

Mainshock and aftershock sequence simulations in a nonplanar fault network

JGR Solid Earth

RESEARCH ARTICLE

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Key Points:

- We reproduce aftershocks on small faults surrounding the mainshock fault in the framework of 2-D quasidynamic earthquake sequence

Mainshock and Aftershock Sequence Simulation in Geometrically Complex Fault Zones

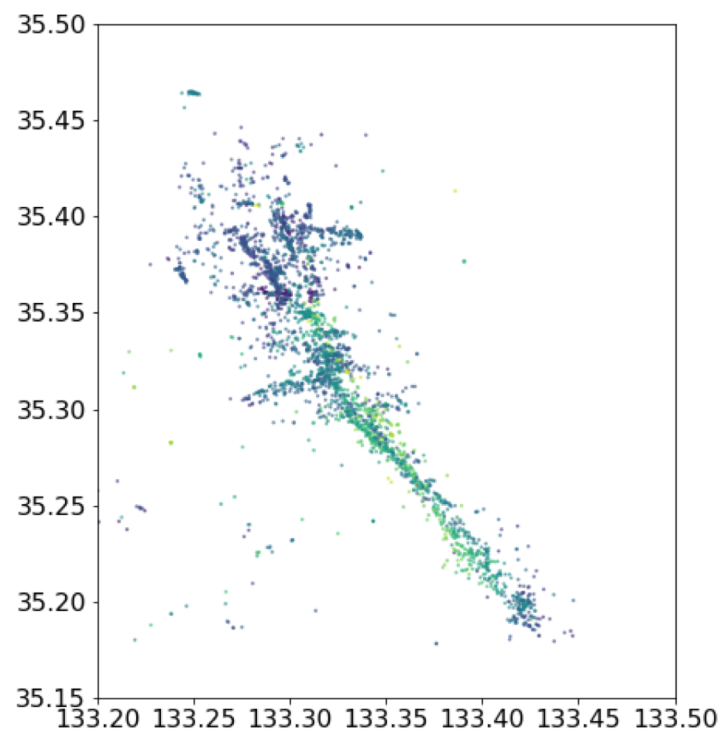
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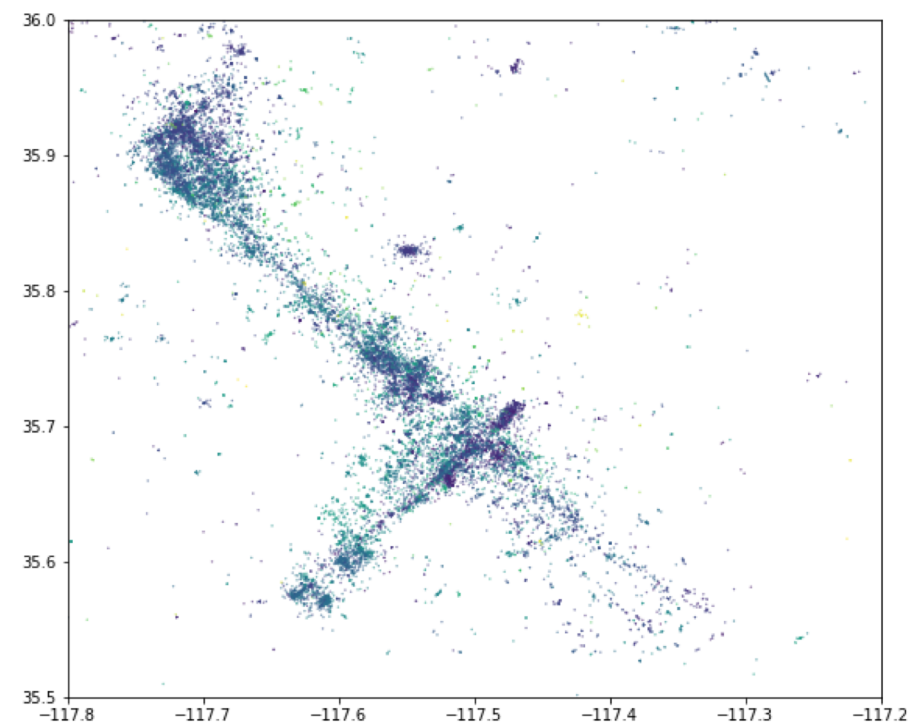
So Ozawa

Department of Earth and Planetary Science, University of Tokyo

Aftershock distribution delineates fault planes



2000 Mw 6.6 Western Tottori



2019 Mw 7.1 Ridgecrest

High resolution aftershock map → estimation of fault plane(s)

courtesy of Y. Yukutake (left) and H. Huang (right)

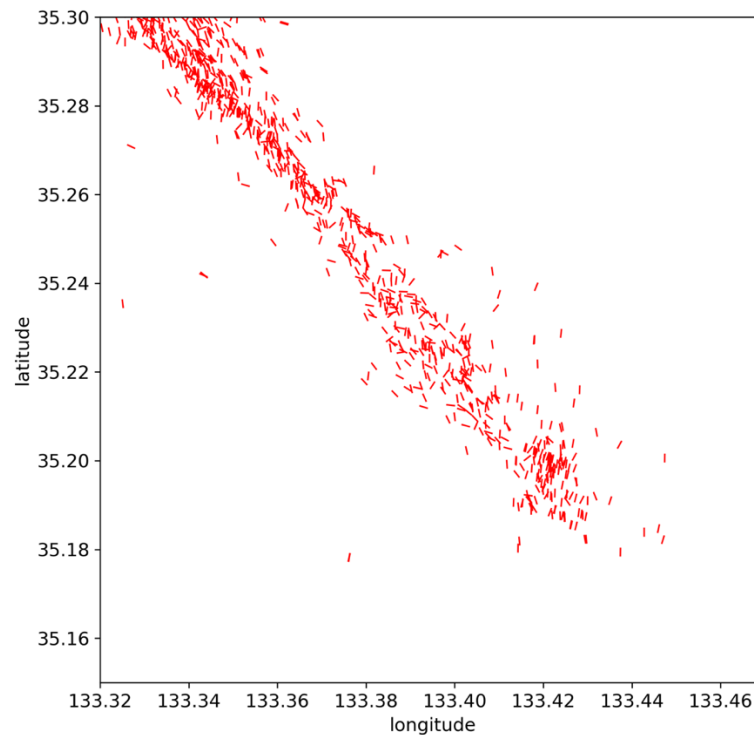
Majority of aftershocks are “off-fault” events

