 complex structures such as fault cores (e.g. Chester et al., 1993; Mitchell & Faulkner, 2009). 76

In this study, we focus on what controls the occurrence of foreshocks (or precursory
 seismicity) in the nucleation phase of laboratory ruptures. Laboratory studies suggest that

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asperities (i.e. frictional heterogeneity) exist on the fault (P. A. Selvadurai & Glaser, 2015a, 79 2017). One mechanism for foreshocks is that as a preslip region grows larger it acceler-80 ates, the increased stressing rate might contribute to the dynamic failure of these asper-81 ities (McLaskey & Kilgore, 2013). Another hypothesis is that asperities have higher lev-82 els of normal stress, thus locally decreasing its critical nucleation distance and if the as-83 perity is geometrically large enough it could potentially lead to dynamic failure in the pres-84 ence of preslip (Veedu & Barbot, 2016; P. A. Selvadurai & Glaser, 2017; Schaal & Lapusta, 85 2019). Studies of the initial onset of seismicity appear to indicate that asperities, which 86 exist at smaller spatial scales, even on natural faults, might provide the initial trigger lead-87 ing to fault failure at larger spatial scale (Iio, 1995; Ellsworth & Beroza, 1995; Beroza & 88 Ellsworth, 1996; Okuda & Ide, 2018). This type of hierarchical breakdown may be indi-89 cating the possible existence of a hierarchical plate interface structure. Foreshocks might 90 be local failures of these asperities that do not fully 'cascade-up. 91

Reasons as to why foreshocks arrest and do not always culminate in large earthquakes 92 are not well understood so far. We believe that ruptures begin to expand in a crack-like 93 manner, then accelerate outwards to a critical velocity, whereby they may transition to a pulse-like dynamic rupture (Heaton, 1990; Meier et al., 2016). The mechanism behind 95 whether a rupture transitions from a crack-like to pulse-like rupture is not well understood 96 and may depend on numerous factors such as heterogeneous presence of frictional barri-97 ers or prestress (Rubinstein et al., 2004; Maegawa et al., 2010; Trømborg et al., 2011; Kam-98 mer et al., 2012; Otsuki & Matsukawa, 2013; Kammer et al., 2015; P. A. Selvadurai et al., 99 2017; Ke et al., 2018). In this study, we assume that the presence of both fast and slow 100 rupture occur in the same region arises from and around asperities formed by topographic 101 mismatch of the two rough surfaces in our laboratory setting. 102

This study is separated into two parts: (i) Surface roughness is measured over a range 103 of length scales using metric from interdisciplinary fields of contact mechanics, tribology 104 and geophysics. (ii) We use the experimental surface roughness measurements, to develop 105 a dynamic friction model that obeys the rate and state friction (RSF). Part (ii) will help 106 us reconcile the seismically observed laboratory foreshocks (P. A. Selvadurai, 2019). The 107 RSF model investigates the concept that heterogeneity is a prerequisite for having syn-108 chronous slow and fast rupture on similar sections of a fault. In our model this was im-109 posed by assuming variable  $D_c$  along the modeled region. Spatial fluctuations in fault rough-110 ness – smoother and more rough sections – assumed properties based on arguments that 111

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follow past laboratory observations (Marone & Cox, 1994; Marone, 1998). Smooth sec-

tions were prescribed as lower  $D_c$ , whereas rough section were given higher levels of  $D_c$ .

- 114 This assumption is based on numerical modelling that explains  $D_c$  in terms of the microme-
- chanics governing friction on dry, gouge-free interfaces (Yoshioka & Iwasa, 1996).

The model developed here was used to simulate a range of experimental conditions 116 that concomitantly produced localized seismicity and aseismic slip on the fault. Seismic 117 source properties were extracted from a quasi-dynamic RSF numerical model and com-118 pared to estimates made from the spectral analysis of the seismic waves in a supporting 119 study (P. A. Selvadurai, 2019). With our frictional model we investigate some open ques-120 tions: (i) How does the level of strength heterogeneity or the evolving stress field affect 121 rupture initiation, propagation and arrest? (ii) How does this affect estimates on dynamic 122 source properties? And (iii) How does kinematic estimates compare to dynamic rupture 123 model with an implicit prescription of heterogeneity through roughness? 124

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# 2 Experimental Methods and Results

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# 2.1 Material Properties

<sup>127</sup> Physical properties of PMMA at room temperature are: Shear modulus G = 2.39 x<sup>128</sup> 10<sup>9</sup> Pa, Poisson's ratio  $\nu = 0.32$  and  $\rho = 1180 \text{ kg m}^{-3}$ . Using a Rockwell B Hardness test <sup>129</sup> the indentation yield strength was found to be Y = 586 MPa and the independently per-<sup>130</sup> formed differential scanning calorimetry (DSC) determined the glass transition to be  $T_g$ <sup>131</sup> = 114 °C. The body and shear wave velocities of the material were  $V_P = 2800 \text{ m s}^{-1}$  and <sup>132</sup>  $V_S = 1330 \text{ m s}^{-1}$ , respectively, giving a ratio  $V_P/V_S \approx$  of 2.1.

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# 2.2 Surface Preparation

The interacting faces of the PMMA slider block and base plate were first sandblasted 134 using 220-440  $\mu$ m particles of aluminum oxide (Al<sub>2</sub>O<sub>3</sub>) for a controlled time, distance and 135 pressure. Sandblasting surfaces is routinely used to produce self-affine properties that are 136 believed to occur during the generation of new faulting via the mechanism of tensile crack-137 ing (Power & Tullis, 1991; Schmittbuhl et al., 2006; Persson, 2014). Initial hand lapping 138 of the surfaces with SiC abrasives (Dieterich, 1994) will not result in worn surfaces resem-139 bling those formed by initially sandblasting then wearing the interface. According to Persson 140 (2014), surface lapping with sandpaper will roughen an initially flat surface without form-141

ing the high, sharp asperities. The removal of material is easier at the top of the asperity than in the valley creating a rough surface with a low fractal dimension. We believe
that sandblasting the freshly machined samples of PMMA was necessary to obtain initial conditions, which upon being frictionally worn past each other exhibited the unique
surface roughness and frictional behavior described in this study.

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# 2.3 Summarized General Findings

A schematic diagram of the direct shear friction apparatus is shown in Figure 1(a). 148 We refer to this scale as the macrosopic scale for the discussion. The reader is urged to 149 consult P. A. Selvadurai and Glaser (2015b) and P. A. Selvadurai and Glaser (2015a) for 150 a more detailed description of the experimental facilities. Full computer aided drawings 151 (CAD) of the all components direct shear apparatus and their technical drawings are given 152 in P. A. Selvadurai (2015). Experiments consisted of loading a long slender PMMA slider 153 (12.7 mm x 406 mm x 80 mm) onto a larger PMMA base plate (610 mm x 305 mm x 51 154 mm). During an experiment, the fault was maintained under constant normal load  $F_n$ . 155 The top slider was driven at a constant macroscopic loading rate  $V_{LP}$  and an in-line shear 156 load cell was used to measure the bulk frictional resistance along the fault. 157

Figure 1(b) shows a typical experiment where the macroscopic loading rate was  $V_{LP}$ = 0.010 mm s<sup>-1</sup> and the normal force was fixed at  $F_n = 4400$  N. We note that the shear force increased until a large dynamic release, or stick-slip event, occurred. This type of behavior is indicative of the shear force evolution for tests performed at various normal force levels of normal force  $F_n$ .

In Figure 1(b) the slip evolution (black line) for the stick-slip event as measured by the non-contact eddy current sensor (NC3) is shown. Figure 1(c) depicts a schematic representation of the eddy current sensor (mounted to the base plate) and the wing target attached to the slider block ~ 2.5 mm on above the interface. The inductive eddy current sensors measured slip  $\delta$  in the x-direction. We refer to this scale as the mesosopic scale for the discussion.

During a stick-slip cycle we observe slow and smooth accumulation of aseismic as detailed in Figure 1(d). We show lines of constant slip rate (magenta), which are superimposed over the slip evolution curve. We see that the fault displayed an acceleration of aseismic slip leading up to the stick-slip event. This type of observation is fairly common in



Figure 1. (a) Schematic details of the direct shear friction apparatus. General loading conditions and sensor placements are shown. For more technical details please consult the literature (P. A. Selvadurai & Glaser, 2015a, 2015b). (b) Typical result demonstrating the bulk frictional evolution in terms of shear slip and shear force leading up to failure. Normal force was constant and the macroscopic loading rate was  $V_{LP} = 0.010 \text{ mm s}^{-1}$ ; the normal force was fixed at  $F_n$ = 4400 N. (c) Schematic details of the non-contact eddy current sensor placement at the mesoscopic scale. (d) Detailed slip measurement during the experiment shown in (b). Mesoscopic slow aseismic slip was observed leading up to macroscopic stick-slip failure. Lines of constant slip velocity are shown for reference. Seismicity (green) is represented schematically to show the presence of local fast slip as the accelerated aseismic slip was observed. (e) An example of precursory seismicity recorded using PZT7. Seismicity showed clear P and S wave arrivals. More detailed source analysis has been performed by P. A. Selvadurai (2019). (f) Surface roughness measurement taken *a posteriori* using the longer length scale optical profilometer (Nanovea P50). The region on the fault associated with this scan is shown by the cross-section A-A in (c).

the laboratory friction experiments. However, we also observe pronounced impulsive events detected using the array of absolutely calibrated piezoelectric transducers (PZT) that measure high-frequency vibrations (100kHz to 1500 kHz) produced by stress waves.

In Figure 1(d) seismicity is shown schematically (green) since the time scales between the slow slip and this impulsive source was  $\sim 6$  orders of magnitude different. Figure 1(e) shows isolated P and S waves from a typical impulsive source as measured by PZT7. Seismological analysis that employed kinematic point source models based on physics associated with dynamic shear crack (e.g. Brune, 1970, 1971) were already used to infer source properties for these emissions in a concerted study by P. A. Selvadurai (2019).

