

1 **Constraining Fault Friction and Stability with Fluid-Injection Field Experiments**

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14 **Key Points:**

- 15 • Multiple frictional models with different stability reproduce the slip observed during the
- 16 pressurization stage of a field experiment
- 17 • The depressurization phase provides additional constraints on hydromechanical
- 18 parameters and hence fault stability
- 19 • Fault stability and the spatial extent of slip relative to the pressurized region depend on
- 20 residual friction vs initial stress levels

21

22 **Abstract**

23 While the notion that injecting fluids into the subsurface can reactivate faults by reducing
24 frictional resistance is well established, the ensuing evolution of slip is still poorly understood.
25 What controls whether the induced slip remains stable and confined to the fluid-affected zone or
26 accelerates into a runaway earthquake? Are there observable indicators of the propensity to
27 earthquakes before they happen? Here, we investigate these questions by modeling a unique
28 fluid-injection experiment on a natural fault with laboratory-derived friction laws. We show that
29 a range of fault models with diverging stability with sustained injection reproduce the slip
30 measured during pressurization. Upon depressurization, however, the most unstable scenario
31 departs from the observations, suggesting that the fault is relatively stable. The models could be
32 further distinguished with optimized depressurization tests or spatially distributed monitoring.
33 Our findings indicate that avoiding injection near low-residual-friction faults and depressurizing
34 upon slip acceleration could help prevent large-scale earthquakes.

35

36 **Plain Language Summary**

37 Fluid injections into the Earth's crust are common practice in the exploitation of
38 subsurface energy resources such as geothermal energy, shale gas and conventional
39 hydrocarbons. These injections can perturb nearby fault structures and hence induce earthquakes
40 and transient slow slip. Understanding what controls the stability (i.e., the propensity to generate
41 earthquakes) and spatial extent of the fault response as well as identifying precarious faults is
42 crucial to minimize the seismic hazard associated with these industrial practices. Here, we take a
43 step towards this goal by modeling a unique experiment in which water was injected into a
44 natural fault and the resulting slip measured directly at depth. We first show that multiple models

45 can explain the observations equally well while pressure is increased in the experiment. In these
46 models, how stable the fault response is with further injection and how large of a zone is
47 reactivated compared to the fluid-affected region depends on frictional properties. We then
48 demonstrate that the slow slip response to a decrease in injection pressure further constrains the
49 range of admissible models. Our work suggests that it may be possible to identify potentially
50 hazardous faults with optimally designed injection tests without inducing damaging earthquakes.

51

52 **1 Introduction**

53 Earthquakes induced by fluid injection into the subsurface pose a major challenge for the
54 geoenery industry and society in general (Ellsworth, 2013; Grigoli et al., 2017). Tectonically-
55 quiescent regions where dormant faults could be reactivated are particularly challenging, as their
56 infrastructure is often not designed for large-magnitude induced earthquakes (McGarr et al.,
57 2015). At the same time, some faults have been observed to slip stably at aseismic speeds of 10^{-7}
58 – 10^{-2} m/s in response to fluid injection (Cornet et al., 1997; Duboeuf et al., 2017; Guglielmi et
59 al., 2015; Scotti & Cornet, 1994; Wei et al., 2015). While induced earthquakes have been located
60 anywhere from a few meters to tens of kilometers from injection wells (Goebel & Brodsky,
61 2018), the spatial extent of fluid-induced aseismic slip is not as well characterized due to the
62 paucity of direct observations. Understanding what conditions lead to seismic versus aseismic
63 and localized versus widespread fault reactivation is central to physics-based hazard forecasting.

64 An outstanding opportunity to investigate these questions is offered by a decametric-scale
65 fluid injection experiment recently conducted in an underground tunnel intercepting a dormant
66 fault in a carbonate formation (Guglielmi et al., 2015) (Figure 1A). During the experiment, the
67 fluid pressure and fault slip were recorded at the injection site. Although the observed slip was

68 mostly aseismic, it is important to understand if the observations contained sufficient information
69 to determine whether slip would have accelerated into an earthquake rupture if injection had
70 continued. Previous efforts to model the field experiment with a slip-weakening friction law
71 concluded that aseismic slip outgrew the pressurized zone, potentially leading to a runaway
72 earthquake with continued injection (Bhattacharya & Viesca, 2019).

73 Here, we use the data from the field experiment to examine the issue of slow and
74 confined vs. fast and runaway slip in models with more realistic, laboratory-derived rate-and-
75 state friction laws (Dieterich, 1979, 2007; Ruina, 1983) consistent with laboratory results on
76 materials from this specific fault zone (Cappa et al., 2019). Furthermore, we use the modeling to
77 identify promising avenues to quantify the fault properties and control injection-induced
78 seismicity hazard. We adopt a fully-dynamic computational framework that resolves both
79 aseismic and seismic slip on faults. We keep other model ingredients relatively simple to better
80 understand frictional effects in the presence of a diffusing fluid. For example, we do not
81 explicitly model the change in fault permeability induced by slip as in previous studies
82 (Bhattacharya & Viesca, 2019; Cappa et al., 2019; Guglielmi et al., 2015). Nonetheless, we find
83 that multiple frictional scenarios of varying spatial behavior and proneness to large earthquakes
84 match the slip observations of the field experiment equally well during fault pressurization. We
85 also find that depressurization provides further constraints that could help identify potentially
86 hazardous faults.

