Untangling slab geometry's influences on the megathrust earthquake cycle

Questions or comments?
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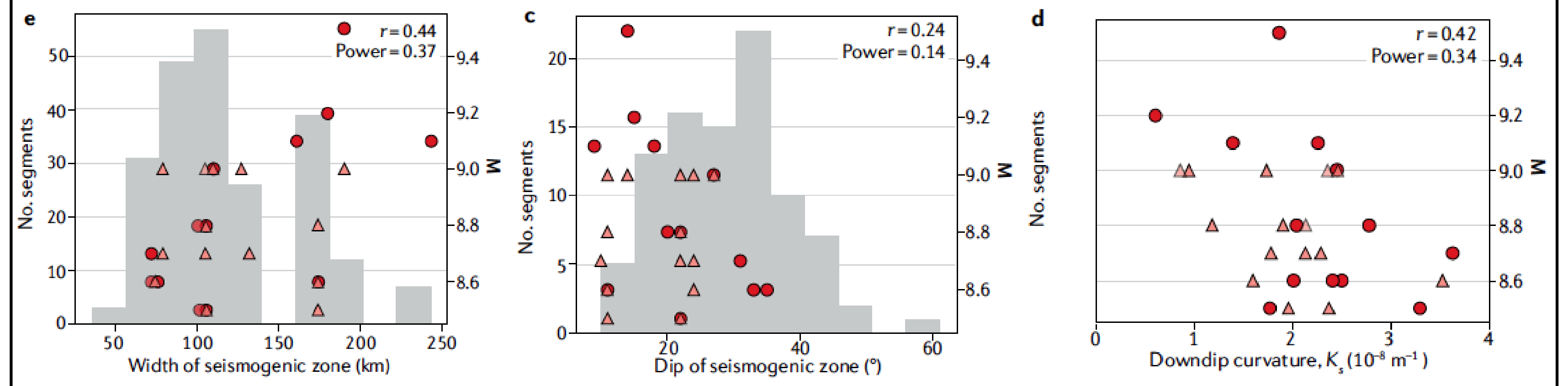
Large Subduction Earthquakes & Megathrust Geometry

- Magnitudes of the largest ($M_w > 8.5$) recorded subduction zone earthquakes appear correlated with the downdip seismogenic width, average dip, and average downdip curvature of the megathrust, as shown by Wirth & Sahakian et al. (2022):

