Seismicity front induced by fluid injection on rough faults

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Abstract

- How does pore pressure diffusion, initial stress and fault roughness affect the migration of induced seismicity?
- How is the apparent diffusivity of seismicity migration related to hydraulic diffusivity?
- What is the origin of seismicity back-fronts?

Rough Surface and Injection Model

- A random self-affine rough fault
- Uniform background stress tensor
- Elasto-static stress transfer (boundary element method)
- Friction drops instantaneously from static to dynamic, then heals immediately after slip stops
- Pore pressure change induced by a linear injector:

$$\Delta p(r,t) = \frac{v\eta}{4\pi k h} E_1\left(\frac{r^2}{4D_0 t}\right)$$

v: constant flow rate
k: permeability
E_1: exponential integral
η: water viscosity
h: fracture thickness
D_0: hydraulic diffusivity

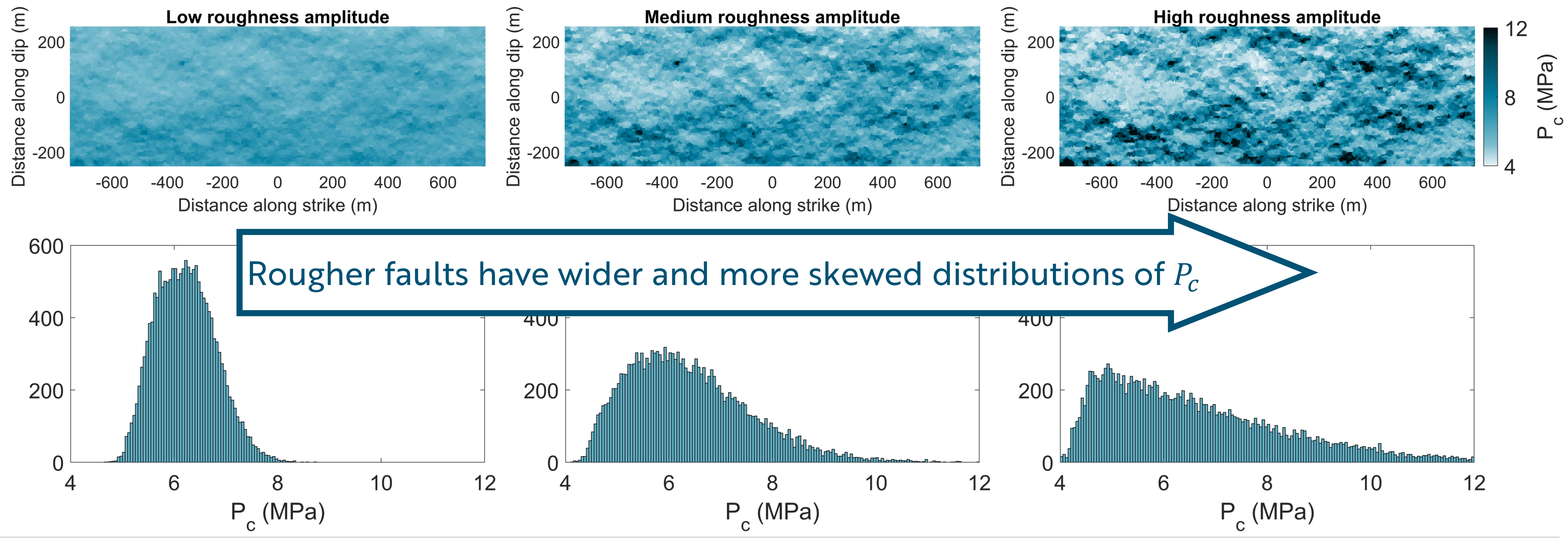

Figure 1 Spatial distribution and histogram of critical pore pressures (P_c, additional pressure needed to reach failure)

Spatio-temporal Evolution and Seismicity Front

- Seismicity migration has diffusion-like behavior : $r = \sqrt{4Dt}$.
- Apparent diffusivity D strongly depends on fault roughness.
- Stress interactions often accelerate seismicity migration.