As mentioned before, our friction model requires spatial heterogeneity to explain the 182 observations of concomitant slow (Figure 1(d)) and fast rupture (Figure 1(e)). We base 183 spatial heterogeneity on the experimental *a posteriori* measurement of surface roughness. 184 Optical profilomerty was performed using two devices that measured longer and shorter 185 length scales with increasing resolution. Figure 1(f) shows the optical scan of the top slider 186 blocks surface through the cross-section A-A' in Figure 1(d). The scans were taken be-187 low the non-contact sensor NC3 as shown. Details of the metrics used to quantify the sur-188 face are given next. 189

#### <sup>190</sup> 3 Characterizing Roughness

#### <sup>191</sup> 3.1 Surface Roughness Analysis

Based on the different metrics used to quantify surface roughness in the fields of contact mechanics, tribology and geophysics we will characterize the interfaces using four standard metrics. We deploy a measure of average roughness known as the root mean square:

$$h_{rms} = \sqrt{\left(\frac{1}{N}\right)\sum_{i=1}^{N}h_i^2},\tag{1}$$

where N is the total number of points and  $h_i$  is the individual surface height. To estimate statistical properties of surface heights we also employ the probability density functions (PDFs) of the surface height h defined by a modal Gaussian distribution. Given as follows:

$$\phi(h) = (2\pi\sigma) \exp\left[\frac{(h-\mu^*)^2}{2\sigma^2}\right],\tag{2}$$

where  $\mu^*$  is the arithmetic mean and  $\sigma$  is the standard deviation. Building on equation (2) we can also describe the PDF for a bimodal Gaussian mixture model as

$$\Phi(h) = p \cdot \phi_1(h) + (1 - p) \cdot \phi_2(h), \tag{3}$$

where p is the mixture ratio between the two Gaussian distribution functions  $\phi_1$  and  $\phi_2$ , each with their individual means and standard deviations. When fitting (2) and (3) to the experimental measurements we employ a maximum likelihood estimation (MLE) of the means, standard deviations and mixture ratio. Finally, we also estimate surface properties using power spectral density (PSD), i.e. the square of the modulus of the normalized Fourier transform, of a self-affine surface profile following

$$P(k) \propto k^{-(1+2H)},\tag{4}$$

where k is the wavenumber and H is the self-affine scaling exponent or Hurst exponent (Schmittbuhl et al., 2003; Candela et al., 2009; Mai & Beroza, 2002). The wavenumber  $k = 1/\lambda$  where  $\lambda$  is wavelength. By plotting equation (4) we can estimate H using linear regression of log-log slope of the relationship between the PSD and wavenumber  $\beta = -(1 + 2H)$ .

A sensitivity analysis was performed by generating two isotropic synthetic surfaces where  $H_{input} = 0.4$  and 0.6 using the algorithm provided by Candela et al. (2009). For each 1-D profile the power spectrum was calculated and PSDs were stacked to reduce the effects of noise. The estimated Hurst exponents for the synthetic surfaces were  $H_{output}$ = 0.45 (3% error) and 0.65 (8.3% error), which was deemed to be an acceptable approximation of this approach according to Candela et al. (2009).

#### 3.2 Surface Roughness of a Worn Interface

Here we employ the methods described in Section 3.1 to quantify the surface characteristics of the slider block. The facilities and measurement techniques are discussed in detail by P. A. Selvadurai and Glaser (2017). A Nanovea PS50 optical profilometer was

used to measure longer length scale variations in surface height (cm to millimeter), whereas 222 the ADE MicroXAM-100 optical profilometer was used to measure small length scales (sub-223 millimeter) on the smoother, worn sections of the fault. We consider both measurements 224 to fall on the mesoscopic scale shown in Figure 1(c).

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In Figure 2(a) we show a 5 mm x 4.8 mm section of height measurements taken from 226 the seismogenic region of the fault. The spatial resolution of the Nanovea P50 was 10  $\mu$ m. 227 Within this region the root mean square roughness was  $h_{rms} = 17 \ \mu \text{m}$ . In Figure 2(b) we 228 examine the surface height probabilities using equations (2) and (3). 229

We note a distinct "bump" in the surface height probability density that was due to 230 wear. It is apparent that the standard modal Gaussian distribution of height probabil-231 ity does not characterize this surface adequately at this length scale. The bimodal esti-232 mate of roughness is reasonable for surface height probabilities  $> 10^{-2} = 0.01$  (1%). The 233 maximum and minimum wavelength considered using the long length scale scans were  $\lambda_1 =$ 234  $1/k_1 = 0.90$  mm and  $\lambda_2 = 1/k_2 = 0.09$  mm. The sensitivity of H is due to the "roll-235 off" at wavelengths greater than  $\sim 1$  mm likely due to the limited size of our experimen-236 tal measurements. 237

To extend our understanding to smaller length scales we used the ADE MicroXAM-238 100 optical profilometer. All scans using this profilometer targeted the flat, worn sections 239 that contributed to the "bump" in the surface height probabilities. A Gaussian window 240 of 2 pixels (~ 0.2  $\mu$ m) was convolved with the scans to remove any experimental errors 241 at lower spatial length scales (Candela et al., 2009). A total of 40 scans were taken on these 242 flat sections and an average root mean square roughness was  $h_{rms} = 0.09 \ \mu\text{m}$  – approx-243 imately 188 times smoother than the larger section by this metric. In Figure 2(c) we show 244 a typical scan of the flat region (0.128 mm x 0.0975 mm). Figure 2(d) shows the accom-245 panying surface height probability density along with the Gaussian modal (magenta) and 246 bimodal (cyan) surface height probability distribution estimates. We note that the im-247 provement of the bimodal model is not as significant at the smaller scale. The values of 248 the means  $(\mu^*)$ , standard deviations  $(\sigma)$  and mixture ratio (p) are shown for the modal 249 (magenta) and bimodal (cyan) models with units of  $\mu$ m. 250

In Figure 2(e) we plot the PSD of the long wavelength measurements using the Nanovea 251 PS50 (purple, see also Figure 2(c)) along with the new, shorter wavelength PSD measure-252 ments obtained from the ADE MicroXAM-100 scans (black dots). Between  $\lambda_1$  and  $\lambda_2$ , we 253



Figure 2. (a) Surface roughness for a 5 mm x 4.8 mm section within the seismogenic region taken from Figure 1(f). (b) Surface height probability of the region in (a) and the bimodal (cyan) and modal (purple) Gaussian estimates are shown. We note the pronounced "bump" in the right-hand tail that is a manifestation of wearing processes. (c) Surface roughness of a random smooth section within the seismogenic region of the fault. (d) Surface height probability of the region in (c) is shown with the bimodal (cyan) and modal (purple) Gaussian estimates. (e) Power spectral density of the surface roughness of both the ADE MicroXAM-100 and Nanovea PS50 optical profilometer.

show our estimate of the Hurst exponent  $H = 0.46 \pm 0.02$ . Estimating the Hurst exponent below  $\lambda_2$  is more complicated since the PSD estimate at shorter wavelengths does not show a clear linear log-log behavior as before. Two estimates of the Hurst exponent H = 0.5 and 1.4 are shown for reference.

# 4 Rate- and state-dependent (RSF) friction model

# <sup>259</sup> 4.1 Theory

In this section we develop a RSF model to help understanding the complex frictional behavior shown in Figure 1. RSF constitutive friction law is phenomenological and derived from laboratory experiments (Dieterich, 1979). The model describes the behavior of a faults resistance to sliding in terms of the shear stress  $\tau$  as a function of the slip rate V and a state variable  $\theta$ . This is given as:

$$\tau \left( V, \theta \right) = \sigma \left[ \mu^* + a \ln \frac{V}{V^*} + b \ln \frac{V^* \theta}{D_c} \right], \tag{5}$$

where  $\sigma$  is the effective normal stress,  $\mu^*$  is the reference steady-state friction coefficient at an arbitrary reference slip rate  $V^*$ ,  $D_c$  is the characteristic slip distance and, a and bare constitutive parameters describing the direct and evolution effects, respectively. The state parameter in our study is referred to as the so-called "slip law and is adopted due to its ability to model recent laboratory studies (Bhattacharya et al., 2015; Kaneko & Ampuero, 2011; Kaneko et al., 2016):

$$\dot{\theta} = -\frac{V\theta}{D_c} \ln \frac{V\theta}{D_c},\tag{6}$$

where friction at steady state ( $\dot{\theta} = 0$ ) is given as

$$\tau_{ss}\left(V\right) = \sigma \left[\mu^* + (a-b)\ln\frac{V}{V^*}\right].$$
(7)

From equation (7) we see that constitutive parameters (a - b) play an influential role as to how the interface behaves at steady-state. For (a - b) < 0,  $\tau_{ss}$  will decrease as slip rate V increases. A fault with these characteristics is known as velocity-weakening (VW) and is prone to spontaneous instability if the fault stiffness is below a critical stiffness. Stiffness of the VW spring-slider system was investigated by Ranjith and Rice (1999) who found
the critical stiffness to be:

$$k_{cr} = \frac{\sigma \left(b-a\right)}{D_c},\tag{8}$$

where  $\sigma$  is the (effective) normal stress on the fault. This implies that quasi-static steadystate slip is stable  $(V \to V^*)$  or unstable  $(V \to \infty)$  as the spring stiffness is greater than or less than the critical value  $k_{cr}$ , respectively. Fault stiffness is inversely proportional to the minimum half-length of a nucleation zone capable of instability:

$$L_c = \eta \frac{G^* D_c}{\sigma \left(b - a\right)},\tag{9}$$

where  $\eta = (7\sqrt{2})/(3\pi)$  (Dieterich, 1992) for a square patch, the corrected shear modulus  $G^* (= G/(1-\nu))$  was employed due to the Mode II plane strain conditions and  $\nu$  is the Poisson's ratio.

The equation of motion controlling slip on a planar fault in our model is given by:

$$\tau_{el}\left(\mathbf{x}\right) - \tau\left(\mathbf{x}\right) = \frac{G^*}{2V_S}V(\mathbf{x}),\tag{10}$$

where  $\tau_{el}$  is defined as the elastostatic shear stress due to the loading boundary condition 286 (Horowitz & Ruina, 1989). The inertial term on the right hand side represents the radi-287 ation damping term for S waves produced along the fault at point  $\mathbf{x}$ , which propagated 288 with a shear wave speed  $V_S$  (Rice, 1993). Quasi-static interactions between fault elements 289 are calculated using the boundary element method (BEM) and all calculations reported 290 in this study was solved using a Quasi-DYNamic earthquake simulator (Luo et al., 2017). 291 QDYN is a boundary element software to simulate earthquake cycles (seismic and aseis-292 mic slip on tectonic faults) under the quasi-dynamic approximation (quasi-static elastic-293 ity combined with radiation damping) on faults governed by RSF and embedded in elas-294 tic media. Solution convergence and mesh discretization of the heterogeneous models de-295 scribed later is given in Supplemental Methods S1. 296

From derivations by Dieterich (1992) we know that RSF combined with elasticity leads to the common length scale

$$L_b \equiv \frac{G^* D_c}{\sigma b}.\tag{11}$$

This characteristic dimension was later theoretically confirmed by Rubin and Ampuero (2005) and controls aspects of earthquake nucleation and the transition from aseismic to seismic behaviour. We define this transition threshold to be:

$$V_{dyn} = \frac{2aV_s}{G^*},\tag{12}$$

which represents the transition point where the inertial term in equation (10) becomes significant.

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## 4.2 Recent advances RSF modelling in the laboratory

Dieterich and Kilgore (1994) showed that the RSF phenomenological behavior holds for various frictional surfaces on a range of materials (granite, soda-lime glass, Lucite plastic and wood among others). Extensive work has shown that this constitutive model also holds for gouge filled interfaces (see review by Marone, 1998). The typical manner used to extract constitute parameters a, b and  $D_c$  is performing shearing experiments where constitutive equations (5) and (6) are fitted to bulk (macroscopic) measurement of friction ( $\mu = F_s/F_n$ ) while performing step-changes in the driving velocity ( $V_{LP}$ ).