87

88 **2 Data and Methods**

89 **2.1 A unique fluid-injection experiment on a natural fault**

90 The unprecedented field experiment involved injecting water directly into the fault zone and
91 measuring the resulting fault slip at a depth of 280 m with a specially designed borehole probe
92 (Guglielmi et al., 2015) (Figure 1A). Prior to the experiment, the shear and normal stress acting
93 on the fault were estimated at 1.65 +/- 0.5 and 4.25 +/- 0.5 MPa, and the permeability and bulk
94 modulus of the initially dry fault at $7 \times 10^{-12} \text{ m}^2$ and 13.5 +/- 3.5 GPa, respectively. Figure 1B
95 summarizes the main observations of the experiment, including the deceleration of slip
96 associated with depressurization not discussed in previous works. The slip measured during the
97 pressurization phase displays three distinct slip stages. At first, the fault is inactive and no
98 significant slip is recorded. The second stage initiates between 300 and 400 s when slip rates
99 attain $\sim 10^{-7} \text{ m/s}$ and the accumulated slip becomes measurable within the timeframe of the
100 experiment. Stage 3 corresponds to the sharp acceleration to slip velocities of $\sim 10^{-6} \text{ m/s}$ without
101 any significant increase in injection pressure at $\sim 1200 \text{ s}$. Hydromechanical modeling suggests
102 that 70% of the 20-fold increase in permeability during the experiment occurred prior to this
103 acceleration (Guglielmi et al., 2015). Laboratory experiments were also performed on grinded
104 materials from the fault zone to further constrain the rate-and-state frictional properties (Cappa et
105 al., 2019).

106 2.2 Diffusion of pore fluid pressure into the fault zone

107 We model the field experiment as a fluid injection into a planar fault embedded in an
108 elastic medium (Figure 1AC). We simulate the fluid injection by prescribing an evolution of pore
109 pressure at the center of the fault that approximates the pressure history of the field experiment
110 (Figure 1B, top). Simulations with a smooth pressure evolution result in similar but easier to
111 interpret simulation results than those with the exact pressure history (Figures S1-S2).

112 The imposed pressure diffuses axisymmetrically into the fault plane as follows:

$$\frac{\partial p(r, t)}{\partial t} = \alpha \left(\frac{\partial^2 p(r, t)}{\partial r^2} + \frac{1}{r} \frac{\partial p(r, t)}{\partial r} \right) \quad (1)$$

113 where p is the pore pressure, r is the radial distance from the injection interval, t is time, and α
 114 is the hydraulic diffusivity. The diffusion is numerically implemented using a forward finite
 115 difference scheme. Injection pressure is prescribed at a distance of $r_{inj} = 0.05$ m from the center
 116 of the fault to mimic the experimental procedure. Although we prescribe zero pressure boundary
 117 conditions to emulate the initially dry fault, the choice of boundary condition is not essential here
 118 because the size of the simulated fault (250 m) is larger than that of the pressure diffusion.
 119 Models with larger fault domains produce nearly identical results (Figure S3).

120 Although both pressure and flow rate are reported as part of the field experiment, the
 121 exact value of the hydraulic diffusivity α is still uncertain because the spatial extent of the
 122 pressurized zone and the fault thickness over which the diffusion occurs, b , are poorly
 123 constrained. The volumetric flow rate, Q , depends on b as:

$$Q = - \frac{kb(2\pi r_{inj})}{\eta} \frac{\partial p}{\partial x} \quad (2)$$

124 where k is the permeability of the fault zone, r_{inj} is the injection radius and η the dynamic
 125 viscosity of water. Hence, for a given flow rate, there is a trade-off between the fault thickness b
 126 over which the fluid diffusion occurs and the permeability k (and hence hydraulic diffusivity $\alpha =$
 127 $\frac{k\rho g}{\eta S_S}$, where S_S is the specific storage) of the fault zone. In Section 3, we use hydraulic
 128 diffusivities of 0.04, 0.20, and 0.85 m²/s to match field experimental measurements of slip for
 129 different friction regimes. Assuming the specific storage of $S_S = 2 \times 10^{-4}$ m⁻¹ as in Bhattacharya
 130 and Viesca (2019), these hydraulic diffusivities correspond to the permeability values of 0.8, 4,
 131 and 17×10^{-12} m² that are within the ranges presented in previous studies that considered

132 permeability enhancement: 0.8 to $1.3 \times 10^{-12} \text{ m}^2$ (Bhattacharya and Viesca, 2019) and 7 to 100
 133 $\times 10^{-12} \text{ m}^2$ (Guglielmi et al., 2015). These permeability values are also consistent with the flow
 134 rates measured in the field experiment, for reasonable values of the fault thickness b of 29 , 6.7 ,
 135 and 1.8 cm , respectively (Figure 1B). While considering permeability enhancement may be
 136 necessary to match the finer features of the pressure and flow rate histories (unless the fault
 137 thickness b affected by fluid flow varies with time or with space), all three combinations of the
 138 parameters we use reproduce the hydrologic observations to the first order. We therefore
 139 consider a range of constant hydraulic diffusivity (and hence permeability) values in our search
 140 for models that reproduce the main features of the experimental observations.

141

142 2.3 Numerical modeling of fluid-induced fault slip

143 As fluid pressure increases and diffuses into the fault plane, fault friction eventually
 144 decreases and measurable slip ensues (Figure 1C). We model this induced fault slip using a fully-
 145 dynamic 2D antiplane boundary integral method capable of simulating the complete seismic
 146 cycle including both aseismic and seismic deformation (Lapusta et al., 2000; Noda & Lapusta,
 147 2013). Fault slip is governed by the following elastodynamic equation:

$$\tau(x, t) = f[\sigma - p(x, t)] = \tau_{ini} + F[\delta(x, t)] - \frac{\mu}{2c_s} V(x, t) \quad (3)$$

148 where τ is the shear stress, f the friction coefficient, σ the normal stress, τ_{ini} the initial (i.e.,
 149 background) shear stress, F a linear functional which depends on the slip history, δ , μ the shear
 150 modulus of the elastic medium, c_s the shear wave speed and V the slip rate. The friction
 151 coefficient in (3) follows an empirical rate-and-state formulation derived from laboratory
 152 experiments which describes the dependence of f on the slip rate and a state variable θ
 153 (Dieterich, 1979, 2007; Ruina, 1983):

$$f(V, \theta) = f^* + a \ln \frac{V}{V^*} + b \ln \frac{V^* \theta}{D_{RS}} \quad (4)$$

154 where a and b are the direct and evolutionary rate-and-state parameters, D_{RS} is the critical slip
 155 distance and f^* is a reference coefficient of friction at reference slip rate V^* . The state variable is
 156 assumed to evolve according to the aging law (Marone, 1998; Ruina, 1983).