Reasons

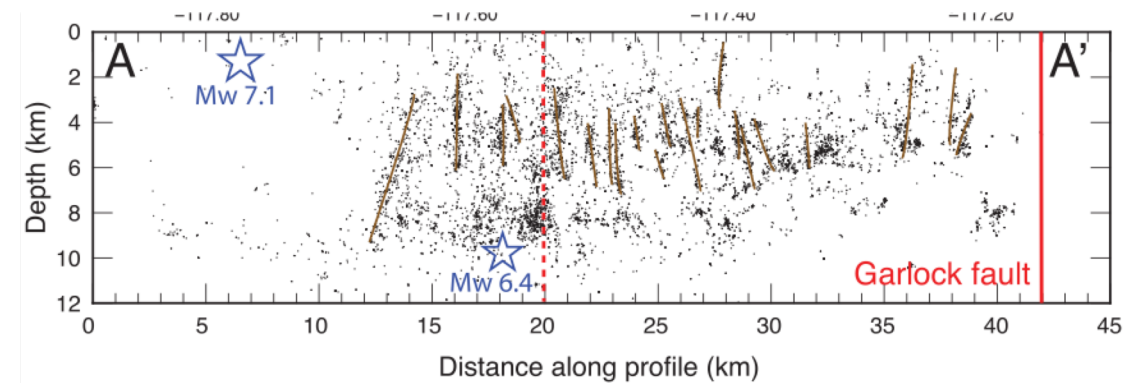
Even if observational error is taken into account... (Yukutake & Iio, 2017)

- Aftershock width > typical fault zone width
- Many focal mechanisms are inconsistent with the mainshock fault plane

Aftershock distribution shows conjugate planes crossing the main fault (Ross et al. 2019)

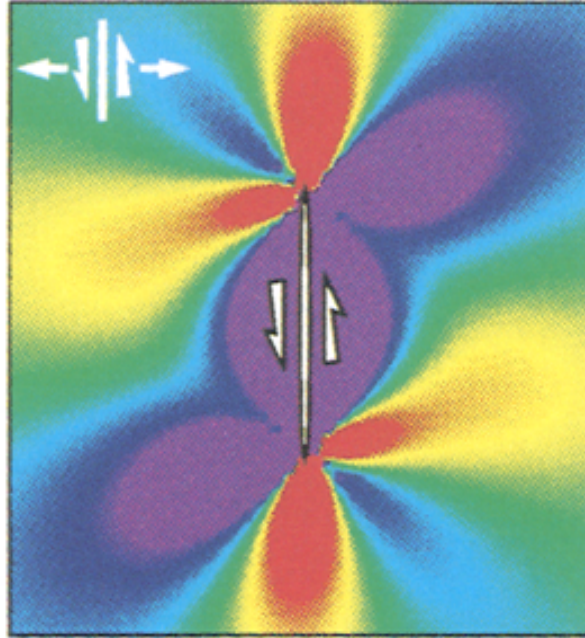


courtesy of Y. Yukutake



Ross et al. (2019)

Unexpected aftershocks at stress shadow



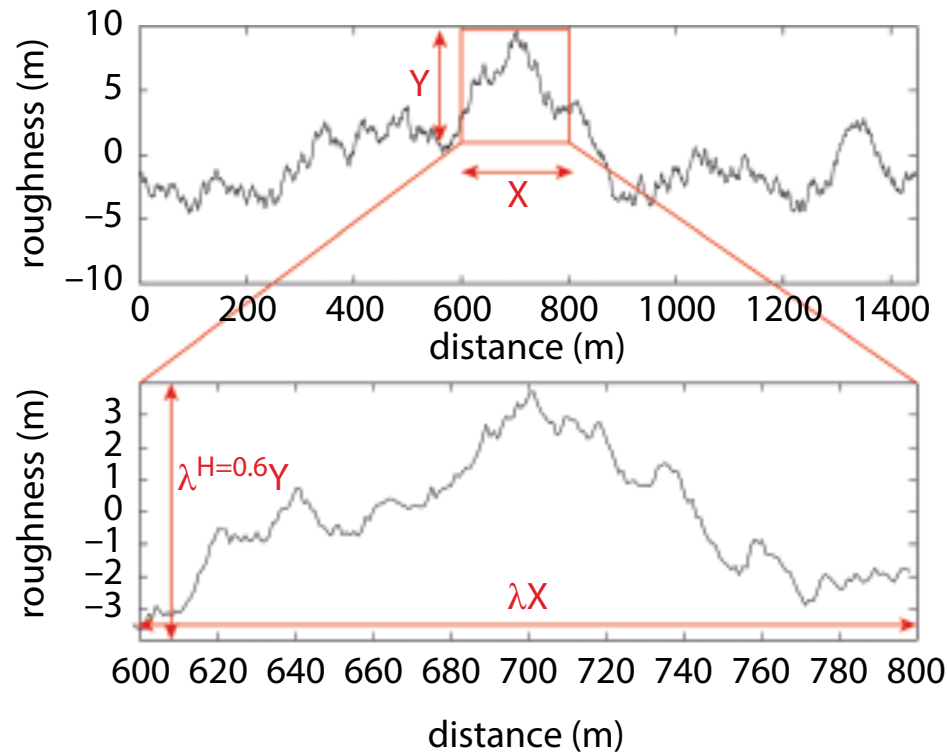
King et al. (1994)

