LMU LUDWIG-MAXIMILIANS-UNIVERSITÄT MÜNCHEN

SCRIPPS INSTITUTION OF OCEANOGRAPHY
UC San Diego

DT-GEO

The complex rupture dynamics of a presumably simple oceanic transform fault: Supershear rupture and deep slip during the 2024 M_w7.0 Cape Mendocino earthquake

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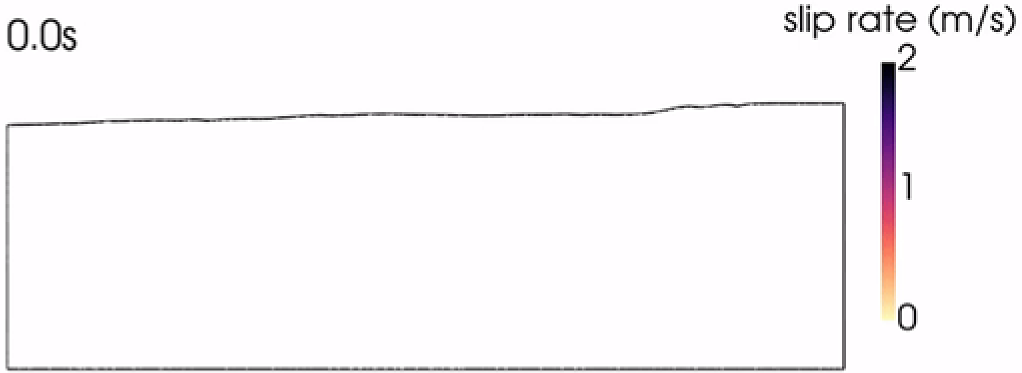
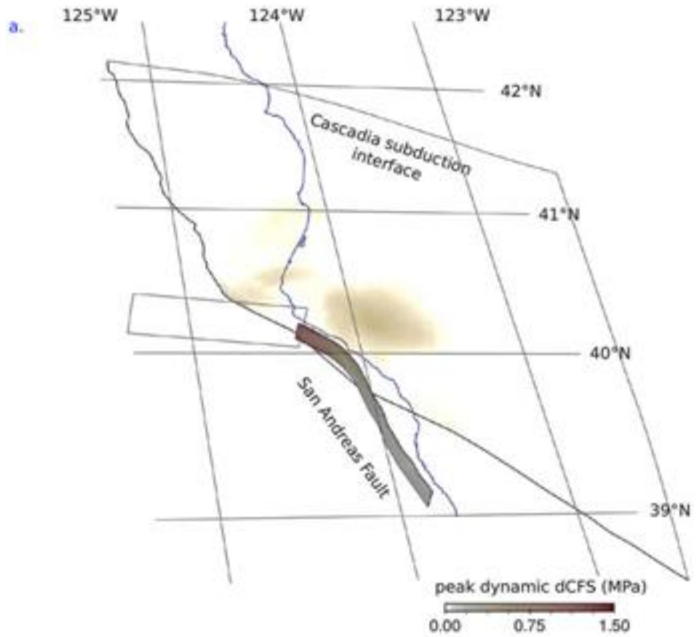
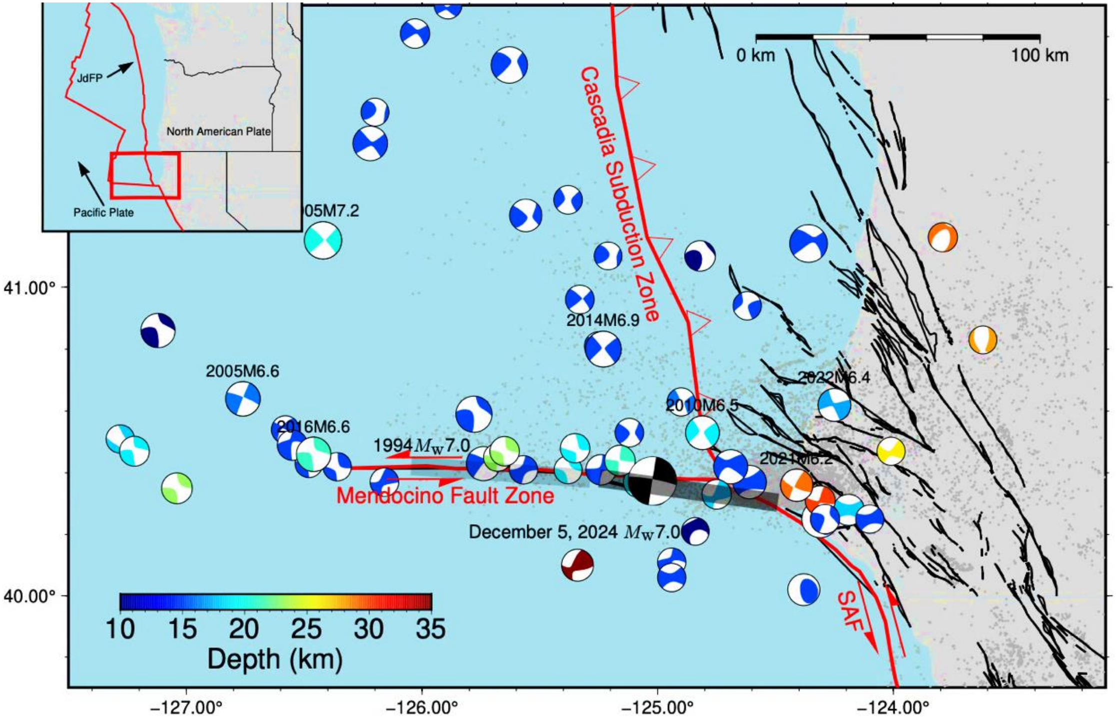
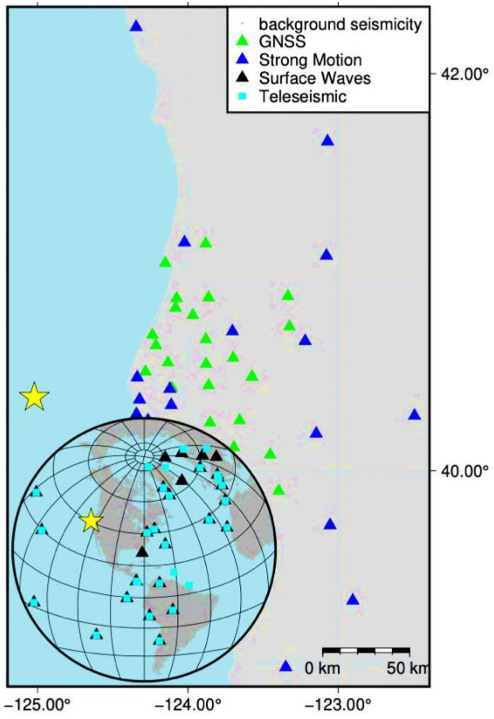