157 As the fault in the experiment is inactive prior to the fluid stimulation, the modeled fault
 158 is not loaded tectonically. Fault slip is thus purely fluid-induced, i.e., no significant slip would
 159 occur without the injection within the time scales considered in the simulations. To initialize the
 160 models, we impose shear and normal stresses in agreement with the values reported at the field
 161 site prior to the experiment (Guglielmi et al., 2015) and initial state variable values consistent
 162 with a dormant, highly healed fault (Text S1; Figures S4-S7). The corresponding initial slip rate
 163 is then computed from Eq. (4).

164

165 **3. Results**

166 3.1 Models in agreement with the slip observations during pressurization

167 By first limiting our analysis to the pressurization stage of the experiment (up to 1400 s),
 168 we find that the observations are equally well reproduced by a family of models. Three
 169 representative cases, which we denote lower-, intermediate- and higher-friction models, are
 170 shown in Figures 2A-C and S8 to S11 and Table S1. Below we explain how we constrained these
 171 models by examining how the various parameters govern the transitions between the different
 172 slip stages and considering the trade-off between friction and fluid pressure.

173 At the beginning of all simulations, slip rates are low and both inertial effects and elastic
 174 stress transfers are negligible. Eq. (3) then reduces to:

$$f(V, \theta)[\sigma - p(x, t)] = \tau_{ini} \quad (5)$$

175 As p increases and τ_{ini} remains constant over time, f must increase via growing slip rates in
 176 order for (5) to remain true, resulting in a balance between the direct frictional effect and
 177 changes in pore pressure (Dublanchet, 2019). Slip rate and friction continue increasing until slip
 178 becomes significant at $V \sim 10^{-7}$ m/s. The onset of significant slip thus approximately coincides
 179 with the maximum friction reached during the simulations (Figures 2AB, S8). The peak friction,
 180 f^p , can be approximated as:

$$f^p \sim f^* + a \ln \frac{V_s}{V^*} + b \ln \frac{V^* \theta_{ini}}{D_{RS}} \quad (6)$$

181 where $V_s = 10^{-7}$ m/s. The state variable remains at its initial value, θ_{ini} , as it has not evolved
 182 significantly yet due to negligible slip and short healing time compared to its large initial value.
 183 Moreover, because the fluid pressure at the injection site is known at all times, we can relate f^p
 184 to the timing of slip initiation, t_s :

$$f^p = \frac{\tau_{ini}}{[\sigma - p(0, t_s)]} \quad (7)$$

185 It is thus possible to control t_s by computing the corresponding f^p with Eq. (7) and selecting f^* ,
 186 a , b , θ_{ini} and D_{RS} such that Eq. (6) is satisfied. The three example models have t_s between 300
 187 and 400s and f^p between 0.84 and 0.99 (Figures 2B, S8).

188 Once significant slip starts accumulating, the fault begins weakening until it reaches
 189 steady state and friction reaches its quasi-static residual value of $f^r = f^* + (a - b) \ln V/V^*$ at
 190 the latest stage of the fault pressurization experiment (Figure 2B, S8). As in Dublanchet (2019)'s
 191 rate-strengthening models, we find that this transition to steady state is accompanied with a
 192 marked acceleration in slip rate (Phase II in Dublanchet, 2019) which we assume to explain the
 193 acceleration observed at 1200s.

194 The critical slip distance, δ_c , over which friction weakens from f^p to f^r can be
 195 approximated as:

$$\delta_c \sim \frac{f^p - f^r}{b/D_{RS}} \quad (8)$$

196 since $\frac{\partial f}{\partial \delta} \sim \frac{b}{D_{RS}}$. Furthermore, from elasticity, slip is related to stress drop by:

$$\Delta\delta \propto \frac{\Delta\tau h}{\mu} \quad (9)$$

197 where h is the length of the slipping zone. By equating Eq. (8) and (9) at the center of the fault,
 198 we can estimate the slipping zone size, h_{ac} , at which steady state is reached and Stage 3 initiates:

$$h_{ac} \propto \frac{\mu D_{RS}}{b} \frac{f^p - f^r}{\Delta\tau} \quad (10)$$

199 Moreover, by choosing V^* to be on the same order of magnitude as the fastest slip rate measured
 200 during the field experiment ($V^* = 10^{-6}$ m/s), we can approximate f^r with f^* since the
 201 contribution of $(a - b) \ln V/V^*$ becomes small compared to that of f^* . Eq. (10) can then be
 202 rewritten in terms of known parameters as:

$$h_{ac} \propto \frac{\mu D_{RS}}{b} \frac{a \ln \frac{V_s}{V^*} + b \ln \frac{V^* \theta_{ini}}{D_{RS}}}{\tau_{ini} - f^* [\sigma - p(0, t_{ac})]} \quad (11)$$

203 where t_{ac} denotes the onset of Stage 3. For all the simulations presented in this work, we find
 204 that adding a pre-factor of 3 to Eq. (11) provides a good estimate of the slipping zone size at t_{ac}
 205 (Text S2). Remarkably, h_{ac} only depends on quantities at the injection site. We can thus control
 206 the initiation of Stage 3 in our simulations by tuning the model parameters such that the slipping
 207 zone reaches length h_{ac} at ~ 1200 s as is the case for our three representative models in Figure 3.