Coulomb stress change by a mode2 crack

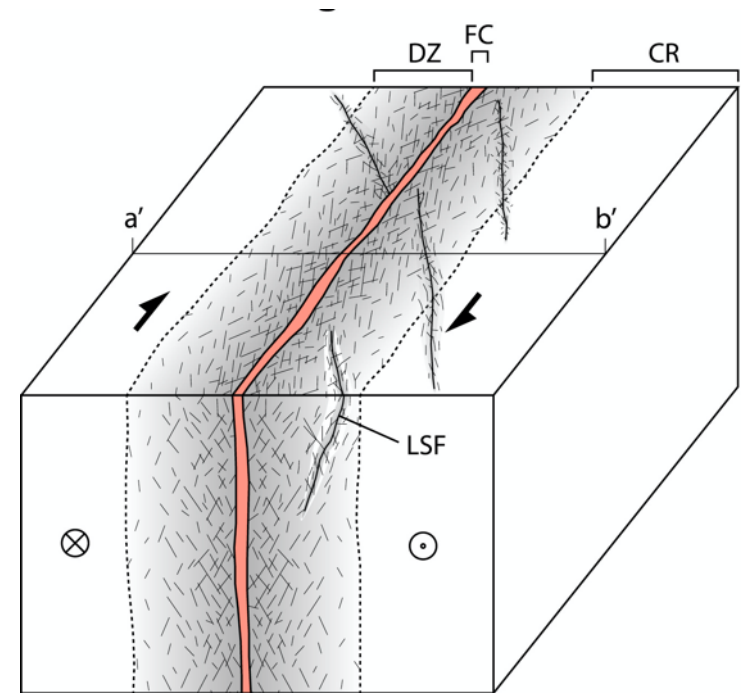
From Coulomb stress perspectives, aftershocks should be concentrated at the edge of the slipped fault

Fault roughness and damage zones

Natural faults are neither flat and isolated

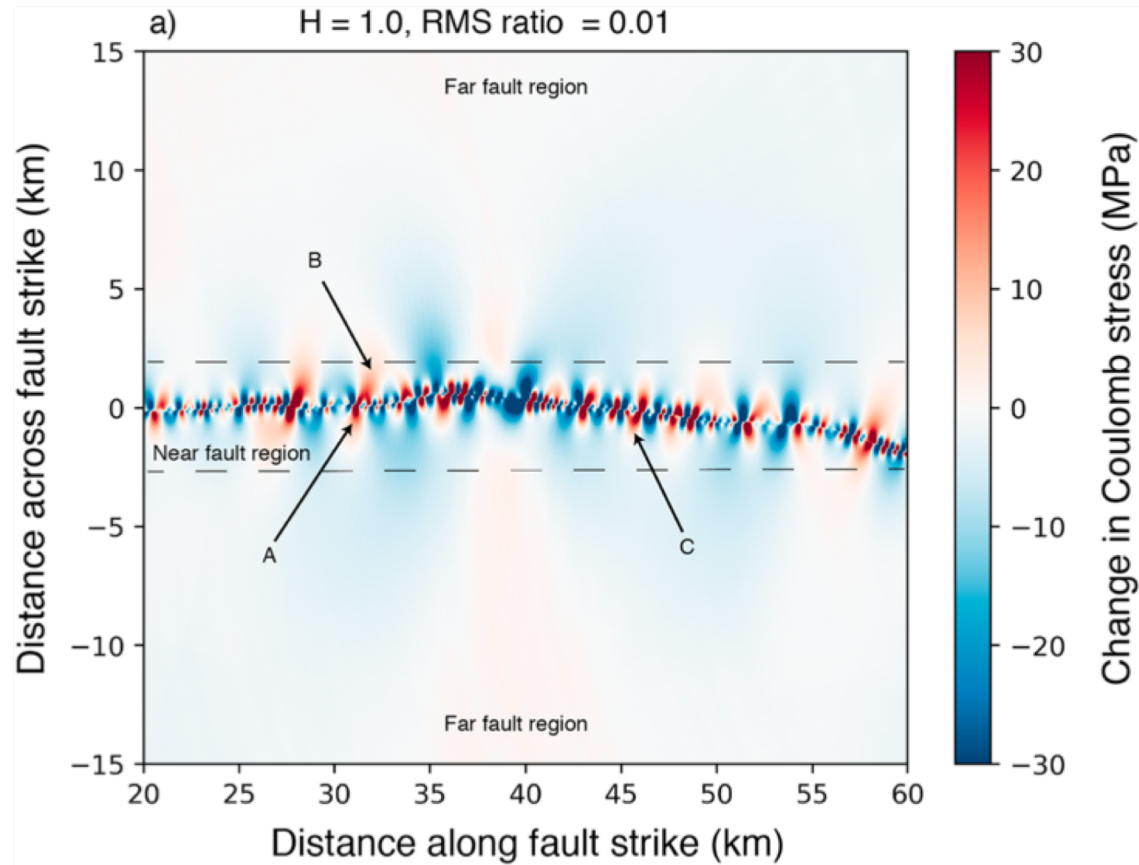


Self-affine geometry of natural fault



Damage zones surrounding the main fault contain numerous subsidiary faults

Slip on a rough fault gives heterogeneous stress near the fault



Aslam & Daub (2018)

Hypothesis: stress heterogeneity coming from fault roughness causes aftershocks on damage-zone subsidiary faults located at apparent stress shadow (Smith & Dieterich, 2010; Aslam & Daub 2018)

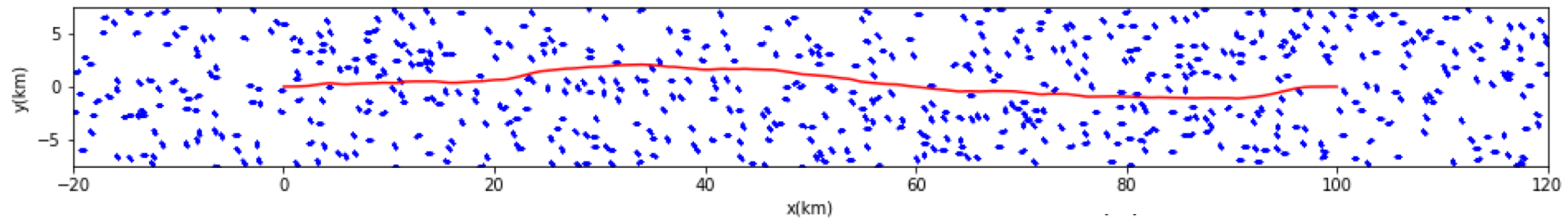
The purpose of this study: putting this hypothesis into physics-based numerical simulation of earthquake sequence

