Role of background stress state in fluid induced laboratory aseismic slip and dynamic rupture on a 3 meter laboratory fault

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Abstract

We know that humans can induce earthquakes on natural faults by injecting fluids at high pressures. However, exactly how fluid injection changes the stresses on the fault causing earthquakes is poorly understood. In this study, we conducted laboratory experiments with a 3 m fault that slips similarly to a natural fault. Our experiments investigated how the initiation of earthquakes differed when they were induced on a critically loaded fault that was ready to host an earthquake (Case A) verses a fault that was far from hosting an earthquake (Case C). In the critical case, earthquakes initiated right after the fluid reached peak pressure. However, when the fault was not critical, earthquakes only initiated after silent slip shifted stress from patches of the fault directly affected by fluid to neighboring stuck patches. Only once stress had shifted enough so the neighboring patches reached a critical state, did an earthquake initiate. In the critically stressed case, the fault had ample fuel to start and drive an earthquake, whereas the low stress case required significant changes to build up enough fuel. Slow slip is effective at building up fuel by shifting stress to neighboring patches. This suggests that how close the fault is to hosting an earthquake, is a significant factor in induced earthquakes.

Introduction/Background

Induced earthquakes initiate based on Coulomb failure stress and nucleation length criteria. Studies have also shown that aseismic slip can induce seismicity indirectly by transferring stress to neighboring faults or asperities that are then able to initiate a dynamic event (Wei et al., 2015; Villiger et al., 2021; Guglielmi et al., 2015; Cappa et al., 2019). We aim to fill in the gap between modeling and decameter scale studies using a 3 m laboratory fault to investigate the effects of initial background stress levels on resulting induced seismicity.

Experimental Procedure

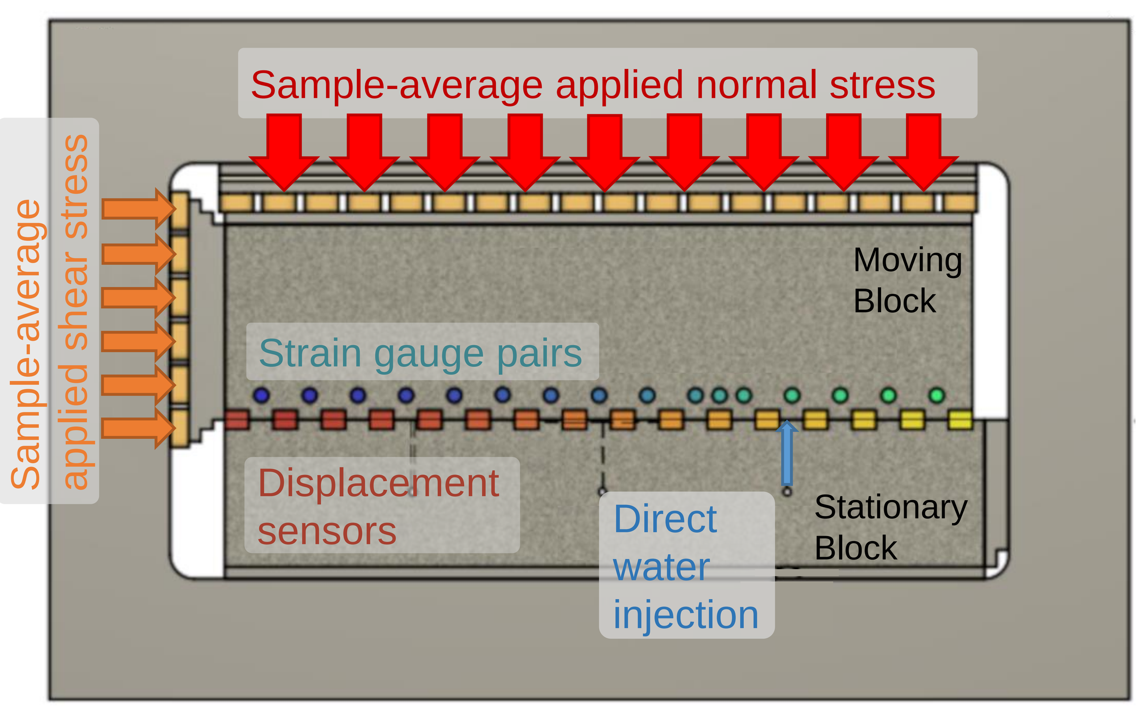


Figure 1: Schematic of Cornell 3 m biaxial shearing apparatus and samples. Colored squares indicate slip sensors and circles indicate strain gauges. During experiments water is injected through the hole located 2.331 m from the forcing end, directly onto the fault interface.