The December 5, 2024, M_w7.0 Cape Mendocino earthquake

- **Largest Californian earthquake** since Ridgecrest, but less well recorded
- **Mendocino Triple Junction,** seismically most active region of CA with history of large strike-slip and thrust faulting earthquakes, incl. the 2022 M_w6.4 Ferndale earthquake
- Seismicity illuminates **geometrically simple** Mendocino oceanic transform fault zone



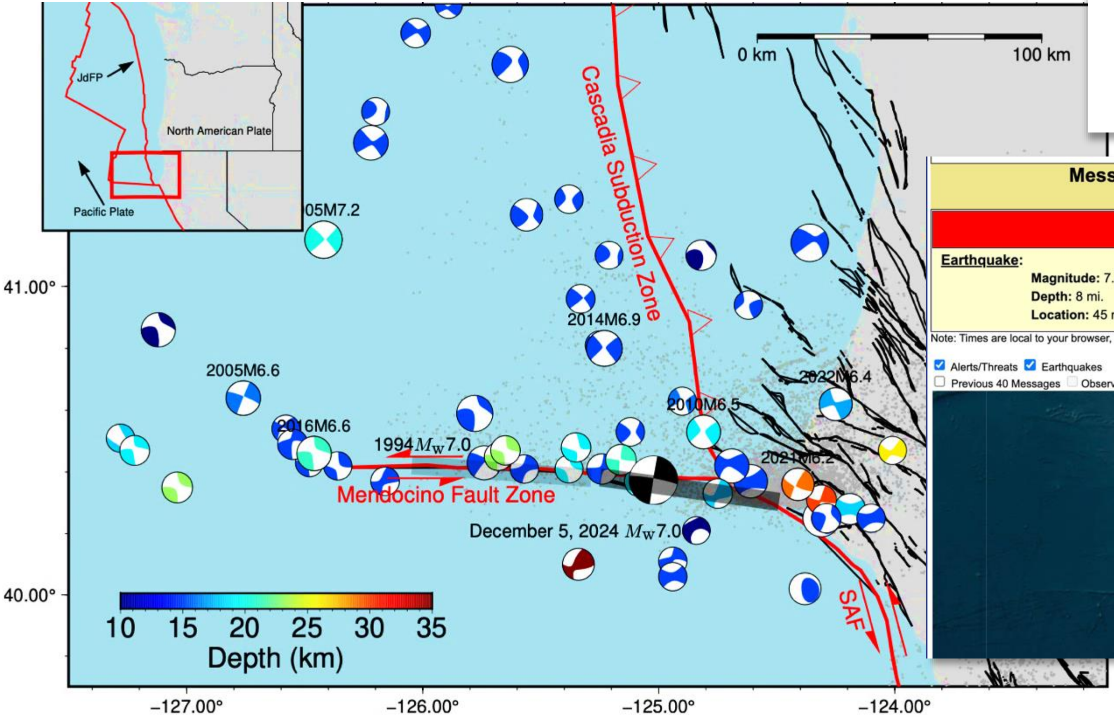


The December 5, 2024, M_w7.0 Cape Mendocino earthquake

- **Tsunami evacuation alert for more than 5 million people,** lifted after ~1h
- Understanding rupture crucial to better understand structural and stress heterogeneity & stress redistribution onto **two high-hazard fault systems:** the northern San Andreas Fault and the Cascadia megathrust

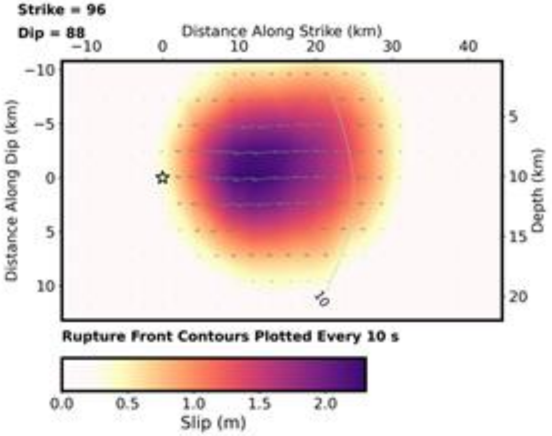
Tsunami Warning in San Francisco 'Felt Like a Science Fiction Movie'

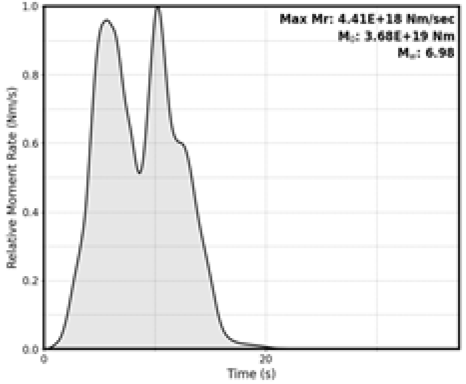
Many Bay Area residents raced away from the ocean after a jolting cellphone alert warned, "You are in danger." Others raced toward it.