Apparent Diffusivity

- **Apparent diffusivity can be much smaller than hydraulic diffusivity, depending on criticality** (Figure 3).
- In theory, $r \approx \sqrt{4\underbrace{\exp\left(-\frac{P_c}{A}-\gamma\right)D_0}_{D}\, t}$, where γ is Euler's constant, $A = \frac{v\eta}{4\pi k h}$.
- Seismicity migrates faster on rougher faults and in higher stress environments.

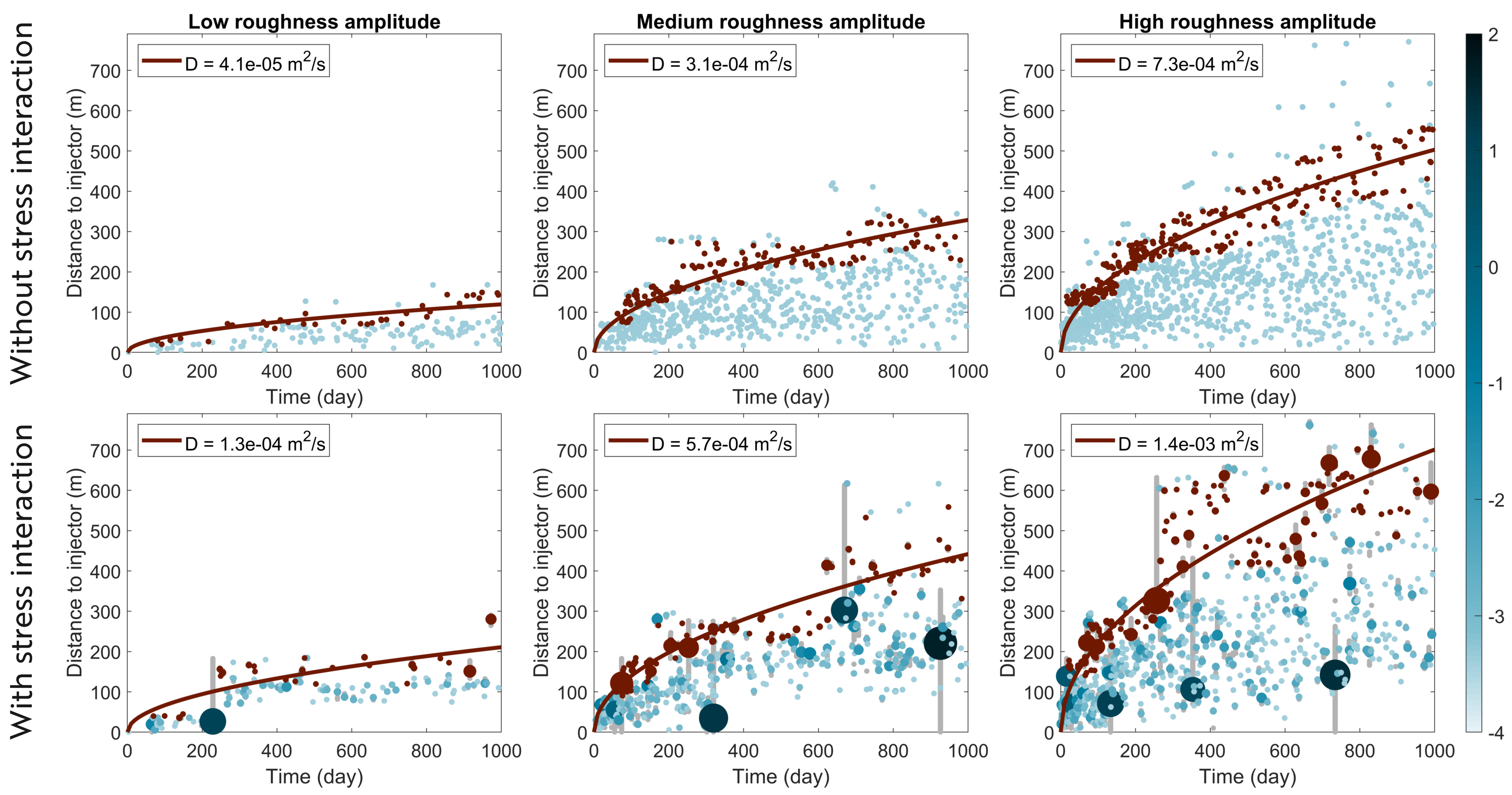

Figure 2 Spatio-temporal evolution of seismicity. Blue circles: seismicity. Gray dots: rupture area. Dark red circles: seismicity front. Dark red curve: best fit to a square root function with apparent diffusivity D.

