Probing low-angle normal fault earthquakes with data-driven dynamic rupture simulations

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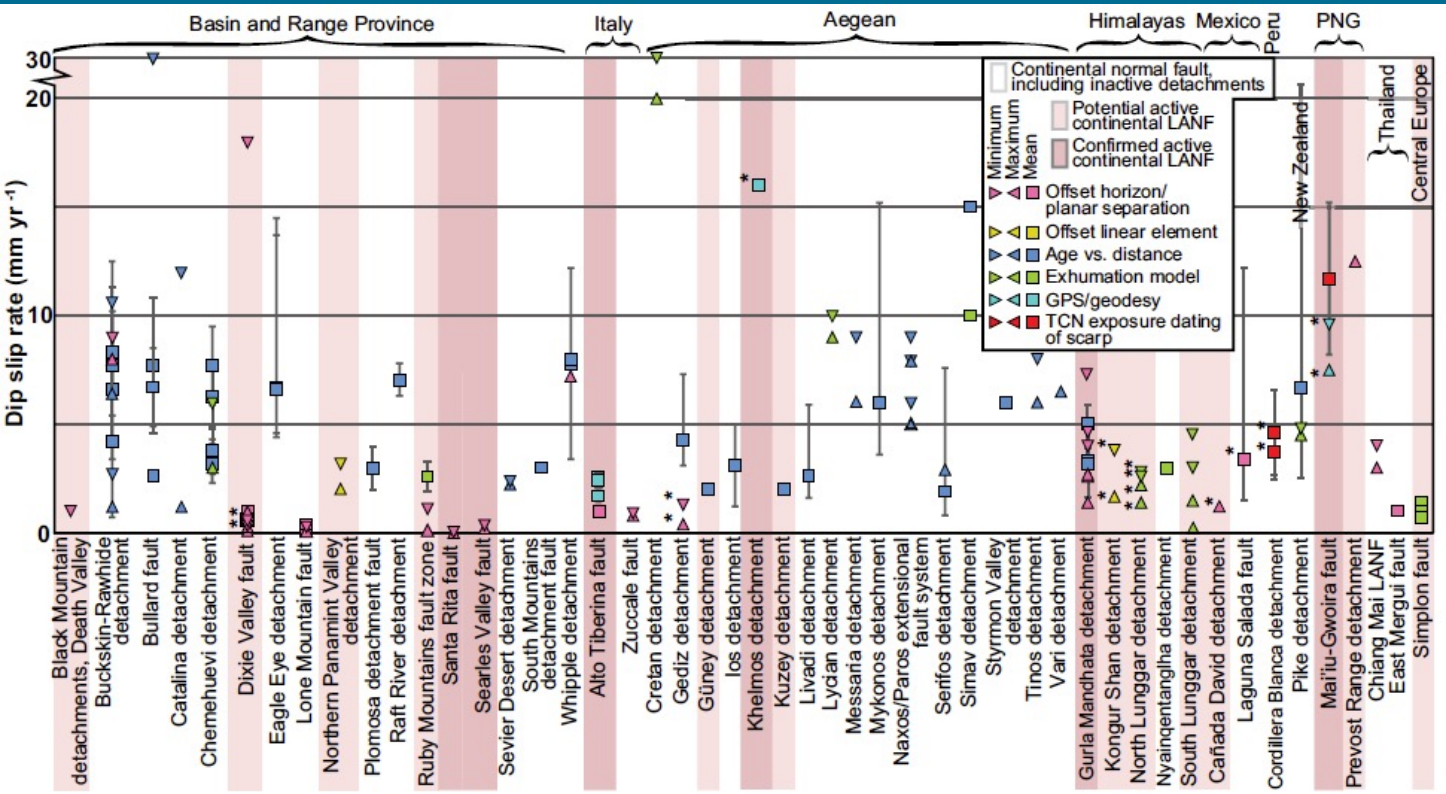
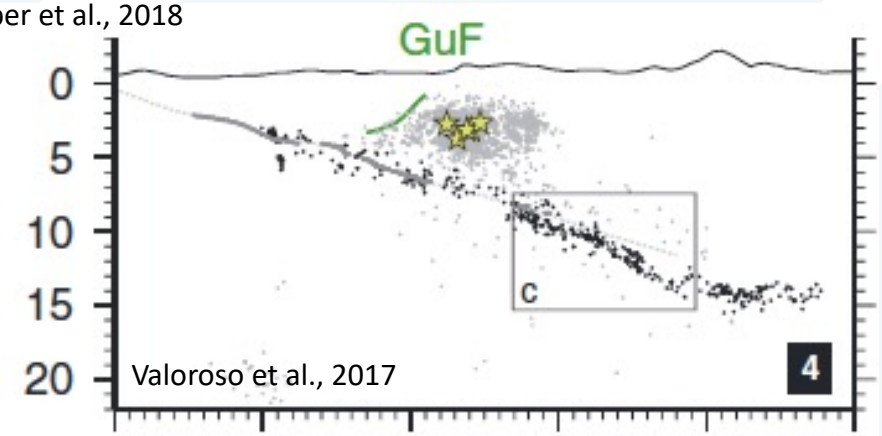
Anderson-Byerlee faulting and the low-angle normal fault ‘paradox’

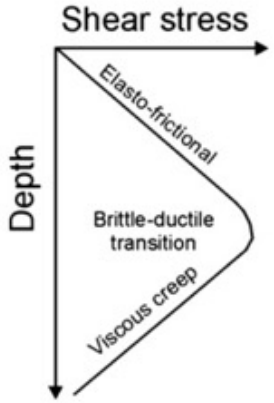


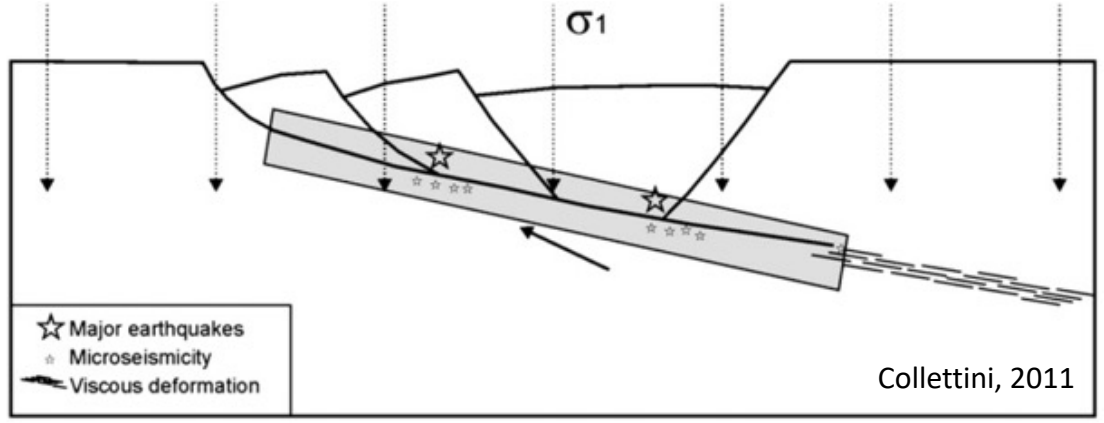
Webber et al., 2018

- Andersonian extension: maximum principal stress (σ_1) is vertical
- Byerlee (static) friction: $0.6 < \mu_s < 0.85$
- Apparent mechanical paradox: under these conditions, normal faults dipping < 30° should be severely misoriented for slip, and should be abandoned by new well-oriented normal faults
- But the geologic record is full of low-angle normal faults, and some remain demonstrably active



Valoroso et al., 2017





Collettini, 2011

Low-angle normal fault seismicity

Active low-angle normal faults are less common and typically slip <1 cm/yr

Microseismic, but few instrumentally recorded M_w 6.0+ earthquakes (and none > M_w 7.0): do these faults creep aseismically?

Yes, but recent seismic, geodetic, microstructural and paleoseismic observations suggest they also slip in large (M_w > 7.0) earthquakes

Active low-angle normal faults appear to host large, potentially hazardous earthquakes, but we know (relatively) little about them:

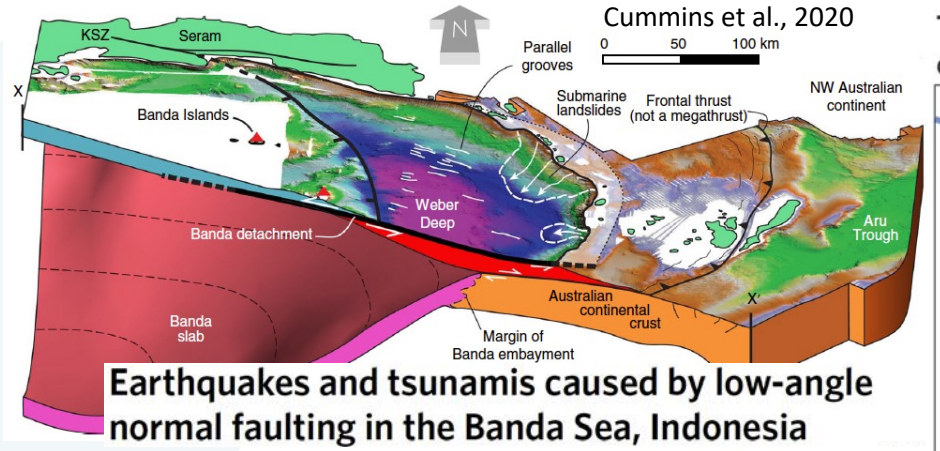
Under what conditions are large low-angle normal fault ruptures dynamically viable?

Do they require favorably inclined principal stresses?

Can they rupture to the surface?

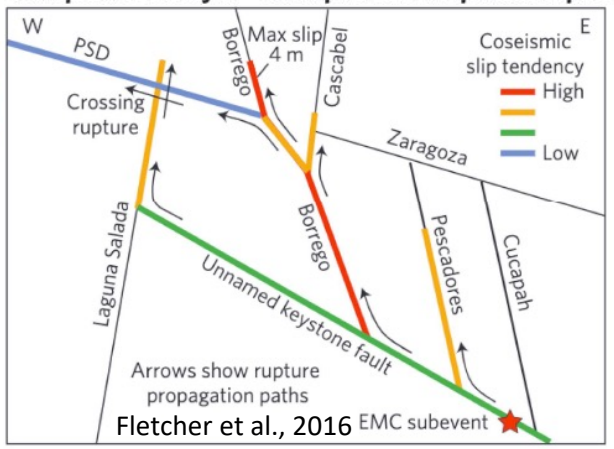
How do these ruptures interact with splay faults?