At the beginning of each experiment, 4 MPa of sample-average normal stress was applied to a wet, unpressurized fault, and was held constant for the duration of the experiment. Sample-average shear stress was increased at roughly 0.03 MPa/s until three sample-spanning rupture event occurred. Shear stress was then set to a prescribed level, τ_0 and was held constant. Water was injected directly onto the fault at a prescribed rate of 10 mL/min. Resulting injection well pressure and shear stress were measured using hydraulic sensors. Fault slip and strain were measured using eddy current displacement sensors and strain gauge pairs.

Resulting Fluid Pressure Distribution

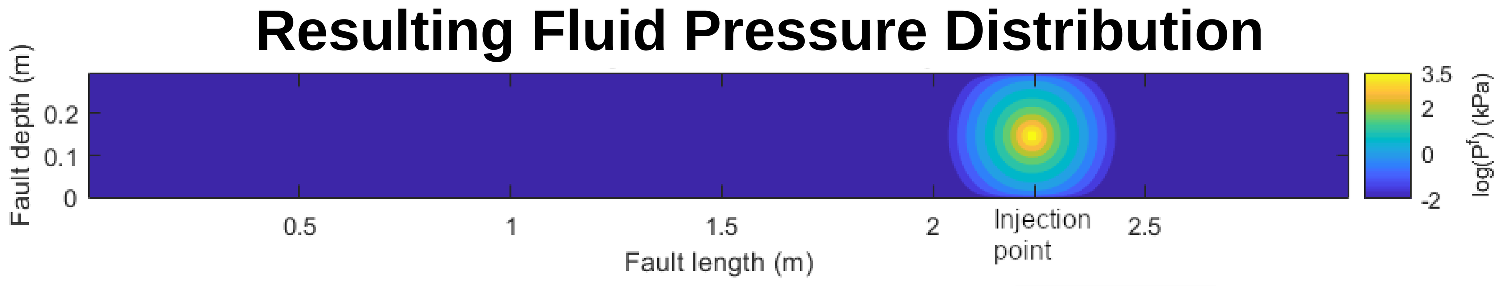
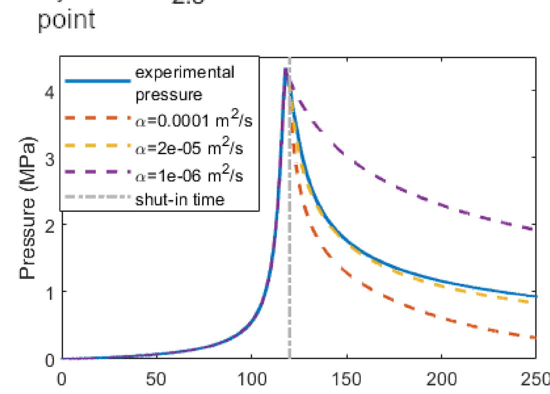


Figure 2: Fluid pressure along the fault at peak injection pressure (above) based on a 2D finite difference diffusion model. Fault diffusivity was estimated by performing a shut-in test using the injection trough and matching the results to a 2D diffusion model. Comparison of the experimental measurements to numerical results for different modeled α is shown on the right. Fault diffusivity was found to be 2x10^{-5} m^2/s.