208 Another critical aspect in these simulations is the balance between friction and the pore
 209 pressure forcing. Figures S20-S23 illustrate how the aseismic slip zone grows with decreasing

210 f^* and increasing α , respectively. In particular, during Stage 3, the spatial extent of the slipping
 211 zone with respect to the pressurized zone and the slip rate at the injection site depend on the
 212 difference between the residual and initial friction, $f^r - f_{ini}$, which controls the elastic energy
 213 available to drive fault rupture once initiated (Bhattacharya & Viesca, 2019; Dublanche, 2019;
 214 Galis et al., 2017; Garagash & Germanovich, 2012) (Figure S19A-C). Note that this is distinct
 215 from the difference between peak and initial friction, $f^p - f_{ini}$ (e.g., Gischig, 2015), which
 216 controls the timing of fault reactivation as discussed above.

217 Given all these consideration, for each diffusion scenario presented in Figure 1B, we find
 218 a corresponding frictional model by adjusting f^* such that the simulated slip matches the
 219 observations during the first 2 slip stages and produces a sufficiently large slip transient during
 220 Stage 3. To be able to use f^* values in agreement with the range $f^r = 0.55 - 0.65$ inferred from
 221 laboratory experiments on the grinded fault zone material (Cappa et al., 2019), we set f_{ini} to 0.54
 222 ($\tau_{ini} = 2.15$ MPa, $\sigma = 4.00$ MPa), which is within the uncertainty range of the initial stress
 223 measurements. The selected values of f^* restrict the range of possible values for the term
 224 $b \ln V^* \theta_{ini} / D_{RS}$ in Eq. (6) in order for slip to initiate between 300 and 400 s, which in turn
 225 restricts factor $\mu D_{RS} / b$ in Eq. (11) in order for Stage 3 to initiates at 1200s. The factor μD_{RS}
 226 which appears in estimates of critical nucleation lengths also needs to be large enough to avoid
 227 nucleation of dynamic events within the experimental time (e.g., Rice & Ruina, 1983; Rubin &
 228 Ampuero, 2005). Finally, we fine tune parameters a and θ_{ini} to adjust the slope and timing of the
 229 acceleration, respectively. Note that decreasing a while keeping b constant increases the slope of
 230 the slip acceleration - due to the (weak) dependence of f^r on $(a - b)$ - and eventually leads to
 231 the nucleation of a dynamic event right at t_{ac} (Figure S16 and S19D-F). This procedure results in
 232 a family of models with $f^* = 0.48$ to 0.60, $a - b = -0.001$ to -0.005 ($b = 0.016$), $\theta_{ini} = 1.2 \times 10^{12}$

233 to 7.0×10^{12} s and $\alpha = 0.04$ to 0.85 m²/s that match the slip observations equally well during
234 pressurization.

235 Although the three models exhibit comparable slip histories at the injection site, they
236 differ in features that were not directly accessible to field observation. In particular, their spatial
237 behaviors differ qualitatively (Figure 3, S9-S11). Defining the pressurized zone with 0.5 MPa
238 pressure contours as in previous works, the lower-friction scenario produces an aseismic front
239 that outruns the pressurized region, within 1400 s, as in slip-weakening models (Bhattacharya &
240 Viesca, 2019) (Figure 3D). By contrast, in the higher-friction model, which reproduces the
241 observations equally well, aseismic slip remains confined well within the pressurized area
242 (Figure 3F). Our models demonstrate that slip did not necessarily extend beyond the pressure
243 perturbation during the experiment; that explaining a slip history at a single point in space is a
244 non-unique problem; and that further hydro-mechanical complexity is not required to explain the
245 observed slip to first order. Monitoring fault slip and fluid pressure along the length of the fault,
246 directly with additional probes or remotely with geophysical methods, would help distinguish
247 between these different scenarios and would allow to study additional fault processes such as
248 permeability evolution and inelastic dilatancy (Segall & Rice, 1995).

249 3.2 Distinguishing between models with depressurization

250 We find that the depressurization stage of the field experiment, which was not discussed
251 or modeled in previous studies (Bhattacharya & Viesca, 2019; Cappa et al., 2019; Derode et al.,
252 2015; Guglielmi et al., 2015), contains valuable information on fault properties. In this pressure-
253 reduction stage, the lower-friction model features a pronounced delayed slip response that is not
254 observed in the experiment or in the other two cases (Figure 2A). The intermediate- and higher-
255 friction models, which also have higher hydraulic diffusivities, thus explain the entire set of

256 observations better than the lower-friction model. Further discriminating between these two
257 models is not possible with the current dataset because, by the time depressurization is initiated,
258 the slip rates in these simulations are too low to produce a detectable difference in incremental
259 slip. However, if the injection pressure is decreased more gradually and earlier in the
260 acceleration phase – at which point the intermediate- and higher-friction scenarios have
261 approximately the same (and higher) slip rate – the three scenarios lead to diverging levels of
262 incremental slip (Figure 2D). As we only investigate a limited portion of the rate-and-state
263 parameter space in this study, we cannot conclude that timely depressurization can uniquely
264 discriminate between all possible frictional scenarios. However, it is clear that timely
265 depressurization can provide additional constraints on the frictional and hydromechanical
266 properties of fault zones.