Can dynamic rupture modeling help answer some of these questions?



Cummins et al., 2020

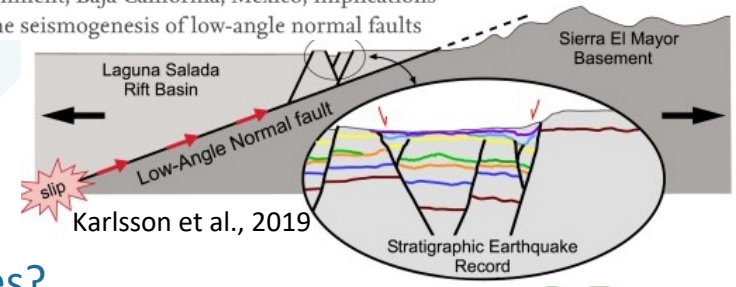
Earthquakes and tsunamis caused by low-angle normal faulting in the Banda Sea, Indonesia



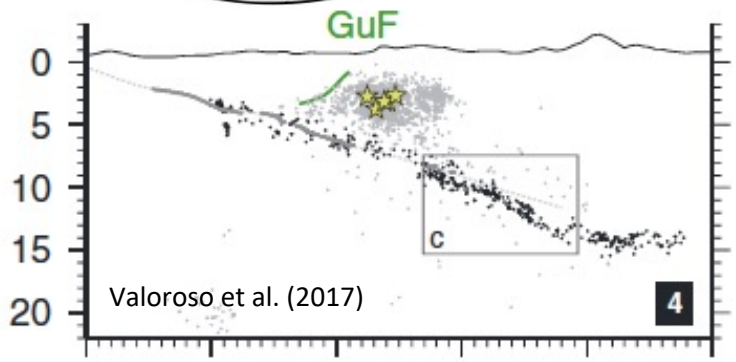
The role of a keystone fault in triggering the complex El Mayor–Cucapah earthquake rupture

Fletcher et al., 2016

Large Holocene ruptures on the Cañada David detachment, Baja California, Mexico; implications for the seismogenesis of low-angle normal faults



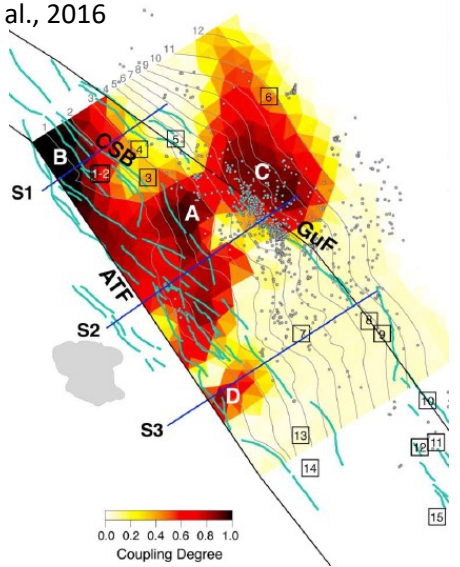
Karlsson et al., 2019



Valoroso et al. (2017)

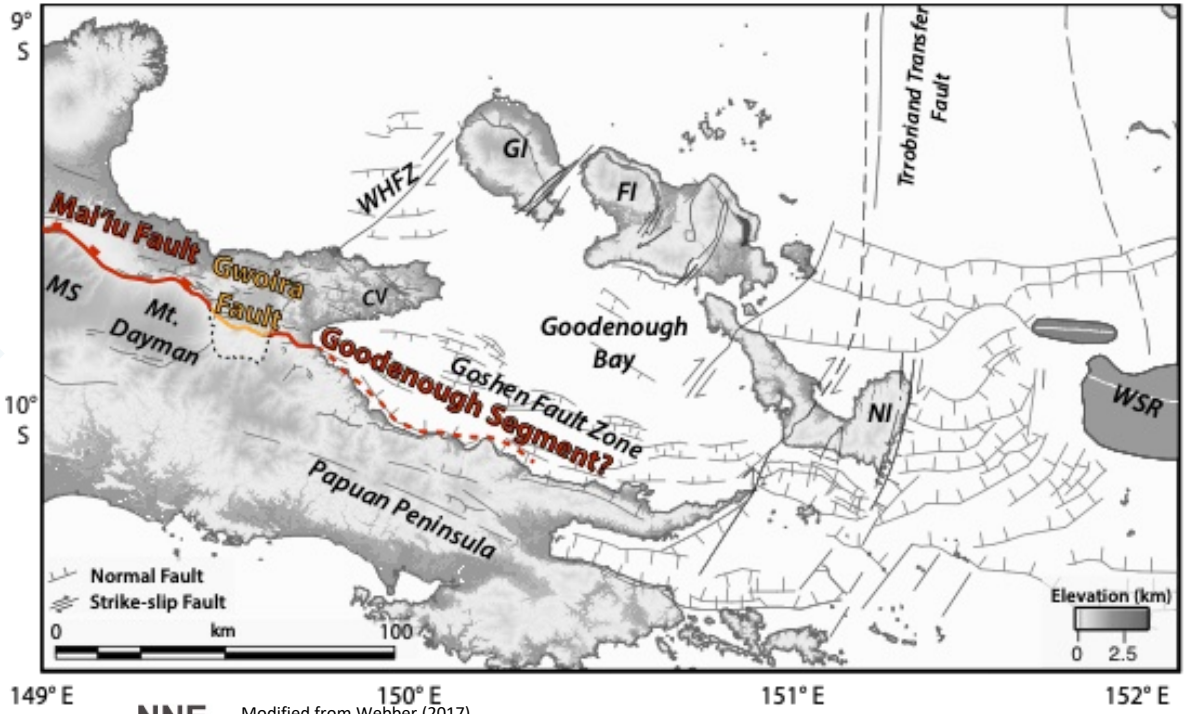
Creep and locking of a low-angle normal fault: Insights from the Altotiberina fault in the Northern Apennines (Italy)