Results

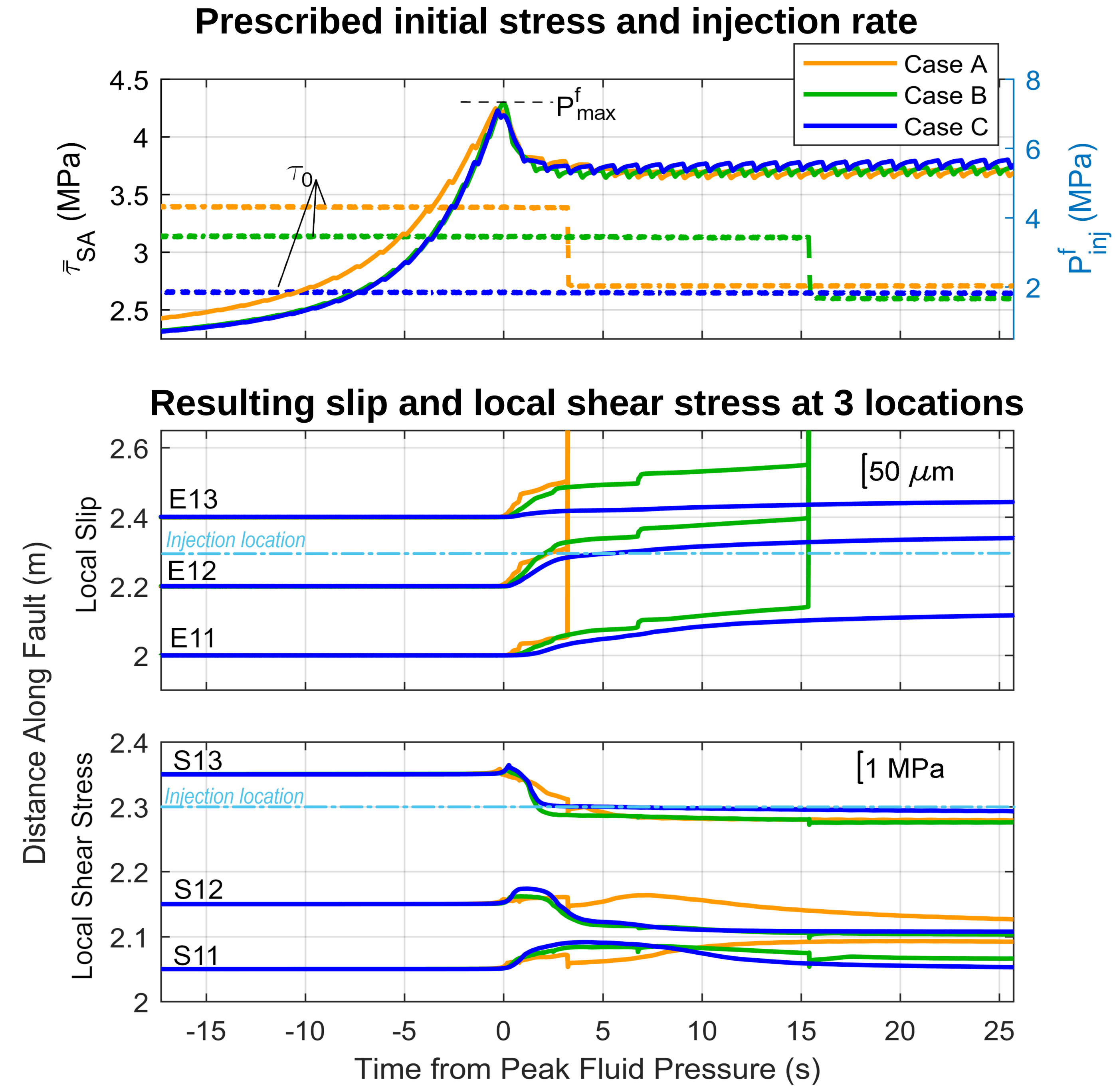


Figure 3: Results for Case A (orange), B (green), and C (blue) overlaid for comparison. Data is lined up according to peak injection fluid pressure. Top graph shows fluid pressure measured in the injection well and sample-average shear stress measured by hydraulic sensors, middle graph shows displacement measurements from three slip sensors, and the bottom graph shows stress measurements from three strain gauges, both offset by the sensor location along the fault.

In all cases fluid pressure induced slow slip. A dynamic event initiated from within the aseismic slipping region, however the timing and extent of the dynamic event varied. Stress changes from dynamic slip was small compared to aseismic slip.

Case A: small amount of aseismic slip occurred before a large dynamic event initiated from within the aseismic slipping region seconds after peak pressure.

Case B: Moderate amount of aseismic slip accompanied by shear stress changes. Large dynamic event initiated 15 seconds after peak pressure.