Problem setting

Geometry

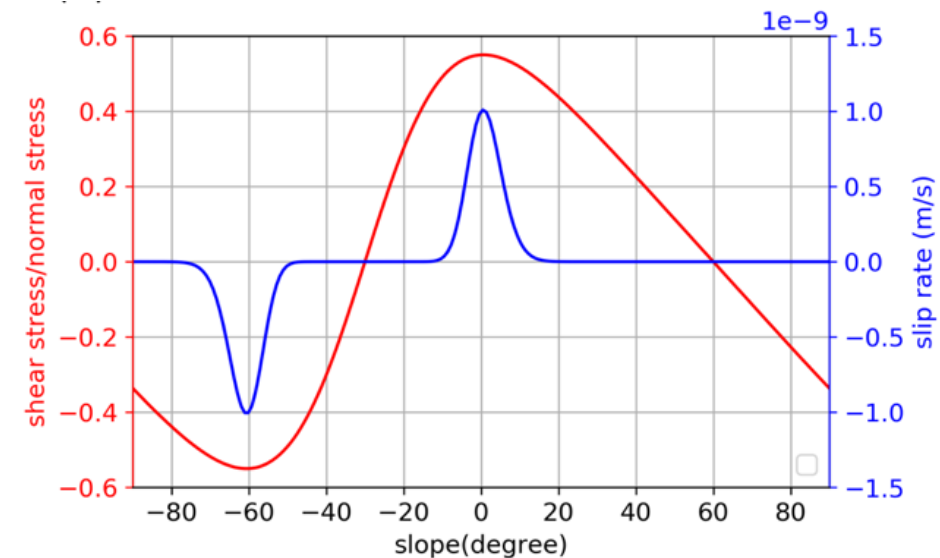
Main fault: fractal with aspect ratio=0.01. Mainshock is initiated by stress perturbation at the center

Subsidiary faults: N=600. Length=0.6km. Randomly oriented.



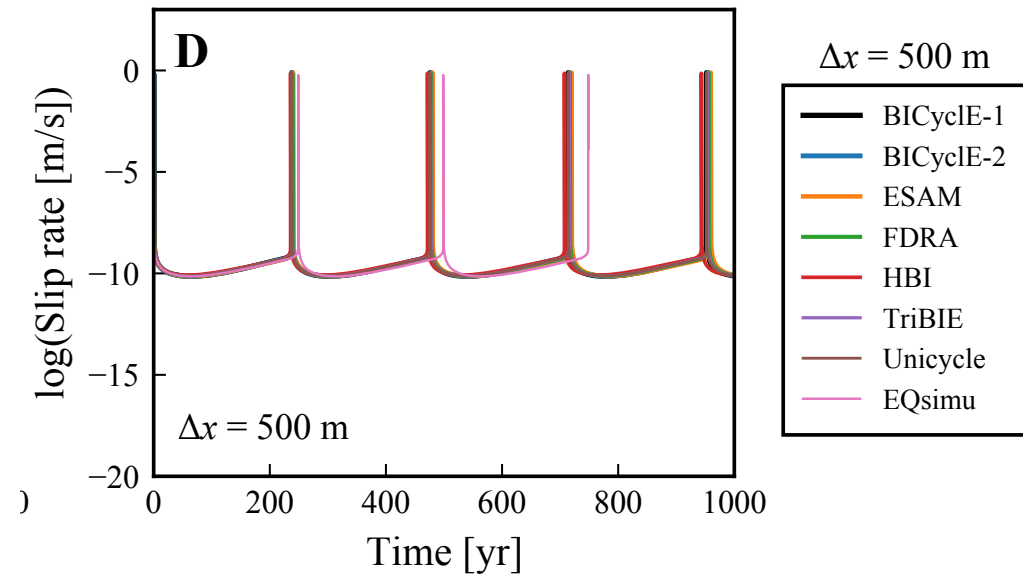
Others

- RSF with aging law
- Velocity-weakening everywhere
- Initial stresses on faults are resolved from spatially uniform stress tensor (σ_1 is 30° against overall fault trace)
- Fixed initial state variable
- Single mainshock and aftershock sequence \rightarrow multiple cycle is future work



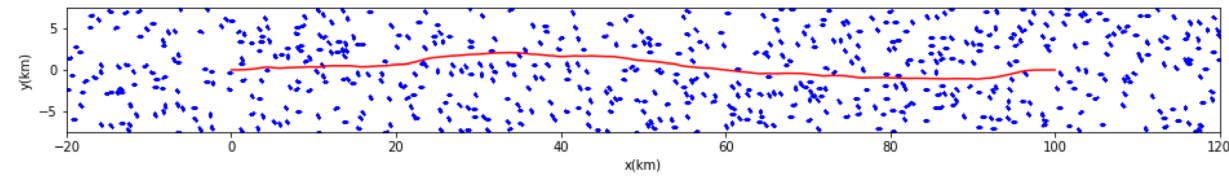
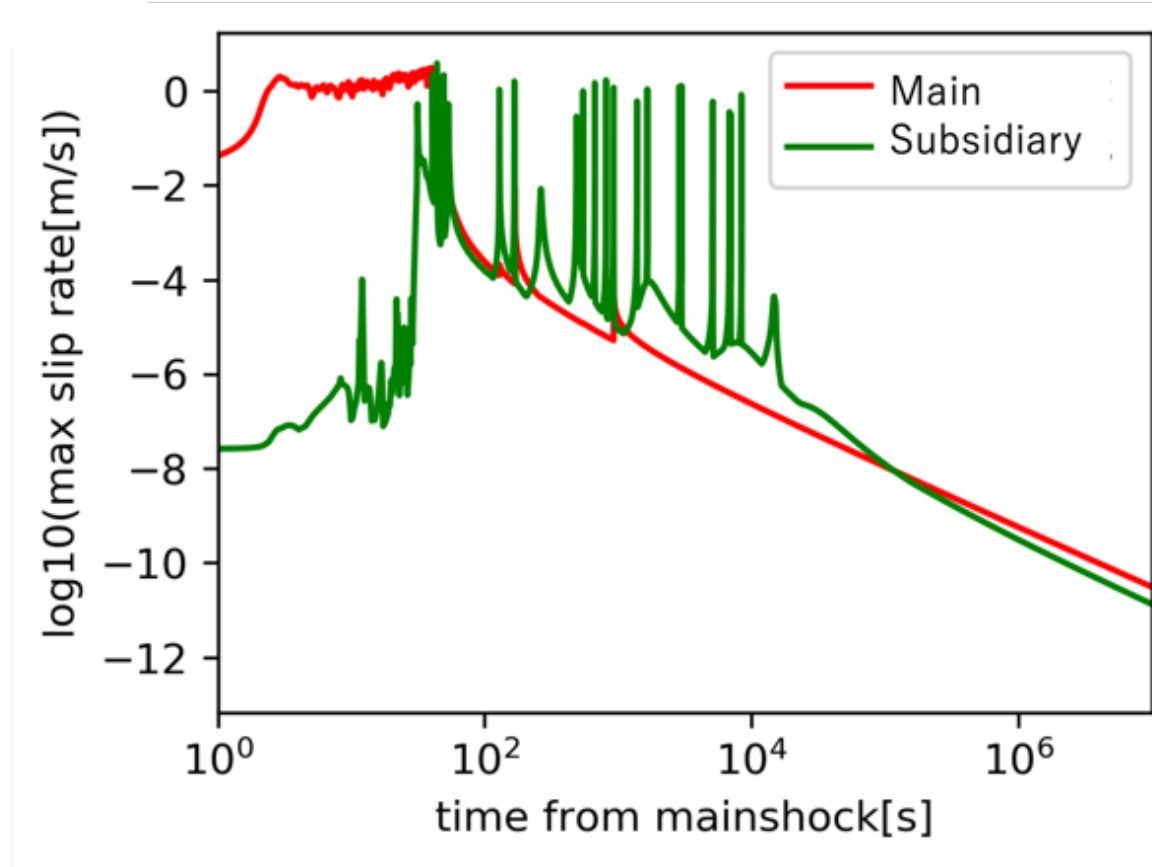
Computational code: HBI