Experiments performed by Nielsen et al. (2010) and Latour et al. (2013) have ben-312 efited from increasing the faults compliance by using analog materials (glassy polymers) 313 in frictional tests. In these experiments, improved spatio-temporal measurement of slip 314 was achieved by using high speed digital cameras. Increased refinement in both spatial 315 and temporal measurements clearly showed the so-called "preslip" or nucleation zone. This 316 nucleation region was predicted in RS models (Dieterich, 1992; Rubin & Ampuero, 2005; 317 Ampuero & Rubin, 2008) but was difficult to show definitively before novel sensing tech-318 niques. 319

Modelling efforts by Kaneko and Ampuero (2011) and Kaneko et al. (2016) have shown that frictional behavior of the 'plastic-on-plastic' sliding experiments can be explained using RS friction models. These models are informative and promote the idea of a 'smooth transition' of frictional sliding over the macroscopic length scale of the experimental fault. It explained both the spatial and temporal evolution of observed nucleation features of

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those laboratory ruptures. Similarly, we also observe a breakout style of rupture at the macroscopic scale. In Figure 1(d) this same smooth quasi-static evolution of slip is present. However, we benefit from additional phenomenological insight. The dynamic piezoelectric (PZT) sensors were able to detect and isolate local instabilities in the same regions experiencing macro-slow slip (Figure 1(e)). To explain these instabilities in the RS framework we need to investigate the type of heterogeneity at a scale below one the dictates the smoother macroscopic behavior.

Roughness induces complex frictional behavior due to the deviation of a fault from 332 planarity. This is believed to impose strong effects on many aspects of the earthquake cy-333 cle. Roughness appears to influence the static deformation at large scales (e.g. King & 334 Nábělek, 1985), dynamic rupture propagation (e.g. Dunham et al., 2011; Fang & Dun-335 ham, 2013; Mai et al., 2018), nucleation physics (e.g. Tal et al., 2018) and the presence 336 aseismic transients (Ozawa et al., 2019). The studies conducted by Tal et al. (2018) and 337 Ozawa et al. (2019) show that RSF in combination of the non-planarity of the fault can 338 help to understand the presence of asymmetric nucleation zones, non-monotonic increase 339 in slip rates and the generation of multiple slip pulse that self-arrests. Most studies that 340 incorporate both RSF and roughness assume mated initial fractures as initial conditions. 341 They predominantly characterize surface topography using the Hurst exponent in equa-342 tion (4). In our study we deviate from the initial condition of perfect matedness in the 343 other studies. We choose to instead create a range of 1-D models with attributes derived 344 from the spatial complexity of the measured roughness profile that exhibited signs of wear. 345 As the level of matedness of the surfaces was unclear at any time in the experiment, we 346 chose to use a roughness *cutting plane method* that is able to separate the two modal Gaus-347 sian distributions of roughness in space. 348

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4.3 Cutting plane method

The cutting plane method splits the roughness into two separate sections: smooth and rough. Using this method we assign two sets of frictional parameters to the smooth (upper) and rough (lower) regions of the roughness profile that appeared due to wear, which will be the input to our numerical rate and state model. A 'cutting plane' was defined to be exactly between the two means of the bimodal distributions that formed due to wear. While this method could be extended to 2-D, in this study we build a simple 1-D model and choose arbitrarily the transect of rough surface at y = 2 mm. Figure 3(a) shows the roughness along x at y=2 mm (black line). This transect is taken from a highly seismo-

genic section of the interface (P. A. Selvadurai & Glaser, 2015a).

The cutting plane (red) was defined as  $h_{cut} = (\mu_1^* + \mu_2^*)/2 = 6.6 \ \mu\text{m}$ . Figure 3(b) shows the probability distribution of the surface heights from the sample transect and the cutting plane in red. We assume that the top surface is relatively "smooth" from the preferential wearing of asperity tops and bottom surface, as is described in more detail in Section 3.2.



Figure 3. (a) 1-D roughness profile (black) taken from the transect at y = 2 mm in Figure 1(f). The cutting plane  $h_{cut} = 6.6 \ \mu$ m is used to separate the bimodal distribution into smooth and rough surfaces. (b) PDF of the height profile in (a) with the cutting plane shown. (c) Small section of the height distribution showing the roughness profile (black line), the cutting plane (red line) and the scaling function (blue line). (d) PDF of the scaling function SF(x) with an order of heterogeneity O = 20.

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A scaling function (SF) is used to partition the smooth and rough sections of the fault. Figure 3(c) shows a detailed view of the roughness (black), the cutting plane (red) and the scaling function (blue). When the roughness was above the cutting plane we defined a scaling function (SF) to have value of unity. All heights below the cutting plane were prescribed as scaled value. This allowed us to control the magnitude of heterogeneity we call the 'order'. For this example the order was O = 20. The SF produced heterogeneity in two manners: (*i*) spatial variations were controlled by the location where the roughness profile crossed the cutting plane and (ii) the level (order) of heterogeneity – the peakto-peak range of SF – could be prescribed by the modeler. The order of the SF is seen more clearly in probability distribution function in Figure 3(d).

The basis for the cutting plane was to separate the interface into the two predomi-374 nant rough and smooth surfaces, that we believe, existed due to wear. Micromechanical 375 simulations performed by Yoshioka and Iwasa (1996) showed that  $D_c$  decreases as faults 376 become smoother in dry, gouge-free scenarios such as in our experimental conditions. We 377 note that smoother surfaces likely produced locations capable of supporting higher local-378 ized patches of normal stress. From equation (9) we see that a combination of high  $\sigma$  and 379 low  $D_c$  might be a viable mechanism for the initiation of localized seismicity. This will 380 be examined using a range of 1-D RS models developed next. 381

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#### 4.4 Frictional parameter space

It is important to know that we are choosing parameters that are based on previous 383 studies surrounding this experiment but also incorporate assumptions from the literature. 384 The goal of the models is to identify conditions that may produce local seismicity – a crit-385 ical experimental observation made from the PZT sensors. In Figure 4 we investigate how 386 the critical nucleation length  $L_c$  (equation (9)) varies with  $D_c$  and the normal stress  $\sigma$ . 387 Based on experiments performed by Berthoude et al. (1999) we set a/b = 0.65 and b =388 0.0144. Curves representing constant critical nucleation length are shown in red for  $L_c =$ 389 25 mm and 0.9 mm, for reference. 390

To further constrain our models, we examined the experimentally measured asper-391 ity normal stress from the concerted study by P. A. Selvadurai and Glaser (2017). Using 392 the calibrated pressure film (P. A. Selvadurai & Glaser, 2015a), they found the asperities 393 attained normal stresses ranging from  $\sigma = 12$  to 25 MPa. This range of normal stress is 394 superimposed in Figure 4, which further bounds the potential nucleation conditions in the 305 RSF model. The goal in our study was to better constrain our numerical models using 396 a wide variety of measurements made at a mesoscopic scale. By constraining the param-307 eterization we can also better understand numerical requirements. 398

Finally, it was necessary to ensure that the fault was properly meshed to correctly capture the dynamic processes at the rupture tip during seismic events. Our calculations were based on the estimates of the cohesive (or breakdown) zone length scale  $L_b$  in equation



Figure 4. (a) Initial estimates of the nucleation parameter space  $(L_c)$  based on measurements of local normal stress (P. A. Selvadurai & Glaser, 2017), minimum mesh discretization  $(\Delta x/L_b)$ and maximum critical nucleation size  $L_c = 0.025$  m. The gray hatched region represents possible nucleation sizes for the mesoscopic length scale. The hatched orange shows the ranges of  $D_c$  and effective normal stress  $\sigma$  that nucleated gross fault in Kaneko et al. (2016, , \*a/b = 0.6944). (b) Example of asperity-level normal stress field measured using an experimental pressure sensitive film (adapted from P. A. Selvadurai and Glaser (2017).)

(11). To accurately capture local frictional breakdown it was necessary to apply a min-402 imum grid size of  $\Delta x/L_b < (1/50)$ , which for a/b = 0.65 was deemed acceptable. In this 403 model we choose to use  $2^{13} = 8192$  grid points over the length L = 25 mm of the meso-404 scopic domain, resulting in a resolution  $\Delta x \sim 3 \ \mu$ m. This is much different that the macro-405 scopic parameter space estimated by Kaneko et al. (2016), shown as orange hatched re-406 gion, for the plastic-on-plastic sliding experiment performed by Latour et al. (2013). Ta-407 ble 1 shows the baseline frictional, material and length scale properties used in this study. 408 More information on the convergence tests for the heterogeneous models (discussed later) 409 is given in the Supplemental Information S1. A summary of the parameters used to de-410 velop the homogeneous and later heterogeneous models are given in Table 1. 411

# 412 5 Computational Results

The general domain for the 1-D frictional model is shown in Figure 5(a). This represents the small region of material under the eddy current target shown in Figure 1(c). The geometry of the domain is L = 25 mm (corresponding to the extent of the roughness measurement in the direction of slip), H = 2.5 mm (corresponding to the height of the

Parameter	Symbol	Value
Shear modulus	G	2.39 GPa
Poisson ratio	ν	0.32
Shear wave speed	$V_S$	$1330 \text{ m s}^{-1}$
Reference friction coefficient	$\mu^*$	0.6
Reference slip rate	$V^*$	$0.1~\mu\mathrm{m~s^{-1}}$
Dynamic sliding threshold	$V_{dyn}$	$0.177 \text{ m s}^{-1}$
Loading plate velocity	$V_{LP}$	$0.1~\mu\mathrm{m~s^{-1}}$
Lower critical slip distance	$(D_c)_{low}$	25 nm
Normal stress	σ	$25 \mathrm{MPa}$
Length of mesoscopic domain	L	25 mm
Height of mesoscopic domain	Н	2.5 mm
Width of mesoscopic domain	W	$\infty$
Grid size	$\Delta x$	$3 \ \mu { m m}$
Grid points	n	$2^{13}$
RS parameter $b$ (VW)	b	0.0144
RS parameter $a$ (VW)	a	0.00936
Simulation time	$t_{sim}$	600 s

 Table 1. General model Parameters used in the 1-D RS mesoscopic models.

material just below the eddy current target) and  $W = \infty$  (corresponding to plane strain 417 conditions). The boundary element code QDYN assumes frictional properties (a, b and b)418  $D_c$ ) and normal stress ( $\sigma$ ) at each node on the interface. The models behavior is described 419 in Section 4.1. Figure 5(b) shows a schematic representation of the boundary value prob-420 lem. A few representative nodes are shown as blocks. Communication between the fric-421 tional nodes is shown as spring elements. This interaction is solved by QDYN and the spring 422 constants are defined in equation (13) equation of motion controlling slip on a planar fault. 423 Before moving to more complex, heterogeneous cases we examine the behavior of the ho-424 mogeneous case to develop a baseline. 425

#### 5.1 Homogeneous case

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From the mesoscopic geometry we build the 1-D homogeneous model, shown schematically in Figure 5(b). For the homogeneous case, each node has velocity-weakening (VW) conditions (a-b) = -0.005, a/b = 0.65, normal stress  $\sigma = 25$  MPa and a critical slip-weakening distance  $D_c = 25$  nm. For the homogeneous case, the steady-state sliding velocity  $V^*$  was assumed to be equal to the load point velocity  $V_{LP}$ . We were able to determine this experimentally from the near-fault slip velocity measurements made using the eddy current slip sensors shown in Figure 1(d).  $V_{LP} = 0.1 \ \mu m/s$ .