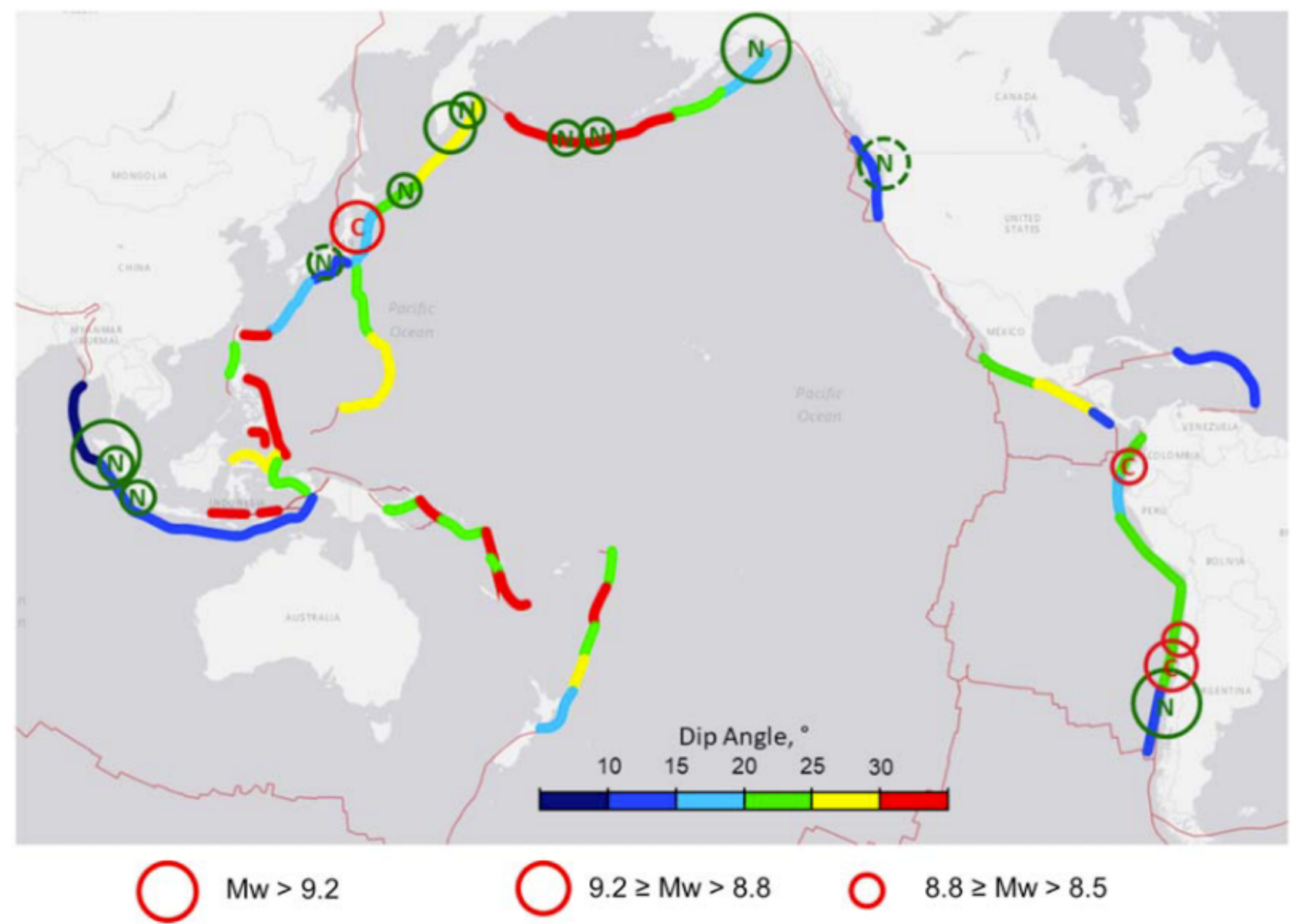


- & highlighted by global compilations which have led to different conclusions about which geometric factor(s) exert the strongest influence on rupture size, e.g.:

Downdip seismogenic width & dip:

What Controls Maximum Magnitudes of Giant Subduction Earthquakes?

Iskander A. Muldashev[1,2,3] and Stephan V. Sobolev[2,3]



Muldashev & Sobolev, 2020

Downdip curvature:

Mega-earthquakes rupture flat megathrusts

Quentin Bletery,[1]* Amanda M. Thomas,[1] Alan W. Rempel,[1] Leif Karlstrom,[1] Anthony Sladen,[2] Louis De Barros[2]

