The complex rupture dynamics of an oceanic transform fault: supershear rupture and deep slip during the 2024 Mw7.0 Cape Mendocino Earthquake

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Abstract

The December 5, 2024, Mw7.0 Cape Mendocino earthquake ruptured an oceanic transform fault within the tectonically complex Mendocino Triple Junction (MTJ), the most seismically active region of California and caused a soon-lifted tsunami evacuation alert for more than **5 million people**. Its offshore location renders accurate analysis of source characteristics challenging.

We integrate **back-projection, geodetic and kinematic slip inversions, ensembles of hundreds of 3D dynamic rupture simulations, Coulomb stress modeling and regional velocity models** to understand the event's rupture dynamics and implications. A preferred dynamic rupture scenario that matches seismic and geodetic observations is **complex and asymmetric**, despite the simple fault geometry, its extent limited by the Mw7.0 1994 earthquake and creeping fault portion. Driven by prestress heterogeneity and fault weakness, we find **localized supershear rupture, and delayed deep slip of eastern fault portions where seismic and aseismic slip may coexist**.

The modest dynamic and static stress changes onto the adjacent **Cascadia** and **San Andreas** fault systems offer insight into possible future stress transfer pathways in the MTJ region. Our findings have important implications for the expected earthquake complexity at oceanic transform faults worldwide, and emphasize the need for **improved offshore observations** to support physics-based hazard assessment for offshore fault systems, including the MTJ.

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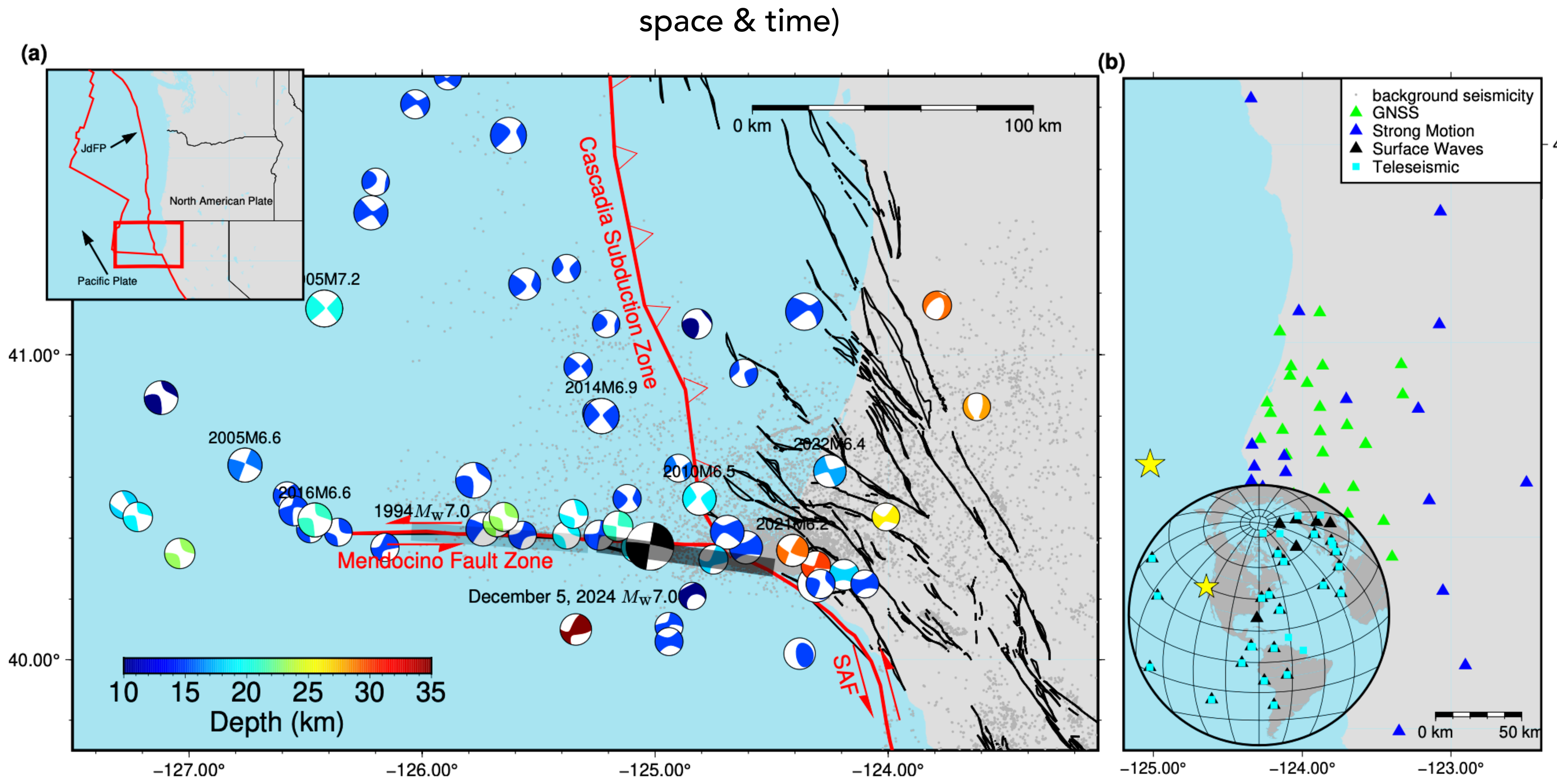
Tsunami Warning in San Francisco 'Felt Like a Science Fiction Movie'