Case C: Significant amount of aseismic slip redistributed shear stress required prior to initiation of a dynamic event hundreds of seconds after peak pressure.

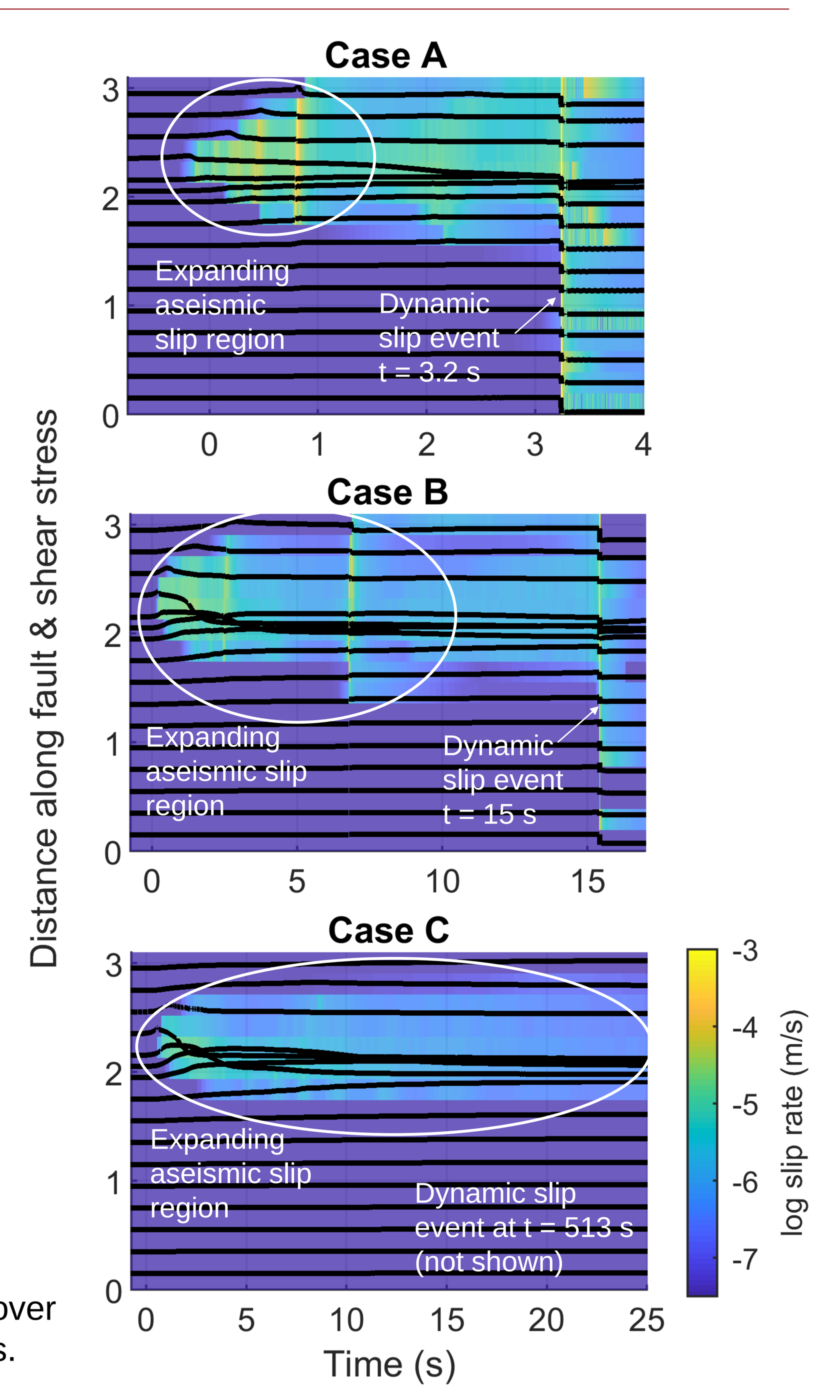


Figure 4: Slip rate and local shear stress over space and time for three initial stress levels.