Bletery et al., 2016

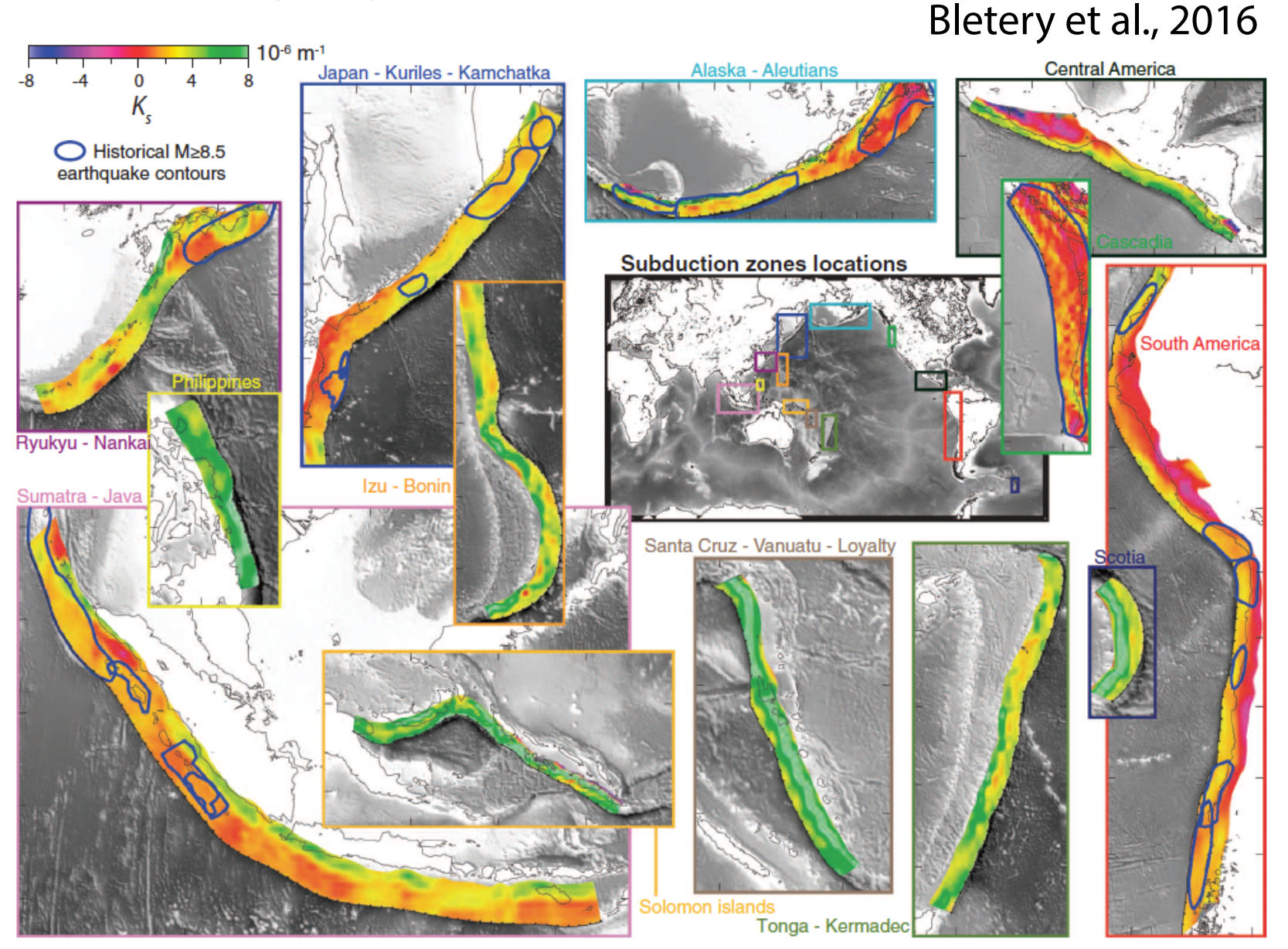


Fig. 1. Variations in megathrust curvature and distribution of historical mega-earthquakes. Along-dip curvature $K_s = d\theta/ds$ on the megathrust is shown for the 13 main subduction zones of the world, overlaid with the estimated slip contours of known historical mega-earthquakes ($M \geq 8.5$) (see table S1 for a list of events). Tick marks in each panel are spaced at 5° increments.

- Overall, larger earthquakes tend to rupture **flatter** (lower curvature), more **shallowly-dipping** megathrusts with **wider** seismogenic zones

Proposed mechanisms

Downdip seismogenic width (W) & average dip (θ):

- [Shallower dip, among other conditions] → larger seismogenic width → larger available rupture area → larger earthquakes
- ±Dip-dependent dynamic processes like enhanced coseismic weakening near the free surface for shallower thrust fault dips (e.g., Oglesby et al., 1998)
- Larger W → larger W/h*, ratio of the frictionally locked area to critical nucleation size h*, linked to the critical stiffness for frictional instability (e.g., Liu & Rice, 2007)

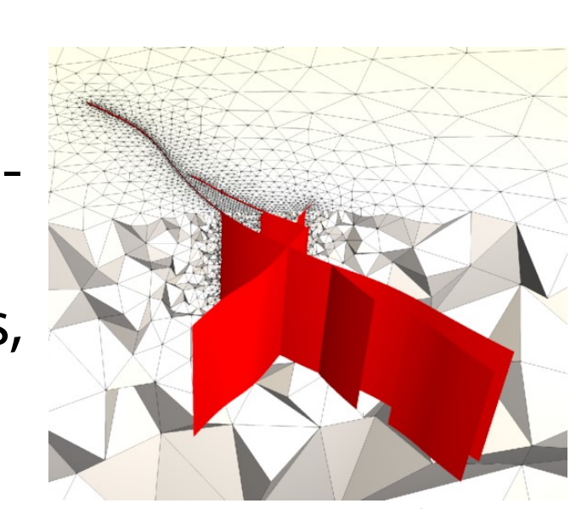
Downdip curvature (K_s):

- Sharper downdip curvature → more heterogeneous fault strength (τ^c) → smaller areas of the fault become critically stressed before some patch nucleates rupture → smaller, more frequent partial ruptures
- As opposed to flatter megathrusts with lower curvature → more homogeneous fault strength → larger areas of the fault approach critical stress before any patch nucleates → higher tendency for large, full-margin ruptures
- Assumes stress & strength heterogeneity (represented by shear strength gradient $d\tau^c/ds$) increases with increasing curvature: $d\tau^c/ds \propto K_s$ (Bletery et al., 2016)
- Models show that fault curvature & roughness enhance on-fault normal stress variability, leading to weaker interseismic coupling (Romanet et al., 2020; Cattania & Segall, 2021)

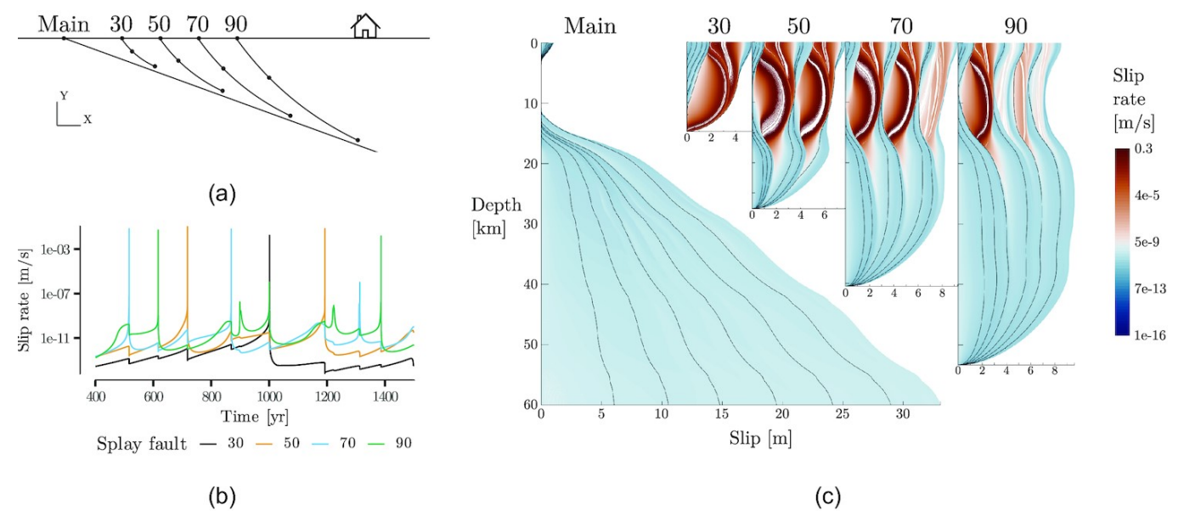
Method & earthquake cycle simulation code: tandem

https://github.com/TEAR-ERC/tandem (Uphoff et al., 2022)