Many Bay Area residents raced away from the ocean after a jolting cellphone alert warned, "You are in danger." Others raced toward it.

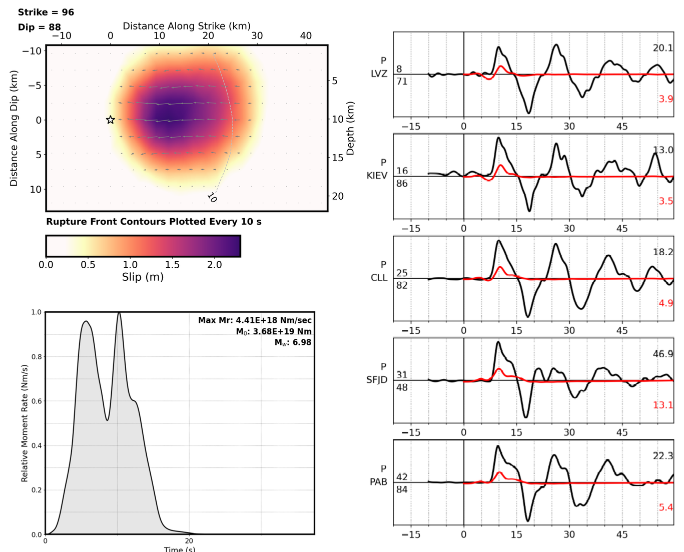
The December 5, 2024 Cape Mendocino earthquake

Figure 1: (a.) Tectonic setting. The main tectonic structures at the triple junction are shown in red, the fault traces of other known faults are plotted in black. Beach balls represent earthquakes with magnitudes larger than 5, color-coded by hypocentral depth. The most recent and significant events are labeled. The along-trace rupture extents of the 1994 and 2024 earthquakes, as constrained by our kinematic finite-fault models, are shown with light and dark shading, respectively. The blue rectangle shows the surface projection of the 1992 M7.2 earthquake. Gray dots represent earthquakes with a magnitude smaller than 5 preceding the December 5 earthquake [54]. Inset: Regional view highlighting the main plate boundaries and their motion relative to the American plate. (b.) Dataset used in the kinematic inversion, which includes static displacements from 28 GNSS stations, velocity waveforms from 20 regional strong-motion accelerometers, and teleseismic recordings from 31 stations for body waves and 29 stations for surface waves.