Each numerical simulation lasted for  $t_{sim} = 600$  s, which allowed for the fault to fully-434 develop a periodic stick-slip response (Hillers et al., 2007). Figure 5(c) and (d) shows a 435 small time window (500 to 600 s) of the slip velocity and shear stress, respectively, aver-436 aged over all nodes in the model. We see that periodic ruptures are analogous to a 'stick-437 slip' event (Scholz, 2002). Over the full simulation, 18 stick-slip were recorded for the ho-438 mogeneous case but only three are shown here. Coseismic slip was defined when any node 439 experienced a sliding velocity  $V > V_{dyn} = 0.177$  m/s as determined from equation (12). 440 To further characterize the homogeneous case, Figure 5(e) shows the relationship between 441 average slip velocity and shear stress. We find a similar behavior as the modelling exer-442 cise performed by Ampuero and Rubin (2008) in that the fault moves through the inter-443 seismic, preseismic, coseismic and postseismic regime. 444

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### 5.2 Heterogeneous $D_c$ -model

We produce heterogeneity by varying the critical slip weakening distance  $D_c$  accord-446 ing to the scaling function (SF) in Figure 3(c). The  $D_c$ -model shares some properties of 447 the homogeneous case (b = 0.0144, a/b = 0.65,  $\sigma = 25$  MPa) and is depicted schemati-448 cally in Figure 6(a). However, the main distinction arises from the non-uniform distribu-449 tion of the critical slip distance. For the  $D_c$ -model we prescribe the lower value of crit-450 ical slip weakening distance  $(D_c)_{low} = 25$  nm. Using the scaling function from the cut-451 ting plane method, we can capture the spatial variation in critical slip weakening distance 452 given as  $D_c(x) = (D_c)_{low} \cdot SF(x)$ . Figure 6(b) shows the spatial fluctuations in  $D_c(x)$ 453 for heterogeneity on the order of O20. Spatial distribution of the homogeneous proper-454 ties is shown in Figure 6(c) for reference. 455



Figure 5. (a) General dimensions of the model domain described in Figure 1(c). (b) Description of the 1-D boundary value problem being solved by QDYN. RS frictional behavior is described by equations (5) to (9). (c) Average slip velocity and (d) average shear stress along the fault between  $t_{sim}$  between 500 to 600s. We see that the fault underwent stick-slip behavior. (e) A diagram of the earthquake cycle for the VW fault that includes preseismic, coseismic, postseismic and interseismic phases.



Figure 6. (a) General schematic showing the heterogeneous model. (b) Heterogeneous distribution of  $D_c$ , with O20. (c) Constant normal stress and VW rheology (a - b < 0) is shown along the x-axis. (d) Average slip velocity is shown along the fault for the heterogeneous model (blue line), which is compared to homogeneous model (black line). (e) Average shear stress along the heterogeneous and homogeneous models.

- The average slip rate and shear stress for this  $D_c$ -model (O20, blue) is shown in blue in Figures 6(d) and (e), respectively. For reference, we also show the results from the homogeneous model O1 (black). We see that the fault does experience some stick-slip behavior – the small spikes in slip velocity – but it does not experience full ruptures with large levels of shear stress drop that occurred in the homogeneous case.
- We investigated the effect of different levels of heterogeneity. In Figure 7 the average 461 fault behavior is shown for three levels O10 (red), O15 (green) and O20 (blue), which all 462 use the same scaling function SF(x). This is again compared to the average behavior of 463 the homogeneous fault O1 (black). The average slip, slip rate and shear stress is given in 464 Figures 7(a), (b) and (c), respectively. We observe an increase in complexity from homo-465 geneity with these models. The first major note is that both O10 (red) and O15 (green) 466 still experienced full system wide rupture (large events that propagated the full extent of 467 the modelled fault). Full rupture would nucleate from a smooth section of the fault and 468 would not arrest in comparison to more localized ruptures that occurred in the O20, which 469 had stronger barriers. 470

While the system wide events did occur on the O10 (red) and O15 (green) faults, they 471 also experienced small localized events that were arrested by the neighbouring barriers. 472 These were denoted as small "foreshock sequences" leading up to the main rupture (larger 473 stress drop), which highlighted in Figure 7(c). These foreshock sequences might be sim-474 ilar to experimentally observed detachment fronts that have been routinely observed in 475 frictional experiments (e.g. Rubinstein et al., 2004; Maegawa et al., 2010; Kammer et al., 476 2012; P. A. Selvadurai & Glaser, 2017). We clearly see that as the order O is increased, 477 the fault exhibits transition from well-behaved fault (homogeneous, O1) to relatively chaotic 478 mixture of system wide events with small localised ruptures (O10 and O15), then return-479 ing to well-behaved creep-dominated fault with small localized events on a preferential patch 480 (O20).481

To better visualize the systems behavior, we plot all models on phase-diagrams de-482 scribed in Figure 5(e) for the homogeneous case. The average fault behavior cycles from 483 co- to post- to inter- to pre-seismic, moving around  $\tau_{ss}$  given in equation (7). With re-484 gards to the full cyclical behavior of the fault, the O10 (red) and O15 (green)  $D_c$ -models 485 appear to observe, in general, lower total stress drop during the full rupture events when 486 compared to the homogeneous case. We also see that during these full ruptures, the av-487 erage slip rate on these faults is in general lower than the homogeneous case. For the most 488 heterogeneous fault with order O20, we see that full rupture events did not occur but there 489 was some deviation from steady state caused by small foreshock sequences that deterred 490 the fault from simply 'creeping' along at the steady state shear stress. Foreshock sequences 491 appeared in all models and were due to a relatively large 'smooth' section of fault deter-492 mined from the cutting place method. We see these foreshock sequences highlighted in 493 the phase diagram (gray regions). Two major sequences were observed for the O10 and 494 O15 models. Timing of these foreshock sequences, relative to the full fault cycle, are shown 495 for O10(red) in the interseismic stages of the larger rupture cycle. For O15(green), one 496 foreshock sequence occurred in the interseismic portion and one closely after the fault en-497 tered the nucleation phase of the larger rupture cycle. As for O20 (blue), this smooth sec-498 tion of the fault prone to localized rupture behaved in a relative synchronous manner. More 499 details to the spatio-temporal complexity of these ruptures are given in the next section. 500

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Figure 7. Three heterogeneous models O = 10 (red), 20 (green) and 30 (blue) are compared to the homogeneous model (black) for a short time window between 300 and 430 s. We show the (a) average slip, (b) average slip velocity and (c) average shear stress. We highlight where small drops in shear stress were seen and relate them small localized events (foreshocks). (d) We examine the phase diagram between shear stress and slip velocity for each heterogeneous model in comparison to the homogeneous model.

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#### 5.2.1 Spatio-temporal behavior

In Figure 8 we examine the spatio-temporal evolution of the  $D_c$ -model with O17.5. We note that this model was not presented in the previous section. The purpose of the previous section was to highlight changes in the general fault behavior at three levels of heterogeneity with distinctly different behavior.

Figure 8(a) shows the spatio-temporal evolution of slip along the fault from time t =506 300 s to 600 s. The time step between each isochron was uniform, taken every 30 inter-507 vals of adaptive time steps. We note that if any point on the fault slipped rapidly, the adap-508 tive time step would decrease to accurately solve the boundary value problem. This lead 509 to higher sampling rates when slip velocities increased and decreased time steps were nec-510 essary to capture the complex slip behavior during localized seismicity. Seismicity (red 511 slip isochrones) was defined as any node in the model experiencing slip velocities  $V > V_{dyn} = 0.177$ 512 m/s. Below this threshold the fault was assumed to be sliding aseismically (blue slip isochrones). 513 Using this description we were able to clearly see the seismic patches. 514

One such patch is highlighted in Figure 8(a) and enhanced in (c) where we examine 515 slip on the transect x = 5 to 8 mm from t = 300 s to 305 s. This asperity section of the 516 fault was prone to seismicity in all models, even the O20 that showed limited localized seis-517 micity. Figure 8(b) shows the spatial variability in heterogeneity in  $D_c$  along that section 518 (for this case with O17.5). In Figure 8(c), we see that the fault actually has blue lines that 519 delineate the seismicity over these five seconds. This indicates that slip rates drop to be-520 low 0.1 m/s allowing us to separate the events into a sequence. Four individual ruptures 521 are shown. We note that these events exhibit typical circular crack-like behavior but are 522 still very complex due to both the spatial variability in  $D_c$ , the level of heterogeneity (O17.5) 523 and the continuously evolving shear stress on the fault. 524

In Figures 8(d) and (e) we investigate the space-time plot of slip velocity and shear 525 stress, respectively, for Event 4 in the asperity failure sequence. The portion of the fault 526 527 is shown (x = 5 to 8 mm) and we have superimposed the heterogeneity from (b) for clarity. We study this rupture in terms of its transition to rapid sliding, how the rupture grows 528 and why it arrests. By modelling ruptures that generate seismicity, we can compare these 529 source features to the ones modelled from an entirely different standpoint, i.e. the seis-530 mic waves (P. A. Selvadurai, 2019). We see that Event 4 nucleates at the edge of a 'smooth-531 rough' boundary ( $x \sim 7.25$  mm) depicted as the purple star. As the rupture expands, it 532

propagates bi-laterally at different rates. We have superimposed three lines of constant velocity  $0.5 \cdot V_S$  (green),  $V_S$  (red) and  $V_P$  (blue). Upon nucleation, the rupture expands outward in a subsonic manner, moving faster (~  $0.75 \cdot V_S$ ) "up-strike" into the smoother, less resistive section than into the "down-strike", rougher and more restive section (~  $0.45 \cdot V_S$ ). This behavior represented typical rupture behavior as they propagated on this dualproperty fault and is shown more clearly in Figure 9(d).

In Figure 9(d) we have enlarged the spatio-temporal rupture behavior of Event 4 for 539 clarity. Here we see more clearly the subsonic rupture propagation that grows at differ-540 ent speeds bi-laterally until arriving at separate barriers. Once the up-strike crack-tip (i.e. 541 that moving on the smooth fault) reached an up-strike barrier, it was abruptly arrested 542 (shown as the red star). As this rupture is arrested a back propagating front is emitted 543 moving closer to the P wave velocity. This front is known as the P stopping phase. This 544 stopping phase was observed by Madariaga (1976) during numerical simulations study-545 ing the kinematic behavior of a circular asperity. In that problem, the P stopping phase 546 is the wave radiated when the rupture front suddenly stops (red stars), for example when 547 encounters a strong enough barrier. Both the up- and down-strike rupture encountered 548 barriers and produced separate P stopping phases. For the down-strike propagating crack-549 tip, this P stopping phase actually caused the overall dimension of the to grow larger, fi-550 nally stopping at the green star. 551

To estimate properties of each rupture we used an image detection algorithm (region-552 props) and examined the 2-D distance-time space. The algorithm is versatile and has been 553 used by P. A. Selvadurai (2015) to map and characterize normal stress on the asperity as 554 shown in Figure 4(b). Using the slip velocity threshold of  $V_{dyn} > 0.177$  m/s, the ruptures 555 were easily separated and properties were easily quantified. Figures 8(d) and (e) are byprod-556 ucts of the search and processing available using the image detection algorithms. One of 557 the more definite metrics is the length scale of the rupture  $L_r$ . However, from these im-558 ages we see that both slip rate (therefore cumulative slip), and shear stress had highly non-559 uniform distributions due to the spatial complexity and heterogeneity in the model. 560

A main purpose of this study is to characterize source properties of the localized ruptures. We developed tools to accurately quantify the cumulative slip  $(\delta)$ , RSF stress drop  $(\Delta \tau)$  and effective fracture energy (G') and rupture hlaf-length  $(L_r)$  for each rupture as to account for their individual complex behavior.



