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Upper plate rigidity and shallow subduction zone slip stability in data-constrained seismic-cycle models of the central Hikurangi margin, New Zealand

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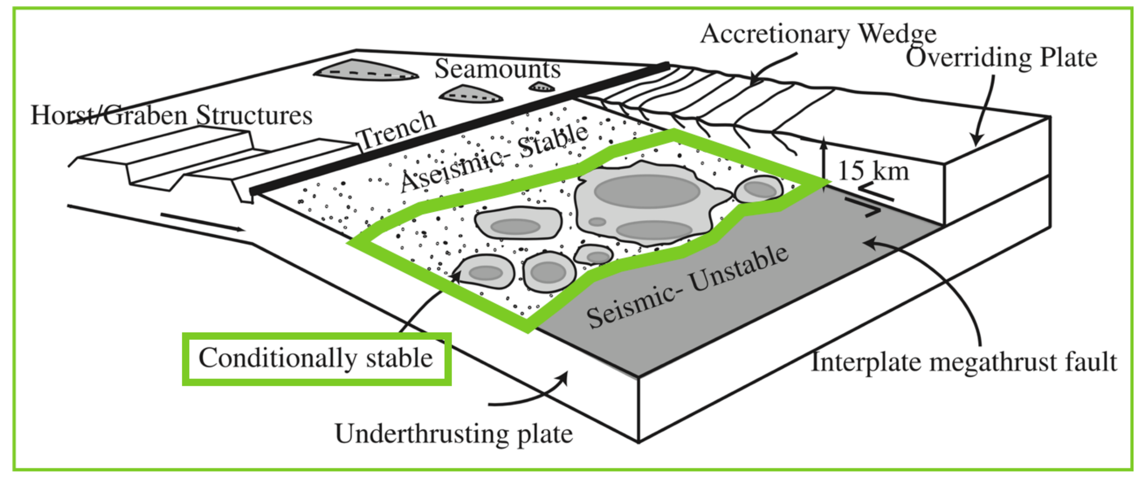
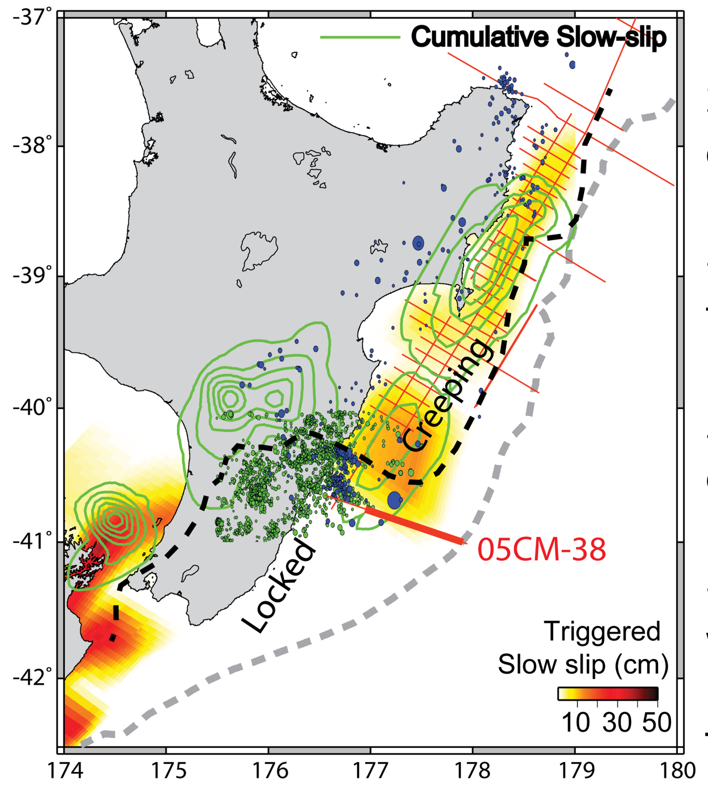
Background & Motivation

Over the last two decades, research has recognized that slow fault slip including slow-slip events, episodic tremor, and (very)-low frequency earthquakes occur in a variety of fault zones and under a seemingly large set of physical conditions (e.g. temperature, pressure, tectonic setting). Seafloor geodesy has shown that large earthquakes can trigger slow-slip events (e.g., Wallace et al., 2017) and it has been suggested that period slow-slip events near subduction megathrusts can trigger large earthquakes (e.g., Uchida et al., 2016) and may be related to pre-seismic stress changes near subduction faults (e.g., Obara & Kato, 2016; Voss et al., 2017; Becker et al., 2018). One proposed mechanism for slow-slip is fluid overpressures, which may be related to dewatering during time-progressive temperature and pressure-dependent mineral transitions (e.g., Schwarz & Rokosky, 2007; Saffer & Wallace, 2015), and recent seismologically inverted stress tensor variations near slow-slip regions appear to indicate that fluid cycling is a key ingredient in some slow-slip events (Warren-Smith et al., 2018). Another common explanation for the slow-slip mechanism is the frictional stability transition between rate-state-friction velocity-weakening and velocity-strengthening fault zone material, which occurs updip and downdip of the locked (and presumably velocity-weakening) seismogenic zone. Support for this mechanism comes from laboratory experiments showing velocity-neutral slip behavior at tectonic strain rates (e.g., Ikari & Kopf, 2017; Ikari, 2019) as well as rate-state-friction numerical models of fault slip, which typically require highly elevated pore fluid pressures and/or near-velocity-neutral frictional conditions to produce spontaneous aseismic transient slip (e.g., slow-slip).