USGS rapidly available kinematic model

- Based on **surface and body wave teleseismics and 7 high-rate and 23 static GNSS stations**
- **Difficulty fitting body wave observations** (limited off-shore resolution off-shore)



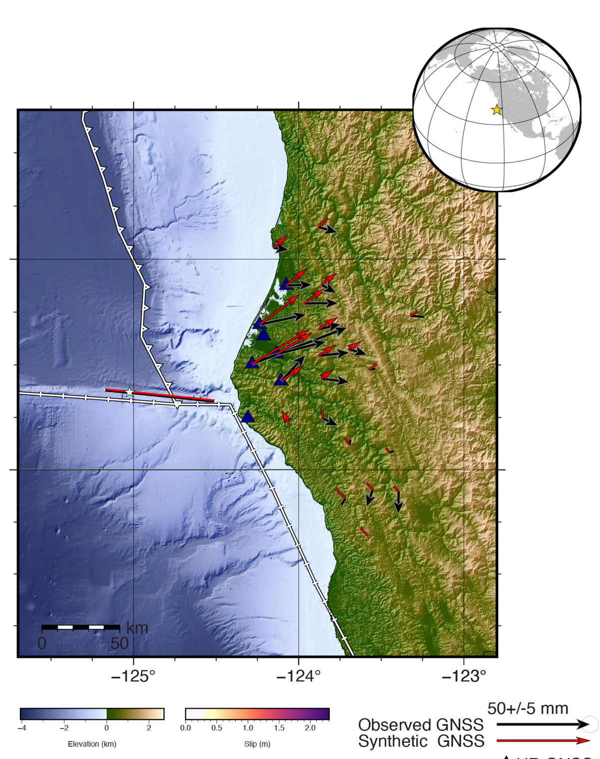


Figure 3 (below): (a) Slip distribution of the finite-fault model constrained using GNSS data only (static inversion). (b.) Slip distribution of the kinematic finite-fault model constrained by GNSS data, teleseismic body and surface waveforms, and regional waveforms (kinematic inversion). The inset shows the associated inferred moment rate function and the beampower from our back projection. (c.) Horizontal co-seismic surface deformation. Blue and pink vectors represent the modeled static and kinematic inversion horizontal displacements, respectively. The figure also includes relocated aftershocks (cyan dots), background seismicity (black dots), repeating earthquakes (red dots), known fault traces, and the fault slip region from our kinematic finite-fault model (shaded area). Inset: Back-projection (0.25-1 Hz)