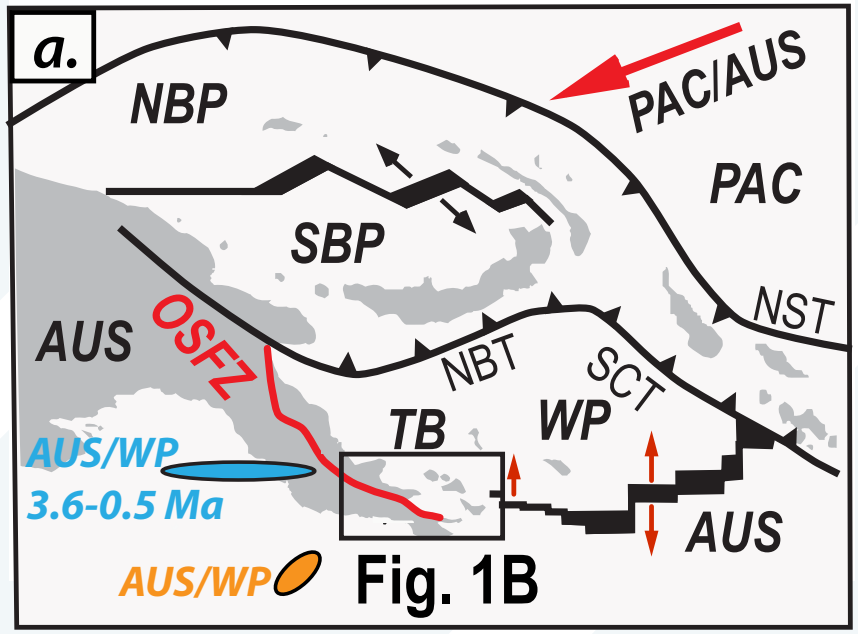
Anderlini et al., 2016

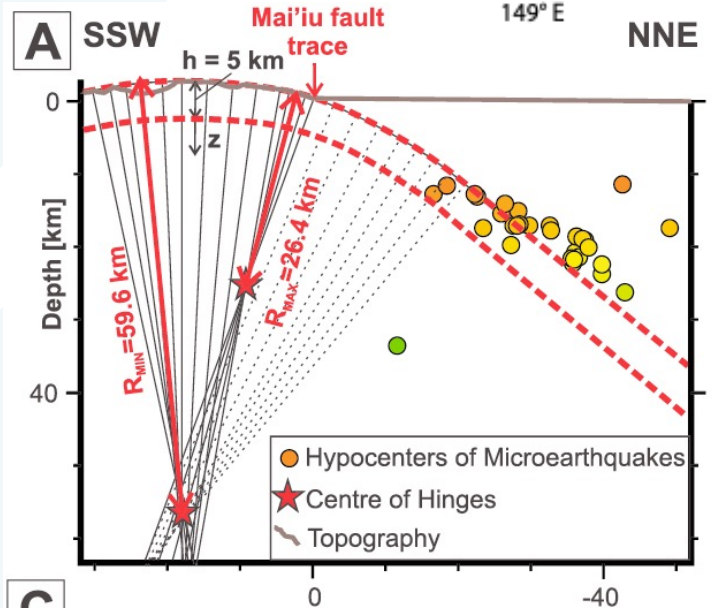


The Woodlark rift & the Mai'iu fault

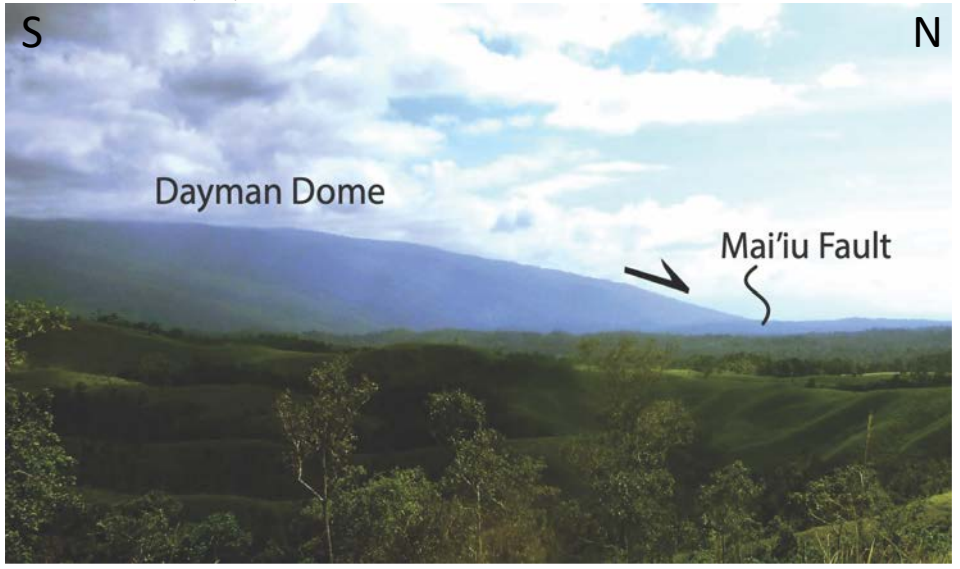
- Within the E-W transition from seafloor spreading to continental rifting, extension localizes on the Mai'iu fault
- Dips 16-24° at the surface where it exhumes the corrugated domal Dayman-Suckling core complex
- Structural and geomorphic record of footwall rotation of up to 42-52° confirms rolling-hinge exhumation, consistent with concave-down fault steepening to dip 30-40° at depths of ~15-25 km as indicated by subplanar-aligned microseismicity
- Geodetic (GPS) + geologic (^{10}Be) dip-slip rates of ~8-10 mm/yr



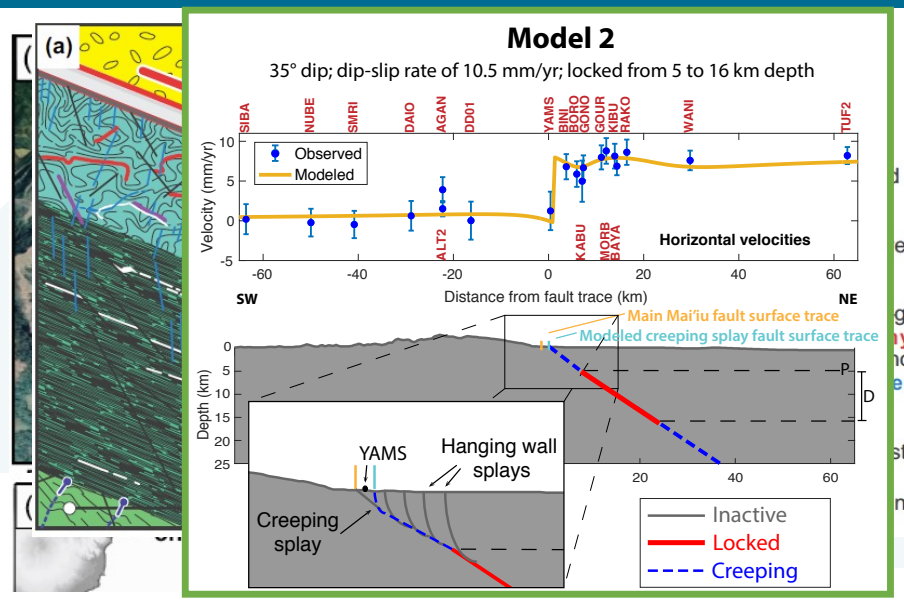


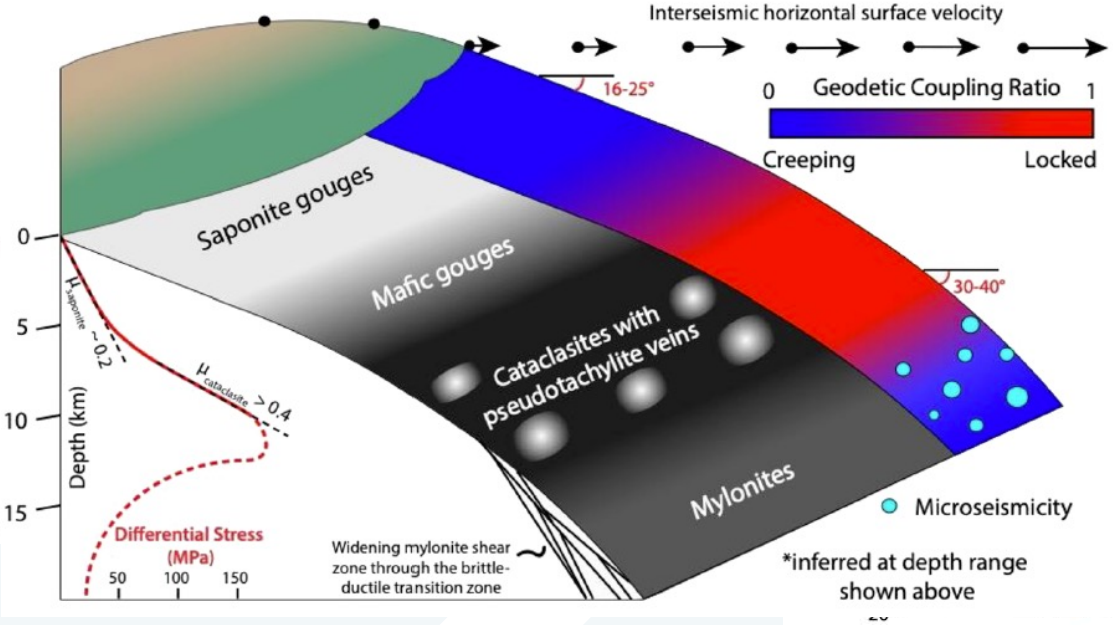


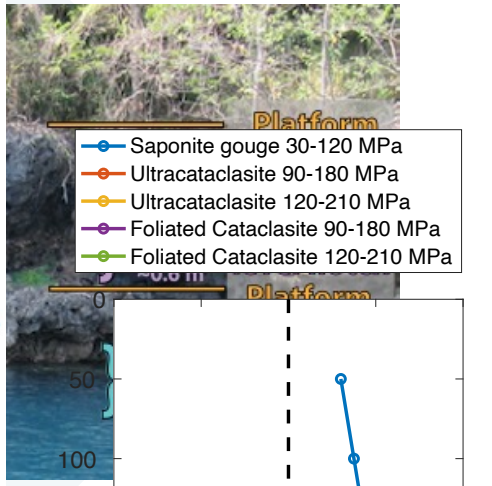
Modified from Webber (2017)