- Quasi-dynamic 2D/3D earthquake cycle code using boundary element method
- Accelerated by H-matrices
- Open source (<https://github.com/sozawa94/hbi>)
- HPC-oriented
- Validated with SEAS benchmark problems (Jiang et al. 2022; Erickson et al. submitted)



Jiang et al. (2022)

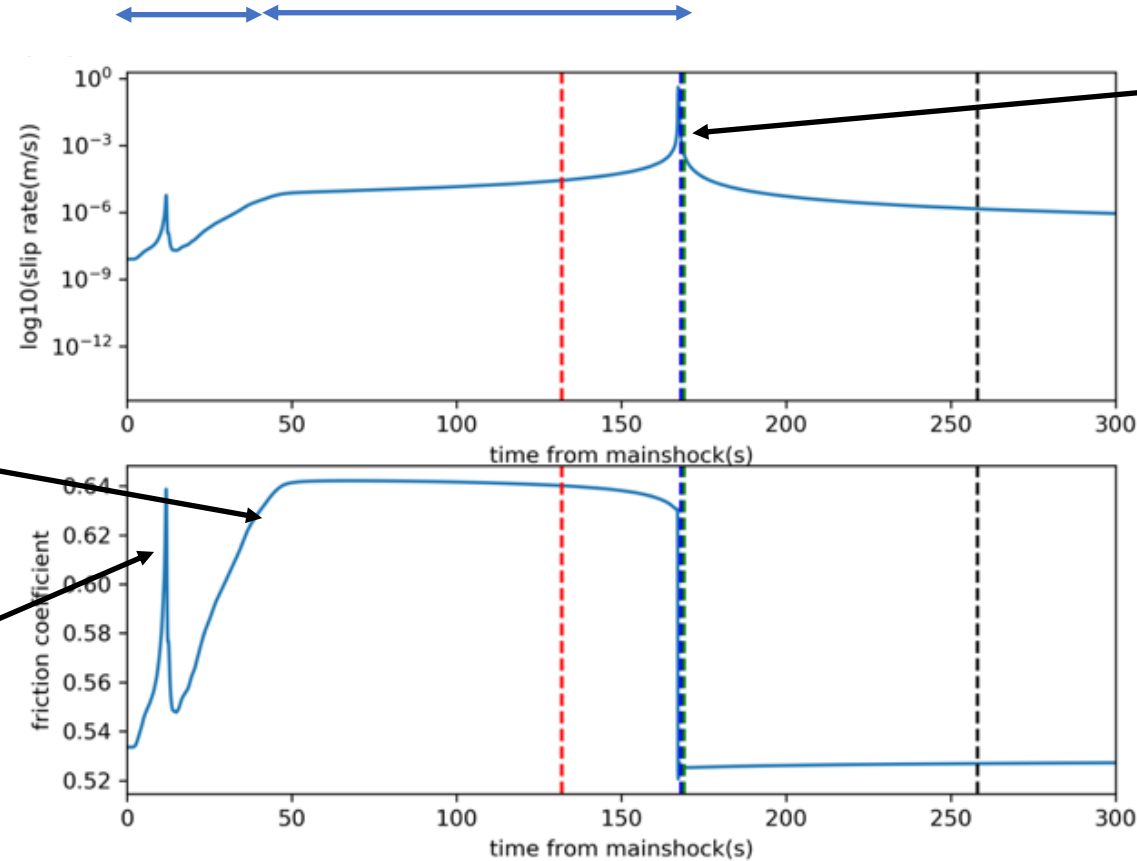
Result: max slip rate evolution



- Mainshock ruptures the entire main fault (no partial rupture)
- No aftershock on the main fault (rerupture is impossible)
- Part of subsidiary faults (10-20 out of 600) produces aftershocks