- scalable, discontinuous symmetric interior penalty Galerkin (SIPG) method for linear elastic + SEAS simulations on curvilinear grids (with high-order elements)
- flexible: 2D/3D, can handle curved faults, multiple faults, heterogeneous material properties, locally refined meshes, optional discrete Green's functions

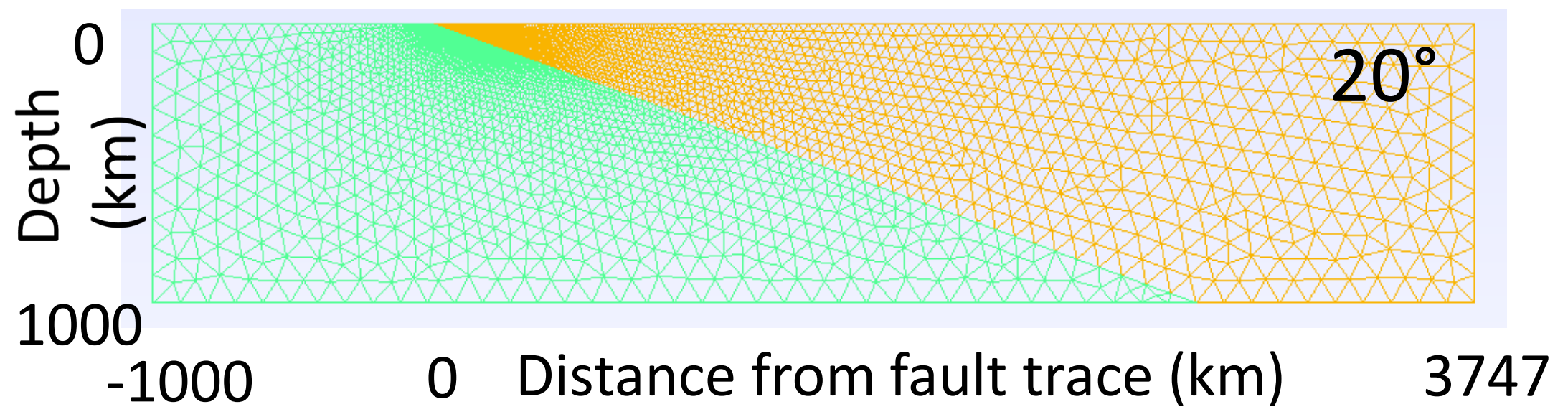


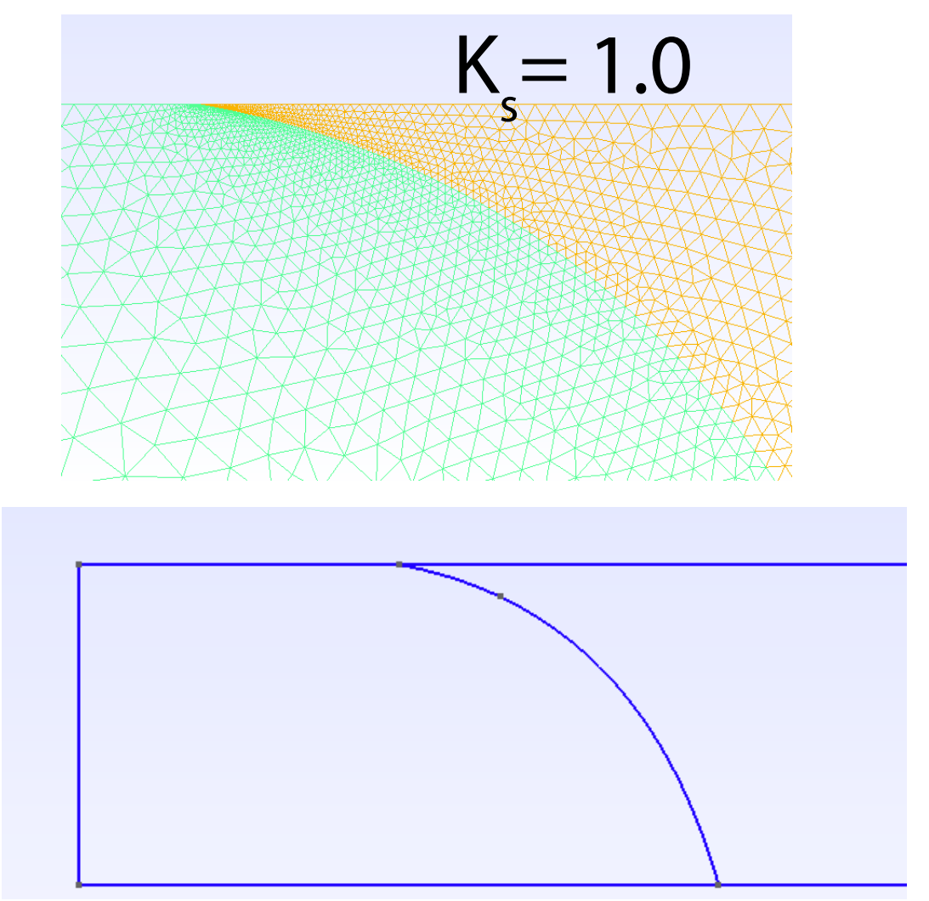
3D RIdgecrest fault geometry + mesh example



