Simulating Swarm-to-Mainshock Evolution at the St. Gallen Geothermal Project

SeongJu Jeong and Junle Jiang

The University of Oklahoma, USA (seongju.jeong-1@ou.edu)

Abstract

Induced seismicity can evolve from swarms to damaging mainshocks. We examine this transition in the 2013 St. Gallen sequence, where localized injection produced swarms and a subsequent gas kick—interpreted as a distributed pore pressure increase—preceded an M_L 3.5 mainshock. Using 2-D physics-based models that couple rate-and-state friction, pore pressure diffusion, aseismic slip, dynamic rupture, and a heterogeneous VW/VS structure under depth-dependent stresses, we find that localized injection yields self-arresting swarms, whereas distributed pressure, together with foreshock-driven aseismic slip, enables runaway rupture. Pore pressure perturbations raise the fault's criticality factor, promoting mainshock nucleation. Post gas kick permeability enhancement can delay or suppress the mainshock. Larger stress drops occur where rupture invades stronger VW patches (more negative a−b). These results suggest that monitoring aseismic deformation and avoiding injection near critically stressed zones may help mitigate hazard.

Introduction

- Induced seismicity can evolve from injection-triggered swarms into runaway mainshocks, but the underlying physics remain poorly understood.
- During the 2013 St. Gallen geothermal project (Switzerland), fluid injection produced swarm-like activity, followed by an M_L 3.5 mainshock after a gas kick (Diehl et al., 2017).
- Stress drops vary and deviate from self-similarity scaling, suggesting the role of complex fault processes (Jeong and Lui, 2025).
- **Key questions:**
- What conditions drive the transition from swarms to a mainshock?
- How do pore pressure diffusion, aseismic slip, and fault heterogeneity interact to control this process and influence earthquake properties?