267 In addition to fitting the entire set of slip observations better, models with f^* of 0.55 and
268 0.60 are also more consistent with the range of residual friction values of 0.55 to 0.65 derived
269 from laboratory experiments on grinded fault gouge (Cappa et al., 2019). Moreover, the initial
270 fault conditions implied by these higher-friction cases are fully consistent with those of a
271 dormant fault whereas the low-friction case is not (Text S1). Our preferred model for the site of
272 the injection experiment is thus a rate-weakening fault with $0.55 < f^* < 0.60$, $0.20 < \alpha < 0.85$
273 m^2/s , $a = 0.011$ and $b = 0.016$. This is in contrast to the original Guglielmi et al. (2015) study in
274 which the authors inferred a rate-strengthening fault from a spring-slider model with
275 permeability enhancement. Within the limited parameter space that we explored through the
276 procedure outlined in section 3.1, we could only find rate-strengthening models with relatively
277 low f^* and hence ones that only match the pressurization stage of the experiment (Figure S24). It
278 is possible that there are 2D models with rate-strengthening parameters that match the entire slip

279 history that we have not considered here, which would further strengthen our conclusions that
280 the field measurements can be matched with multiple friction scenarios and that the
281 depressurization stage provides further constraints than pressurization alone.

282 3.3 Diverging fault stability with sustained injection

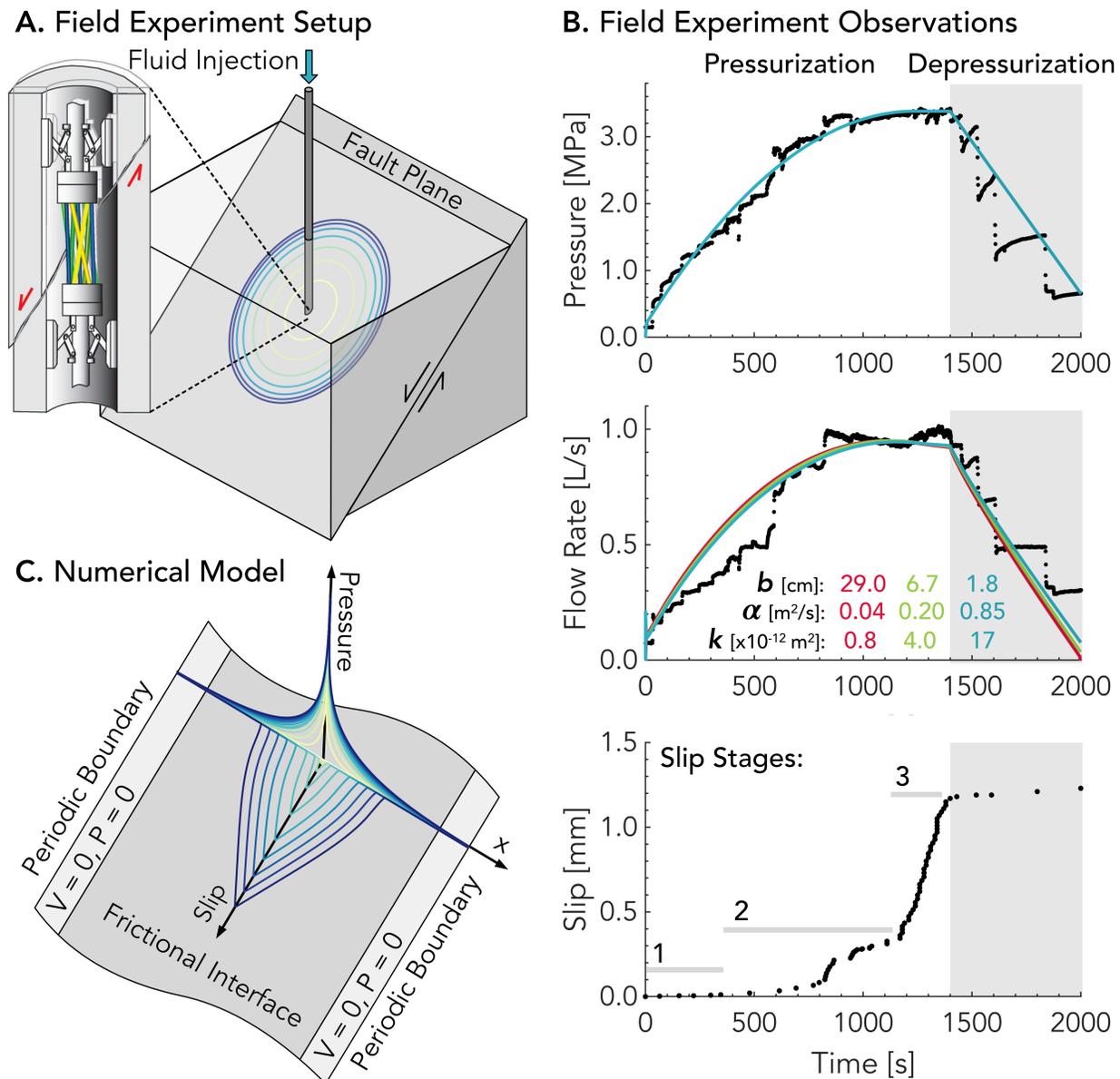
283 Modeling what would have happened if the fluid injection had continued for longer
284 highlights why distinguishing between the three qualitatively different scenarios identified in this
285 study is crucial. In response to an extended constant-pressure injection (Figure 4, Figures S3,
286 S25-S27), the low-friction fault nucleates an earthquake almost immediately, while the
287 intermediate and higher-friction faults decelerate and continue slipping aseismically before
288 eventually transitioning to seismic slip rates. Once a seismic rupture initiates, whether it is self-
289 arrested or run-away depends on the *dynamic* residual friction, f^d , which is generally slightly
290 lower than f^r (Galis et al., 2017; Garagash & Germanovich, 2012). If $f^d < f_{ini}$, as in the low-
291 and intermediate-friction cases (Figure 4B), the rupture may release enough elastic energy to
292 propagate beyond the fluid-affected regions and would only be stopped by less favorably
293 stressed fault patches, geometrical barriers, or more stable materials not present in the current
294 model (Figures 4C,D). Such runaway ruptures may be preceded by smaller ruptures or aseismic
295 slip transients (Figures S15 and S19A); indeed, in fracture mechanics models (Galis et al., 2017),
296 the transition to runaway rupture requires a certain balance between fluid pressurization and
297 background stress to be reached. If $f^d < f_{ini}$, as in the high-friction case, the rupture self-arrests
298 once out of the pressurized zone (Figure 4E). For low- to intermediate-friction faults, the
299 maximum expected earthquake magnitude, M_{max} , is thus controlled by hydro-mechanical and
300 geometrical fault properties as opposed to injection attributes (e.g., cumulative volume injected)
301 (van der Elst et al., 2016; Galis et al., 2017; Gischig, 2015; McGarr, 2014). For example, varying