2D SEAS model of low-angle normal fault with four curved splay faults in its hanging wall

Earthquake Cycle Model Setups



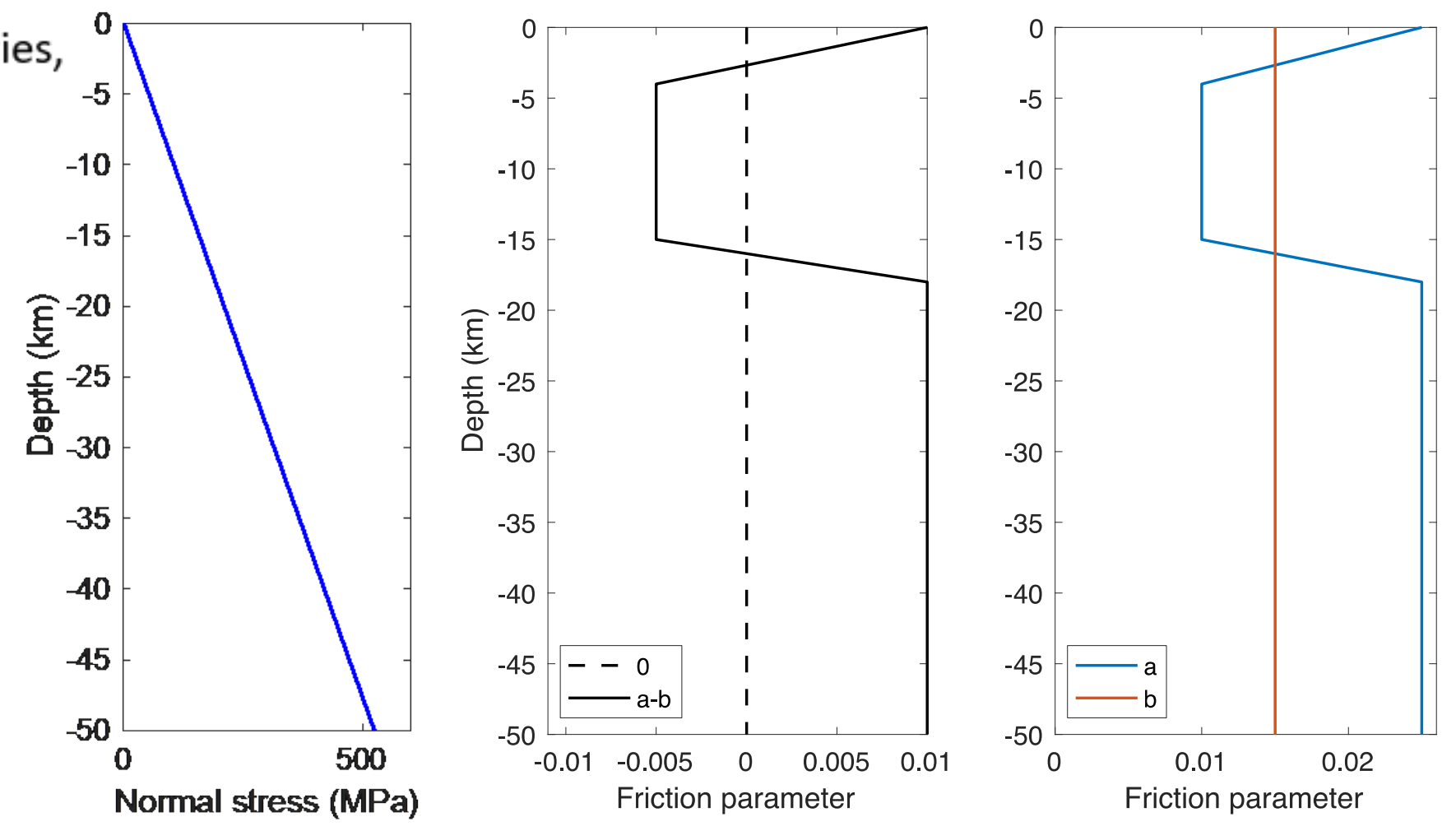


Planar models with dips (θ) ranging from 10 - 50°

Curved models with curvatures (K_s) ranging from 0.5 - 4.0 (x 1000 km^{-1}): $z = K_s x^2$