Back-front

- Back-fronts can occur because earthquake-induced stress drops push the fault farther from failure near the injector.
- Faster back-fronts are associated with large early-stage events.
- Fault roughness has little effect on back-front migration (Figure 4).
- The spatial arrangement of critical patches strongly influences back-front behavior (Figure 5).

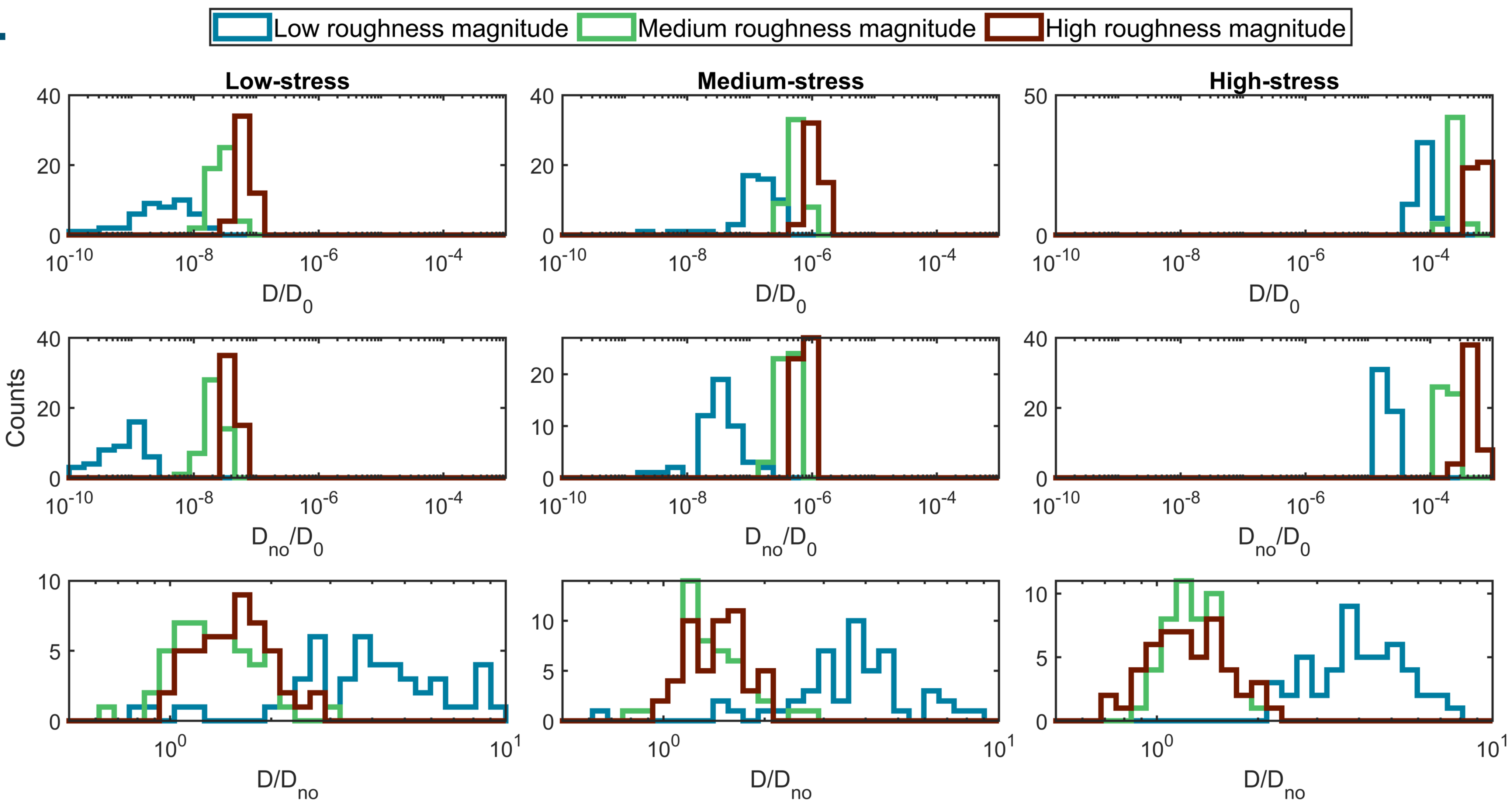

Figure 3 Histograms of apparent diffusivity of seismicity front D with different random seeds. Models with the same roughness and initial stress state have comparable apparent diffusivities.