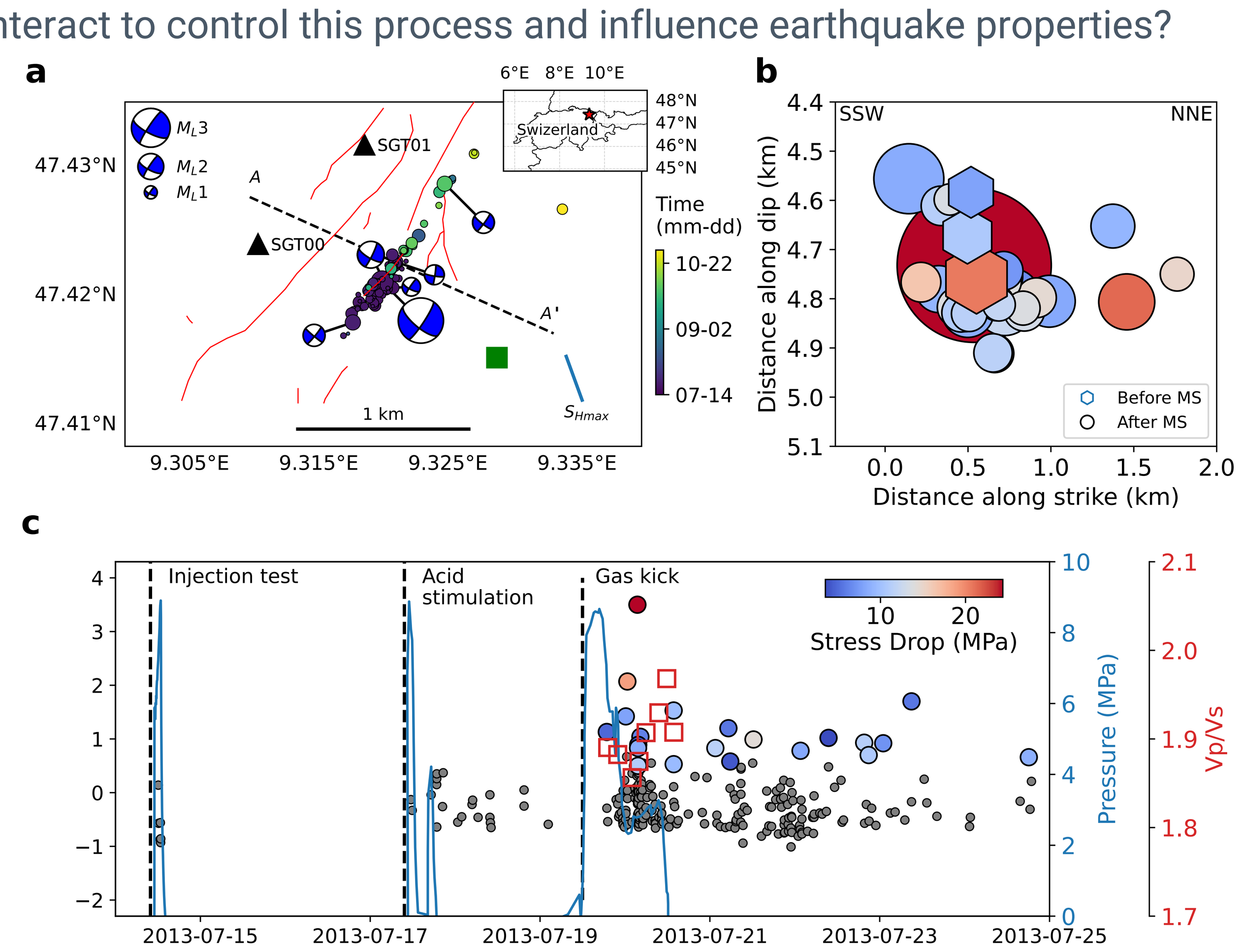

Figure 1: **Induced earthquakes at the St. Gallen site, Switzerland.** (a) Map view: events colored by time, scaled by M_L, with focal mechanisms of major events; stations, GT-1 well, faults, $S_{H\,max}$, and profile A–A' shown. (b) Fault-plane view: rupture areas and stress drops for M_L > 0.5; hexagons = pre-mainshock, circles = post-mainshock. (c) Time series: magnitudes and stress drops over wellhead pressure, injection phases, and V_P/V_S ratios (Convertito et al., 2022); gray circles = smaller events.

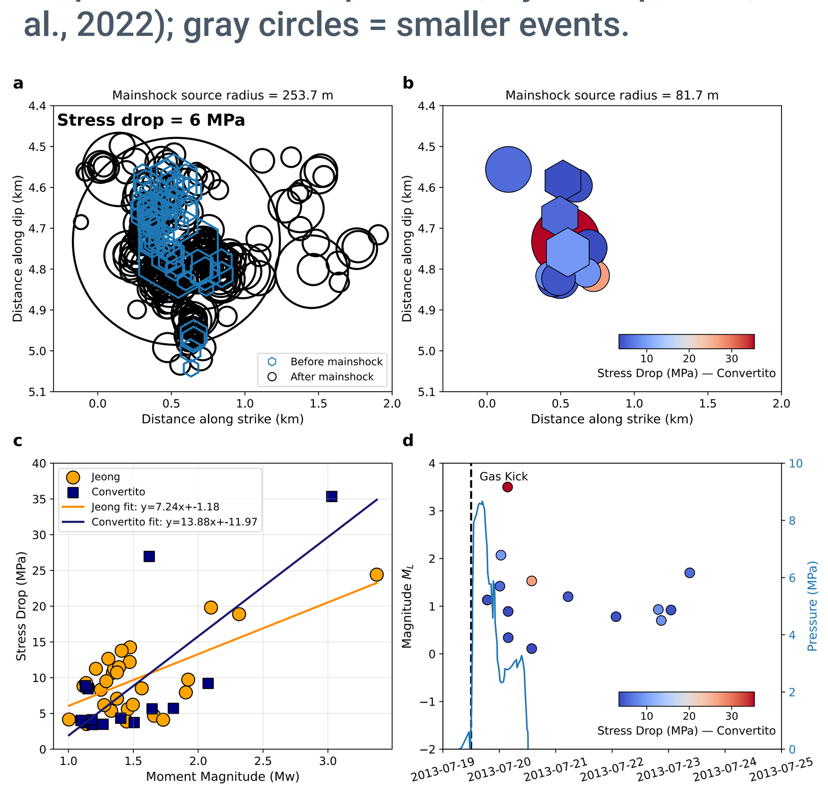

Figure 2: **Comparison of earthquake rupture areas under different stress drop assumptions.** (a) Rupture areas computed with fixed stress drop ($\Delta\sigma$ = 6 MPa). (b) Rupture areas using event-specific stress drops from Convertito & De Matteis (2025). (c) Stress drop versus M_W for the events shown in (b) and in Fig. 1b, suggesting non-self-similar scaling. (d) Time series: plotting conventions follow Fig. 1c, but with stress drop values from (b).

Methodology

- 2-D simulations of dynamic earthquake ruptures and aseismic slip with rate-and-state friction (Dieterich, 1979; Lapusta et al., 2000).
- Fault heterogeneity in frictional stability via alternating velocity-weakening (VW) and velocity-strengthening (VS) patches, with depth-dependent normal and shear stresses.
- **Two fluid perturbation scenarios**: (1) localized injection (injection test) and (2) distributed perturbation (gas kick episode), with bottom hole pressures from Zbinden et al. (2020).
- Outputs analyzed include slip rate, rupture propagation, earthquake stress drop and source parameters.