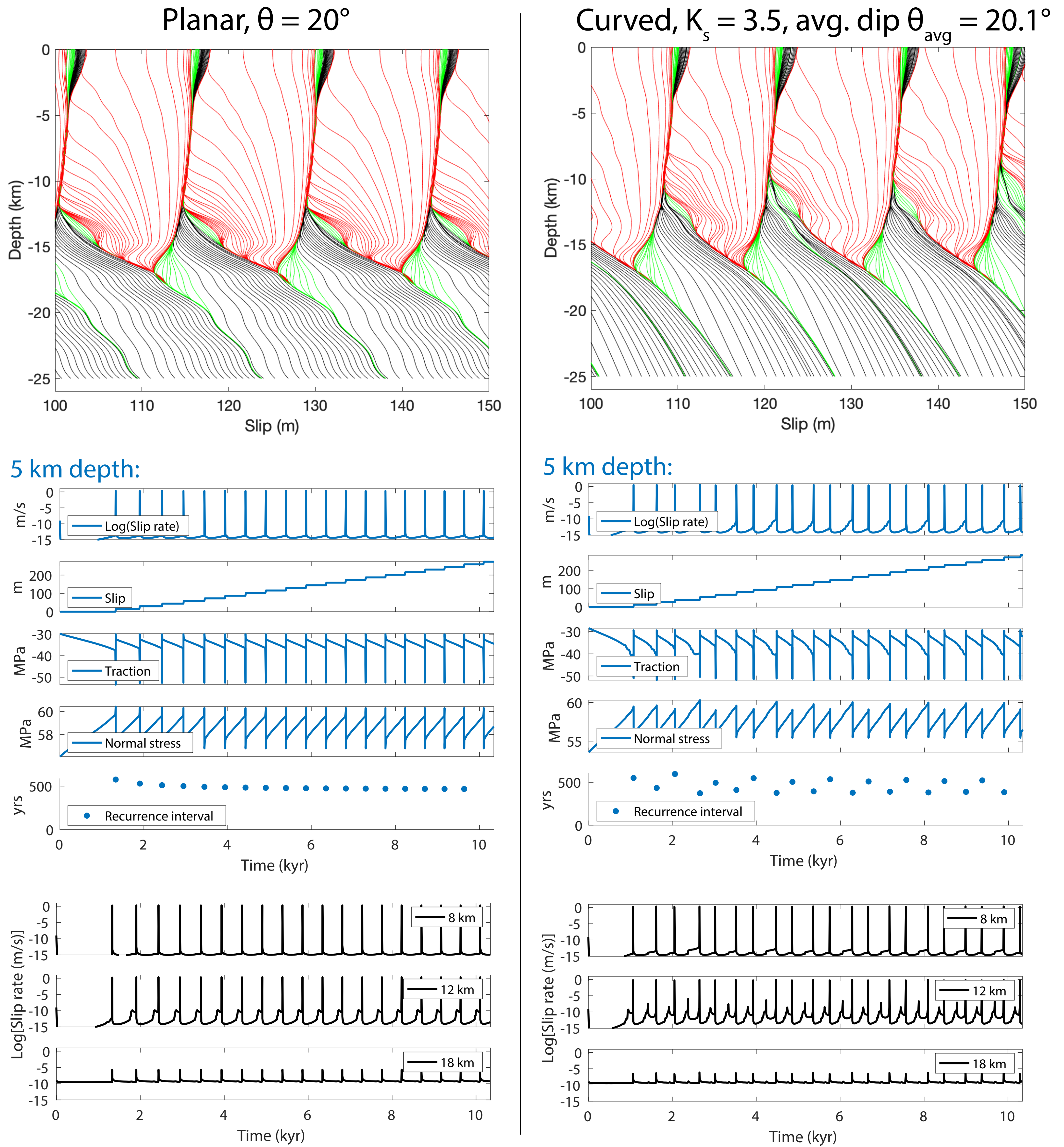
Parameters & loading conditions:

Loading: symmetric far-field convergence at left and right boundaries, summing to plate rate V_p = 3.15 cm/yr
Free surface at top and bottom boundaries
Bulk mechanical properties:
Shear modulus, G = 32 GPa
Poisson's ratio, $\nu = 0.25$
Density, ρ = 2.67 g/cc
Fault friction- ageing law with:
Reference velocity, $V_0 = 10^{-6}$ m/s
Steady state friction coefficient at V_0, $f_0 = 0.6$
Characteristic slip distance, d_c = 5 cm
Initial normal stress, $\sigma_n{}^i = \rho g z(1-\lambda_{pf}) + \sigma_n{}^0$, with
Pore pressure ratio $\lambda_{pf} = P_f / \rho g z = 0.6$
Initial background normal stress, $\sigma_n{}^0$ = 1 MPa