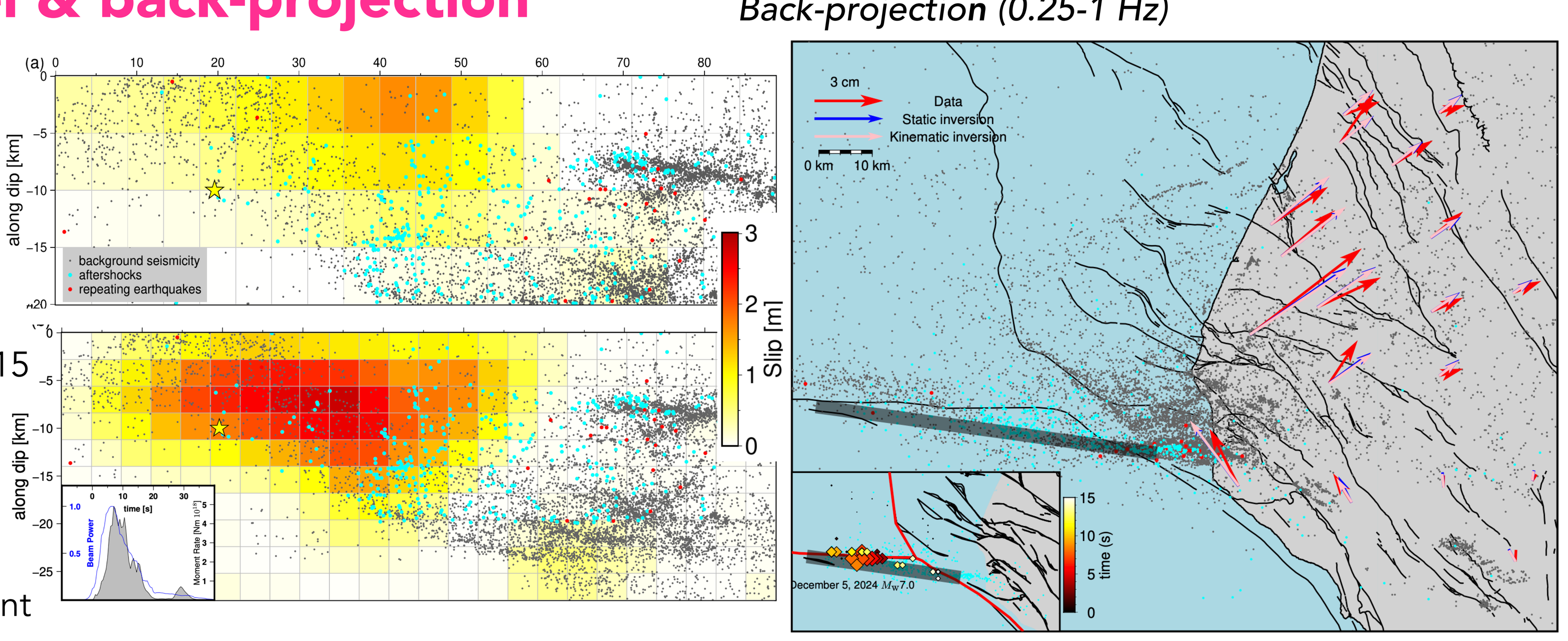
New static model & kinematic model & back-projection

Geodetic, static slip model:

- Static GNSS inversion using 89 stations, smoothness constraint β maximizes the alignment with relocated aftershocks (A. Lomax)
  $\|Am - d\|_2 + \beta\|\nabla m\| \to 0$
- Primary asperity centered ~30 km offshore, shallow slip <1.8m
- Slip deepens and stops to the East, where repeating earthquakes indicate creep, but where also a Mw 5.7 earthquake occurred in 2015

Kinematic, joint seismic & geodetic model:

- Geodetic model fault geometry, geodetic, teleseismic and regional broadband data at 108 stations using WASP
- Rupture initially propagates bilaterally, coinciding with a high moment rate release, then unilateral eastward rupture, during which slip rate amplitudes progressively decreases and rupture width narrows
- 15 km thick low-velocity crustal layer required to kinematically model the Mendocino earthquake in agreement with seismic observations