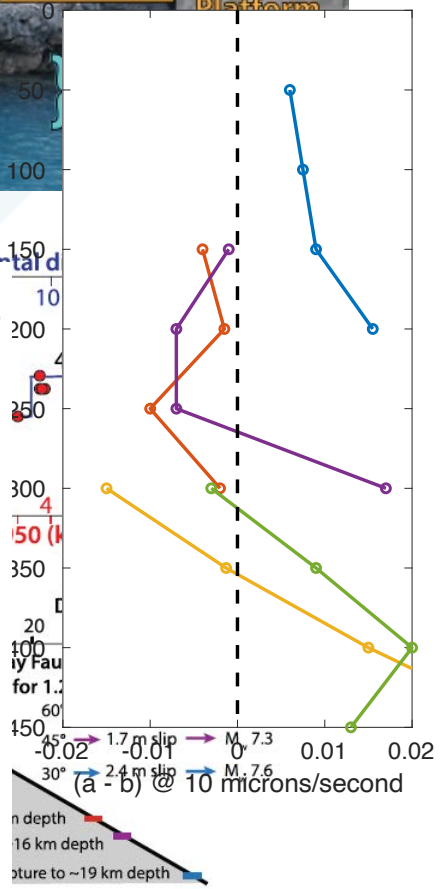


Summary: the Mai'iu fault hosts infrequent large earthquakes





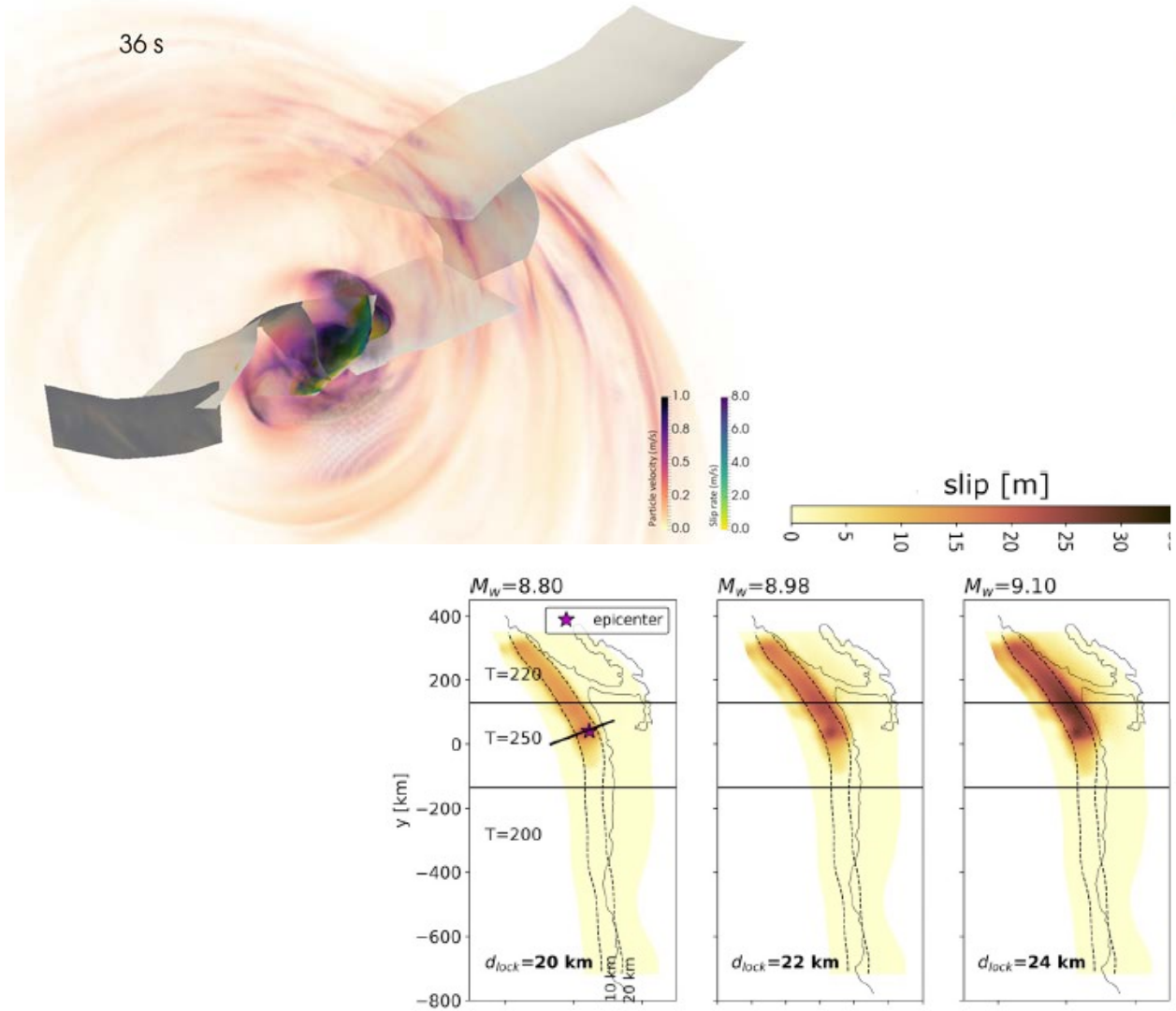




- Rapidly emerged meter-scale Holocene coral platforms consistent with M_w ~7.1-7.6 events with recurrence intervals of 482 – 1590 yrs
- Exhumed fault rocks contain pseudotachylites formed at depths of ~10-12 km based on $^{40}Ar/^{39}Ar$ dating
- Pseudotachylite-bearing cataclastic fault rocks are strong ($\mu > 0.6$) and velocity-weakening (-.0015 < a-b < 0) at P-T conditions equivalent to ~7-15 km depth (vs. weak, v-strengthening gouges above ~5 km)
- Geodetic coupling models suggest strong interseismic locking from ~5-15 km depth; microseismicity suggests creep below ~15 km

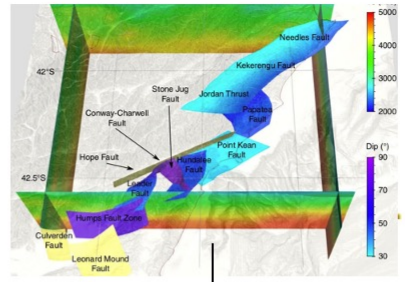
Data-fused dynamic rupture modelling (of recently quiet faults)

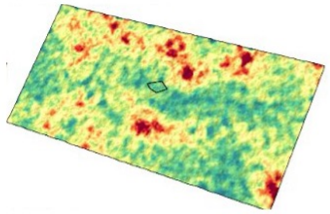
- Physics-based: simulate spontaneous dynamic earthquake rupture by simultaneously solving for frictional fault failure and seismic wave generation + propagation
- Goal: overcome observational limitations in a self-consistent, dynamically viable manner using geologic, geodetic, geophysics & experimental friction data



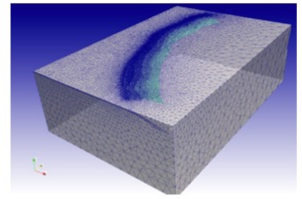
Geology

Adapted from Harris et al., SRL 2011, 2018

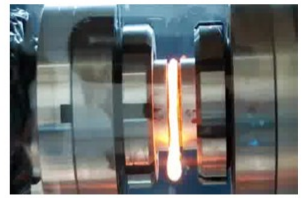




Initial fault stresses



Mesh generation

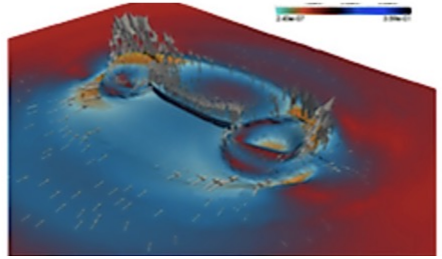


Friction experiments

"Input"

SeisSol

Ground deformation



"Output"

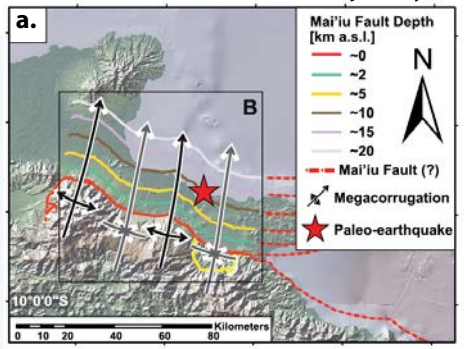
Synthetic observables

Data-constrained models (dynamic rupture, SEAS, etc.) can help untangle inter-,co-, and postseismic mechanics of seismogenic faults with limited instrumental records of large earthquakes (e.g., Cascadia)

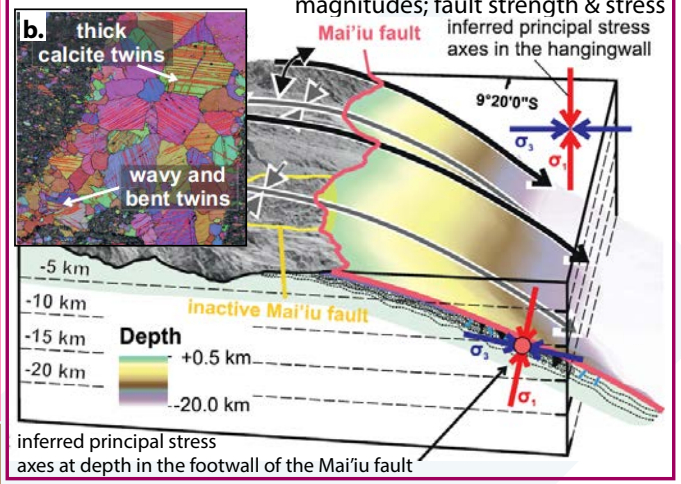
Ramos et al., 2021

Geologic & geophysical constraints on dynamic rupture model parameters

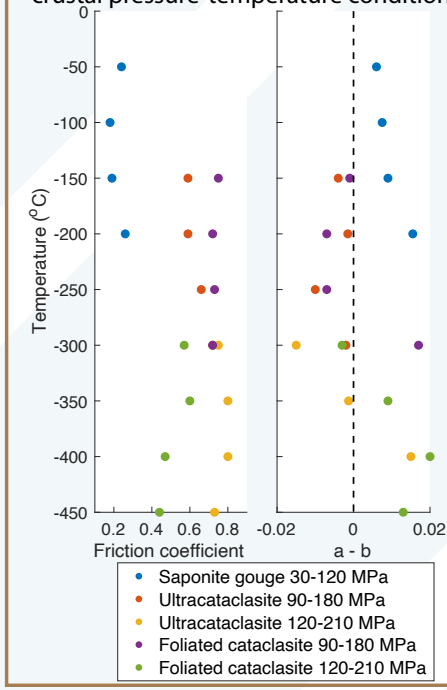
Field mapping & geomorphology: fault geometry; lithology; secular tectonic deformation & kinematic trajectory



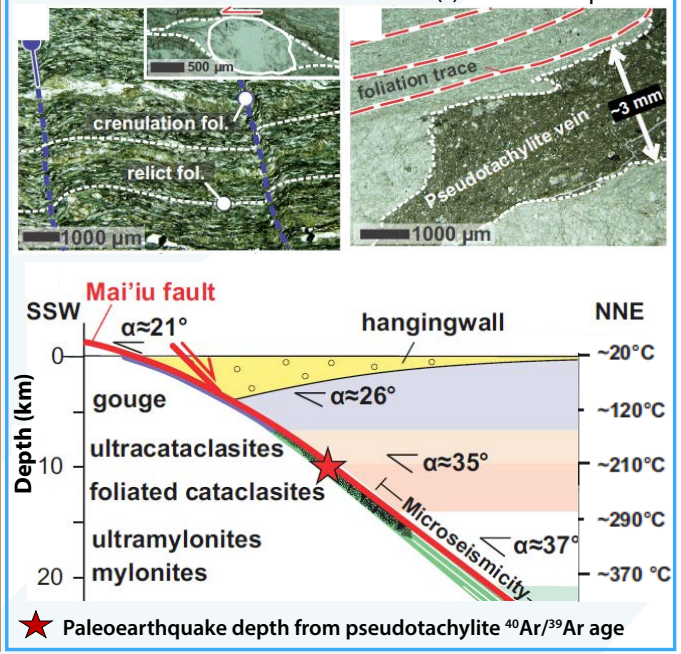
Calcite-twin paleopiezometry: principal stress orientations & magnitudes; fault strength & stress



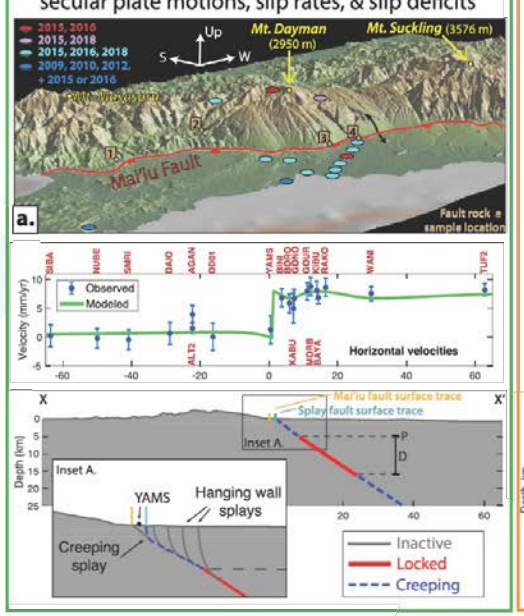
c. Velocity-stepping laboratory friction experiments on exhumed fault materials: fault frictional strength & stability at various crustal pressure-temperature conditions