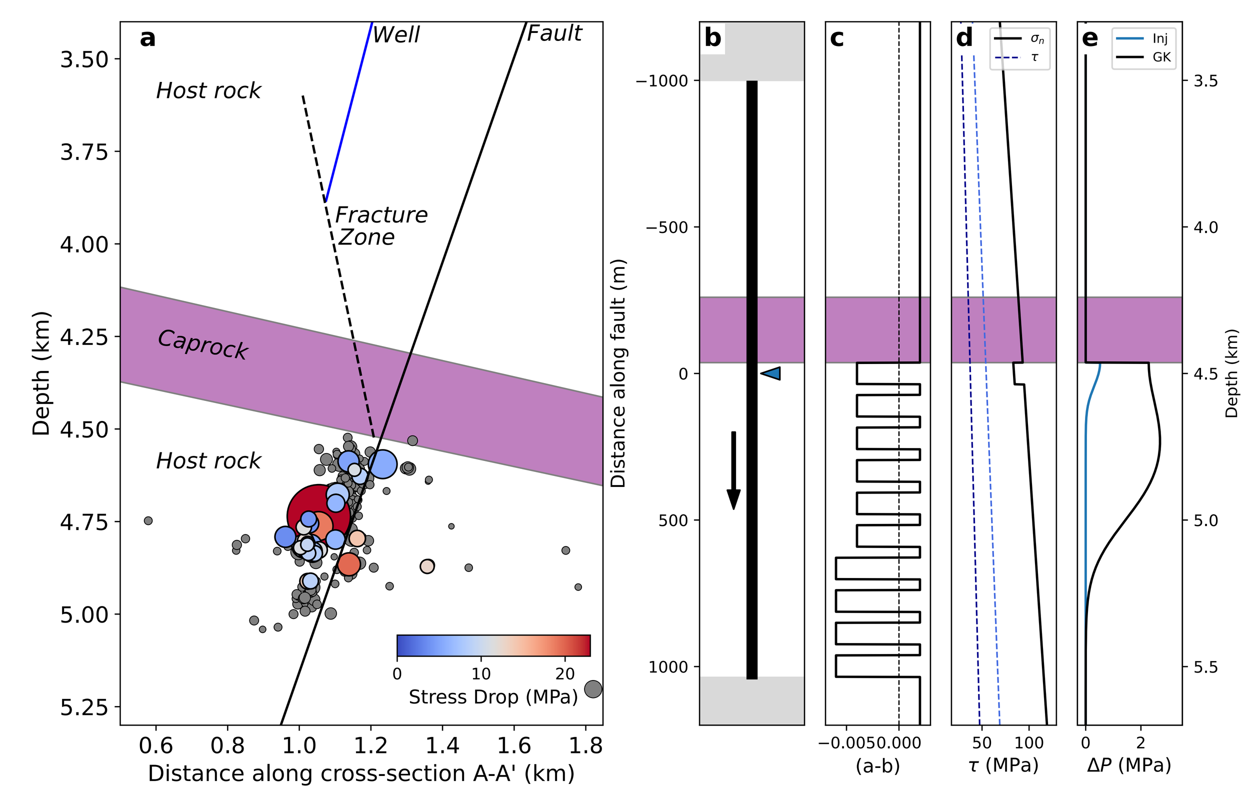

Figure 3: **Geological setting and model setup.** (a) Cross-section A–A': fault (black), well (blue), fractures (black dashed), caprock (grey dashed); The plotting conventions follow Fig. 1b. (b) Model geometry: fault with layered caprock, VS zones (gray), injection point (blue arrow), and slip direction (black arrow). (c) Frictional structure: alternating VS/VW, with deeper VW patches; shallow depth set to VS. (d) Initial stresses: σ_n and τ increase with depth; τ elevated (C=1.45); 6 MPa σ_n reduction at injection center. (e) Pore pressure profiles: injection test (Inj; blue) vs. gas kick (GK; black).