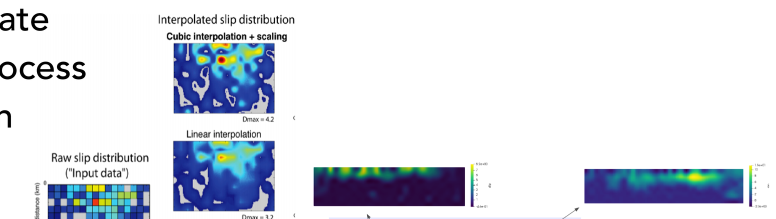


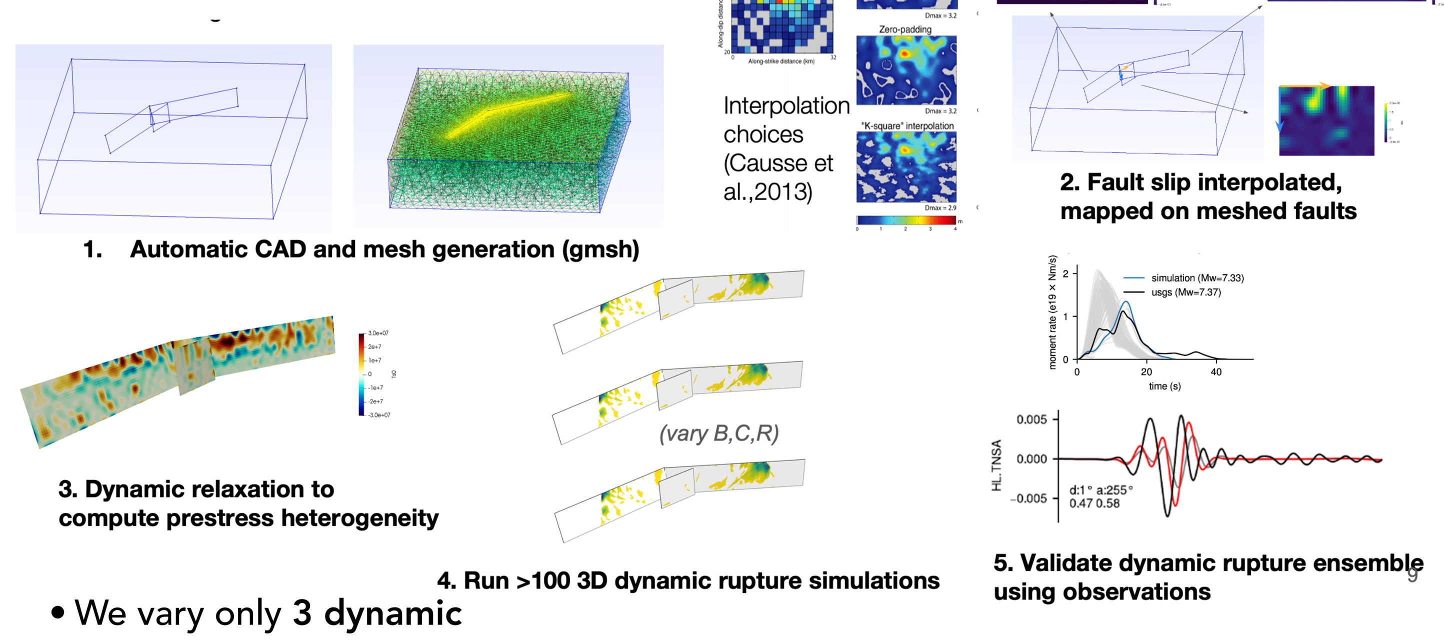
Back-projection

- P-wave back-projection using Central America array
- Bilateral rupture with late slip to the East, aligns well with kinematically inferred moment release & rupture extent

Fast, automated generation of hundreds of 3D dynamic rupture using HPC

- **Ensembles of dynamic rupture models** to test the physical plausibility of candidate source models and resolve rupture process that remains ambiguous in data-driven inversions





- We vary only **3 dynamic parameters** (adapt. Weng & Yang, 2019)
- **Ensemble of 120 3D dynamic rupture models, requiring 44k CPUh** (0.5 Hz, 27 million elements, O(5) accuracy in space & time)