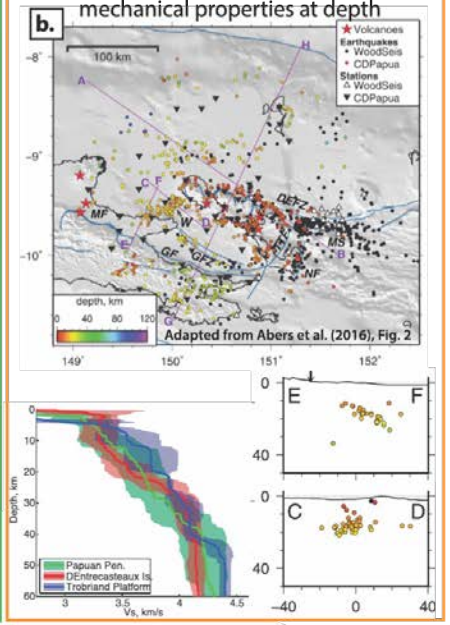
d. Microstructures + chlorite geothermometry + $^{40}Ar/^{39}Ar$ dating of exhumed fault rocks: fault deformation mechanism(s) active at depth



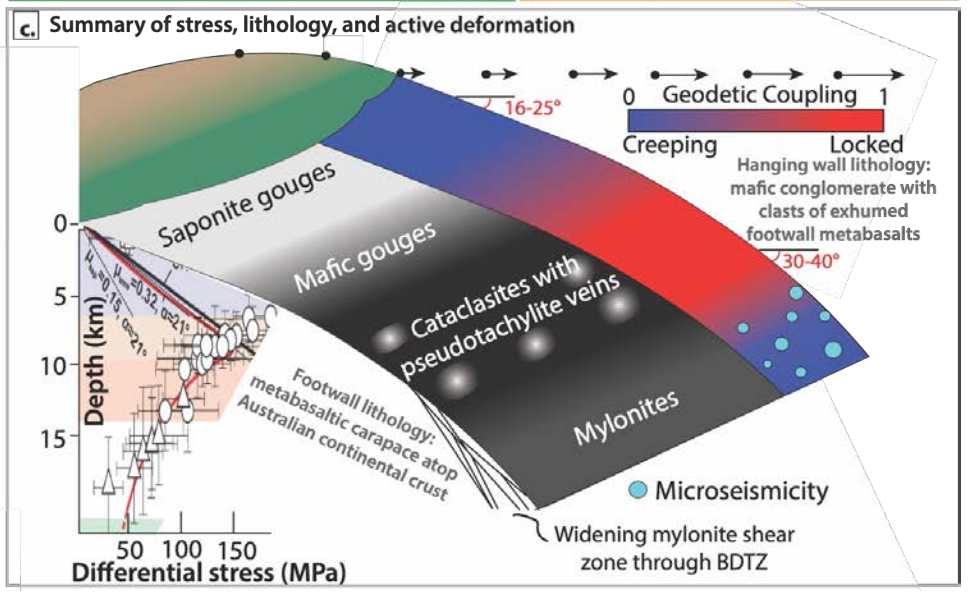
GNSS geodesy: interseismic deformation & locking; elastic strain & stress accumulation; secular plate motions, slip rates, & slip deficits



Microseismicity: fault geometry; active deformation mechanisms & patterns; mechanical properties at depth



c. Summary of stress, lithology, and active deformation



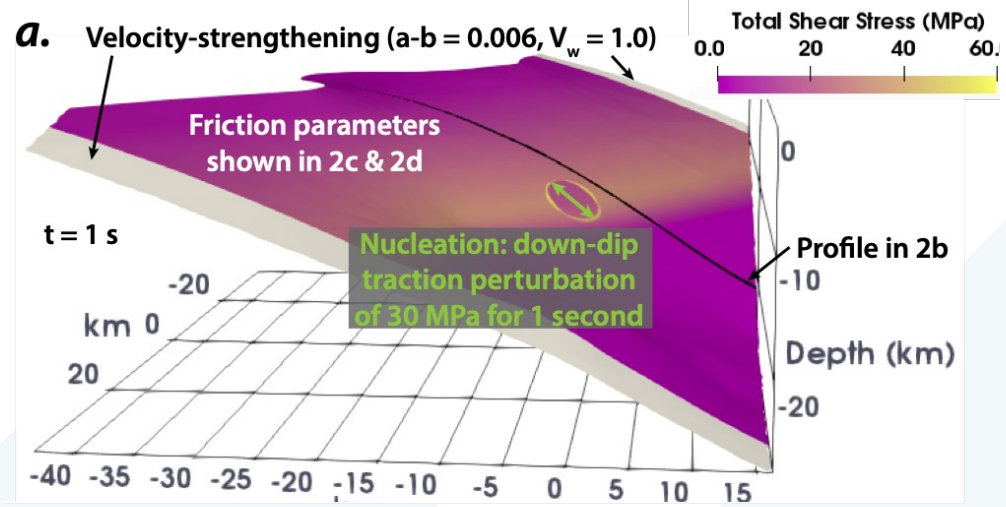
Model setup

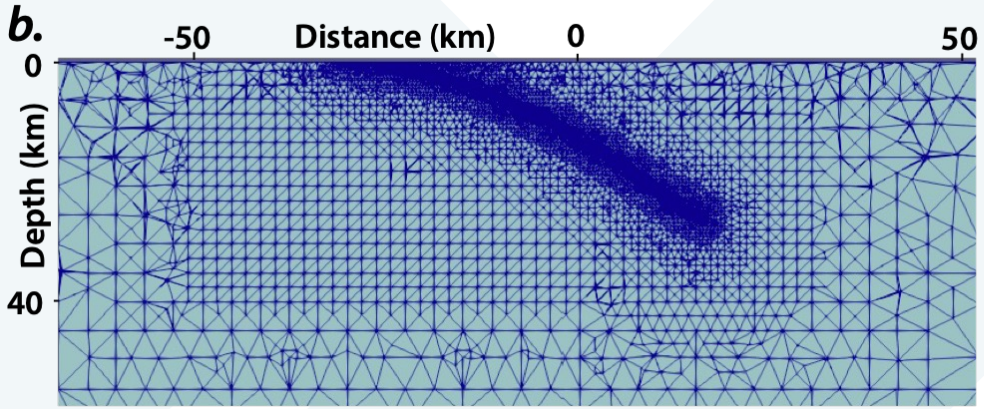
Fault geometry from Webber et al (2020)'s surface model based on field mapping and microseismicity

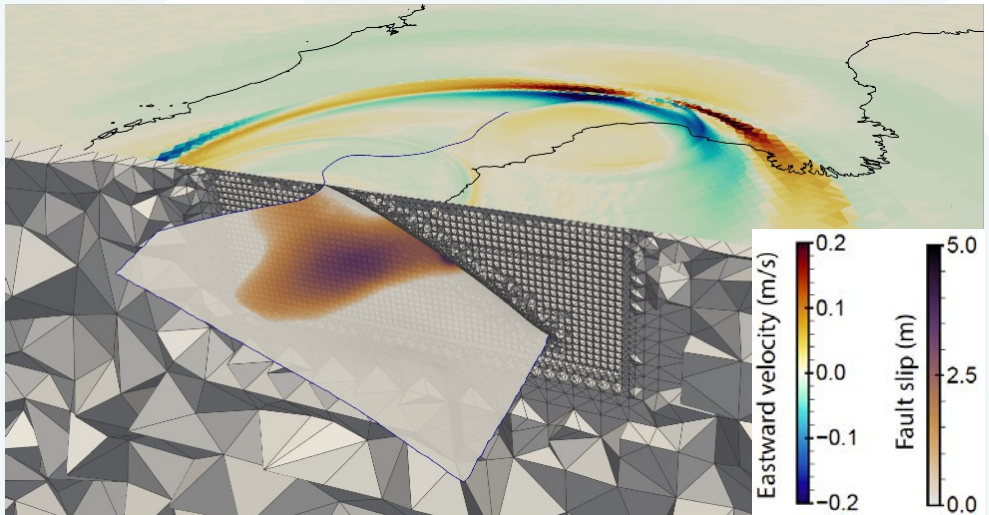
Depths of nucleation (11 km) & deviatoric stress decay (12-15 km) based on exhumed microstructures & peak footwall differential stress conditions from calcite twin paleopiezometry (Mizera et al., 2021), and depths of shallowest fault-related microseismicity

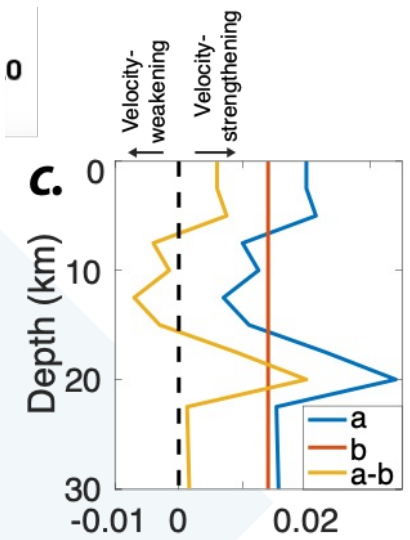
Density & elastic moduli from local Papuan Peninsula seismic velocity models of Abers et al. (2016)

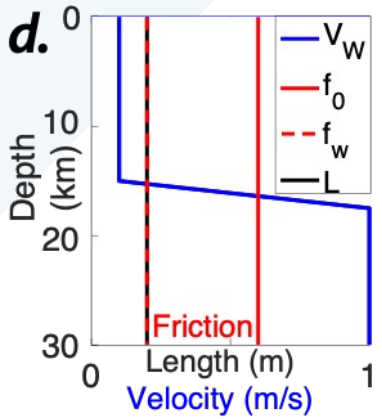
Depth-mapped rate-state frictional velocity-dependence (a-b) from laboratory friction experiments on exhumed Mai'iu fault materials