Local stress changes

Prior to dynamic rupture, aseismic slip redistributed stress from within the pressurized region to neighboring locked patches (left). This redistribution is largest in Case C, since it is initially far from critically stressed, and smallest in Case A which is critically stressed at the start of fluid injection. Stress drop during dynamic rupture (right)

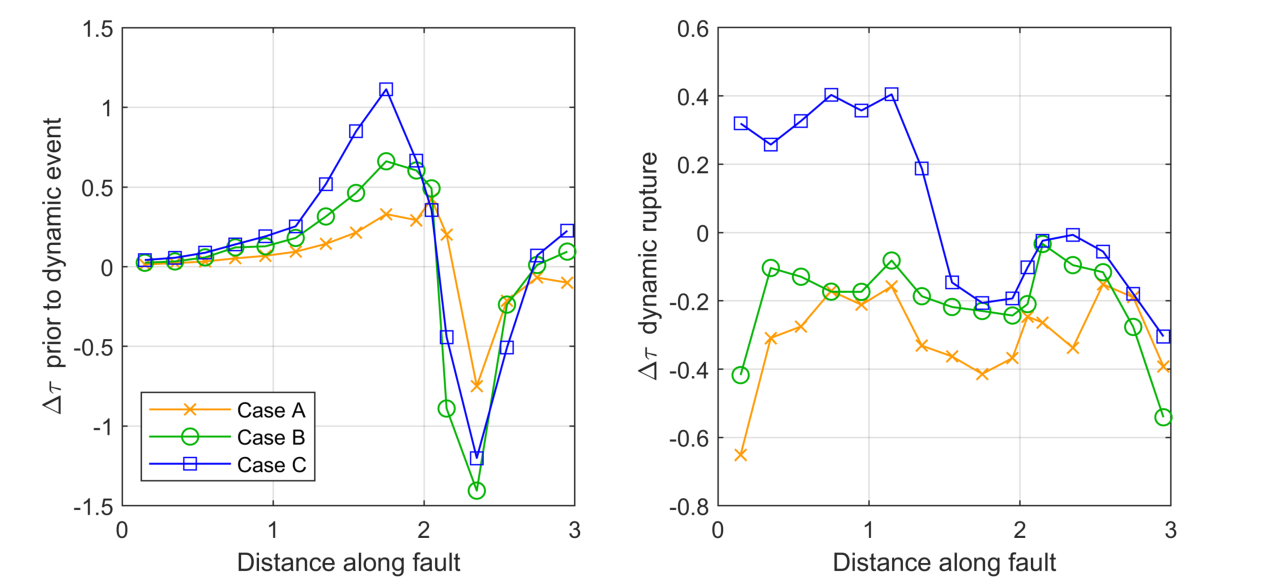


Figure 5: Shear stress change from the start of injection to just before initiation of a dynamic event and shear stress change during a fluid induced dynamic slip event.

Conclusions

- Initial stress levels are important since they affect the initiation and termination of induced seismic events.
- High background stress levels provides ample fuel for rupture beyond the pressurized region whereas initiation in a low background stress environment requires significant stress redistribution.
- Aseismic slip is an effective means of redistributing stress beyond the pressurized zone, priming the fault for dynamic slip.