Potential stress drop ∝ stress change

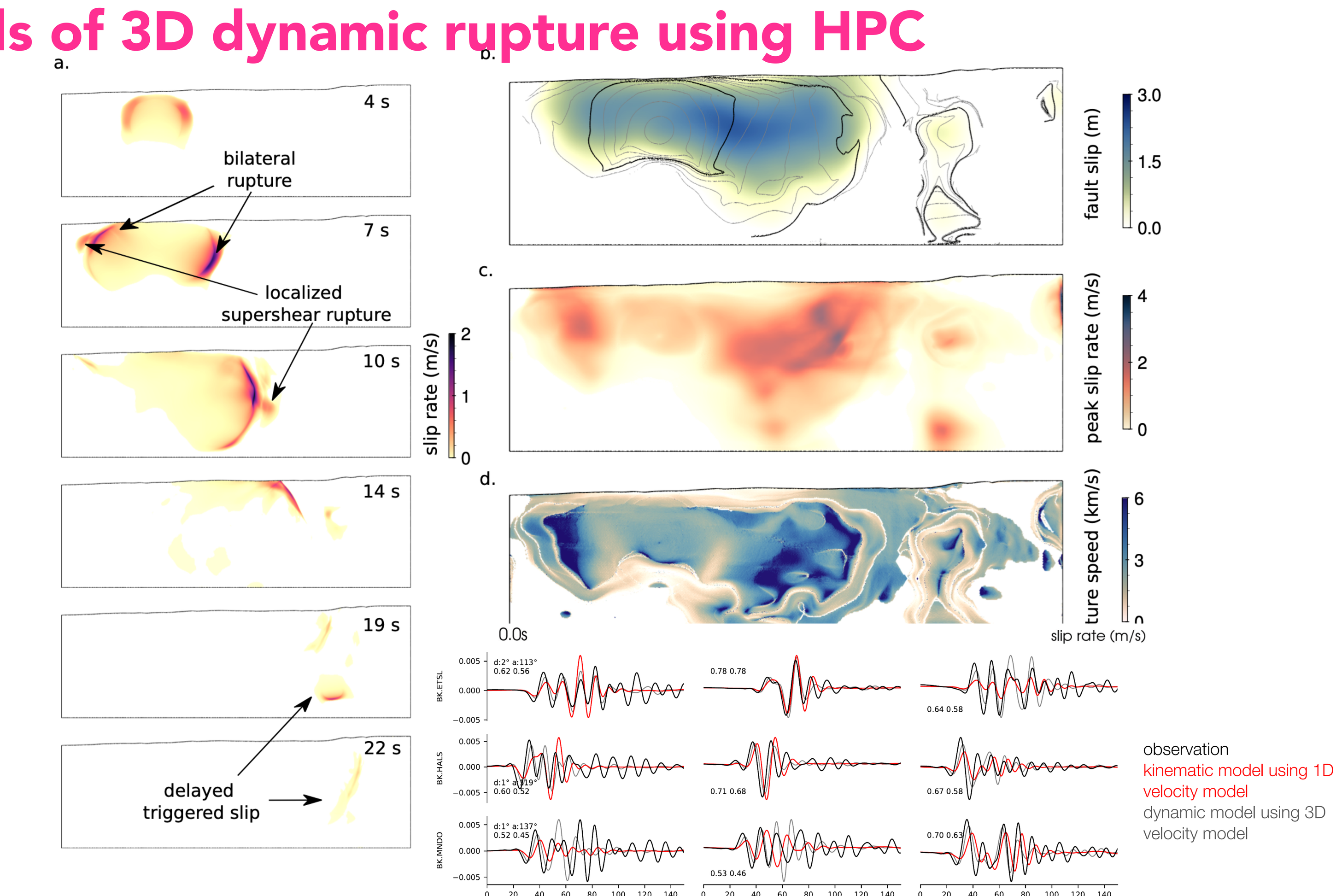
$$\tau_0 = B\tau_{kin} + \tau_d \quad (1)$$

Slip weakening distance ∝ slip (Gabriel et al., Science, 2024)