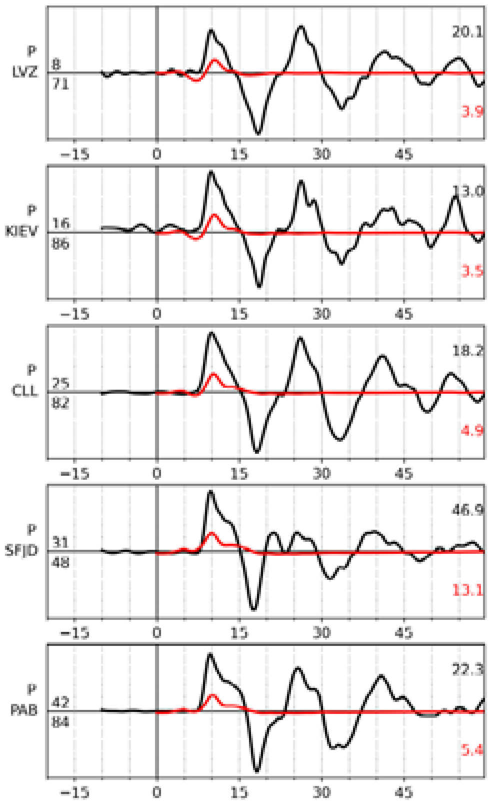


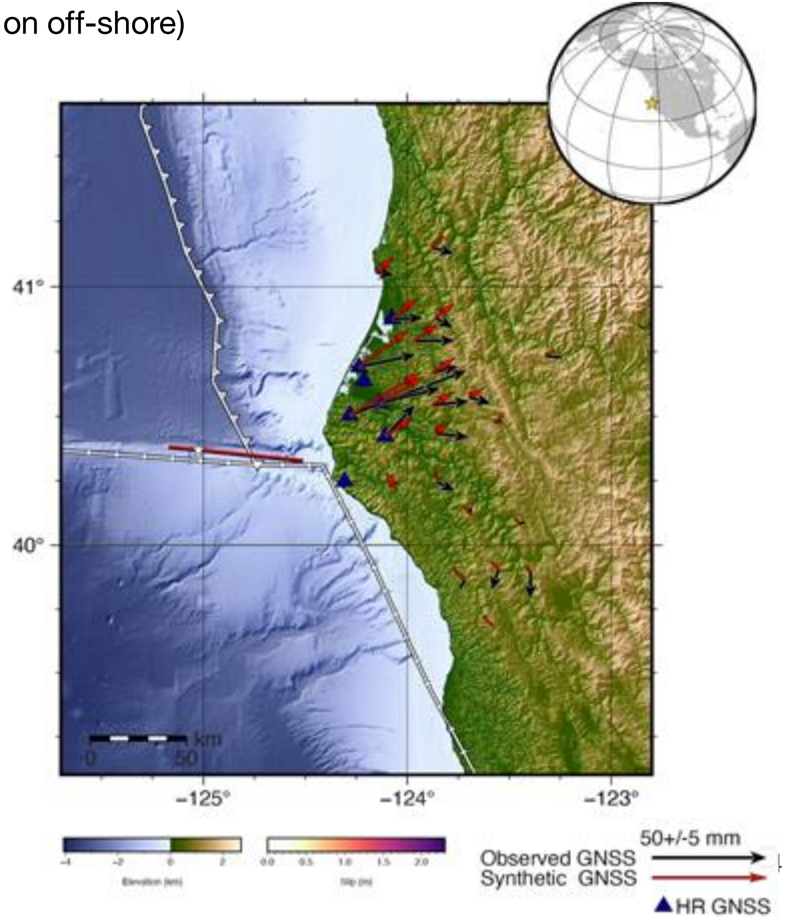
USGS rapidly available kinematic model

- 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)









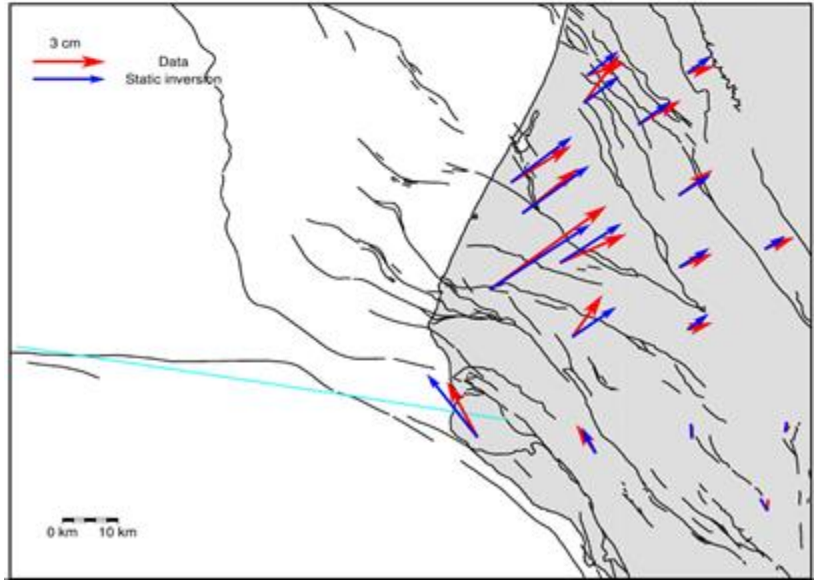
New geodetic slip model

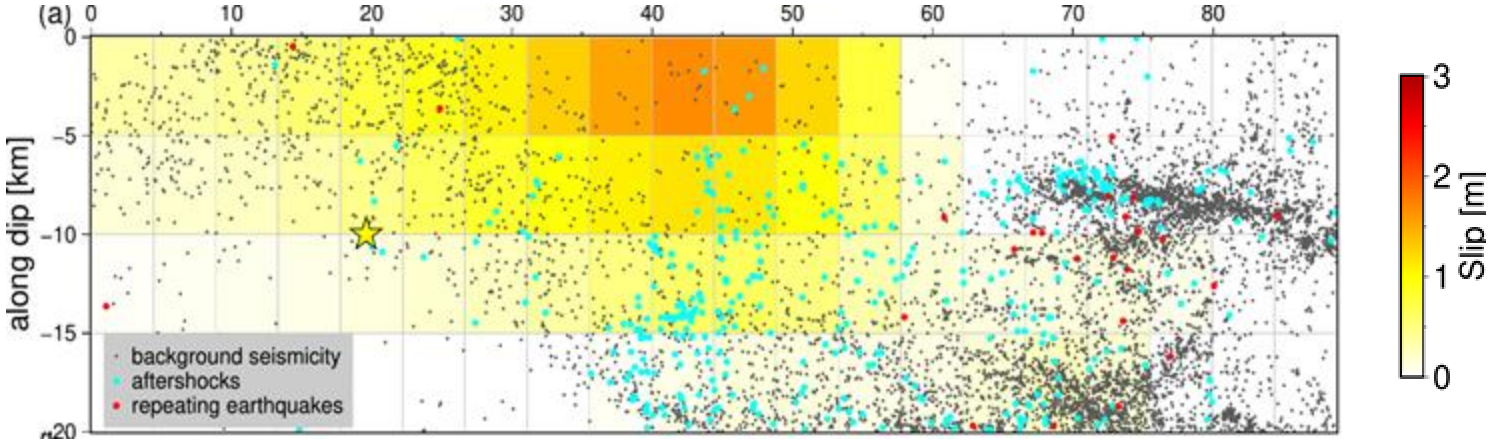
- Static GNSS inversion using 89 stations, smoothness constraint **β** maximizes the alignment with relocated aftershocks (A. Lomax)