Result: evolution of a subsidiary fault

mainshock nucleation



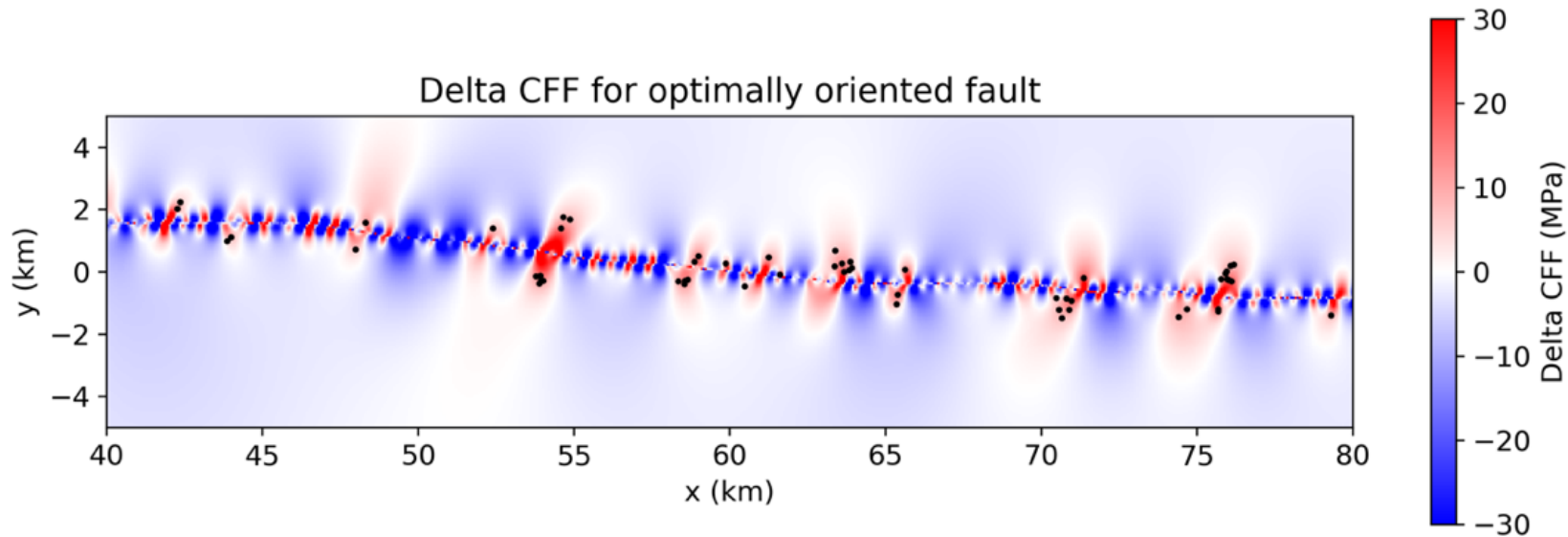
static slip effect

aftershock

passage of the rupture front

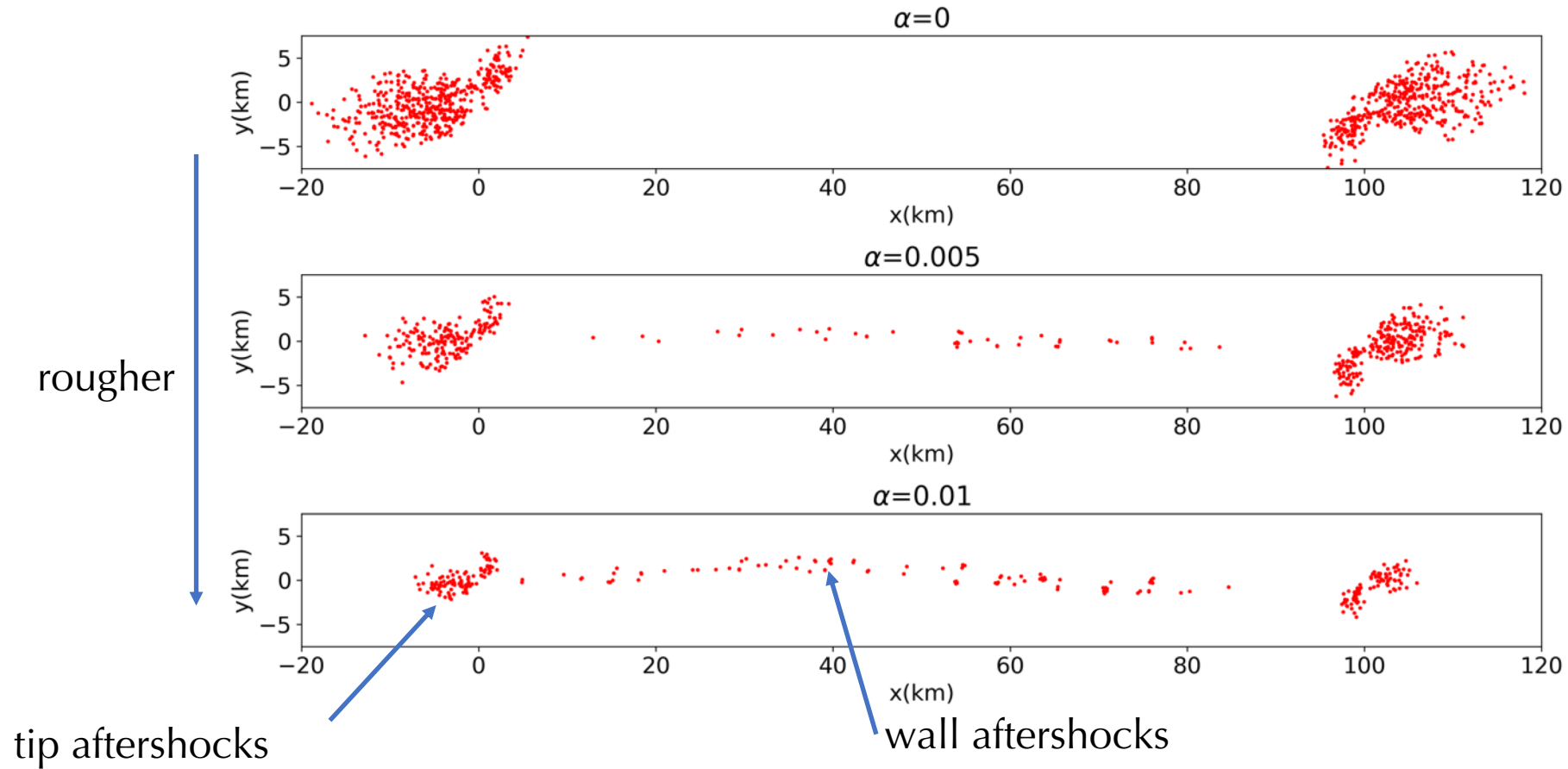
- The elevated (static) stress due to mainshock slip causes nucleation of an aftershock
- If the first rise is much higher, this fault produces coseismic off-fault damage (like Okubo et al. 2019)