Results

Reference Model (RM) Initial Conditions:

1. Less critically stressed fault (criticality factor, C = 1.45)
2. Characteristic state evolution distance D_{RS} = 15 μm
3. Alternating VS (a−b = 0.002) and VW patches (a−b = −0.004)
4. Deep patches of higher VW properties (a−b = −0.006)
5. Normal stress reduction $\Delta\sigma_n$ = 6 MPa at the injection point

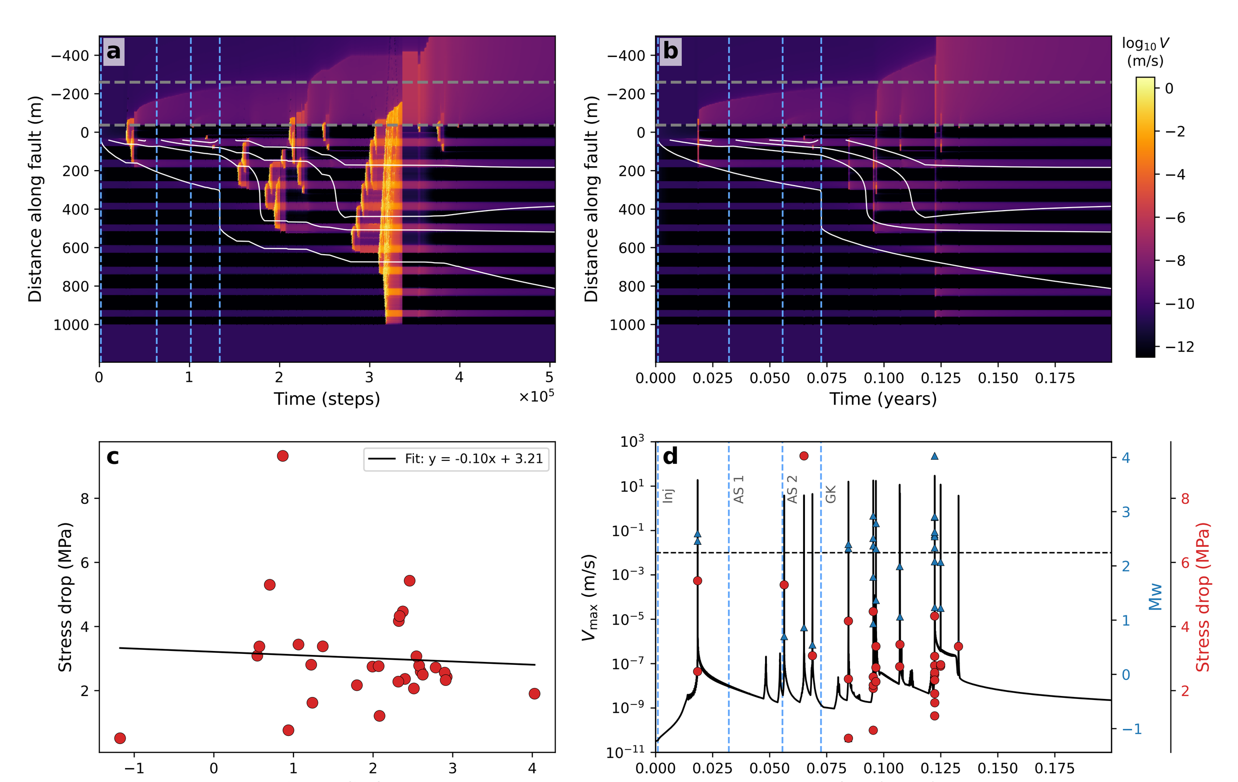

Figure 4: **RM results.** (a-b) Slip rate evolution with pore pressure contours shown in model vs. physical time. (c) Stress drop vs. M_W shows a negative trend, unlike observed non−self-similarity scaling. (d) Time series of V_{max}, magnitude, and stress drop with injection phases marked. AS=Acid stimulation.

- Swarm-like activity during the injection test and stimulation phases, and a runaway mainshock following the gas kick.
- Simulated events: M_W 0.54−4.03; stress drop = 0.51−9.32 MPa with mean of 3 MPa.
- Stress drop values are constant against M_W, inconsistent with observations.

Preferred model (PM) criteria:

(i) minimize the lag between injection onsets and first seismicity or mainshock
(ii) generate a mainshock under injection
(iii) suppress a mainshock without injection
(iv) reproduce the observed non−self-similar stress drop−magnitude scaling.

- Grid search outcome: keep C, D_{RS}, alternating VS/VW, and deep VW patches (a−b = −0.006) unchanged; raise $\Delta\sigma_n$ = 6 → 10 MPa (only RM→PM change).
- Stronger VS barriers → swarm-like behavior without a clear mainshock.
- More unstable/deeper VW asperities → larger magnitude and stress drop.
- Smaller D_{RS} → more events.
- Slightly lower pre-stress → mainshock suppressed.