$$\|Am - d\|_2 + \beta \|\nabla m\| \to 0$$

- **Primary asperity** centered ~30 km offshore, **shallow slip** <1.8m

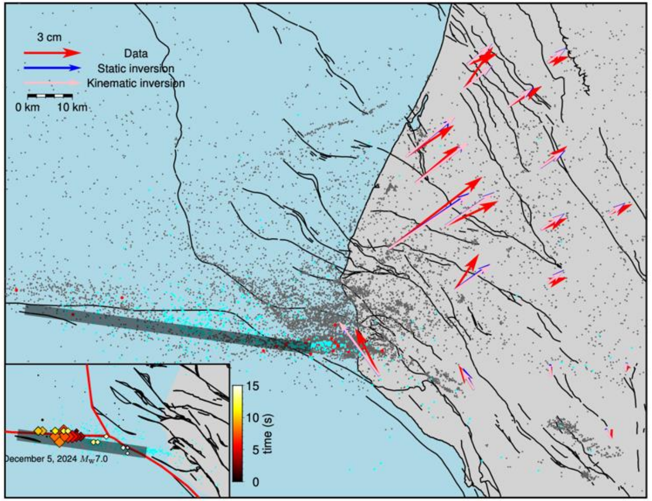
- Slip deepens and stops to the East, where **repeating earthquakes indicate creep**, but where also a Mw 5.7 earthquake occurred in 2015

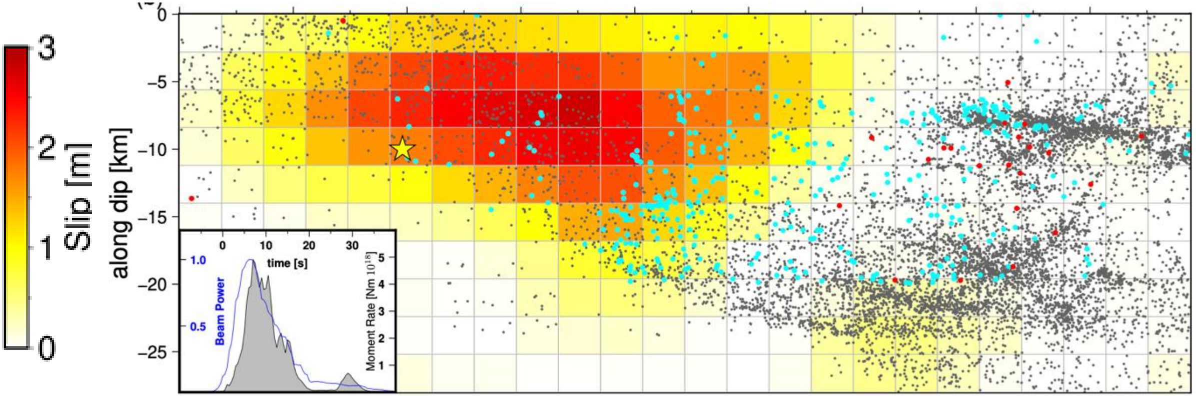




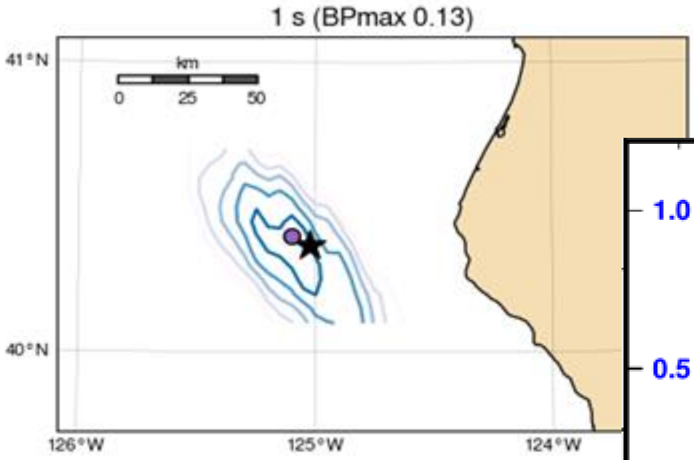
New kinematic model

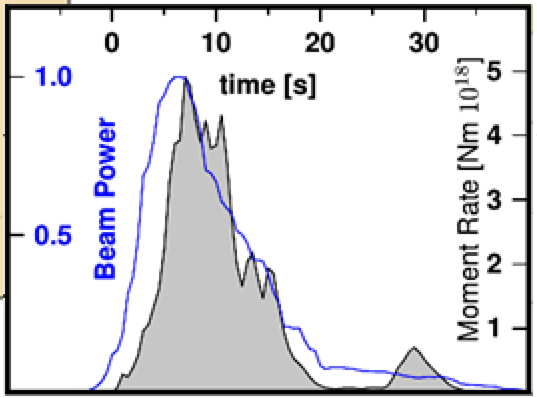
- Geodetic model fault geometry, geodetic, teleseismic and regional broadband data at **108 stations using WASP** (USGS, D. Goldberg et al., extended from rapid USGS model)
- Rupture initially propagates **bilaterally**, coinciding with a high moment rate release, then **unilateral eastward** rupture, 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