302 the injection rate in our simulations does not alter the event size (Figure S28). In the
303 intermediate-friction case, the fault ultimately undergoes a runaway earthquake despite having
304 stably released energy for over an hour, thus demonstrating that aseismic slip does not signify an
305 absence of earthquake hazard. Fortunately, comparing the depressurization and prolonged
306 injection scenarios reveals that reducing the injection pressure might be sufficient to suppress
307 earthquake nucleation at the injection site. The lower the friction on the fault, the faster the rate
308 of this depressurization needs to be (Figure S29). Note, however, that earthquakes could still be
309 triggered by aseismic slip itself on more unstable heterogeneities away from the injection site
310 (Eyre et al., 2019; Guglielmi et al., 2015).

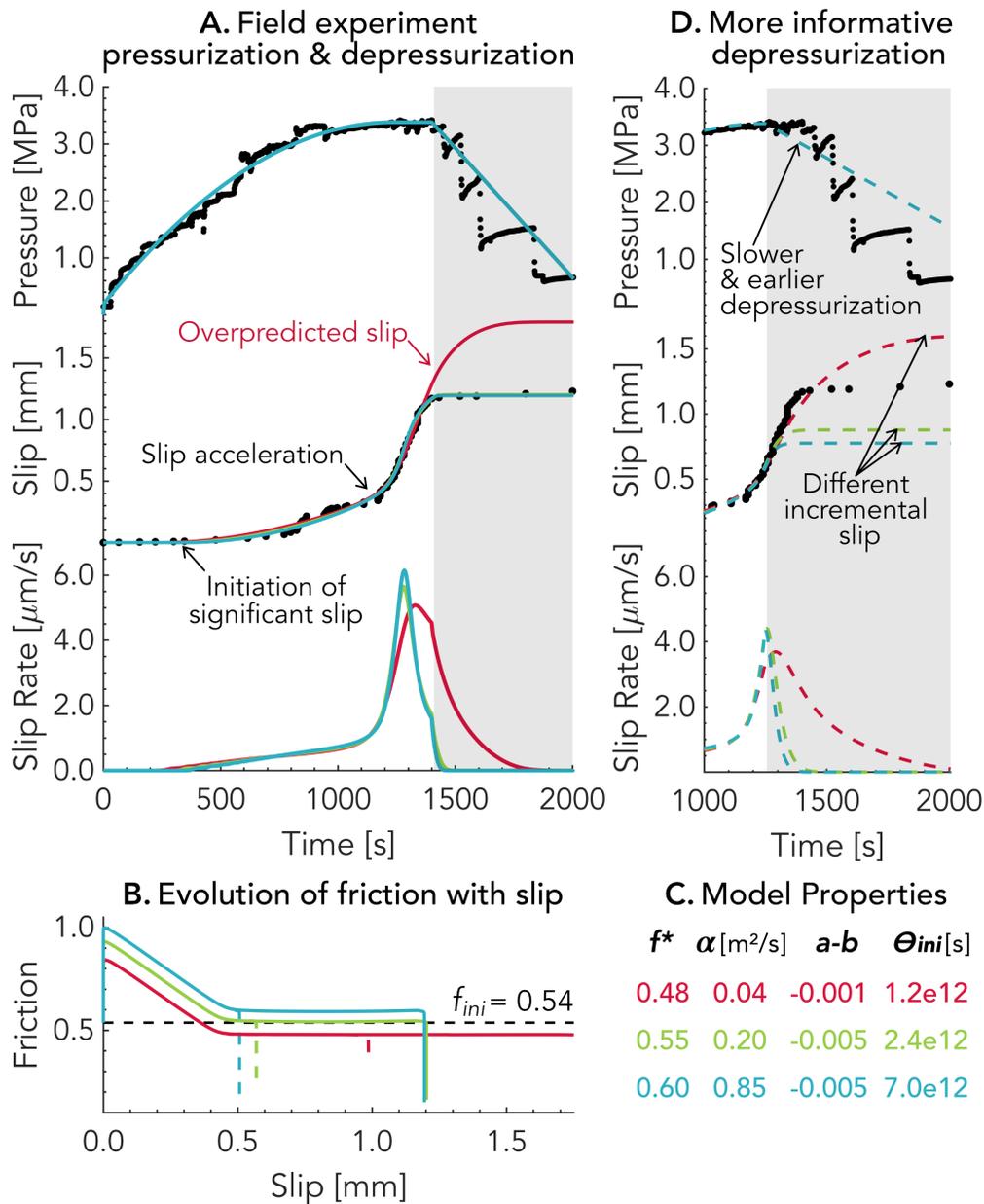
311 **4 Discussion and Conclusions**

312 To summarize, our modeling of a fluid-injection experiment into a fault zone reveals that
313 the difference between fault prestress and quasi-static or dynamic fault friction controls whether
314 slip is confined to the fluid-affected zone or outruns it. We find that: (i) multiple scenarios with
315 different hydrologic assumptions and friction levels are consistent with the measured slip at the
316 injection site during the pressurization phase, (ii) the low-friction scenario in which slow slip
317 outruns the pressurized region is inconsistent with slip during the depressurization phase, and
318 (iii) the high-friction scenario, in which the slipping zone is well confined within the pressurized
319 region, is most consistent with the full range of information from the experiment, including the
320 fault behavior during fault depressurization and laboratory friction measurements on the
321 materials from the fault zone. Key hydro-mechanical parameters such as the difference between
322 quasi-static friction and initial normalized prestress, $f^r - f_{ini}$, the rate dependence of friction,
323 $a - b$, and the hydraulic diffusivity, α , exercise a first-order control on the stability and spatial
324 extent of a fault response to fluid injections. Further constraining these parameters is thus critical