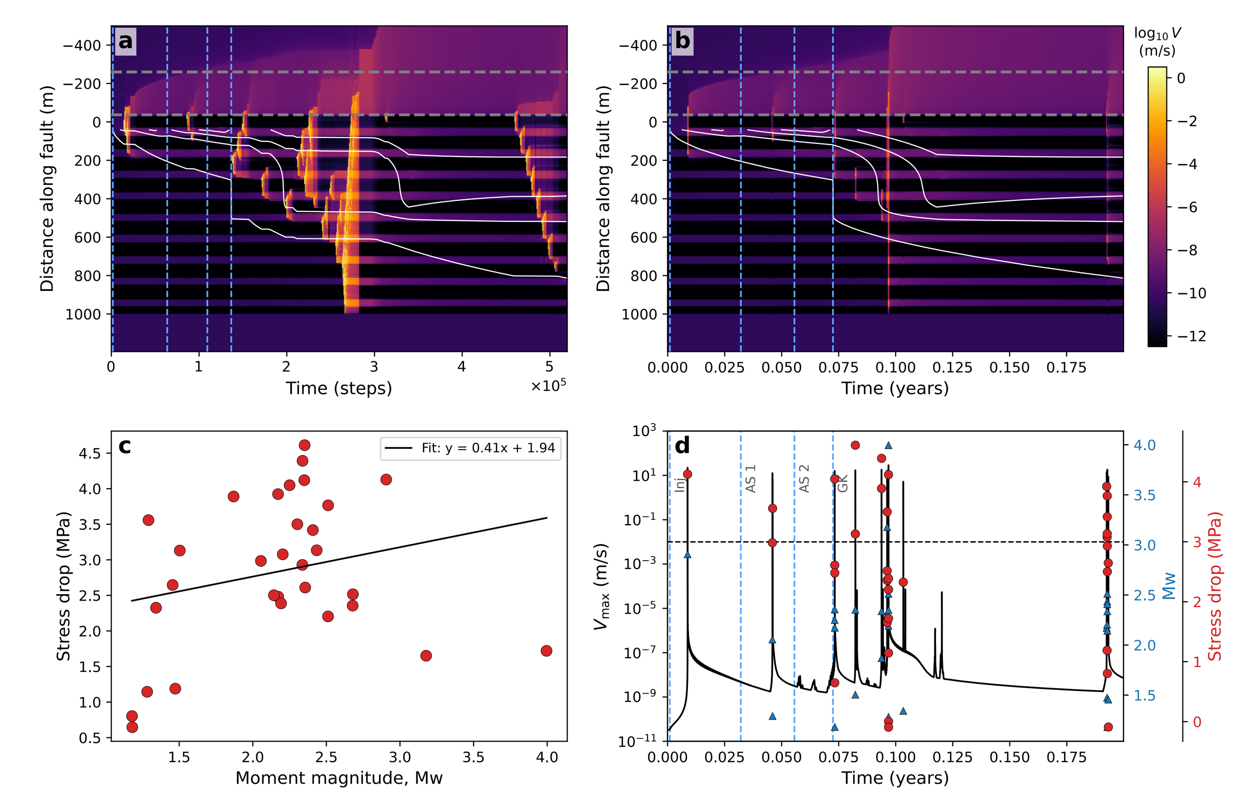

Figure 5: **Preferred model (PM) results.** Slip rate evolution with pore pressure contours, time series of magnitude, stress drop, and V_{max}, and stress drop vs. M_W showing a positive trend, consistent with non−self-similarity scaling.

- Simulated events: M_W 1.17−3.99; stress drop = 0.03−4.48 MPa with mean of 2.75 MPa.
- Non-self-similarity scaling: larger stress drop when rupture propagates into stronger (more negative a−b) VW patches.

- **Both RM and PM:**
- ✓ Reproduce swarm-like activity during the injection test and stimulation phases, and a runaway mainshock following the gas kick.
- ✓ Swarms: self-arrested ruptures; M_W < 3.5; migration confined near pore-pressure front.
- ✓ Mainshock: barrier-overrunning rupture; M_W ≈ 4; rupture area no longer limited by injected volume. No aseismic slip before the mainshock.

Discussion/Conclusion

- **Mechanism**: The 2013 St. Gallen swarm-to-mainshock transition was governed by damage-zone heterogeneity and distributed overpressure from the gas kick, which increased the fault's criticality factor and triggered the mainshock.
- **Stress drop interpretation**: Larger stress drops likely reflect stronger VW zones (more negative a−b) rather than permeability enhancement.
- **Limitations**: The simulated non-self-similarity scaling is significantly lower than observed, and the model excludes poroelastic stress changes.
- **Implications**: Monitoring aseismic slip and avoiding injection near critically stressed VW zones may help mitigate induced-seismicity hazards.

References

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