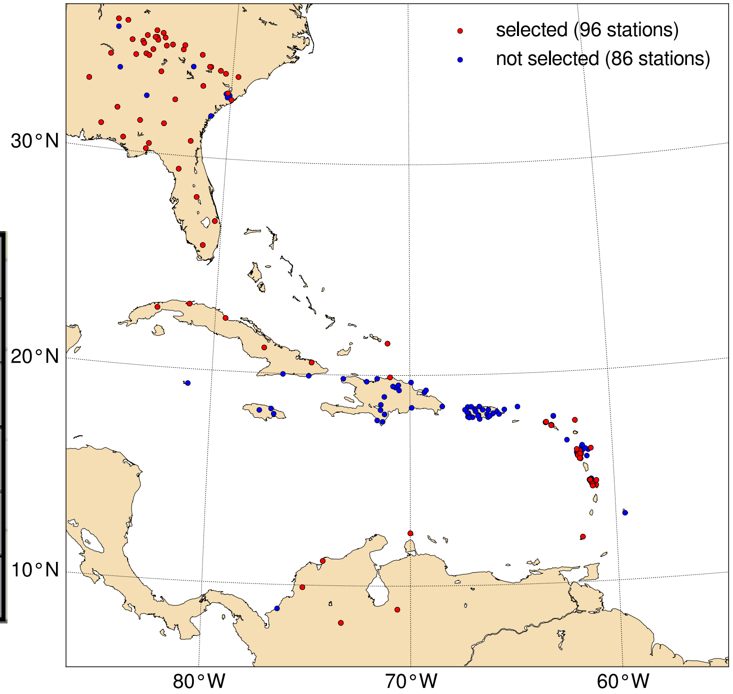


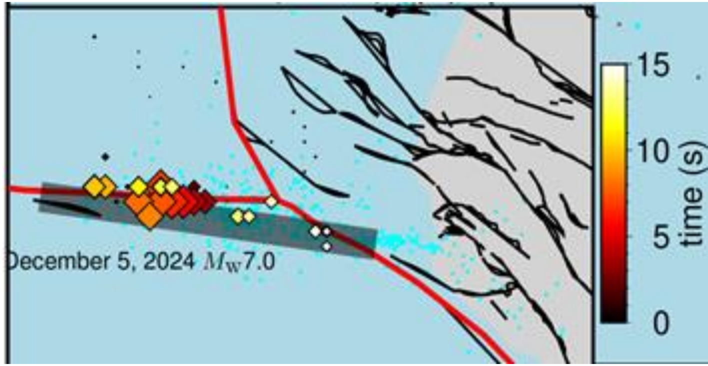


New back-projection





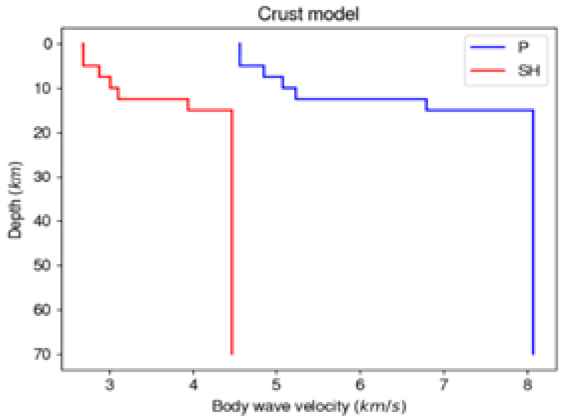


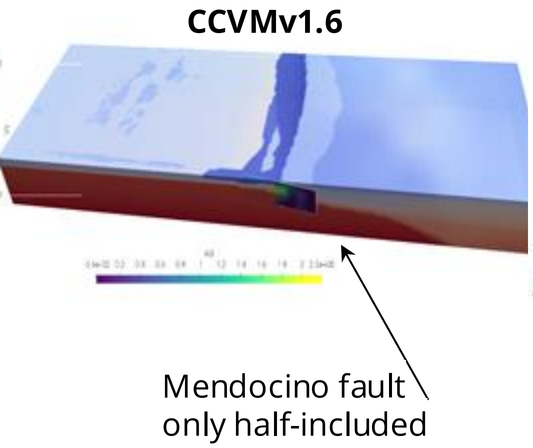


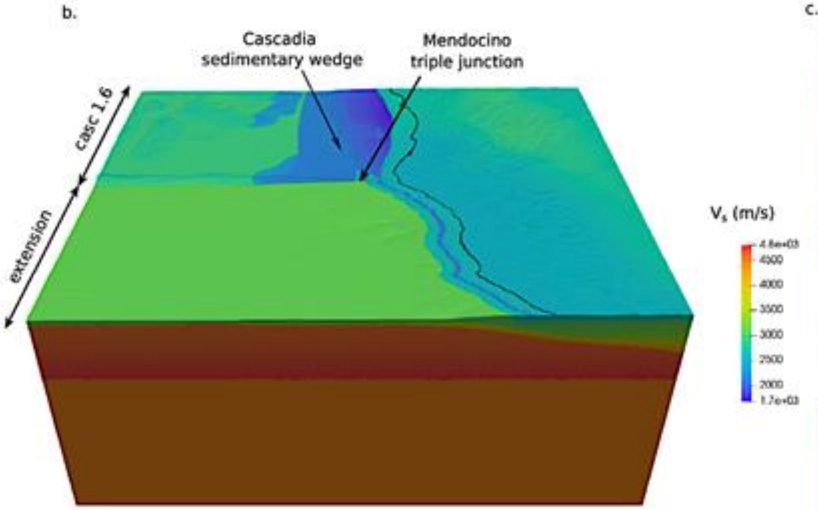
- P-wave back-projection using Central America array
- **Bilateral rupture with late slip to the East, aligns well with kinematically inferred moment release & rupture extent**

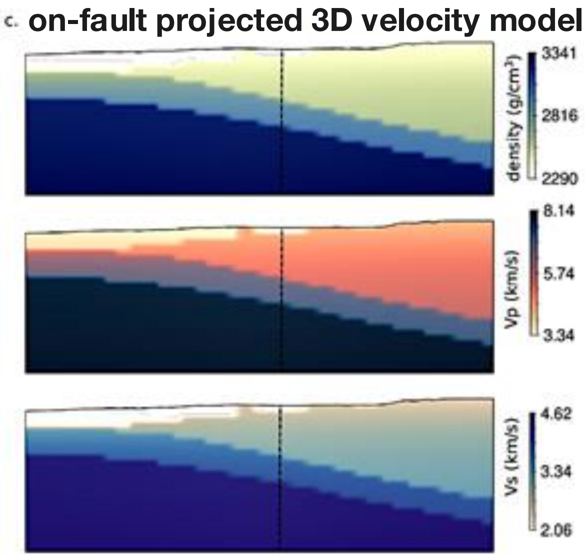
Regional 1D and 3D structural models

- 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**



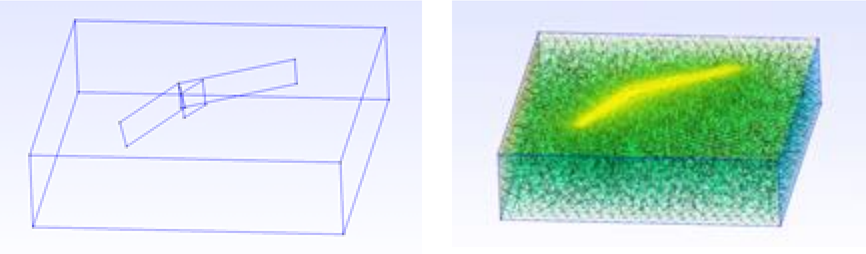




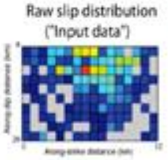


Fast, automated generation of 3D dynamic rupture ensembles

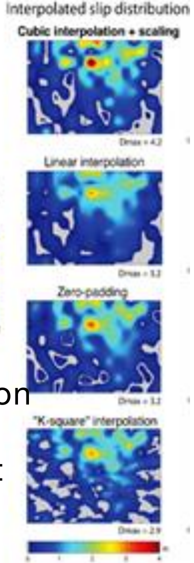
- Dynamic rupture models to test the physical plausibility of candidate source models and resolve rupture process that remains ambiguous in data-driven inversions