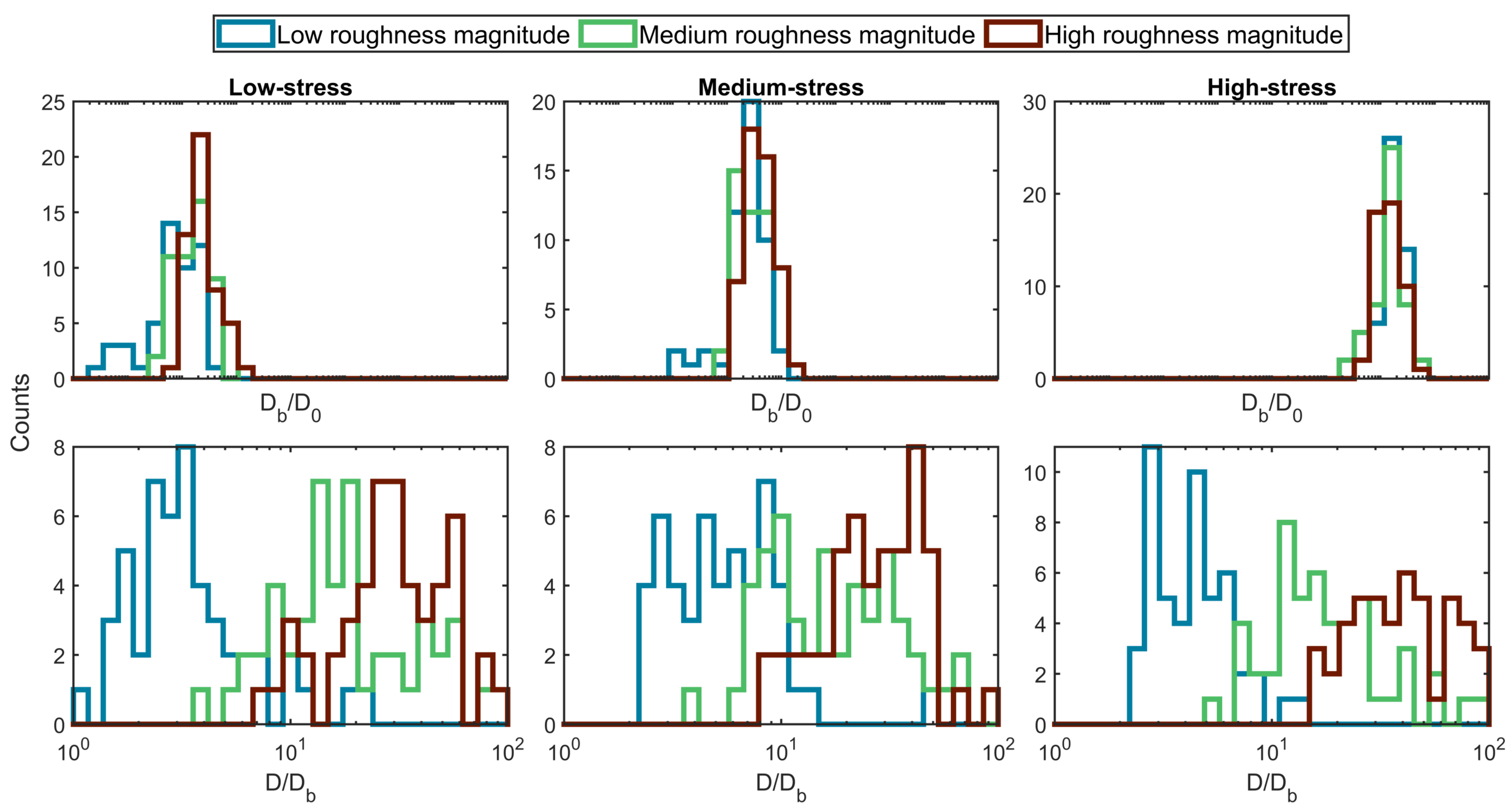

Figure 4 Histograms of apparent diffusivity of back-front D_b with different random seeds. The ratios D/D_b fall within a similar range for the same roughness, regardless of initial stress state.