Spatial distribution of aftershocks

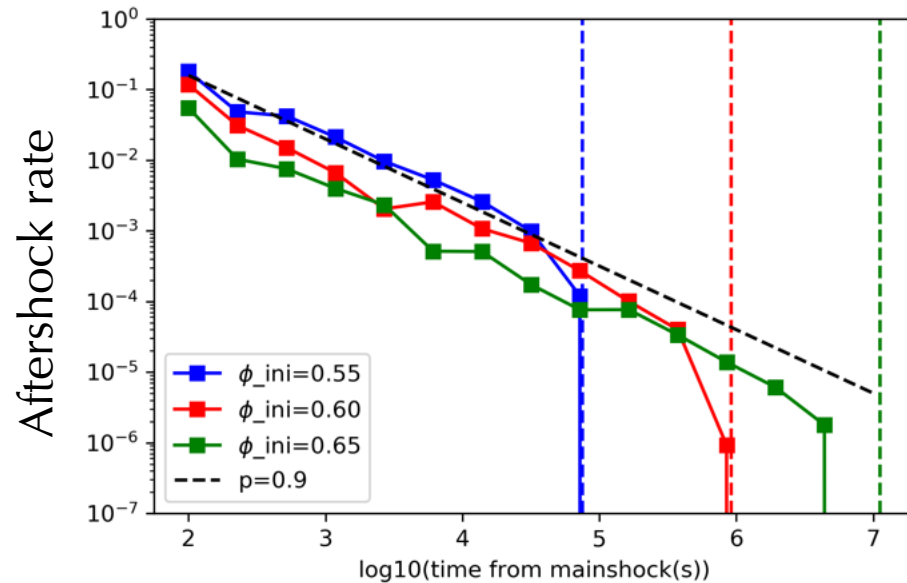


- Aftershock locations = locally elevated CFF (often correspond to releasing bends)
- all aftershocks are within ~ 1 km from the main fault trace
- Larger and short-wavelength stress heterogeneity at closer locations from the main fault

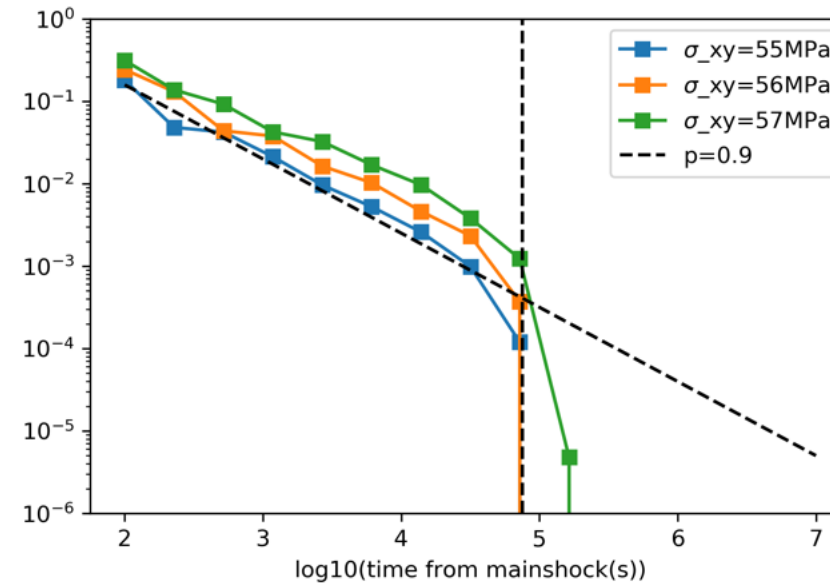
Main fault roughness is necessary to reproduce realistic aftershock distribution