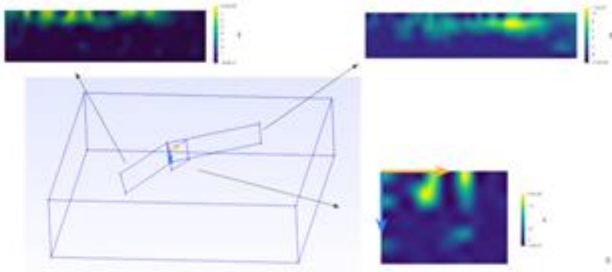


1. Automatic CAD and mesh generation (gmsh)

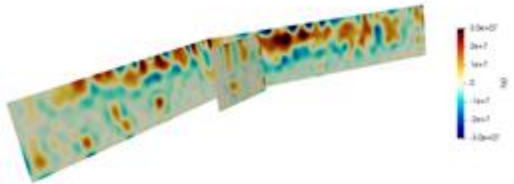


Interpolation choices (Causse et al.,2013)

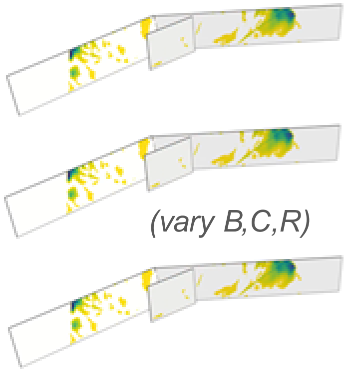




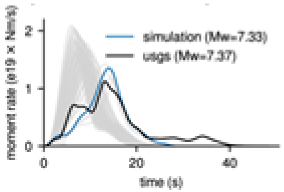
2. Fault slip interpolated, mapped on meshed faults

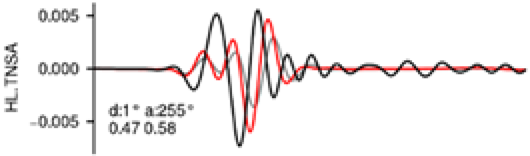


3. Dynamic relaxation to compute prestress heterogeneity



4. Run >100 3D dynamic rupture simulations

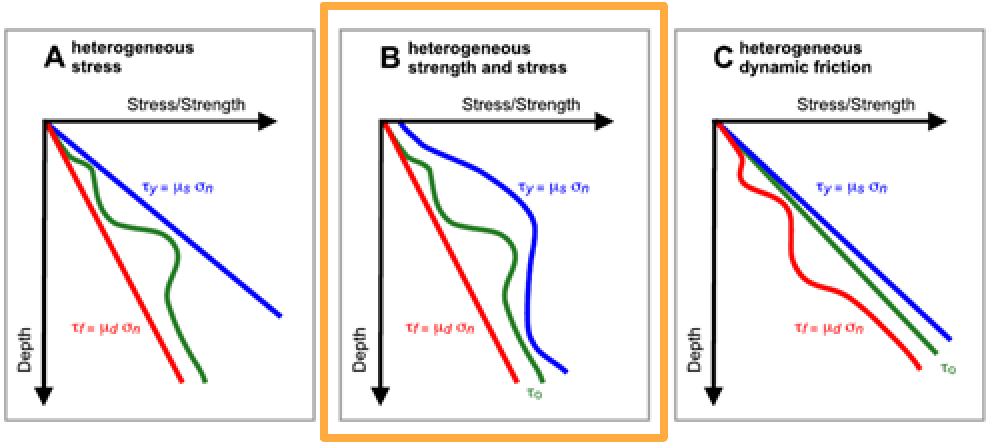




5. Validate dynamic rupture ensemble using observations

Constraining 3D dynamic rupture ensembles from finite slip models

Tinti et al, 2021 (EPSL)



dynamic fault strength
initial fault stress
static fault strength

Our framework, following Weng and Yang (2019), uses ***only*** **3 dynamic parameters:**

Potential stress drop ∝ stress change

$$\tau_0 = B\tau_{\mathrm{kin}} + \tau_{\mathrm{d}} \qquad (1)$$

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

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

Static fault strength based on uniform prestress ratio R

$$\tau_s = \tau_{\mathrm{d}} + (\tau_0 - \tau_{\mathrm{d}})/R \qquad (3)$$

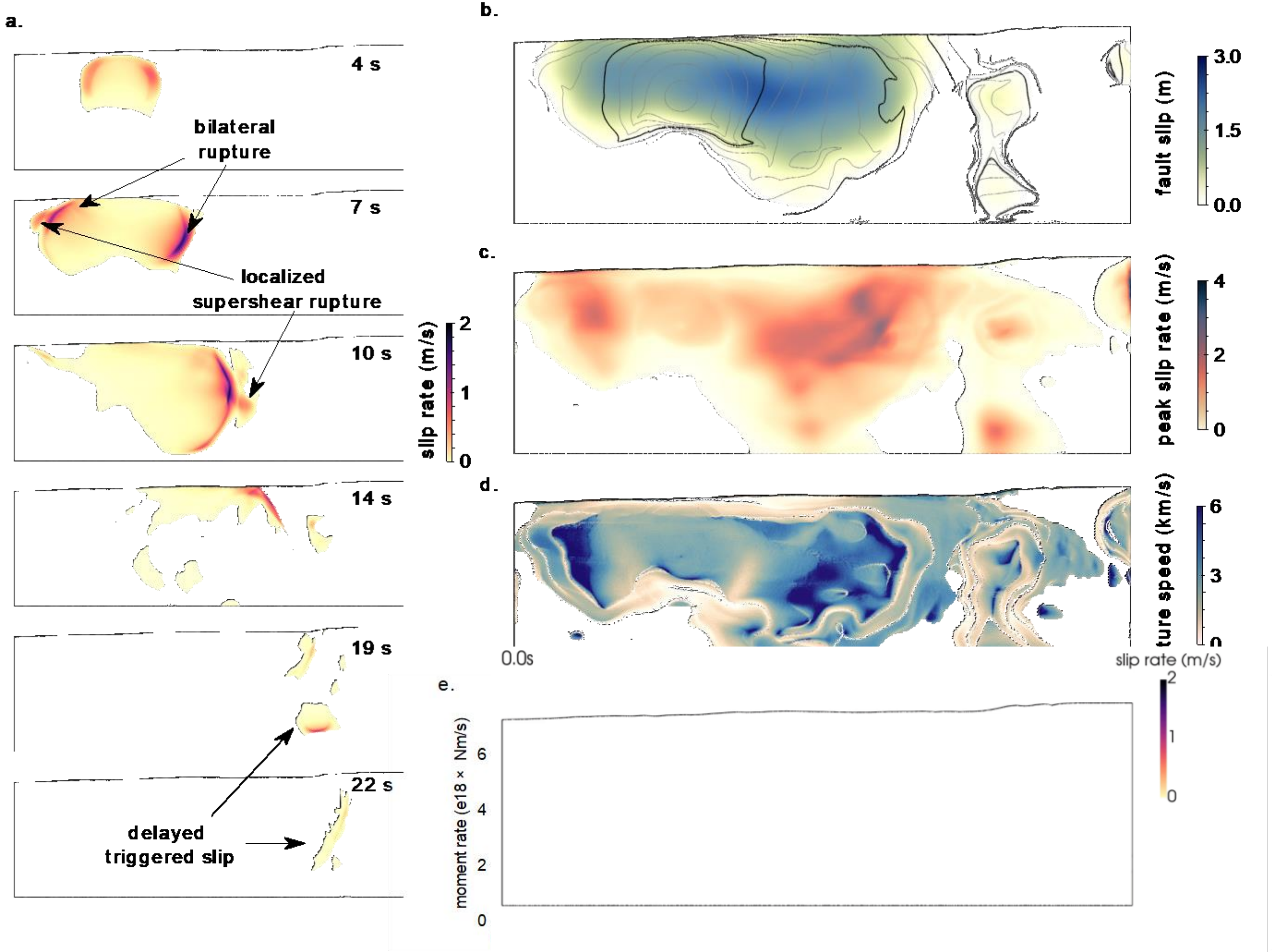
Grid search:

B in [0.9, 1.0, 1.1, 1.2]
C in [0.1, 0.2, 0.3, 0.4, 0.5]
R in [0.5, 0.55, 0.6, 0.65, 0.7,0.8, 0.9]

=> Ensemble of 120 3D dynamic rupture models, requiring 44k CPUh
(0.5 Hz, 27 million elements, O(5) accuracy in space & time)

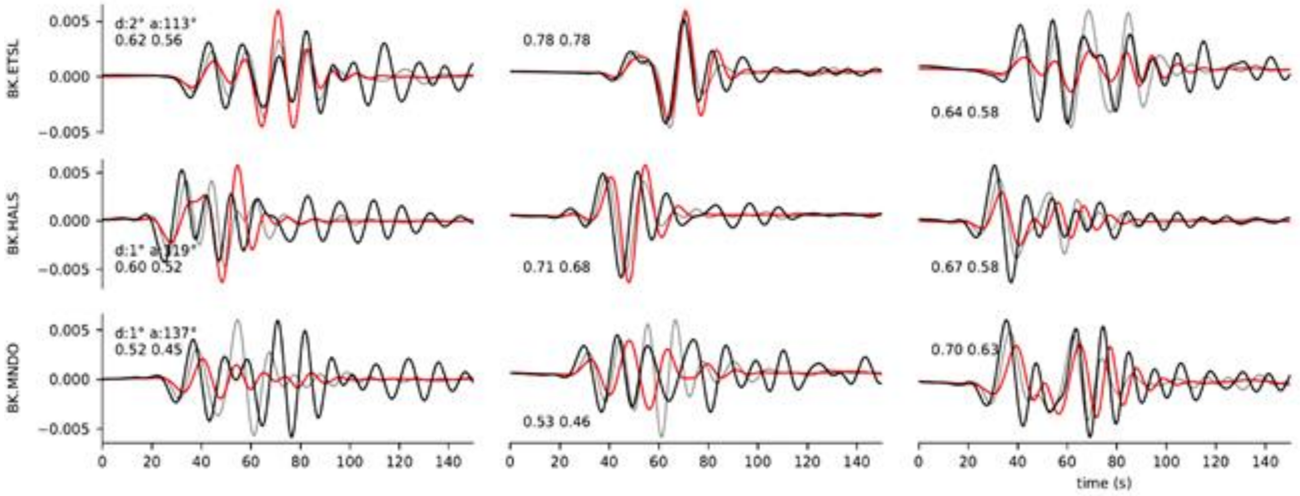
Best-fitting dynamic rupture model

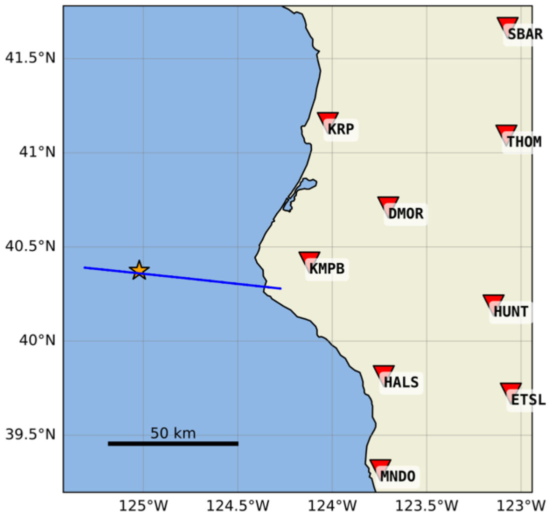
- **Ensemble validation**: moment rate release & slip distribution of kinematic model, strong motion fit at 9 stations
- Despite **geometric simplicity**, best-fitting dynamic rupture model has complex multi-front dynamics, including **delayed rupture** of isolated deep fault portions in the east and localized **supershear** propagation across 16% of the total rupture area
- **Explained by dynamically weak fault** (e.g., due to high fluid pressure) **and pronounced stress heterogeneity**



Strong motion synthetics

- 3D dynamic rupture models reproduce strong ground motion records **better** than our 1D kinematic inversion, especially ringing effects in verticals