Key Takeaways

- A fast physic-based model to simulate injection-induced seismicity on a rough fault.
- The apparent diffusivity of seismicity fronts can be much lower than hydraulic diffusivity, especially on non-critical faults (large P_c).
- Fault roughness strongly affects the seismicity migration rate, but affects little the back-front migration rate.
- Back-fronts occur due to large rupture events near the injector.

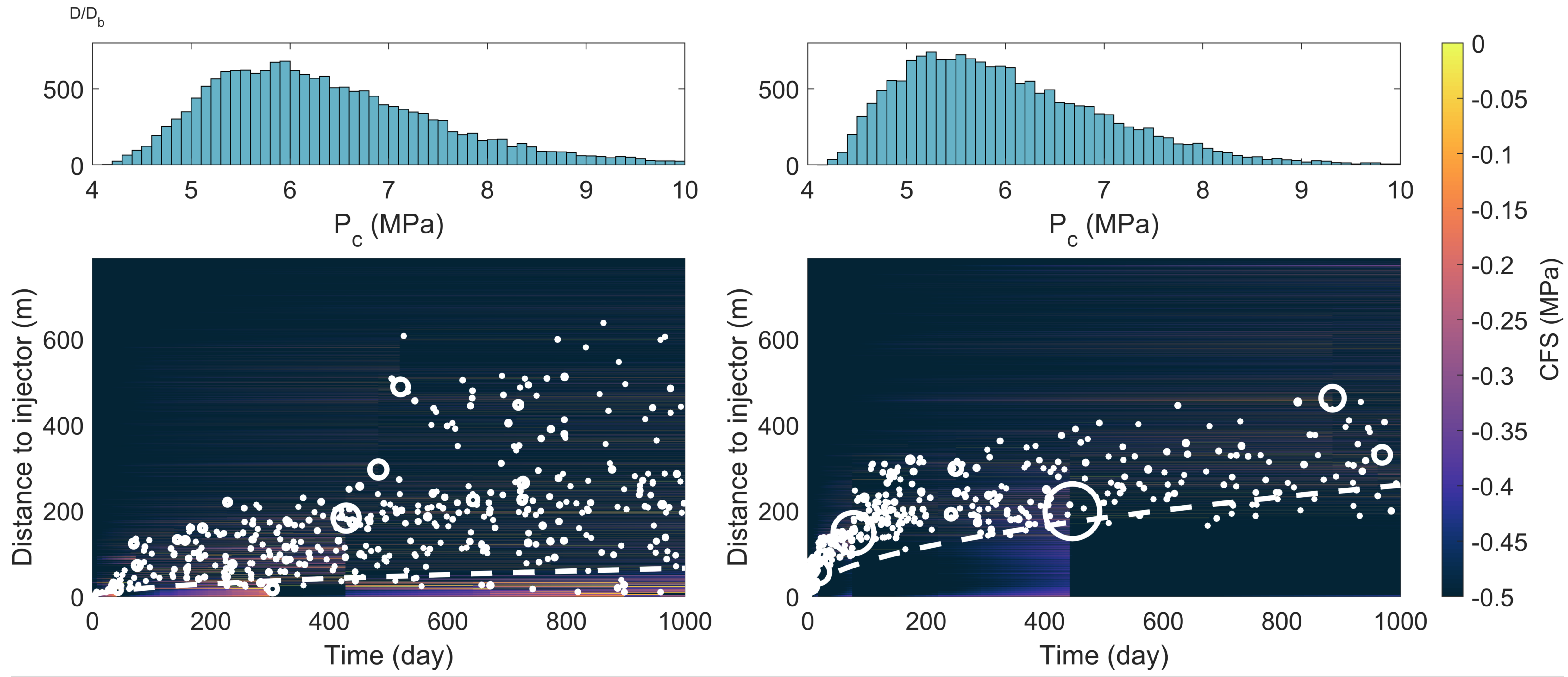

Figure 5 Slower (left) and faster (right) back-front. Background color: spatio-temporal evolution of Coulomb stress. White dashed curve: best fit to a square root function for back-front.