Figure 8. (a) Complex rupture for a fault with heterogeneity order O = 17.5. Slip along the fault is shown for isochrones when the fault was sliding seismically (red,  $V_{dyn} > 0.177 \text{ m/s}$ ) or aseismically (blue, V < 0.1 m/s). Results are only shown for simulations times between t = 300 s and 600 s. We use these results to calculate the properties of the localized ruptures that showed local nucleation, dynamic rupture and arrest behavior due to heterogeneity in  $D_c$ . (b) We show spatial heterogeneity for a small section of the fault from x = 5 to 8 mm. (c) For this section, we look at a small sequence composed of four individual ruptures between time t = 300 s to 305 s. We see that the rupture has complex distributions of slip and spatio-temporal distributions. To better understand the temporal changes of the rupture we show the spatio-temporal evolution of Event 4 in terms of its (d) slip velocity and (e) shear stress.

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# 5.2.2 Characterizing Constitutive Behaviour

In Figure 9 we look at the complex behavior of Event 4 from the previous section. In 566 Figure 9(d) we show an enlarged view of Event 4 that ruptured a section with linear rup-567 ture dimension  $2L_r$ . To better understand the complex behavior of any seismic rupture 568 moving forward, we divide the full length of the rupture into 25 equally spaced points along 569 the x-axis. Event 4 is used as a typical example. The number of transects used must suf-570 ficiently sample a rupture, and a parametric study investigating the number of required 571 sampling transects is discussed in Supplementary Section S2. This was required to bet-572 ter understand the complexities of the ruptures with our unique description of heterogene-573 ity. 574

These plots provide a more concise temporal understanding that clearly shows the diversity in the temporal evolution of: (a) slip, (b) slip-rate and (c) shear stress along the transects shown in Figure 9(d). In Figure 9(a) we observe that the rupture has a non-uniform distribution of accumulated slip. The average slip along the 25 estimates was  $\delta = 0.37 \ \mu m$ . This average can be used with the relationship for seismic moment  $M_0$  given by Aki (1966):

$$M_0 = GA\delta,\tag{13}$$

where A is the fault area and  $\delta$  is slip. For a penny-shaped fault  $A = \pi r^2$  and for a square fault  $A = (2L_r)^2$ . We calculated the average slip from the final amount on each transect of the fault which was  $\delta = 0.37 \ \mu$ m for this example. Using this formula we find this rupture to have an average scalar seismic moment  $M_0 = 0.0014 \ \text{N}\cdot\text{m}$ . This is equivalent to a moment magnitude  $M_w = (2/3) \cdot (log_{10}(M_0) - 9.05) = -7.94$  (Kanamori & Hanks, 1975).

In Figure 9(b), we see the complexity in slip rate along each transect of the rupture 586 more clearly. For further clarity, the important aspects of the rupture (colored stars) are 587 superimposed and correspond to the important moment associated with Event 4 rupture 588 (stars). As mentioned earlier, the rupture appears to have higher slip rates along the smoother 589 section of the fault, whereas the rough section shows more resistance to the rupture. This 590 is seen in Figure 9(c) in that the smooth portions of the fault (red transecting lines) drop 591 shear stress very quickly with little accumulated slip, whereas the rough sections (black 592 transecting lines) offer resistance and exhibit slower rates of weakening. 593



Figure 9. Rupture complexity of Event 4 in Figure 8(d) and (e) in space-time plots. (a) Temporal evolution of slip along 25 different transects of the rupture spaced evenly on the fault. (b) Temporal evolution of slip rate along the same transects as in (a). Key moments of the rupture are given by the colored stars. (c) Temporal evolution of shear stress for the same positions as in (a). (d) Space-time plot of the rupture with the transects depicted graphically. (e) We investigate the traction-slip from each transect. The inset image shows how we measure (static) stress drop ( $\Delta \sigma$ ) and effective fracture energy (G') for each position on the fault.

We use this analysis to better understand the intrinsic source properties of the rup-594 ture and how it varied along the fault. In Figure 9(e) we show the normalized slip-traction 595 relationship for each transect of Figure 9(a). The normalization is with regards to the in-596 set image that describes how to calculate stress drop  $(\Delta \tau)$  and effective fracture energy 597 (G'), also known as breakdown work in the literature (e.g. Tinti et al., 2005; Cocco et al., 598 2016). We see from Figure 9 that there appears to be obvious participation of both the 599 rough and smooth sections of the fault. For clarity we have highlighted the critical slip 600 weakening distance for both the smooth  $(D_c)_{low}$  and rough section of the fault  $(D_c)_{high}$ . 601 We see that in some cases slip was greater than  $(D_c)_{high}$  which can be explained as dy-602 namic overshoot (Madariaga, 1976). Calculating  $\Delta \tau$  is relatively straight forward, but to 603 determine the effective fracture energy G', we numerically integrated the area under this 604 curve. For Event 4, the average stress drop was  $\Delta \tau = 3.25$  MPa and average effective frac-605 ture energy  $G' = 0.13 \text{ J/m}^2$ . 606

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#### 5.2.3 Seismic moment versus source size

We investigate seismic source properties and their scaling relationships over multiple 608 ruptures and by using different models. In Figure 10(a) we examine the relationship be-609 tween source area  $A_r = (2 \cdot L_r)^2$  and seismic moment  $M_0$ . Source properties in this study 610 are determined using dynamic RS models but this model is simplified in our analysis to 611 the quasi-dynamic case. Due to the simplification, our model does not produce seismic 612 waves (Freund, 1990; Rosakis, 2002). However, we know these waves were produced since 613 they were recorded using the array PZT sensors. Estimations of source properties inferred 614 from seismic waves are already available in the concerted study by P. A. Selvadurai (2019). 615 Kinematic source shear crack models (Brune, 1970; Madariaga, 1976; Hanks, 1979) are 616 commonly used to interpret source information of moderate to small to medium earth-617 quakes where finite source inversion is not possible. Please see table 2 in Cocco et al. (2016) 618 for an overview of studies that employ these techniques for a range of earthquakes sizes 619 and settings. We use the RSF results from this study to compare the kinematic estimates 620 of source properties to those made independently here using roughness-based dynamic fric-621 tion models. Chen and Lapusta (2009) have prepared a similar plot, comparing source prop-622 erties from RSF model to seismologic estimates; however, to the authors' knowledge this 623 has not been directly shown in a laboratory setting at such detail and more control on fea-624

tures affecting kinematic source models, such as wave scattering in heterogeneous media,
which is not the case for PMMA.

In Figure 10(a) we show the results five  $D_c$ -models (circles) against the kinematic estimates made from P and S wave arrivals (triangles) using shear crack models detailed by P. A. Selvadurai (2019). The kinematic estimates shown here used assumptions that the instantaneous rupture velocity was  $V_r = 0.9 \cdot V_S$  following the numerical simulations by Madariaga (1976). We see that the RSF models produce similar estimates of source length scale and seismic moment from the kinematic source models. The general scaling relationship  $M_0 \propto$  (length scale)<sup>3</sup> is observed for both methods to calculate source properties.

634

## 5.2.4 Frequency-magnitude distribution

We look at the frequency-magnitude distributions (FMDs) from the acoustic emis-635 sion (AE) data and RSF model in Figure 10(b). The colors are the same as legends in Fig-636 ure 10(a). The Gutenberg-Richter (Gutenberg & Richter, 1944) relationship is the most 637 commonly observed empirical relationship in seismology. It states that large earthquakes 638 occur less frequently than small earthquakes following the standard relationship  $log_{10}(N) =$ 639  $a_{GR} - b_{GR}M$ , where N is the number of events equal or above magnitude M and  $a_{GR}$ 640 and  $b_{GR}$  are constants (e.g. Wiemer & Wyss, 2002). This relationship is commonly used 641 to convey hazard and risk by detailing the productivity  $(a_{GR}$ -value) and size distribution 642  $(b_{GR}$ -value) in the volume of interest. While these values are typically used to assess vol-643 umes of rock, we employ it here to study patterns in on-fault seismicity – caution should 644 be used if extrapolating any findings to natural faults where off-fault seismicity might fac-645 tor into the observations. 646

Figure 10(b) shows the different seismic responses and a  $b_{GR} = 1$  is shown for refer-647 ence. We note that the  $D_c$ -models O10 (red) and O20 (blue) do no appear to capture the 648 full catalog of AE estimates for P waves (thick orange line) or S waves (thick gray line). 649 The O15 (green) show a relatively similar productivity  $a_{GR}$  but slightly lower  $b_{GR}$ -value. 650 Both O17.5 and O18.5 (gray) show the highest level of productivity. We mainly use the 651 FMD metrics as qualitative comparison of the two different source modeling methods. Goebel 652 et al. (2016) also investigated the effect of roughness on b-values and found that polished 653 faults had lower b-values than roughened samples. This appears to follow our results if 654 we consider that 'smoother' is related to smaller levels of heterogeneity (O10, red) has the 655

lowest b-value and it progressively increases until the relatively 'rougher' O18.5 model.

<sup>657</sup> However, the b-value drops again for the O20-model, which coincides with a more creep

dominated frictional response (Section 5.2.7) but we are not sure how to interpret this.

659

# 5.2.5 RSF Stress drop with seismic moment

Figure 10(c) looks at the relationship between stress drop and seismic moment release 660 given by equation (13). We see that event with lower  $M_o$  appear to have slightly dimin-661 ished levels of stress drop  $\Delta \tau$ . We found this was not to be a feature of under-sampling 662 and is was related to the amount of stress corrosion that will occur on smaller asperities 663 as portions of their shear stress is partially released in the nucleation phase prior to them 664 transitioning to a becoming a dynamic event. This is discussed in more detail in Section 665 6.2. Detail A shows enhanced view of only the O10, O15 and O20 models, where we no-666 ticed variable stress drops earthquakes that had very similar magnitude, a feature to re-667 peating earthquakes observed recently by Cauchie et al. (2020) when revisiting seismic-668 ity patterns from the 1993 stimulation of a geothermal reservoir in Soultz-sous-Forêts, France. 669

670

# 5.2.6 Fracture energy scaling

We look into the scaling behavior between effective fracture energy and slip and the 671 effect of the heterogeneous  $D_c$ . Abercrombie and Rice (2005) showed that effective frac-672 ture energy G' scales with slip ( $\delta$ ) according to the empirical relationship  $G' \propto \delta^{\gamma}$ . This 673 is of interest to the seismologic community since it helps to understand how strain energy 674 is partitioned during rupture. Whether this scaling relationship holds universally is not 675 agreed upon. Laboratory experiments where G' is directly measured show that a variety 676 of mechanisms might lend to deviation from the trend documented by AR. For example, 677 frictional mechanisms such as flash-heating of asperities caused by elevated temperatures 678 on the fault from frictional dissipation (e.g. Passelègue et al., 2016; Brantut & Viesca, 2017) 679 or off-fault damage due to high strain rates in the vicinity of rupture tip (e.g. Andrews, 680 2005: Nielsen et al., 2016), among other mechanisms, can lead to deviations from the AR 681 scaling trend. P. A. Selvadurai (2019) put together a compendium of seismologic estimates 682 from natural, mining and laboratory studies. He found that the empirical trends vary at 683 each scale. 684



Figure 10. (a) Source length scale is calculated from the numerical models with various levels of heterogeneity (colored circles) and compared to their respective scalar seismic moment  $M_0$ . These are compared to the kinematic estimate of source properties determined using shear crack models described in P. A. Selvadurai (2019) for both P and S waves (triangles). (b) Frequency-magnitude distributions (FMDs) are given for each catalog shown in (a). Values for FMD properties a and b are given in the text, and the magnitude of completeness  $M_c$  is shown as color coded arrows. (c) Relationship between frictional stress drop ( $\tau_d$ ) and rupture area. (d) Effective fracture energy (G') versus slip is shown. We compare the models to empirical scaling estimates from laboratory seismicity (black line P. A. Selvadurai, 2019), mining seimsicity (brown line P. A. Selvadurai, 2019) and field estimates (blue line Abercrombie & Rice, 2005), in which the latter has been extrapolated.