Omori-Utsu law



Initial state variable determines the duration

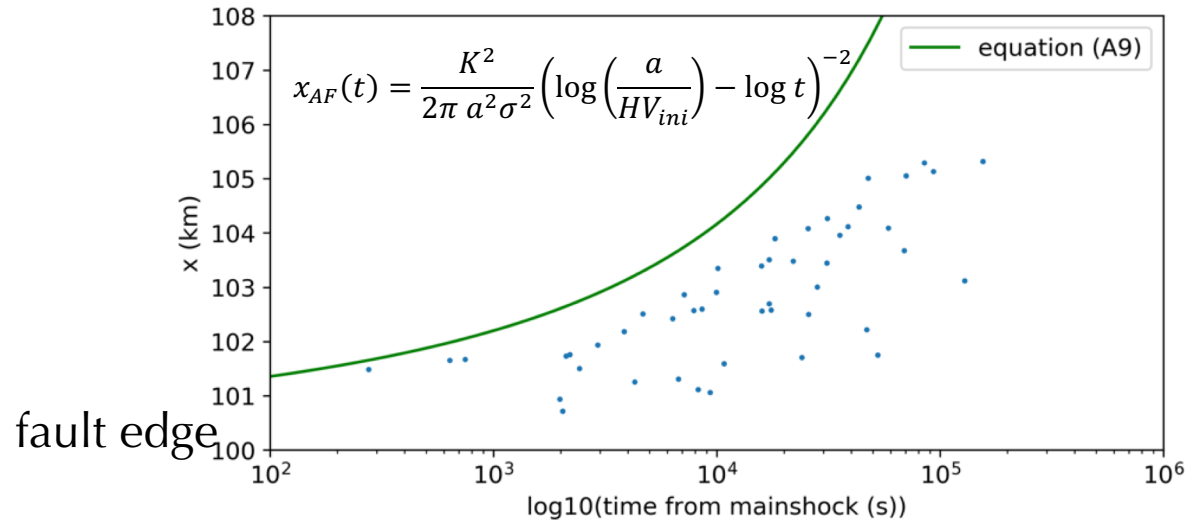


Initial stress determined the productivity

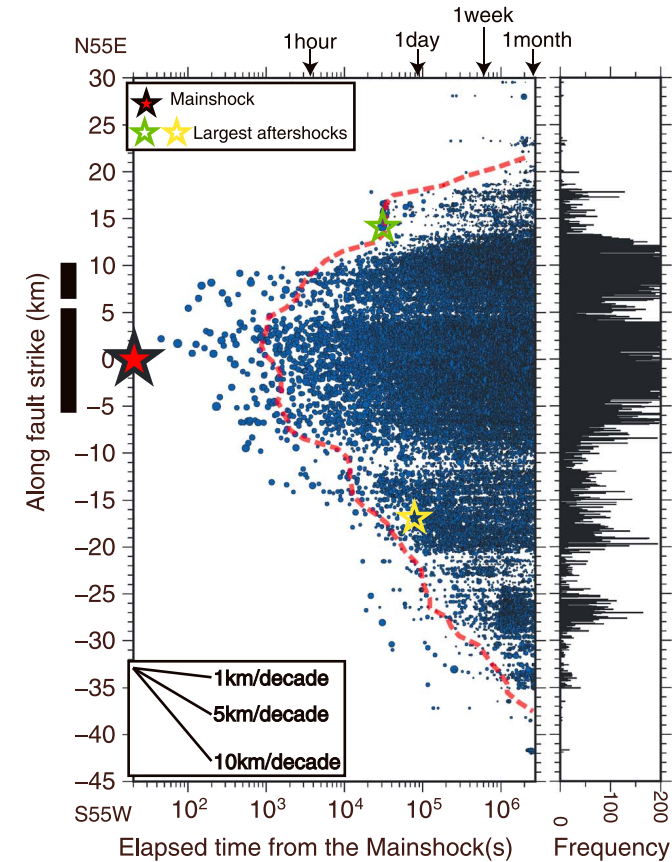
- Omori's law can be derived from RSF (Dieterich 1994)
- Many assumption in Dieterich (1994) are invalid: interaction of sources, finite size, and well-above steady state
- $p \sim 0.9$ and zero $c \sim 0$
- Finite duration of aftershocks in our **uniform initial state** and **no loading** model. What about cycle simulations with external loading?

Aftershock migration

Simulation



(extreme) natural example
2007 Mw6.7 Noto-Hanto, Japan



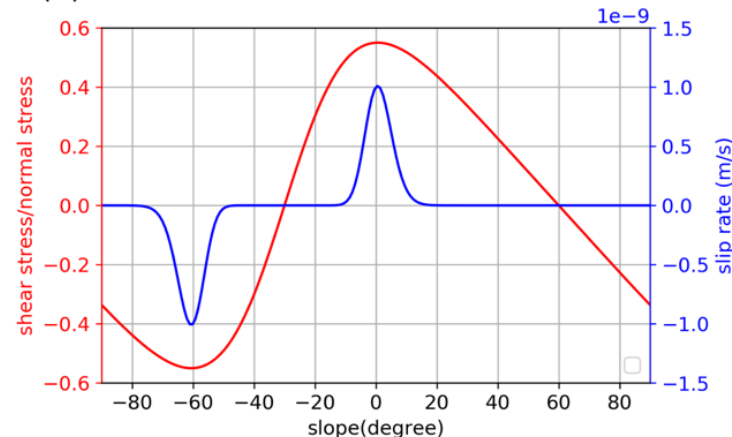
- Aftershock zone expands with time ($\sim \log t$) consistent with some observations
 - away from the fault edge \rightarrow lower stress (sqrt singularity) \rightarrow longer time to instability
 - No afterslip as velocity weakening everywhere. No fluid effects
- \rightarrow Migration of aftershocks does not necessarily mean aseismic slip or fluid diffusion

Kato & Obara (2014)

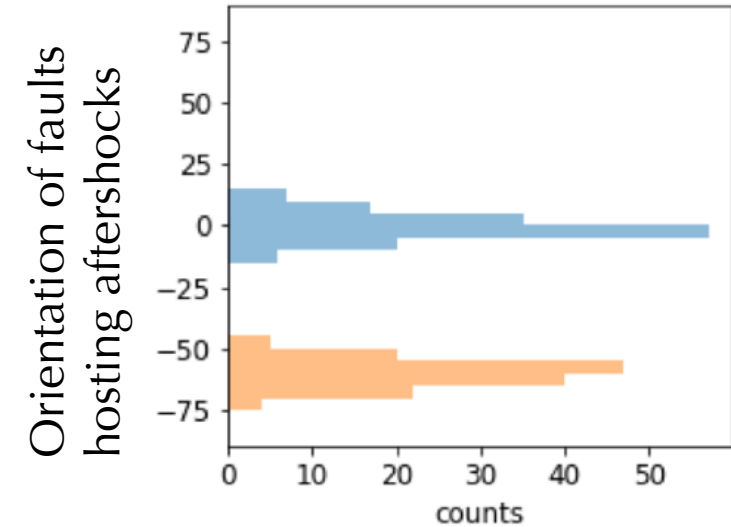
Focal mechanism statistics

- Bimodal distribution (two peaks = optimal planes against the background stress field)
- Lower friction coefficient \rightarrow more diverse focal mechanism due to larger stress rotation
- The scattering of focal mechanisms is an indicator of the absolute stress

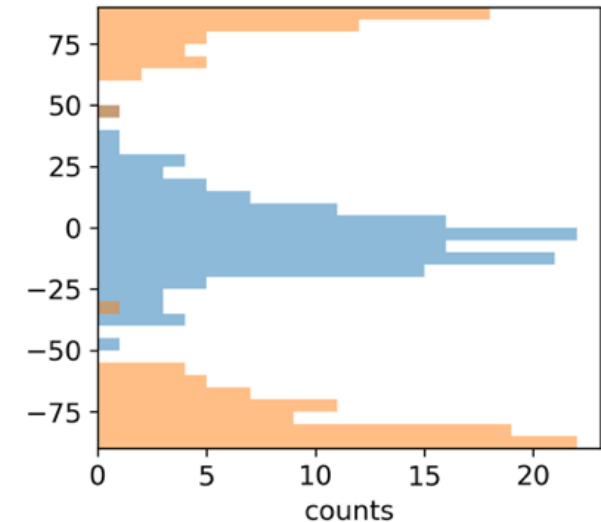
background stress
($\mu=0.6$)



strong ($\mu=0.6$)



weak ($\mu=0.2$)



Summary

- Earthquake sequence simulations showing the spatiotemporal characteristics of aftershocks
- Aftershocks are ruptures of small subsidiary faults in the damage zone
- Fault roughness is necessary to explain aftershocks distribution delineating mainshock fault
- The Omori-Utsu law is a robust property for fault populations obeying RSF experiencing stress perturbation
- Diverse focal mechanisms of aftershocks for weak faults