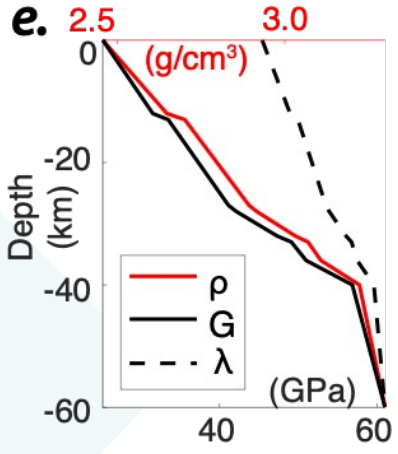






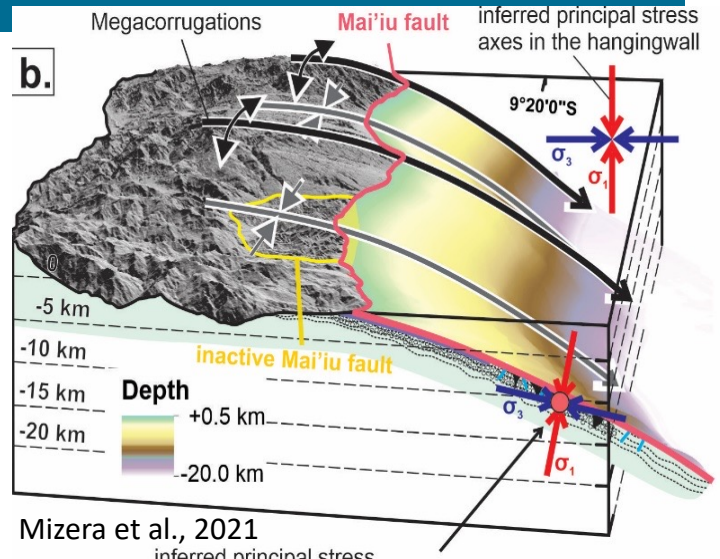






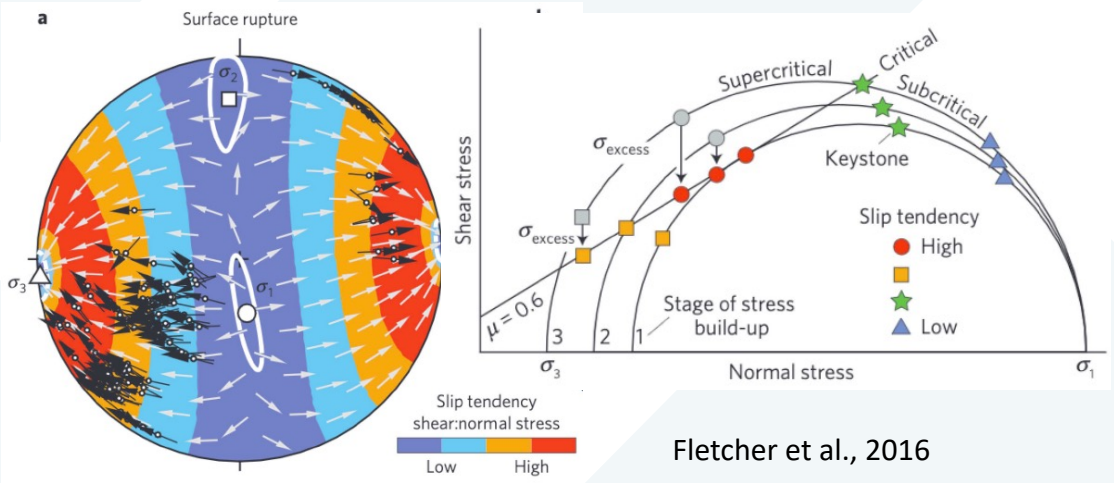
Stress: are low-angle normal faults actually misoriented for slip?

- Keystone fault hypothesis: misoriented detachments control seismic failure of neighboring & intersecting faults, as proposed for the El Mayor-Cucapah sequence
- Constraints on stresses on the Mai'iu fault: joint inversion of calcite twin paleopiezometric principal stress directions and mapped orientations of late brittle faults indicate constrictional state **with subvertical σ_1 ~= σ_2 > σ_3 , with σ_2 along-strike (~N60W) and σ_3 in the extension direction (~N30E)** (Mizera et al., 2021)
- Vertical σ_1 in the hanging wall, but σ_1 plunges 15-20° SSW in the footwall
- Reference model: Andersonian extension, as inferred in the hanging wall
- Alternatively, we also consider models where σ_1 plunges NE to be well-oriented for low-angle normal-sense slip, as reported for some detachments like the Whipple

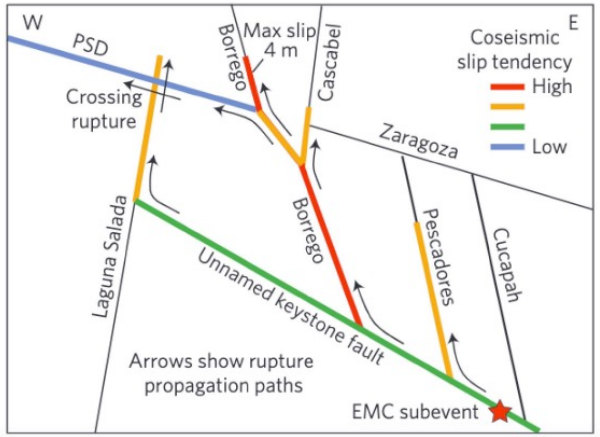


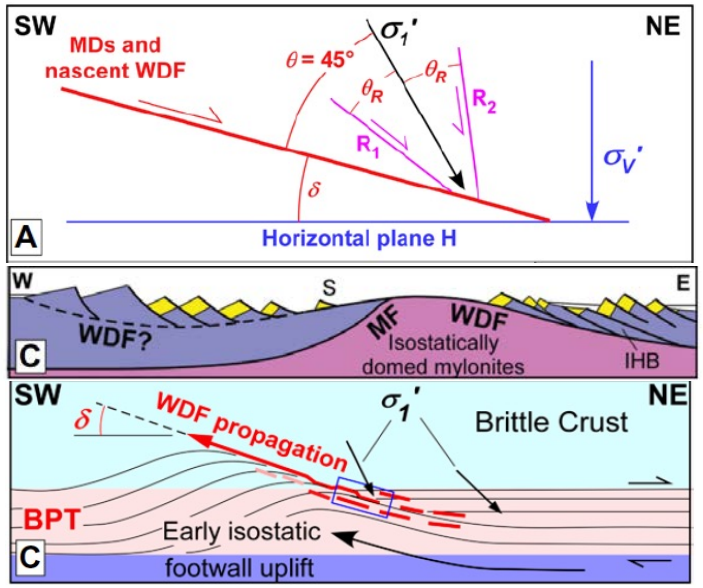
Mizera et al., 2021

inferred principal stress axes at depth in the footwall of the Mai'iu fault



Fletcher et al., 2016



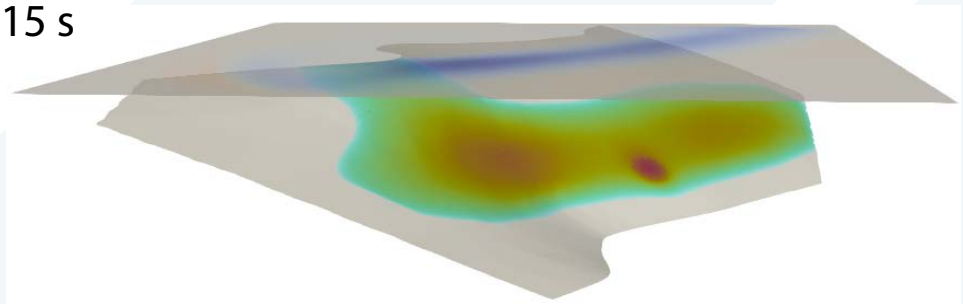


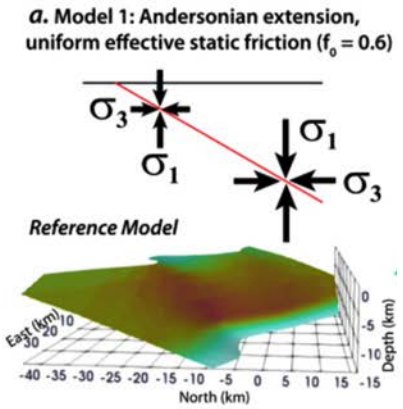
Axen, 2019

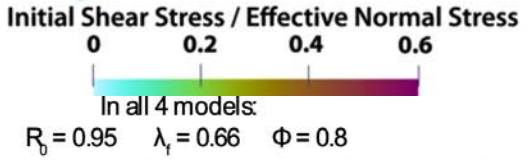
What is the state of stress around active, seismogenic low-angle normal faults?