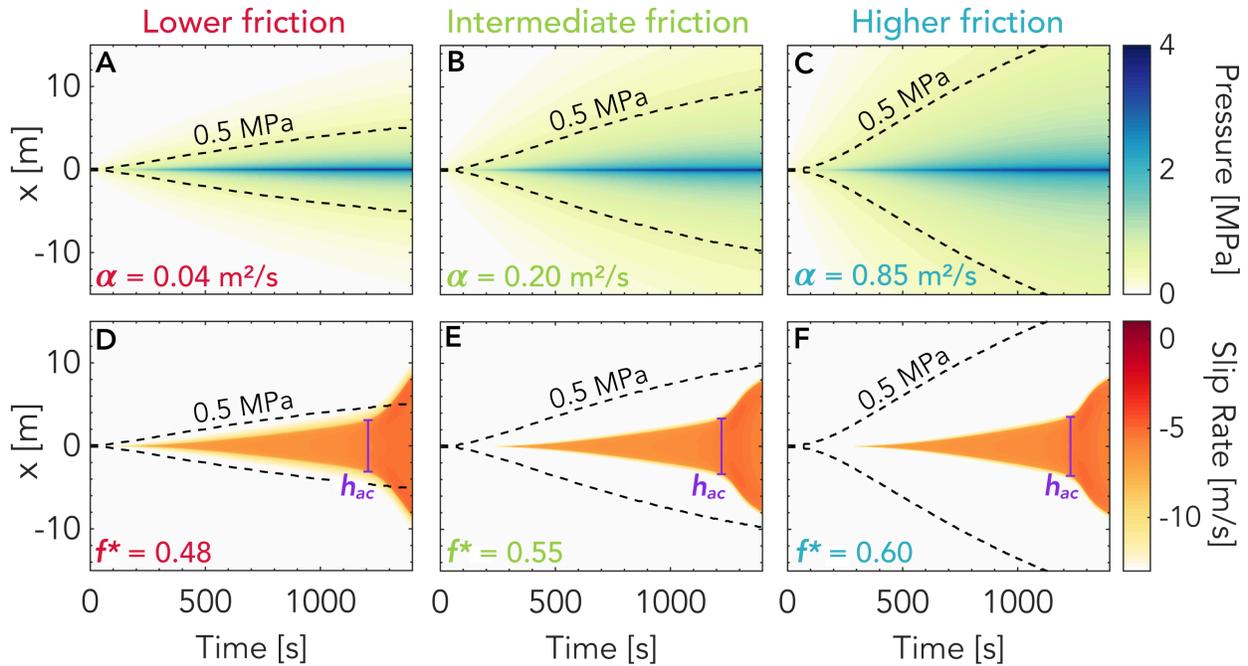
325 for seismic hazard management. In the geoenery industry, test injections with timely
326 depressurization and spatiotemporal monitoring of fluid pressure and aseismic slip could be
327 performed prior to exploitation to ensure that there are no low-friction faults nearby. Our
328 findings show that augmenting fault-pressurization experiments with suitably designed
329 depressurization phases and multiple monitoring locations along the fault could provide
330 invaluable insight into the physics of both induced and natural earthquakes (Savage et al., 2017)
331 and friction properties of dormant faults. Such more advanced injection experiments and
332 corresponding modeling work will potentially be able to assess the effects and relative
333 importance of additional mechanisms (e.g., poroelastic stresses (Deng et al., 2016; Goebel et al.,
334 2017; Segall & Lu, 2015), slip-induced dilatancy (Cappa et al., 2019; Segall & Rice, 1995), bulk
335 fluid diffusion, and enhanced dynamic weakening) and complexity (e.g., material heterogeneities
336 (Eyre et al., 2019)).