In Figure 10(d) we compare the estimates of G' for the different models using the meth-685 ods described in Section 5.2.2. These are compared to the previously discussed empiri-686 cal relationship for shear crack source models from laboratory (S<sub>L</sub>,  $\gamma$  =2.35) and min-687 ing estimates  $(S_M, \gamma = 1.86)$  (P. A. Selvadurai, 2019). We also compared this to get es-688 timates made at regional scales from natural earthquakes (AR,  $\gamma = 1.28$ ) following the 689 observations by Abercrombie and Rice (2005). This empirical relationship was later con-690 firmed by Mai et al. (2006). We see that the results from the model tend to follow the same 691 slope as AR but if we look more closely, shown in Detail B, we see that some of the re-692 peating patches show steeper trends in scaling (see highlighted clusters). This can be ex-693 plained by the fact that there were preferential patches – worn smooth sections – that, 694 when they ruptured, would remain relatively constant in size but the stress drop varied 695 as is shown in Detail A in Figure 10(b). This behavior have been seen in reservoir-scale 696 studies in a recent seismological study by Cauchie et al. (2020) and might describe why 697 repeaters are observed on worn and mature faults in nature (see discussion in Section 6.3). 698

699

#### 5.2.7 Recurrence rates

In Figure 11(a) we show the average slip (black) and shear stress (red) for a small por-700 tion of simulations for stong barriers O20 (left-hand side, LHS) to weaker barriers O10 701 (right-hand side, RHS). The transitional case O17.5 is shown in the middle. We see the 702 average behavior of the fault transition from one that is creep-dominated (O20) to one 703 that stick-slip dominated (O10). For this analysis, we look closely at the recurrence rate 704  $T_r$  of the localized events. We consider  $T_r$  to be the time between any two events at any 705 location on the fault. Since we do not consider nucleation processes in this analysis, we 706 look at the recurrence time between two sequential ruptures. To disseminate triggered seis-707 micity versus repeater events, we adopt the methodology described in Lengliné and Marsan 708 (2009). They looked at the frequency distribution of the recurrence times normalized by 709 the average recurrence time  $T_r^*$ . They found that below  $T_r/T_r^* < 0.1$  the distributions 710 followed a power-law distribution, which is consistent with Omori's law that described af-711 tershocks in nature (e.g. Lengliné & Marsan, 2009). 712

In Figure 11(b) we show the probability distribution of  $T_r/T_r^*$  for the five  $D_c$ -models. The purple region highlights portions of the distribution that are likely not triggered events. A small fall-off is observed when  $T_r/T_r^* <$  1e-6 and is likely due to saving computational solutions every 10 times steps because of memory constraints, thus decreasing informa-

-34-



Figure 11. Earthquake recurrence rate for each  $D_c$ -model from higher O20 to lower O10 levels of strength heterogeneity. (a) We show the average behavior of the entire fault for small portion of time t 300 to 400 s for the O20 (creeping-dominated), O17.5 (transitional) and O10 (stick-slip dominated) models. (b) Probability density of the lognormal distribution of normalized recurrence rates  $T_r/T_r^*$  for all models. The probabilities above  $T_r/T_r^* > 0.1$  in purple are highlighted.

tion for those bins. We see that for the creep-dominated O20 model there is relatively equal 717 probability in recurrence time but a slight increase in  $T_r/T_r^{\ast} > 0.1$  lending to the idea 718 that this is a more repeater-like behavior. In the transitional models (O18.5, O17.5 and 719 O15) we fit a power law distribution (gray lines) between  $1e-5 < T_r/T_r^* < 0.1$  and found 720 its slope to decrease as the heterogeneity was decreased. We note a small 'bump' in prob-721 ability above  $T_r/T_r^* > 0.1$ , denoted with the small arrow in O15. This appears to have 722 been amplified in O10, or the stick-slip dominated model, and this is discussed later in 723 the context of possible ties of foreshock-like behavior. 724

725 5.3 Composite-model

<sup>726</sup> So far we have chosen to investigate the  $D_c$ -model. We note that this study aims at <sup>727</sup> providing an understanding of the differences between RSF- and AE-driven estimates of <sup>728</sup> source properties. We are not attempting to exactly match each independent measure-<sup>729</sup> ment to each other since we believe that both methods have considerable assumptions;
<sup>730</sup> furthermore, perfect matching by tweaking input parameters defeats the inherent bene-<sup>731</sup> fit of these comparison exercises.

For completeness we investigate the *Composite*-model that aims at capturing addi-732 tional complexity that may exist in the spatial distribution in normal stress. We see from 733 the experimental observations with the pressure sensitive model (Figure 4(b)) that nor-734 mal stress asperities exist. According to the contact mechanics literature (Nayak, 1971, 735 1973), the preferentially smooth sections above the cutting plane (Figure 3) will likely pro-736 duce localized patches of normal stress asperities. To model such conditions, we again use 737 the scaling function. However, now on smooth sections (low  $D_c$ ) we prescribe constant nor-738 mal stress  $\sigma_{high} = 25$  MPa. In rough sections, we apply a constant low normal stress level, 739 which was set to the lower measurable limit of the pressure sensitive film  $\sigma_{low} = 12$  MPa 740 (P. A. Selvadurai & Glaser, 2015b). 741

In Figure 12(a) we show a section of the spatial heterogeneity from x = 5 to 8 mm for variations in  $\sigma$  (red) and  $D_c$  (blue). The scaling function was chosen to be O20, which was a model that had a relatively well-behaved response from before. We use the same methods to calculate source properties and examine similar relationships for this compositemodel (O20C).

Figure 12(b) shows the relationship between  $M_0$  and  $A_r$ . We find that it produces sim-747 ilar estimates to the kinematic shear crack model shown in Figure 10(a). However, here 748 we have made an additional improvement assumptions in the shear crack model regard-749 ing the rupture speed. We now apply a correction factor to account for slower ruptures 750 in the kinematic models for example  $V_r = 0.6 \cdot V_S$ . This analysis was performed by Kaneko 751 and Shearer (2015) for a range of rupture scenarios: circular or elliptical and symmetric 752 or asymmetric. They found that decreasing the rupture speed can produce deviations of 753 up to 2.5 times more stress drop depending on the model and the wave. From the RSF 754 simulations, an example shown in Figure 9(d), we found that the average rupture veloc-755 ities were much lower than the  $0.9 \cdot V_S$ , more close on average to  $0.6 \cdot V_S$ . From table 1. in 756 Kaneko and Shearer (2015), we updated the estimates form P. A. Selvadurai (2019), which 757 minimized the deviations between the kinematic (triangles) and RSF (circles) estimates 758 of source properties. The correction factor used to scale the original kinematic estimates 759 were taken from asymmetric circular asperity model for a rupture velocity  $0.6 \cdot V_S$  that 760



Figure 12. Results from the *Composite*-model. (a) A small section of the 1D fault form x = 5 to 8 mm showing the spatial variation in both  $D_c$  and  $\sigma$ . (b) The scaling relationship between  $A_r$  and  $M_0$  (gray circles) is compared to the corrected kinematic estimates of source properties from P. A. Selvadurai (2019) (triangles). (c) Constitutive behavior for a large event in the *Composite*-model. (d) Relationship between effective fracture energy G' and slip  $\delta$ . Empirical relationship between black and blue lines is similar to the one shown Figure 10(d).

led to an increase in seismic moment of 2.63 and 2.74 from P and S waves estimates, re spectively.

Figure 12(c) shows the constitutive shear stress versus slip behaviour for a large random asperity. For reference, we mark the levels of  $(D_c)_{low}$ ,  $(D_c)_{eq}$  and  $(D_c)_{high}$ . The term  $(D_c)_{eq}$ , or equivalent critical slip weakening distance, appears to be a representative critical slip weakening distance that always lies between the two  $D_c$  limits but will likely vary on each rupture and is a function of the ratio of high to low resistance of the interface participating in rupture.

Using the methods described in Figure 9, we looked at the relationship between G'769 and slip. In Figure 12(d) we see that the relationship appears to have a "kink". This kink 770 is observed about  $(D_c)_{eq}$ . As the smooth rupture front moves out, it propagates more ef-771 ficiently into the smooth section but still accrues large amounts of fracture energy per unit 772 slip as it moves less quickly into the rough-barrier in the opposite direction. As the effi-773 cient rupture encounters its first barrier, it is either arrested or breaks through. This might 774 indicate that the equivalent critical slip weakening distance  $(D_c)_{eq}$  could be related to the 775 average length scale of worn sections and the level of the discontinuity it encounters. 776

#### **6** Discussion

We have summarized findings from a well-documented laboratory experiment where 778 worn surfaces of two PMMA blocks were pressed together, forming a frictional interface, 779 then sheared to failure (P. A. Selvadurai & Glaser, 2015a, 2015b, 2017). Macroscopically, 780 the fault displayed a quasi-statically slipping nucleation zone that expanded until reach-781 ing a critical size, upon which the entire fault produced macroscopic stick-slip events (see 782 Figure 1(b)). Slow slip was captured using an array of low-frequency sensors (Figure 1(c)). 783 As slow slip accumulated, high frequency impulsive emissions were also detected using acous-784 tic emission sensors (Figure 1(d)). These were in fact elastodynamic stress waves (Fig-785 ure 1(e)) that contain source information associated with small seismic asperities that per-786 sisted in a larger slow sliding region. 787

<sup>788</sup> Upon inspection, the fault appeared to be worn in the region of the fault that pro-<sup>789</sup> duced seismicity. Roughness measurements were taken (Figure 2) and were used to im-<sup>790</sup> pose heterogeneity in a quasi-dynamic RSF model. Roughness profiles appeared to show <sup>791</sup> preferential wear (smooth flat asperities) that is commonly mentioned in the tribological

-38-

<sup>792</sup> literature. A cutting plane method (Figure 3), was used to mathematically quantify the <sup>793</sup> spatial variation in smooth and rough sections. Two sets of RSF properties were chosen <sup>794</sup> based on the fact that smooth surfaces have lower critical slip weakening distance  $D_c$  than <sup>795</sup> rougher sections.