$$d_c = C\min(0.15\max(u_{kin}), u_{kin}) \quad (2)$$

Static fault strength based on uniform prestress ratio R

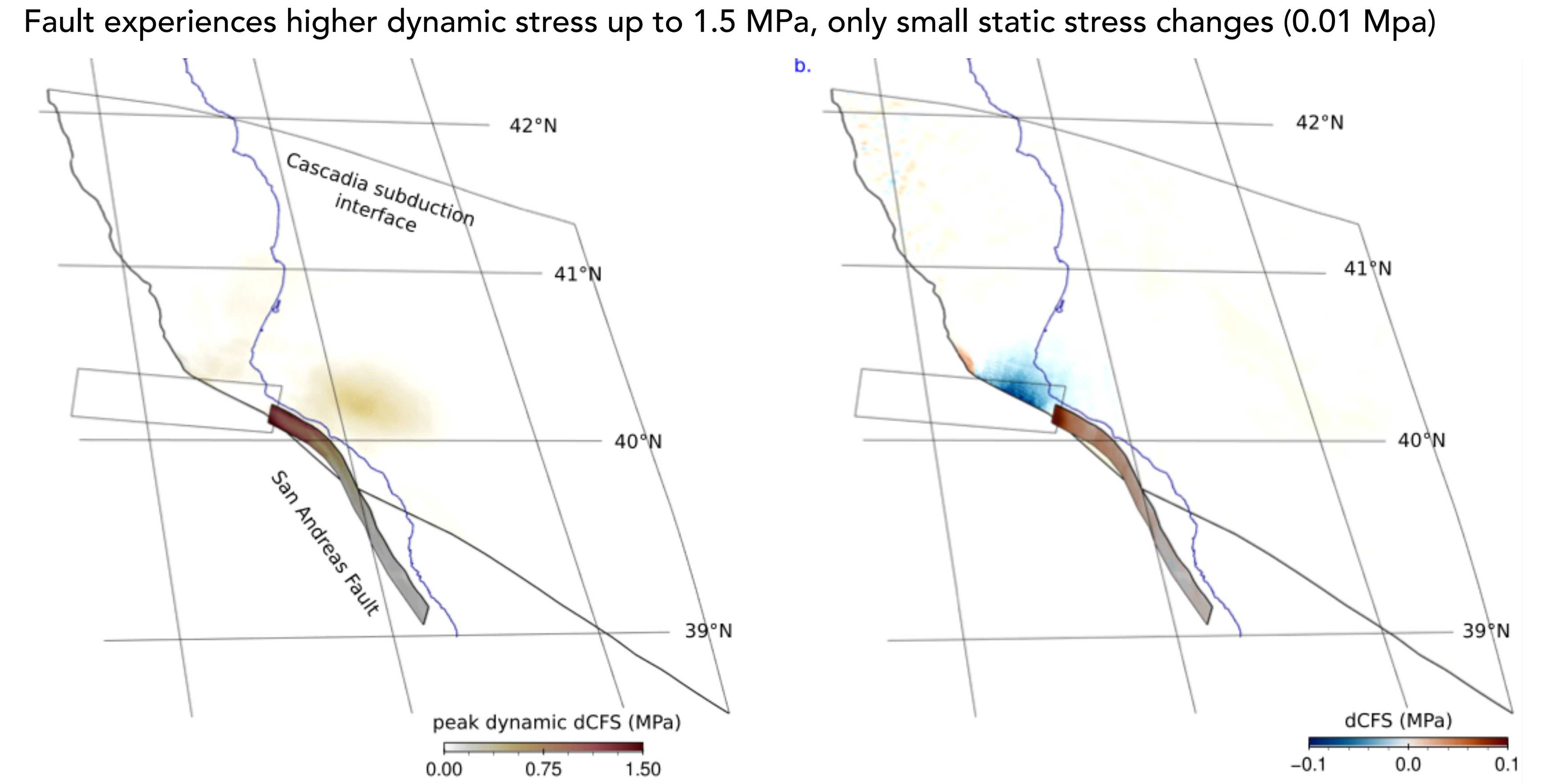
$$\tau_s = \tau_d + (\tau_0 - \tau_d)/R \quad (3)$$



- Best fitting model validation: observed moment rate release & slip distribution, strong motion fit
- Static model does not produce realistic rupture dynamics, a higher degree of smaller-scale initial stress **heterogeneity** is required
- Despite geometric simplicity, complex multi-front dynamics, including delayed rupture of isolated deep fault portions in the east and localized supershear propagation across 16% of the total rupture area, may be explained by dynamically weak fault (e.g., due to high fluid pressure) and pronounced stress heterogeneity