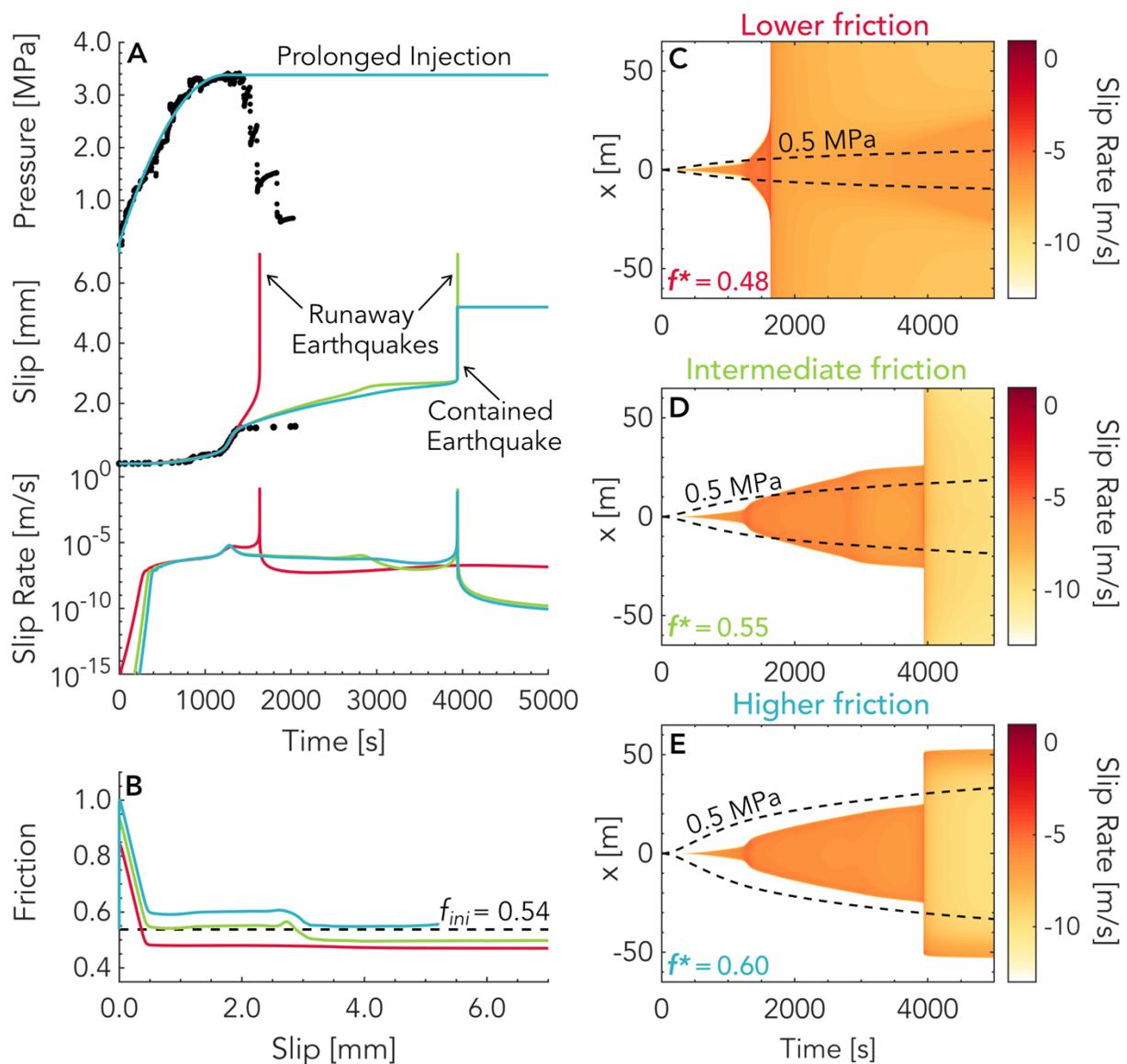
337
 338 **Figure 1. In situ measurement and modeling of fault slip induced by fluid injection. (A)**
 339 Schematic of the field experiment presented in Guglielmi et al. (2015) in which fluid injected
 340 into a borehole crossing a natural but inactive fault caused its reactivation. A special borehole
 341 probe (SIMFIP) was used to measure the fault displacements directly at the injection site. **(B)**
 342 Pressure, flow rate, and fault slip measured during the field experiment. The colored lines and
 343 associated parameters correspond to the three different hydrological models considered in this
 344 study. The grey area indicates the depressurization stage that has not been shown nor modeled in
 345 prior studies. **(C)** Schematic of the model used to simulate slip on a fault plane embedded in an
 346 elastic bulk medium. Snapshots of a sample fluid pressure diffusion scenario and its resulting
 347 fault slip are shown for illustration (the darker colors indicate later times). Schematics **(A)** and
 348 **(C)** are not to scale.
 349



350
 351 **Figure 2. Multiple simulated scenarios match the pressurization stage of the experiment**
 352 **but respond differently to depressurization. (A)** Temporal evolution of pore fluid pressure,
 353 slip and slip rate for three model scenarios (solid curves) that reproduce the observations (black
 354 black dots) during the field-experiment pressurization. **(B)** Simulated evolution of friction with slip at
 355 the injection site; the three scenarios correspond to lower (red), intermediate (green), and higher
 356 (blue) residual friction in comparison to the fault prestress (black dashed line). Note that only the
 357 intermediate and higher-friction faults result in slip consistent with the depressurization part. **(C)**
 358 Key frictional and hydraulic properties of the three scenarios. **(D)** Similar to (A) but for an
 359 improved depressurization: Reducing injection pressure once slip starts to accelerate would
 360 allow to distinguish between all three cases, helping to constrain the fault friction properties.



361
 362 **Figure 3. Whether the slipping zone is contained within or outruns the pressurized zone**
 363 **depends on fault friction.** Spatial and temporal evolution of (A-C) pore fluid pressure and (D-
 364 **F)** slip rate for the three scenarios of Figure 2 during pressurization. The purple line shows the
 365 estimate h_{ac} of the slipping zone for the acceleration stage. Black dashed lines indicate the extent
 366 of the pressurized zone defined by 0.5 MPa fluid pressure contours. During the pressurization
 367 stage, the slipping zone of the lower-friction case outruns the pressurized zone while the
 368 intermediate- and higher-friction cases remain confined to the pressurized zone.



369

370 **Figure 4. Prolonged injection reveals the diverging stability of the different fault models.**

371 Same as Figure 2 (A-B) and Figure 3 (C-E) but for a longer injection scenario, keeping the
 372 pressure at the center of the fault constant past 1400 s instead of decreasing it. The low-friction
 373 case (red in A, C) produces a runaway earthquake rupture much sooner than the intermediate-
 374 friction case (green in A, D), while the higher-friction case (blue in A, E) - which is consistent
 375 with most known information about the fault - results in a self-arresting earthquake confined to
 376 the pressurized zone (blue).

377

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379

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