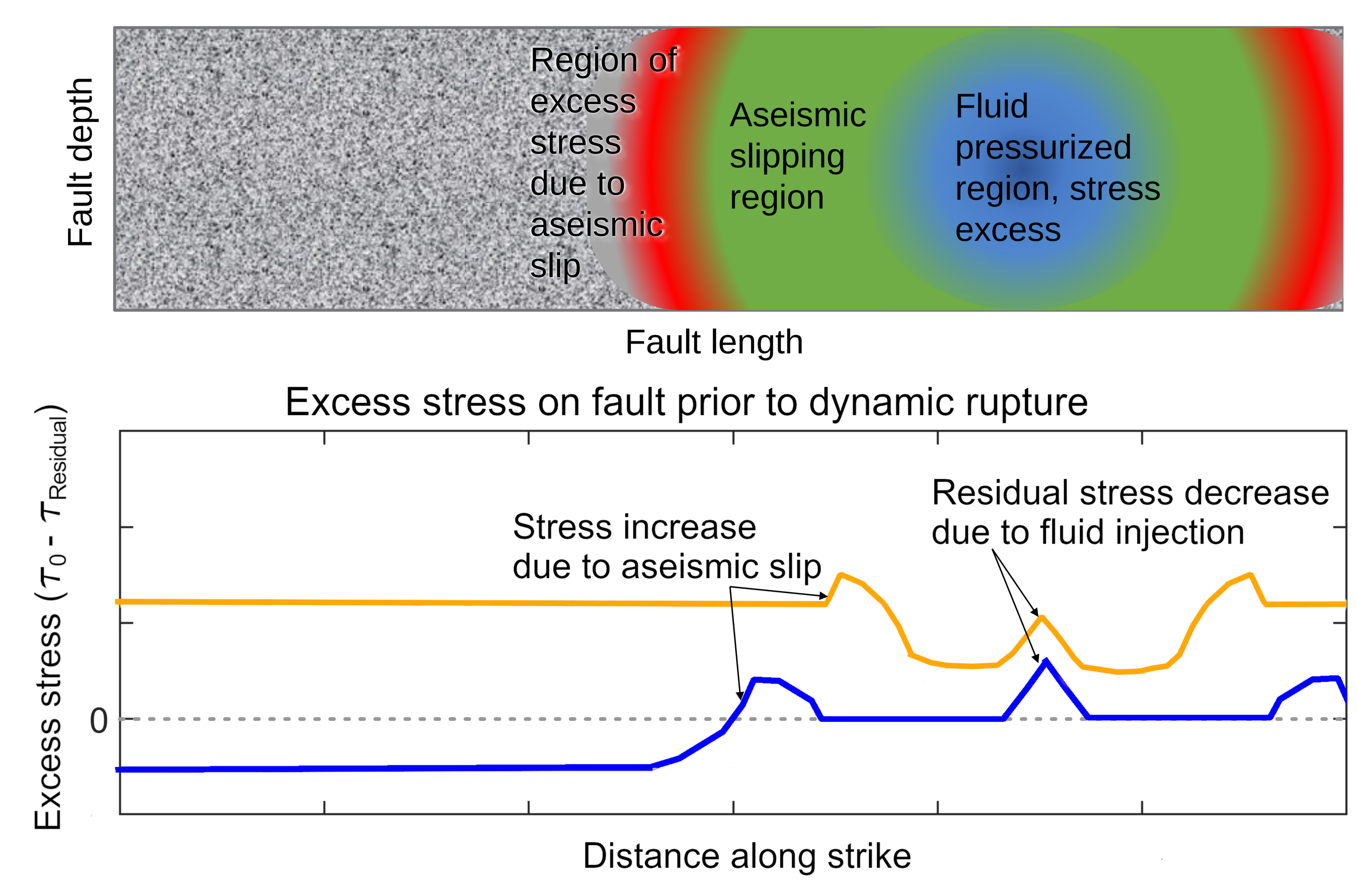


Figure 6: Schematic depiction excess stress along the fault prior to dynamic slip initiation for a high stress case (orange) and a low stress case (blue). Increases in excess stress are caused by an increase in fluid pressure and aseismic slip. Background stress state affects the initiation of a dynamic event (initial stress above residual) and the likelihood of a runaway rupture.

References

- Cappa, F., Scuderi, M., Collettini, C., Guglielmi, Y., & Avouac, J.-P. (2019). Stabilization of fault slip by fluid injection in the laboratory and in situ. Sci. Adv. 5, doi: 10.1126/sciadv.aau4065.
- Guglielmi, Y., Cappa, F., Avouac, J., Henry, P., & Elsworth, D. (2015a). Seismicity triggered by fluid injection-induced aseismic slip. Science, 348(6240), 1224-1226. doi: 10.1126/science.aab0476.
- Villiger, L., Gischig, V., Kwiatek, G., Krietsch, H., Doetsch, J., Jalali M., Amann F., Giardini, D., & Wiemer, S. (2021) Metre-scale stress heterogeneities and stress redistribution drive complex fracture slip and fracture growth duing a hydraulic stimulation experiment. Geophys. J. Int. 225, 1689–1703. doi: 10.1093/gji/ggab057.
- Wei, S., Avouac, J., Hudnut, K., Donnellan, A., Parker, J., Graves, R., . . . Eneva, M. (2015). The 2012 Brawley swarm triggered by injection-induced aseismic slip. Earth and Planetary Science Letters, 422, 115-125. doi: 10.1016/j.epsl.2015.03.054.

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