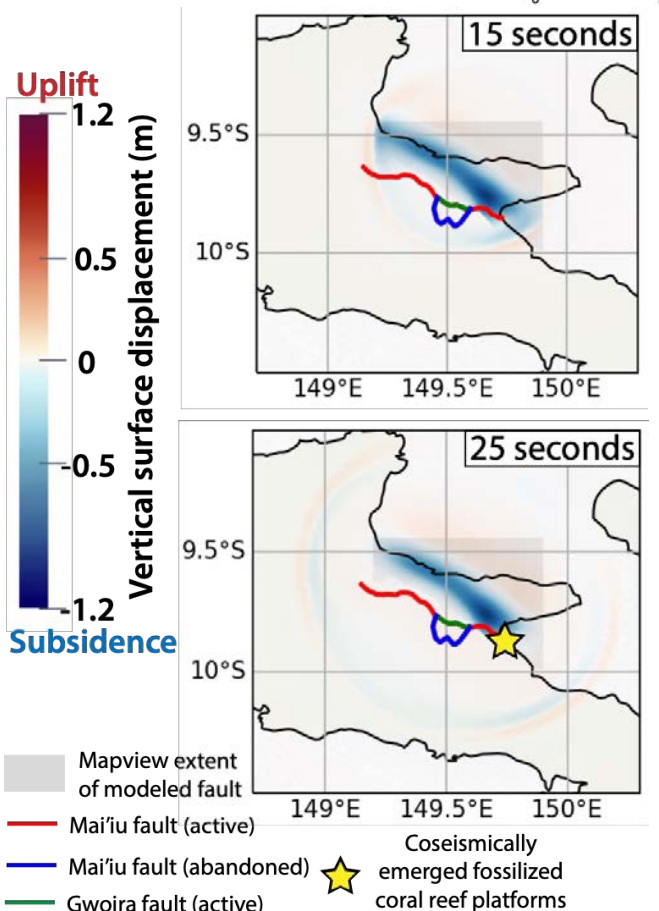
1) large low-angle normal fault earthquakes are **dynamically viable under various stress conditions including perfectly Andersonian extension** and without being interseismically critically stressed: ruptures do not require inclined non-Andersonian principal stresses

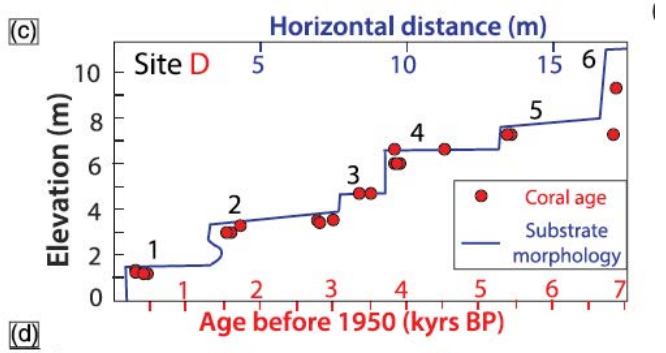
2) Surface rupture is possible in the largest events, but the **stabilizing effects of velocity-strengthening gouges, gentler dips, and dip-dependent dynamic stress interactions with the free surface impede shallow slip**

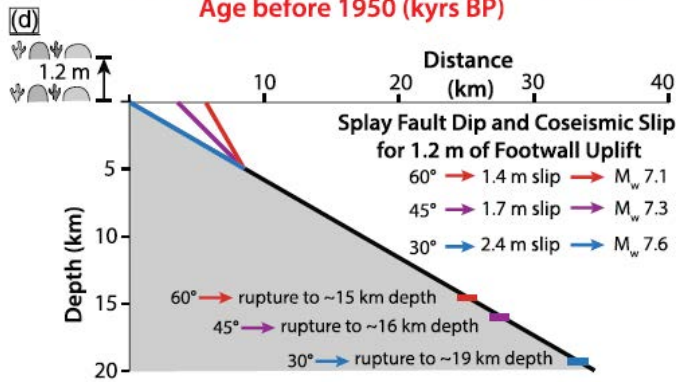






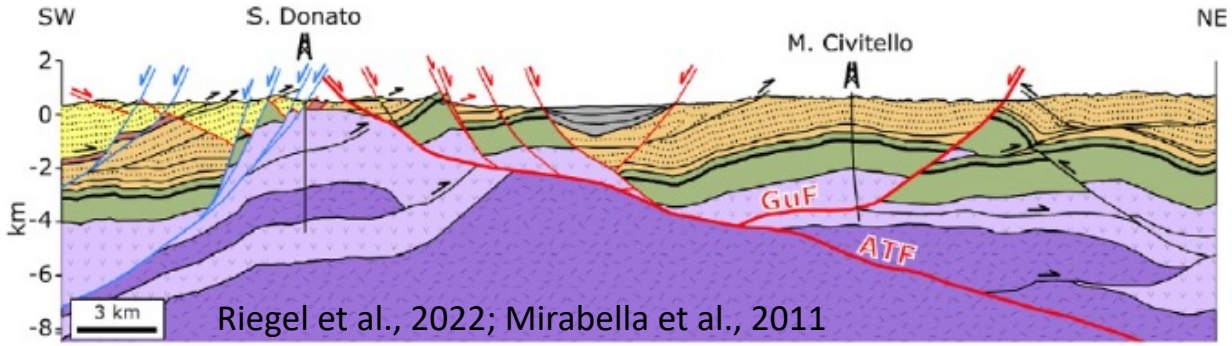




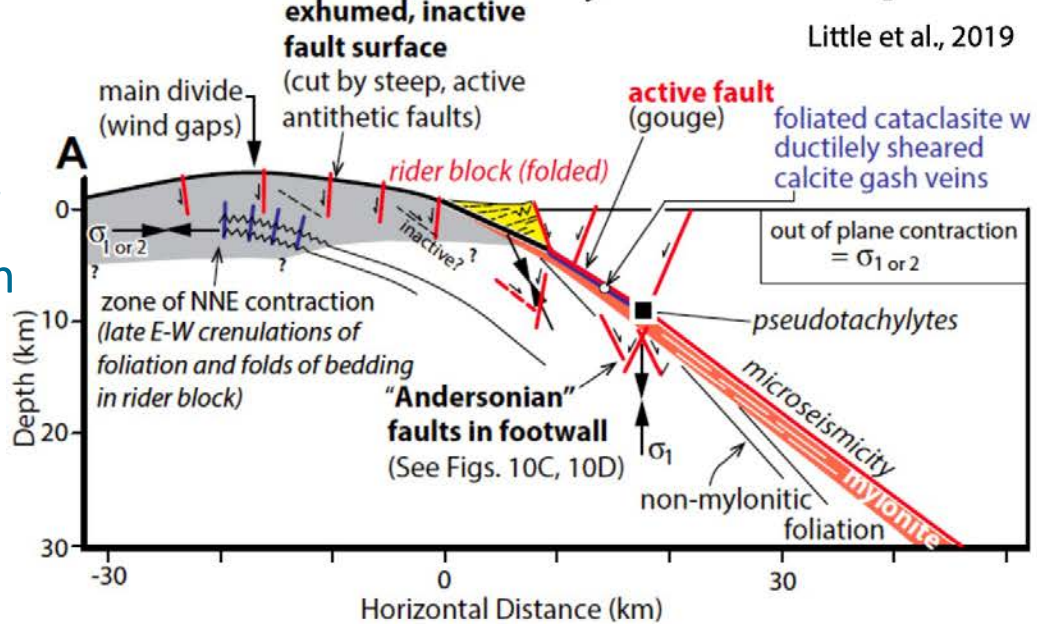


How do splay fault slip and off-fault damage interact with large low-angle normal fault ruptures?

Steeper **splay faults** are common in the hanging walls of active detachments, but their coseismic behavior is unknown

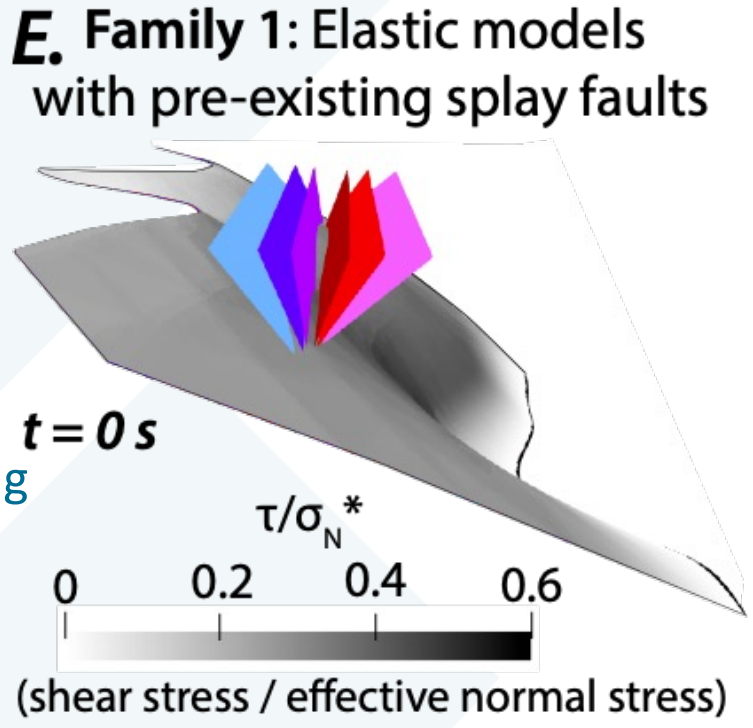


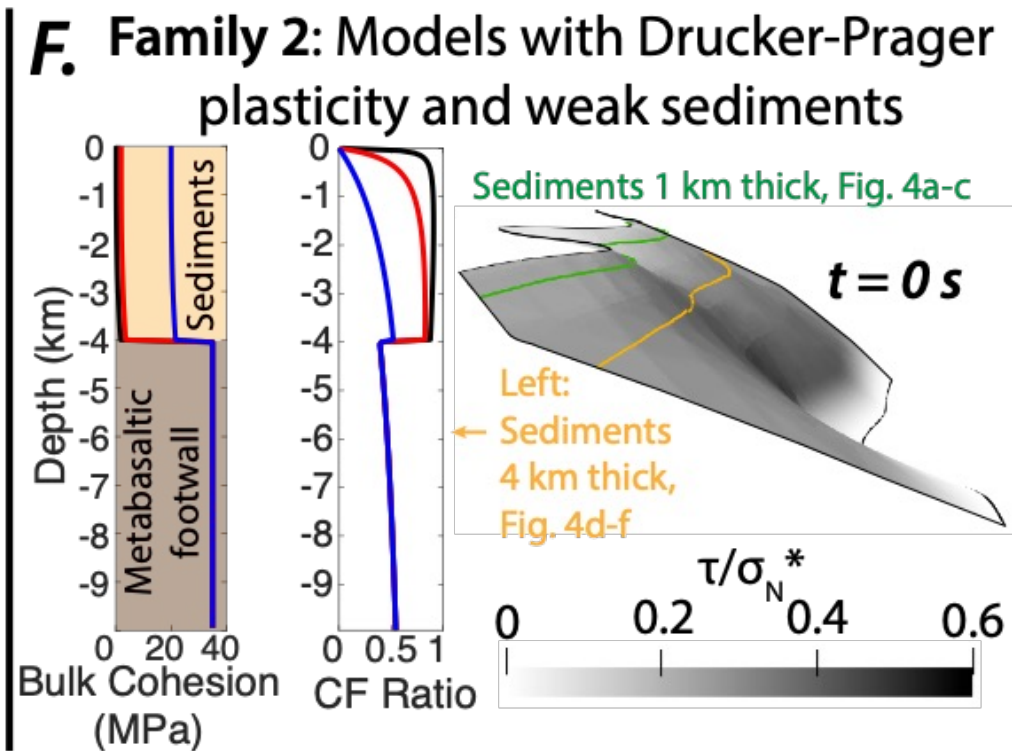
Riegel et al., 2022; Mirabella et al., 2011