The models showed very complex behaviour (Figure 7) that differed from the homo-796 geneous case (Figure 5). We developed algorithms to isolate ruptures (Figures 8 and 9). 797 These allowed us to estimate a range of source properties, such as scalar seismic moment 798  $(M_0)$ , rupture length  $(L_r)$ , seismic slip  $(\delta)$ , RSF stress drop  $(\Delta \tau)$ , RSF fracture energy 799 (G'), frequency-magnitude distributions and recurrence rates of five different  $D_c$ -models 800 and a composite-model (Figures 10, 11 and 12). These calculations were compared to in-801 dependently estimated source properties made from interpreting the seismic waves (P. A. Sel-802 vadurai, 2019). Building from our assumption that spatial variations in roughness caused 803 similar variations in  $D_c$ , we found that estimates of source size and moment release were 804 similar in both methods; however, some discrepancies exist. 805

806

#### 6.1 Dynamic RSF versus kinematic estimates of source features

Our model has successfully reproduced aspects of seismicity that were produced from 807 an experimental fault using two independent methods. It appears as if this is the first time 808 such a highly comparative study has been performed and, more so, a RSF fault that has 809 used experimental measurements to make a pseudo-roughness model. Our model does not 810 just take information from the roughness scans (Figures 2 and 3) but also builds on the 811 novel estimates of asperity normal stress using a pressure sensitive film to better constrain 812 the mesoscopic section of fault that is responsible for concomitant slow and fast sliding 813 (Figure 4). 814

The model displays a wide variety of complexity at the mesoscopically (Figure 7) and microscopically (Figures 8 and 9). Ruptures showed similar scaling behavior between seismic moment and source radius as was found by analyzing ground vibrations produced by the seismic waves (see Figure 10(a)). While the dynamic and kinematic source estimates highlighted here differ slightly, the magnitude and trends between estimates are similar and, without any *a priori* knowledge, comparing these two different models is an important step forward. Discrepancies may be caused by numerous features that we discuss next, <sup>822</sup> but similar types of laboratory study, with more controlled and well-posited experiments, <sup>823</sup> may help quantify how influential these assumptions affect our shear crack kinematic model.

Our numerical model was only quasi-dynamic and fully dynamic solvers may be needed. 824 Our numerical model does not incorporate dilation (A. P. S. Selvadurai et al., 2018), which, 825 even in a static sense might affect behavior and stress intensity factors. The 1-D approx-826 imation might not capture some of the inherent 2D spatial complexity in the preferentially 827 worn surface. This will be subject of future work. There are numerous simplifications in 828 the kinematic approach that may also impose errors in estimates of source properties. These 829 are well covered by P. A. Selvadurai (2019). While we attempted our best to absolutely 830 quantify their instruments response with high-frequency sources (see fig. 2 therein), fre-831 quency dependent attenuation of PMMA might not have been characterized sufficiently 832 with their empirical Green's functions. The main author is currently investigating numer-833 ical calibration methods to quantify this more accurately moving forward (Wu et al., 2020). 834

We see that stress drop is dependent on the rupture velocity  $(V_r)$  (Kaneko & Shearer, 835 2015). From our RSF models we needed to correct the simple circular asperity model used 836 by P. A. Selvadurai (2019), for a slower rupture velocity  $(V_r = 0.6 \cdot V_S)$ . In most cases, 837 shear crack models assume rupture velocities of 0.9 or  $1.0 V_S$  and there is yet to be a jus-838 tifiable reasoning as to why this is assumed (Cocco et al., 2016; P. A. Selvadurai, 2019). 839 We found that results from the RSF modelling, rupture velocities are more likely closer 840 to  $0.6 V_S$  making this analysis a useful one to better constrain parameters such as rup-841 ture velocity. From the improved understanding, we were able to apply numerical stud-842 ies performed by Kaneko and Shearer (2015) to update the kinematic source estimates made 843 for faster rupture velocities. This correction minimized the deviations between source es-844 timates from the independent models. This type of analysis could help to better under-845 stand the effects of asperities and barriers on the choices of parameters in kinematic source 846 models, using a laboratory-based understanding, that can better constrain assumption when 847 interpreting small to moderate natural earthquakes. 848

849

# 6.2 Comparison of RSF stress drop versus shear crack stress drop

The theory surrounding a penny-shaped shear crack embedded in an elastic homogeneous material is frequently employed to estimate the stress drop from an earthquake following the derivation by Eshelby (1957). This theory is used to calculate stress drop

- ( $\Delta\sigma$ ), which is different than the RSF stress drop  $\Delta\tau$  in terms of the defining frictional
- laws. Stress drop calculated on a shear crack is the average shear traction required to dis-
- locate the interface by the amount of average slip  $\delta$  in equation (13). For a circular shear
- crack embedded in a Poissonian material with radius r, stress drop  $\Delta \sigma$  is given as:

Circular : 
$$\Delta \sigma = \left(\frac{7\pi}{16}\right) \frac{G\delta}{r}.$$
 (14)

For a rectangular fault with side lengths  $L \ge W$  we can rewrite this stress drop as (Appendix A, N. Kato, 2003):

Rectangle : 
$$\Delta \sigma = \frac{2G\delta}{3\pi} \left( \frac{3L^2 + 4W^2}{LW\sqrt{L^2 + W^2}} \right),$$
 (15)

and for the square crack (L = W) with side length  $2L_r$  this simplifies to:

Square : 
$$\Delta \sigma = \left(\frac{7\sqrt{2}}{3\pi}\right) \frac{G\delta}{L_r}.$$
 (16)

Estimating stress drop by using this method remains controversial in the seismological com-860 munity (Beresnev, 2001). Assumptions regarding equations (14) to (16) might not accu-861 rately capture the physical realities of the problem. For example, there is no frictional dis-862 sipation (heating) and the process of dislocating the interface in shear is solved in an en-863 tirely reversible manner; if we were to unload the static shear traction  $\Delta \sigma$ , the crack would 864 return to its original position, which appears to be ill-conceived from at minimum the vi-865 sual evidence of damage on and near faults in nature (e.g. Mitchell & Faulkner, 2009). 866 While there are inherent assumptions embedded in the phenomenological RSF formula-867 tion, it is aimed to provide a more representative approximate behavior of the physical 868 processes and to better capture sources of energy dissipation not present in a model with 869 reversible assumptions. 870

Cattania and Segall (2019) have performed an important study on this topic. They compared rupture behavior of a circular VW weakening asperity with radius r, surrounded by a creeping VS region, using a quasi-dynamic RSF analysis (see also N. Kato, 2003; Chen & Lapusta, 2009). They found that aseismic preparation of the patch affected the level of seismically released stress drop. In this study we do not quantify aspects of nucleation

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explicitly but we find similar trends existed in our estimates of seismic RSF stress drop  $\Delta \tau$  when compared to the shear crack stress drop  $\Delta \sigma$  from equation (16).

To compare the two models, we first look at the computed RSF stress drop  $\Delta \tau$  for 878 the isolated events in the  $D_{c}$ - and composite-models. From these events we also have the 879 metrics for slip  $\delta$  and rupture length half-length  $L_r$ . Metrics of  $\delta$  and  $L_r$  are used with 880 equation (16) to estimate the shear crack stress drop  $\Delta\sigma$ . By normalizing the RSF esti-881 mates of stress drop  $\Delta \tau$  by  $\Delta \sigma$  we find that stress drop on smaller ruptures is consistently 882 overestimated by the stress drop from the crack model and that this overestimate decrease 883 weakly with  $L_r$  (Figure 13(a)). Cattania and Segall (2019) show similar results and con-884 cluded that this is due to portions of shear stress being pre-released in the nucleation phase, 885 what we call stress-corrosion. We believe that this is the case for our RSF models. This 886 is verified by re-analysing the ruptures but artificially setting the threshold for seismic-887 ity two orders of magnitude lower  $V_{dyn} = 0.001$ . We find that the differences between  $\Delta \tau / \Delta \sigma$ 888 are less on the smaller ruptures since the shear stress corrosion associated with the nu-889 cleation phase is now captured. 890

Theoretical studies in the behavior of RSF models have been used to non-dimensionalize the problem and identify parameters such as  $L_c$  (equation (9)) and  $L_b$  (equation (11)) (Ruina, 1983; Ranjith & Rice, 1999; Rubin & Ampuero, 2005; Ampuero & Rubin, 2008). Cattania and Segall (2019) applied this theory to understand how the circular asperity behaves with respect to the ratio of  $L_r/L_b$ . In Figure 13(b), we estimate  $\bar{L}_b$  but this is clearly different from standard description of  $L_b$  given in equation (11) since  $D_c$  varies with x. We estimate  $\bar{L}_b$  using the average  $D_c$  with elements that participated in the rupture.

<sup>898</sup> but show clearly complex behavior due to the prescription of  $D_c$  in the model. The <sup>899</sup> trend shown in Figure 13(b) shows that smaller values of  $L_r/\bar{L}_b$  over-predicted stress drop <sup>900</sup> when using the shear crack model  $\Delta\sigma$  since this model does not account for 'stress cor-<sup>901</sup> rosion' in the nucleation phase.

The trends shown in our models are predicted theoretically by Cattania and Segall (2019) (see fig. 13 and appendix C therein). They summarized the behavior of a single circular asperity with radius r into four types of behaviors **Type-I**: fully aseismic asperity; **Type-II**: surrounding creep erodes asperity and rupture nucleates from the center but stress drop increases weakly with r; **Type-III**: surrounding creep partially erodes asperity and rupture nucleates with stress drop strongly linked to r; **Type-IV**: minimal stress



Figure 13. (a) Comparison of RSF stress drop  $(\Delta \tau)$  and the shear crack stress drop  $(\Delta \sigma,$ equation (16)) with side length  $L_r$ . (b) The ratio of  $\Delta \tau / \Delta \sigma$  is compared to the normalized side length  $L_r/\bar{L}_b$ . The yellow region shows the range of asperities that will have a portion of their shear stress alleviated in the nucleation phase (stress corrosion). (c) [Adapted from P. A. Selvadurai and Glaser (2015a)] Photometry was performed through the transparent side of the PMMA top slider block. A schematic diagram shows how strong contacts (red) will transmit light whereas weak contacts will diffract light (blue). This is superimposed over a sample image of the interface (blue) used to qualitatively study the strong contacts. The image color is from blue to red which translated dark to light in physical terms. This image was taken exactly 5 seconds before macroscopic stick-slip failure. (d) Enhanced (4X) view of the interface where strong contacts (red pixels) were present. A single large strong contact is enhanced (20X) for the frame taken at  $t_{fail}$ -5 seconds. (e) Changes in light transmitted through the large contact changed over the ~ 4.9 seconds of the macroscopic nucleation phase, which might be qualitative evidence of stress corrosion. The periphery of the strong contact pixels in (d) is shown (dashed-line) for comparison.