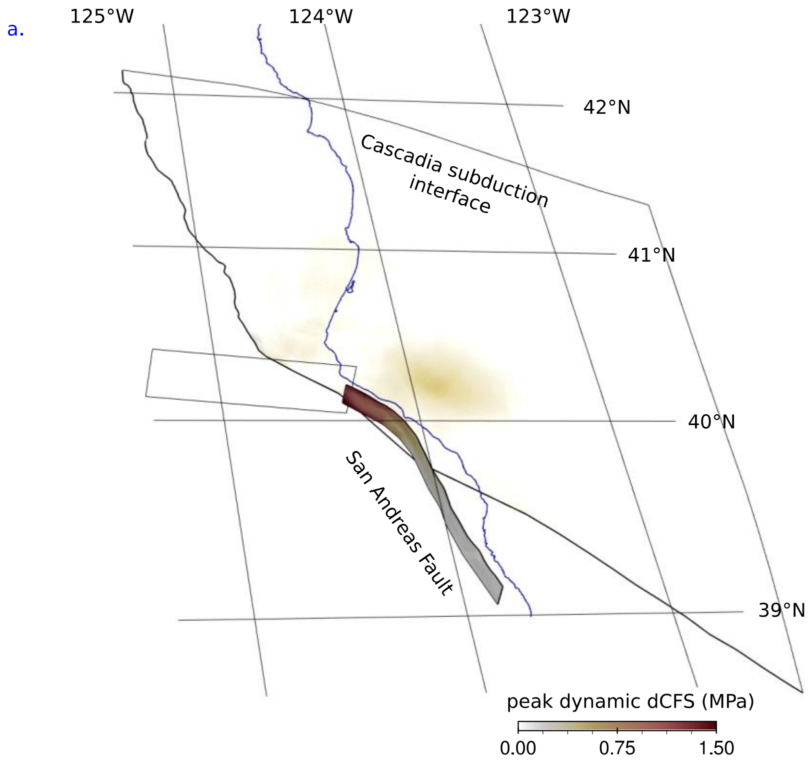


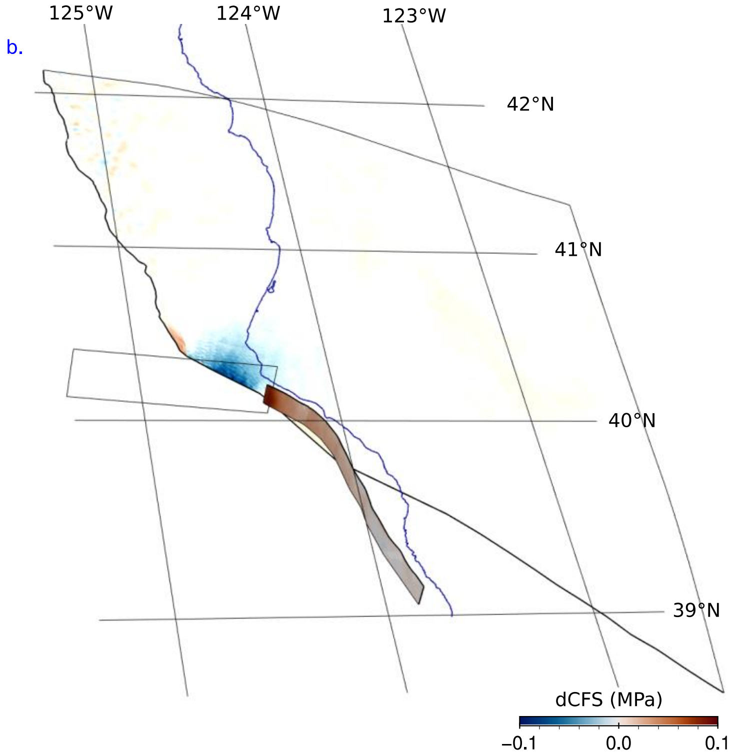


observation
kinematic model using 1D velocity model
dynamic model using 3D velocity model

Dynamic and static Coulomb stress changes

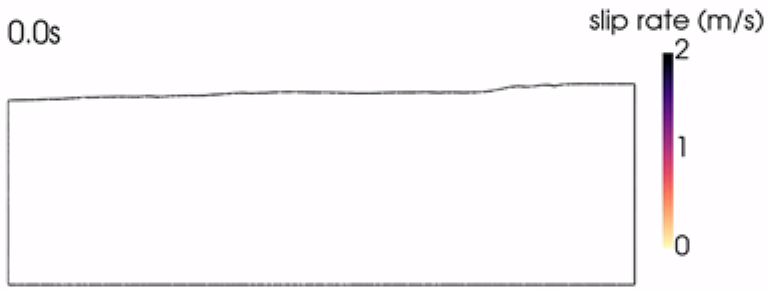
- Cascadia with moderate **dynamic** stress perturbations reaching 0.5 MPa, while Northern San Andreas Fault experiences higher **dynamic** stress up to **1.5 MPa**
- Only small static stress changes (0.01 Mpa)

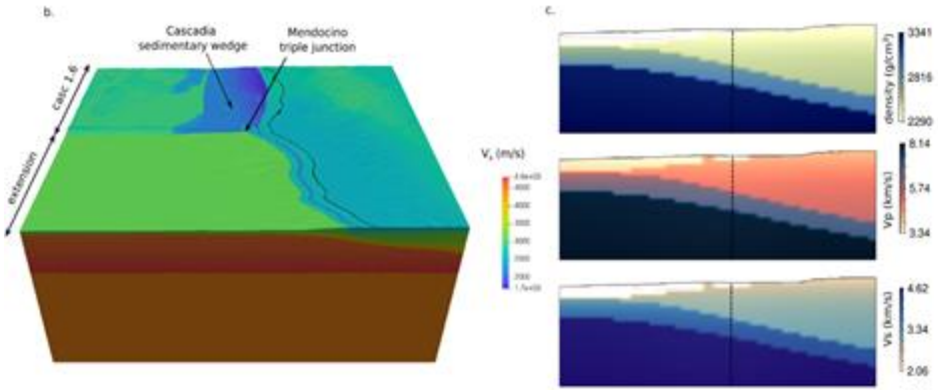


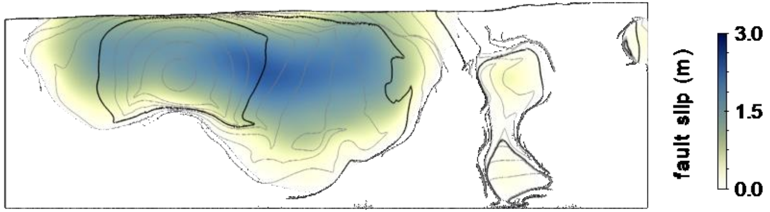


Conclusions

- We can model >100 dynamic rupture scenarios quickly after large earthqaukes & tightly integrated with data-driven approaches
- Low fault strength and stress heterogeneity govern dynamic rupture complexity of the geometrically simple Mendocino Fault Zone
- The M_w7.0 Cape Mendocino Mendocino 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







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