Field & geodetic mapping show **inelastic off-fault damage** is an important shallow deformation mechanism in large earthquakes in other tectonic settings, but its role in low-angle normal fault ruptures is unresolved

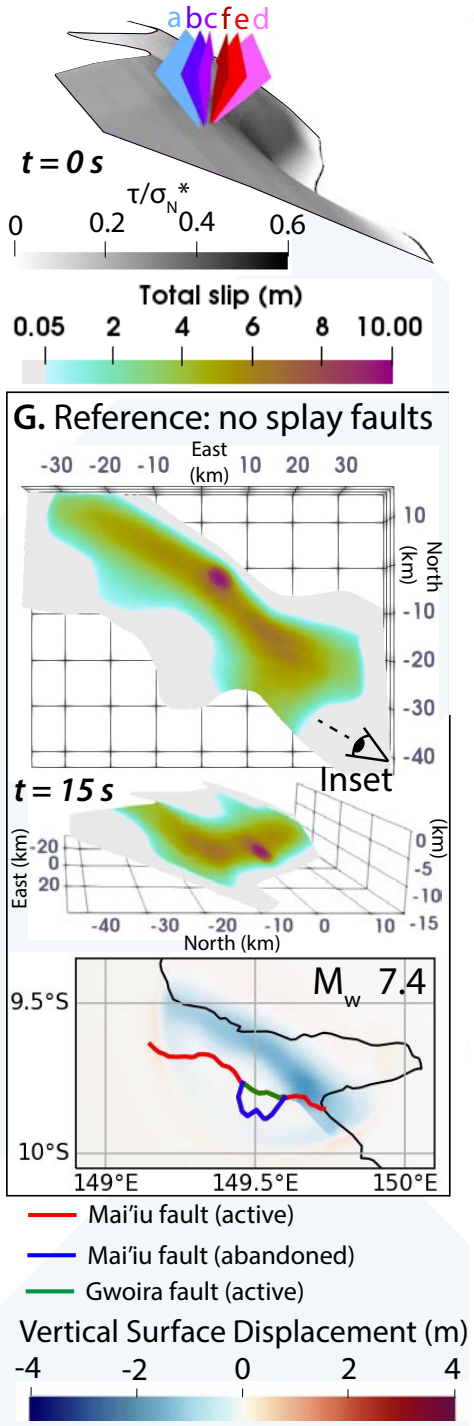
We analyzed targeted dynamic rupture simulations with pre-existing splay faults and/or non-linear Drucker-Prager plasticity to explore these mechanisms and dynamic interactions between them during low-angle normal fault ruptures





How does splay fault geometry influence coseismic reactivation tendency, shallow deformation, and surface displacements?

- Splay slip limits shallow detachment slip, enhances & localizes subsidence
- **Synthetic shallowly-dipping** splays host more slip, more effectively limit shallow slip on the main fault, and more strongly enhance/localize subsidence than antithetic and steeply-dipping ones



What controls the distribution and magnitude of off-fault plastic damage?

Bulk cohesion $C(z)$:

Sediments:

$$C(z) = C_0 + C_1(z)\sigma_c'$$

$$\sigma_c' = \sigma_c - P_f$$

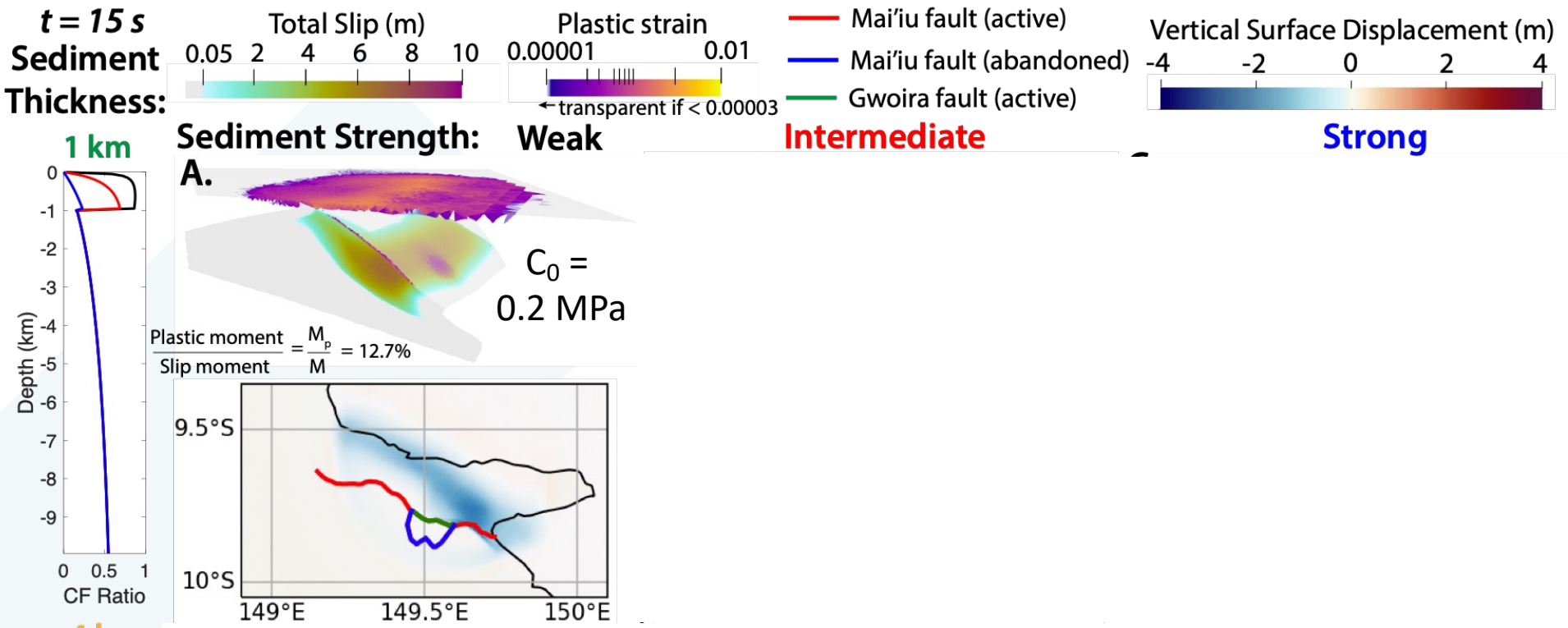
Otherwise: $C(z) = 35$ MPa

CF: closeness to failure

$$CF = \frac{\sqrt{I_2}}{\tau_c}$$

Plastic deformation in the hanging wall reduces shallow detachment slip and localizes + enhances subsidence, particularly in **weak, thick** sedimentary basins

Shallow inelastic yielding is widely distributed, but includes localized subplanar plastic shear bands, suggesting new coseismically initiated splay faults (dip ~60°)



Summary & Conclusions

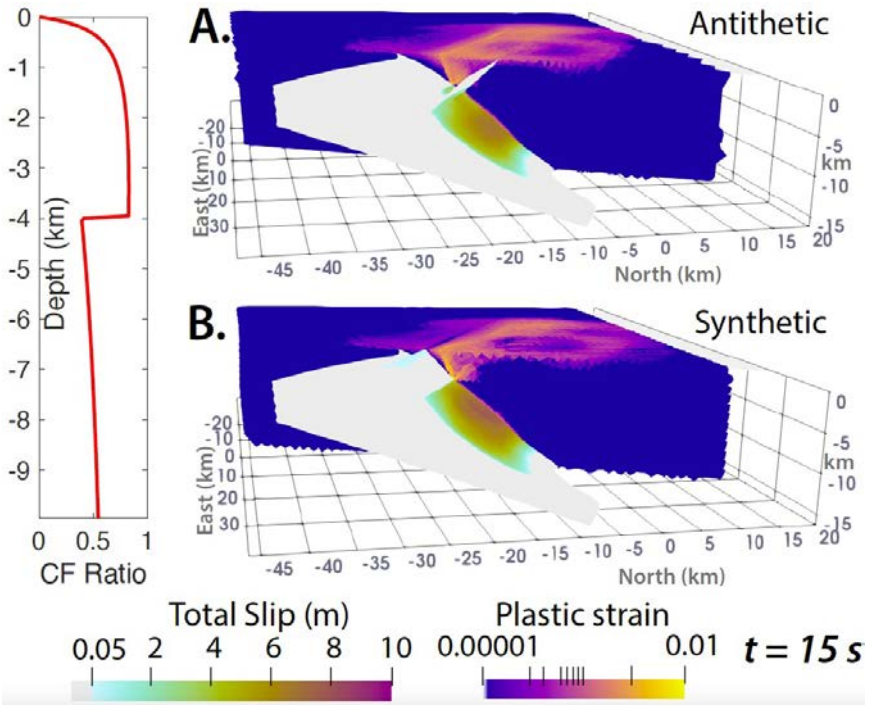
Large low-angle normal fault ruptures are dynamically viable in typical extensional stress fields without being uniformly near-critically stressed

Surface rupture is possible, but multiple processes act to limit shallow slip

Coseismic reactivation of splay faults and inelastic failure of weak shallow sedimentary hanging-wall basins appear viable and are expected to reduce shallow slip on the main fault and enhance/localize surface displacements outboard of the main fault trace

These shallow processes appear most efficient when the hanging wall contains thick deposits of weak sediments cut by gently-dipping synthetic splay faults

Thank you!

Questions, comments, feedback?

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