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corrosion and energy required to propagate a rupture is less than that needed to nucleate resulting in a partial rupture. In our study it is difficult to absolutely pin down the true value of  $L_c$  and  $L_b$  due to the model heterogeneity, but the trends are similar. Moreover, we present qualitative evidence originally noted by P. A. Selvadurai and Glaser (2015a) that further promotes this idea of stress corrosion on potentially seismic asperities.

Using a standard complementary metaloxidesemiconductor (CMOS) camera, P. A. Sel-913 vadurai and Glaser (2015a) took advantage of the translucent nature of PMMA and video-914 graphed selected asperities using photometry loosely following the methods in the liter-915 ature (Dieterich & Kilgore, 1994, 1996). More details of the photometric setup is given 916 (P. A. Selvadurai & Glaser, 2015b). Figure 13(a) schematically shows the premise behind 917 asperity photometery. Stronger (red) asperity contacts transmit light more efficiently than 918 weaker (blue) regions of the interface. Figure 13(d) enhances a region on the interface that 919 highlights a larger asperity (see inset). This image was taken 5 seconds before failure. Fig-920 ure 13(e) shows the changes in light transmitted through the asperity 4.9 seconds ( $\sim 294$ 921 frames) later. We see qualitative evidence that support the idea that nucleation processes 922 may be responsible for the degraded light transmitted through the contact. While these 923 images are only qualitative, the interference (loss of contact) caused by the slipping pe-924 riphery of the asperity can be explained following the RSF models presented here and also 925 theoretically in the Cattania and Segall (2019) analysis, which also follow our results in 926 Figure 13(b).. 927

928

## 6.3 Implications for repeating earthquakes

Developing a more accurate understanding of asperities and how they behave collec-929 tively on a fault may also be useful when interpreting physics associated with repeating 930 earthquakes. 'Repeaters' are ruptures that repetitively break the same patch on the fault. 931 The general concept behind repeaters that a patch on the fault is susceptible to rupture 932 but resists sliding and becomes slowly loaded aseismically by its creeping surrounding. The 933 quasi-static loading eventually results in localized failure of the fault, causing the patch 934 to catch up to the creeping surroundings. During this event, the patch radiates seismic 935 waves and the term 'repeater' is actually associated with the high similarity level of the 936 recorded waves sometimes observing correlation coefficients  $\geq 0.9$ . Uchida (2019, see ta-937 ble 1 therein) have compiled a comprehensive overview of 23 studies on repeating earth-938 quakes and should be consulted for a more thorough appreciation of the topic. 939

-44-

Repeaters can be used to gain important insight into local variations of slow fault slip 940 (e.g. Nadeau et al., 1994; A. Kato et al., 2012; Igarashi et al., 2003). Since it is more dif-941 ficult to map slow slip occurring over large scales – especially at depth – repeaters can be 942 used to do so. While this phenomena is widely used at larger regional scales – originally 943 stemming from research using the Parkfield High-Resolution Seismic Network – repeaters 944 have also been observed during geothermal simulations at reservoirs-scales (Lengliné et 945 al., 2014; Cauchie et al., 2020). Kinematic shear crack source models are used to inter-946 pret both seismic moment  $M_0$  and source area  $A_r$  from seismic waves (e.g. Brune, 1970; 947 Madariaga, 1976; Hanks, 1979). Using equations (13), we can estimate the average slip 948  $\delta$  over the rupture. By knowing the amount the patch has slipped and the time between 949 events, or the recurrence time  $T_r$ , we can estimated the general slip rate on the creeping 950 region. 951

Problems estimating source parameters of repeaters have been closely looked at over 952 the years. Seismologists often use the theory surrounding a penny-shaped shear (equa-953 tions (14)) couple with their estimates of  $M_0$  and A from kinematic models to calculate 954 stress drop  $\Delta\sigma$ . We can see from Figure 13 that it may not be so straightforward as the 955 original formulations suggested. It is likely that the original estimates by Nadeau and John-956 son (1998), which assumes constant stress drop approximation, will overestimate smaller 957 repeaters (see Figure 13(a)) and therefore pollute the final estimates of creep rates at that 958 section of the fault. Looking at the review by Uchida (2019), 18 of the 23 studies use this 959 approximation. Beeler et al. (2001) was the first to mention that creep corrosion might 960 lead to improper slip rates. This appears evident at even the in the laboratory scale pre-961 sented here. 962

To the authors knowledge there is no unifying mechanism to explain the presence of seismic patches that produce such similarity in seismicity. While the correlation coefficient between seismic events associated with our study was not explicitly examined by P. A. Selvadurai (2019) there appears to be evidence that this phenomena might have been occurring in our experiments (see fig. 4 there). For this reason we choose to examine how seismicity varied using the tools and methods detailed in the study of repeaters for the  $D_c$ model at the different orders of heterogeneity. 970

# 6.4 Prescribing Heterogeneity to Numerical RSF models

The goal of this study was to understand and explain the behavior of isolated asper-971 ities that appeared to produce seismicity in a larger slow slipping front. Our  $D_c$  and composite-972 model was based on the maturity of the fault and that preferentially smooth surfaces are 973 produced which had frictional conditions favorable to nucleate seismicity. To our knowl-974 edge this is the first time the cutting plane method has been used to generate a represen-975 tative interface. While we do not say this is the best model, it may be an accurate proxy 976 for worn interfaces suject to wear and polished fault surfaces that have been seen in na-977 ture and reproduced on rock surfaces in the laboratory. 978

Typical RSF models promote the idea of heterogeneous friction using a variety of VS-979 VW scenarios, which allows for the synchronous slow and fast slip from similar faulting 980 segments. Dublanchet et al. (2013) modeled this complexity where VW asperities were 981 embedded in a VS regime but they varied the density of circular asperities and examined 982 their collective behavior and its implications on repeaters. Noda et al. (2013) chose a model 983 that may be more similar to ours: a smaller VW asperity embedded on a larger VW as-984 perity, with variable properties (multi-VW asperities), surrounded by a creeping VS re-985 gion. They observed very complex behaviors but the models parameterization, albeit very 986 well constructed, was used dependent on the geometric descriptions. An even more com-987 plex and equally interesting study by Schaal and Lapusta (2019) produced important un-988 derstanding of another case of a multi-VW asperity, however, it is unclear how these clean 989 geometric boundaries might be up-scaled to nature. These types of asperity models have 990 high importance and individual contributions to complex RSF models. However, moving 991 forward, it will be important to understand how these smooth sections of fault – thought 992 to be responsible for seismicity – evolves with slip and how this influences the produced 993 seismicity. 994

995

### 6.5 Attributes of wear on natural interfaces

In nature, faults show wear by either abrasive or adhesive mechanisms (Scholz, 2002; Ben-Zion & Sammis, 2010). Wear occurring between rock samples has been observed in the laboratory (e.g., Wang & Scholz, 1994; Blanpied et al., 1998; Siman-Tov et al., 2015) as well as on fault outcrops at natural scales (Brodsky et al., 2011; Siman-Tov et al., 2013; Candela & Brodsky, 2016; Goldberg et al., 2016; Brodsky et al., 2016). Wear processes

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are complex and appear to display a length scale-dependence; furthermore they are con-1001 trolled by local slip and slip rates. Kirkpatrick and Brodsky (2014) studied exposed slick-1002 ensides on the Corona Heights fault, San Francisco, USA and found that at short wave-1003 lengths, asperities fail inelastically and 'flatten' during the accumulation of fault slip (Brodsky 1004 et al., 2016). Similar wear processes appear to create fault mirrors (FM) (Siman-Tov et 1005 al., 2013). Laboratory rock friction experiments have shown that as surfaces wear, fric-1006 tional heating leads to intracrystalline plasticity that accommodates high intragranular 1007 strain in the slip zone, and play a key role in producing nanoscale subgrains ( $\leq 100$  nm) 1008 (Goldsby & Tullis, 2011). Siman-Tov et al. (2013) found that asperities formed in a duc-1009 tile, flattening manner were also accompanied by the deposition of nano-metric wear par-1010 ticles (powder formed in a brittle manner) that filled voids on the already flattened as-1011 perities giving them a polished finish (Siman-Tov et al., 2015). For this reason, studying 1012 worn surfaces in the analog laboratory experiments is of interest to develop a more thor-1013 ough understanding of the frictional behavior of worn surfaces in nature. 1014

Recent work by Dascher-Cousineau et al. (2018) has shown evidence that this type 1015 of smoothing is present and occurs on a larger length scale than previously assumed. They 1016 studied pristine slip surfaces from 123 faults, finding slip patterns to progress from rough 1017 joints and deformation bands toward smooth, continuous, and mirror-like surfaces as slip 1018 was increased. We believe that a large point to this study was that the Hurst exponent 1019 did not change over scale, which they concluded that this indicated that wear behaves on 1020 a multi-scale. If this is true, it bodes well for our roughness-based RSF model that has 1021 implicitly implemented wear in our simulations. 1022

Developing a better understanding of fault roughness' effect on the parameters related to the dynamic rupture will be useful to determine how secondary seismic phenomena (swarms, foreshocks, tremor, LFEs, VLFs, etc.) interact with nucleation sequences. Increased knowledge of fault strength heterogeneity will also increase our understanding of dynamic rupture propagation and arrest sequences of natural earthquakes.

#### 1028 7 Conclusions

A laboratory fault showed complex behavior during its nucleation phase prior to the characteristic stick-slip event. We studied a detailed region of the fault that was prone to allowing for slow slip and localized seismicity. We developed a RSF roughness-based

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model that accounted for smooth and rough sections of the fault prescribed using direct
experimental roughness measurements. Smooth sections were responsible for genesis of
small ruptures. Once an event nucleated, it ruptured into its surroundings and the behavior of the fault dependent level-heterogeneity. Larger heterogeneity caused constrained localized rupture that never breached the entire fault length – in general a creep-dominated
slip patterns. Less heterogeneity caused ruptures to nucleated that sometimes propagated
the entire fault length – in general a more stick-slip-like response.

Local properties of the ruptures and compiled into catalogues which were compared to kinematic shear crack models from the acoustic emissions (P. A. Selvadurai, 2019). Typical scaling relationships for source dimension to seismic moment  $(M_0 \propto L_r^3)$  was conserved. Rupture velocity obtained from the RSF models estimated subsonic ruptures propagating at speeds closer to  $V_r = 0.6 \cdot V_S$ . By adjusting kinematic estimates made by P. A. Selvadurai (2019) for the slower ruptures, a better match was observed between the two techniques.

Worn faults have been observed in nature as mirror-like surfaces but it is unclear how they truly evolve over time and how this evolution will affect the frictional response. In our roughness-based model the reduction in heterogeneity caused a change in the behavior of a seismically prone asperities to change from a repeater- to foreshock-like while it was embedded in a large VW region that entertained slow slip. Future experiments that investigate this behavioral evolution more closely with aspects of wear on the interface will be beneficial moving forward.

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All data sets required to reproduce the results presented here are freely available at this site (doi.org/10.3929/ethz-b-000405620). Please contact the corresponding author for access.

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Figure 1.



Figure 2.



Figure 3.



Figure 4.





Figure 5.


Figure 6.





Figure 7.





Figure 8.



Figure 9.





Figure 10.



Figure 11.



Figure 12.



Figure 13.