Reference Model Outputs

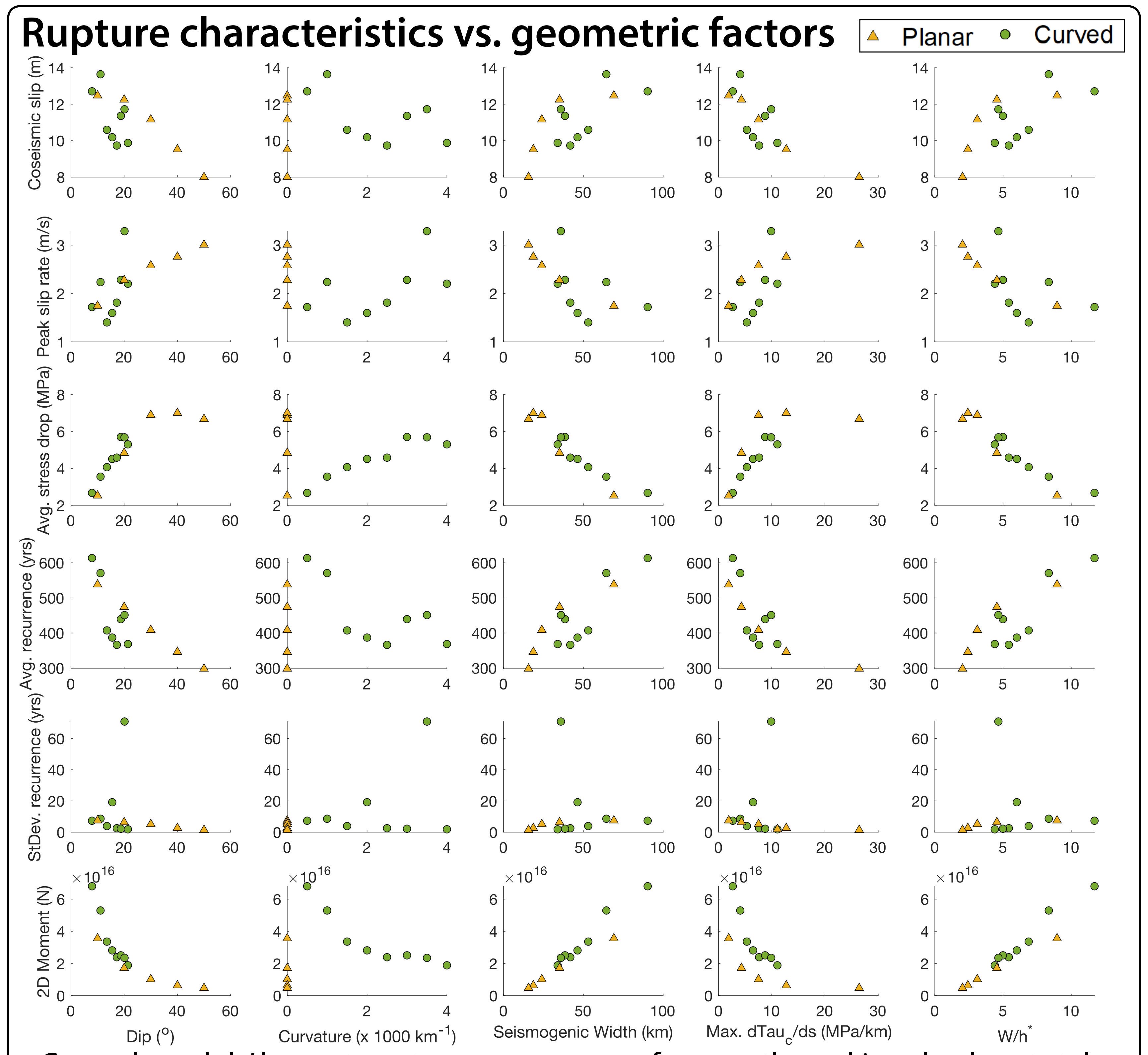
Cumulative slip contours colored by instantaneous maximum slip velocity, V_{max}
$V_{max} > 0.01$ m/s $10^{-8} < V_{max} < 0.01$ m/s $V_{max} < 10^{-8}$ m/s



- Planar models host uniform, large, periodic events that rupture the entire seismogenic zone, which remains strongly locked interseismically
- Curved models host a wider spectrum of slow-to-fast slip events with more variable slip behaviors & recurrence (e.g., slow-slip events, bimodal earthquakes)