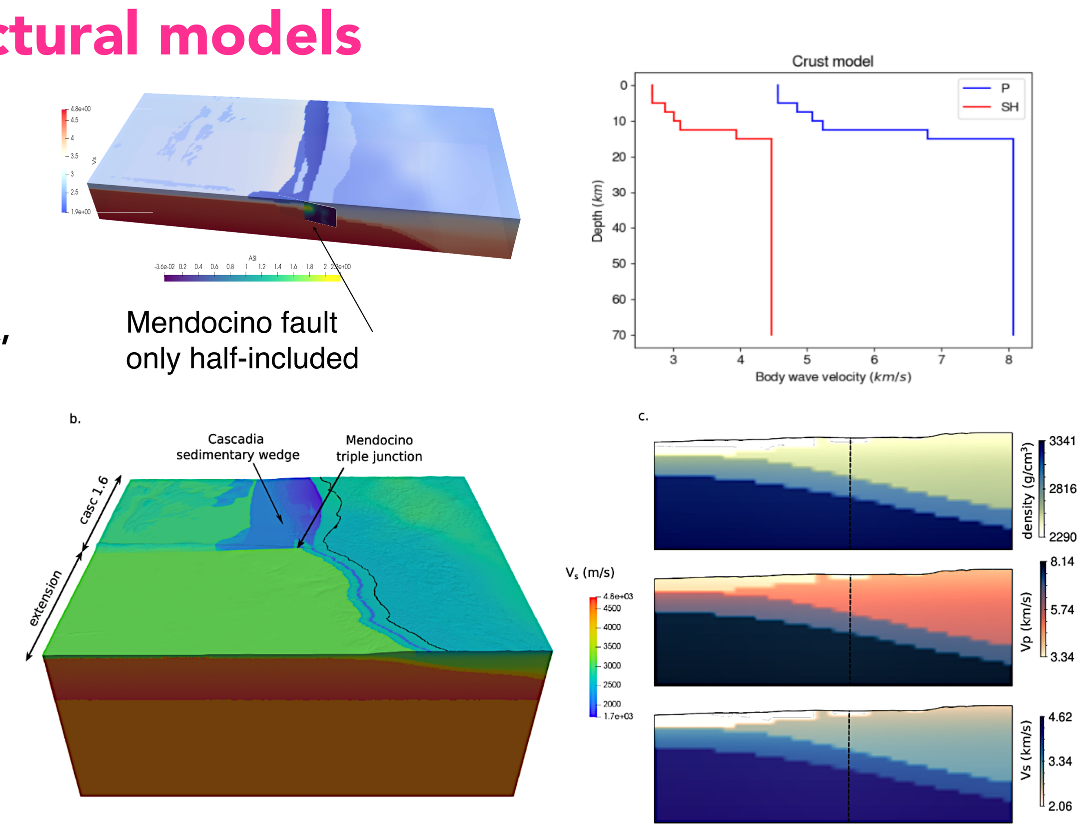
Dynamic and static Coulomb stress changes

- Cascadia with moderate dynamic stress perturbations reaching 0.5 MPa, while Northern San Andreas Fault experiences higher dynamic stress up to 1.5 MPa, only small static stress changes (0.01 Mpa)



Regional 1D and 3D structural models

- USGS rapid finite fault inversions use 1D model (Litho1.0), with shallow (7.5km) and stiff crust
- We extract a **1D velocity model with thick, low-velocity layers** from the 3D Cascadia crustal velocity model (Stephenson et al., 2017, CCVMv1.6) for our **kinematic** inversion
- We extend the **CCVMv1.6 3D velocity model,** southward of the Mendocino Triple Junction, for our **dynamic rupture models**



Summary

- **Using HPC, we can model hundreds of dynamic rupture scenarios quickly after large earthquakes and tightly integrated with data-driven approaches**
- **Low effective fault strength and stress heterogeneity may govern dynamic rupture complexity of the geometrically simple Mendocino Fault Zone**
- **The earthquake may have included delayed dynamic activation of deep slip at eastern fault portions, multiple rupture fronts, and localized supershear propagation**
- **Seismic and aseismic slip may coexist along the Mendocino fault system**
- **Our forward and inverse models demonstrate the importance of regional velocity models**
- **The complex rupture dynamics of this offshore fault system highlight the need for continued improvement of off-shore observations**