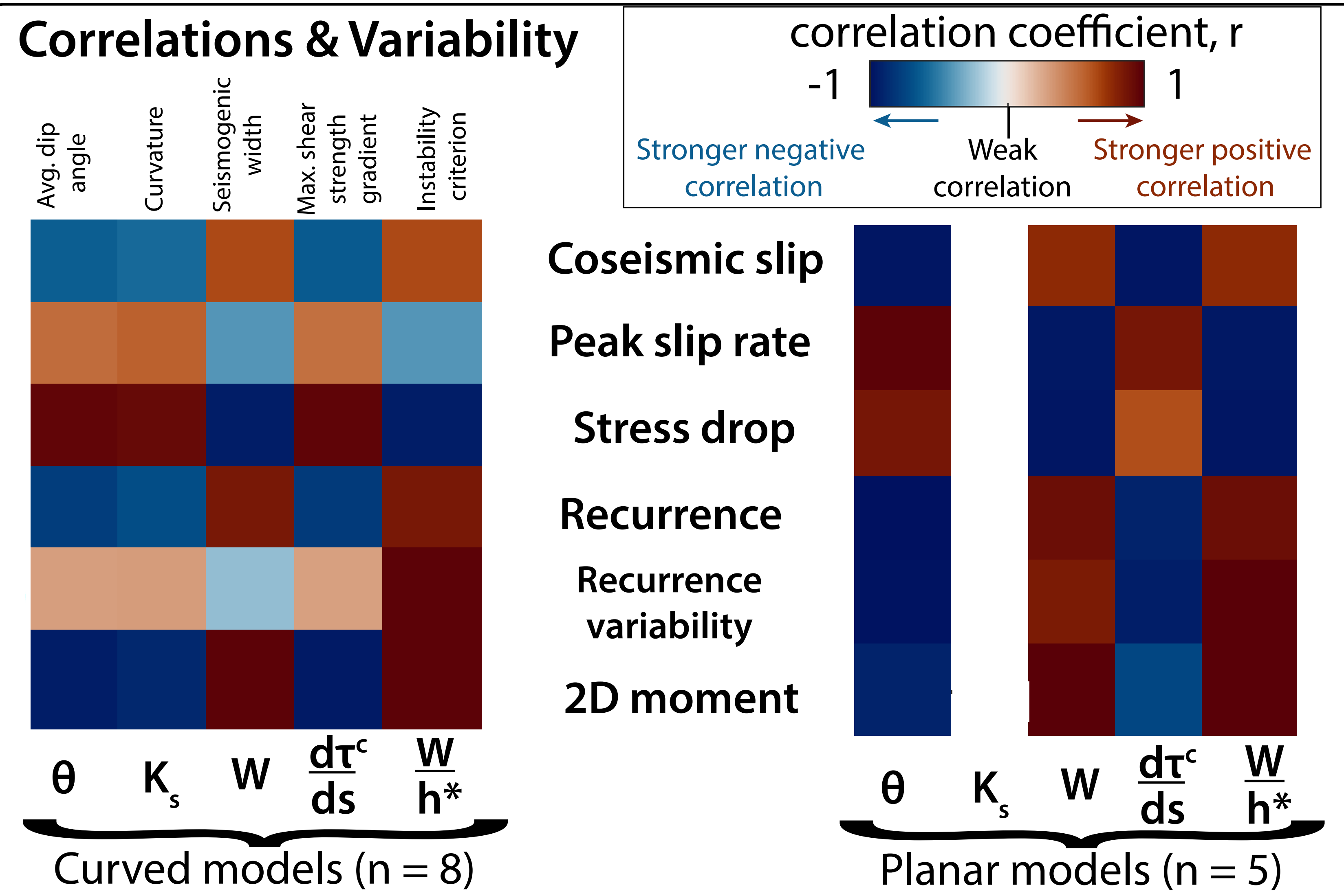
Bletery, Q., Thomas, A. M., Rempel, A. W., Karlstrom, L., Sladen, A., & de Barros, L. (2016). Mega-earthquakes rupture flat megathrusts. Science, 354(6315), 1027–1031.
Cattania, C., & Segall, P. (2021). Precursory Slow Slip and Foreshocks on Rough Faults. Journal of Geophysical Research: Solid Earth, 126(4), 1–20. https://doi.org/10.1029/2020JB020430
Liu, Y., & Rice, J. R. (2007). Spontaneous and triggered aseismic deformation transients in a subduction fault model. Journal of Geophysical Research: Solid Earth, 112(9).
Muldashev, I. A., & Sobolev, S. v. (2020). What Controls Maximum Magnitudes of Giant Subduction Earthquakes? Geochemistry, Geophysics, Geosystems, 21(9).
Oglesby, D. D., Archuleta, R. J., & Nielsen, S. B. (1998). Earthquakes on dipping faults: The effects of broken symmetry. Science, 280(5366), 1055–1059.
Romanet, P., Sato, D. S. K., & Ando, R. (2020). Curvature, a mechanical link between the geometrical complexities of a fault: Application to bends, kinks and rough faults. Geophyss J. Int., 223(1), 211–232.
Uphoff, C., May, D. A., & Gabriel, A.-A. (2022). A discontinuous Galerkin method for sequences of earthquakes and aseismic slip on multiple faults using unstructured curvilinear grids. Geophys. J. Int, 1–28.
Wirth, E. A., Sahakian, V. J., Wallace, L. M., & Melnick, D. (2022). The occurrence and hazards of great subduction zone earthquakes. Nature Reviews Earth and Environment, 3(2), 125–140.

Rupture characteristics vs. geometric factors



- Curved models' largest ruptures occur more frequently and involve less total slip than those in planar models with similar dips and seismogenic widths

Correlations & Variability



- Planar models exhibit overall stronger correlations between individual geometric properties and rupture characteristics than curved models

Key Preliminary Results + Initial Interpretations

- Simple geometric heterogeneity like slab curvature enhances rupture variability and introduces a wider array of slow-to-fast slip events
- Dip, seismogenic width, and slab curvature all correlate strongly with modeled rupture characteristics, but curved faults host more frequent and more variable ruptures with less total slip and slower peak slip rates
- We suggest that the downdip seismogenic width (which scales with avg. slab dip) determines the 'maximum' rupture a given megathrust can host, but slab curvature modulates rupture variability and limits how often this 'maximum magnitude' is achieved by increasing interseismic strength & stress variability on the fault (e.g., Bletery et al., 2016), leading to more frequent smaller partial ruptures