Here, we examine conditions leading to slow-slip in rate-state friction models and compare them to mechanical properties inferred from seismic reflection data from the Southern Hikurangi subduction zone, which experiences period slow-slip events. We use these mechanical properties to constrain new rate-state friction models to better understand what physical conditions promote slow-slip.



Arnulf et al., (2018) modified from Wallace et al. (2017)

Hikurangi Slow-Slip Events

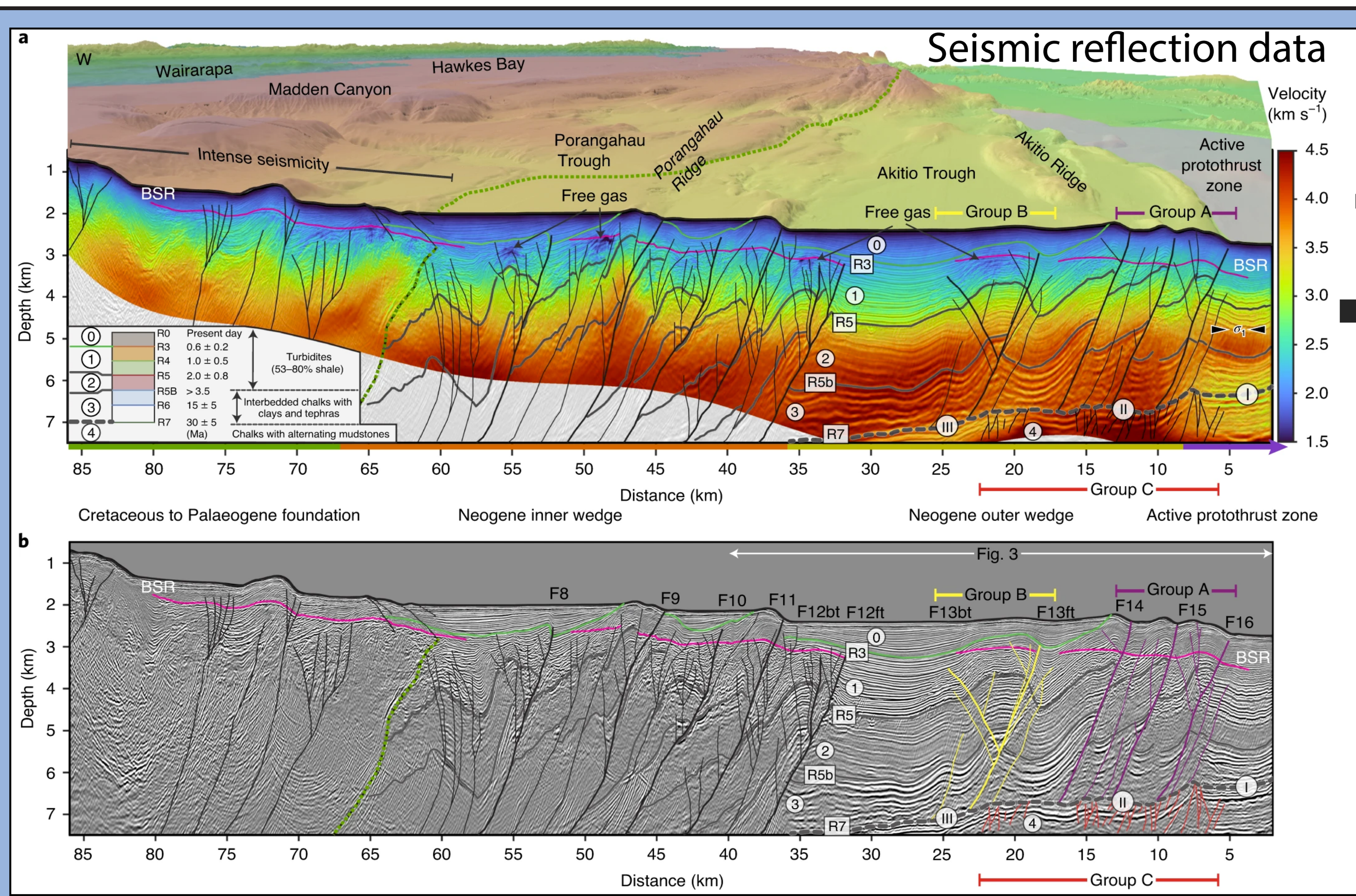
Shallow (~ 6-12 km depth) offshore slip

~5 year recurrence interval

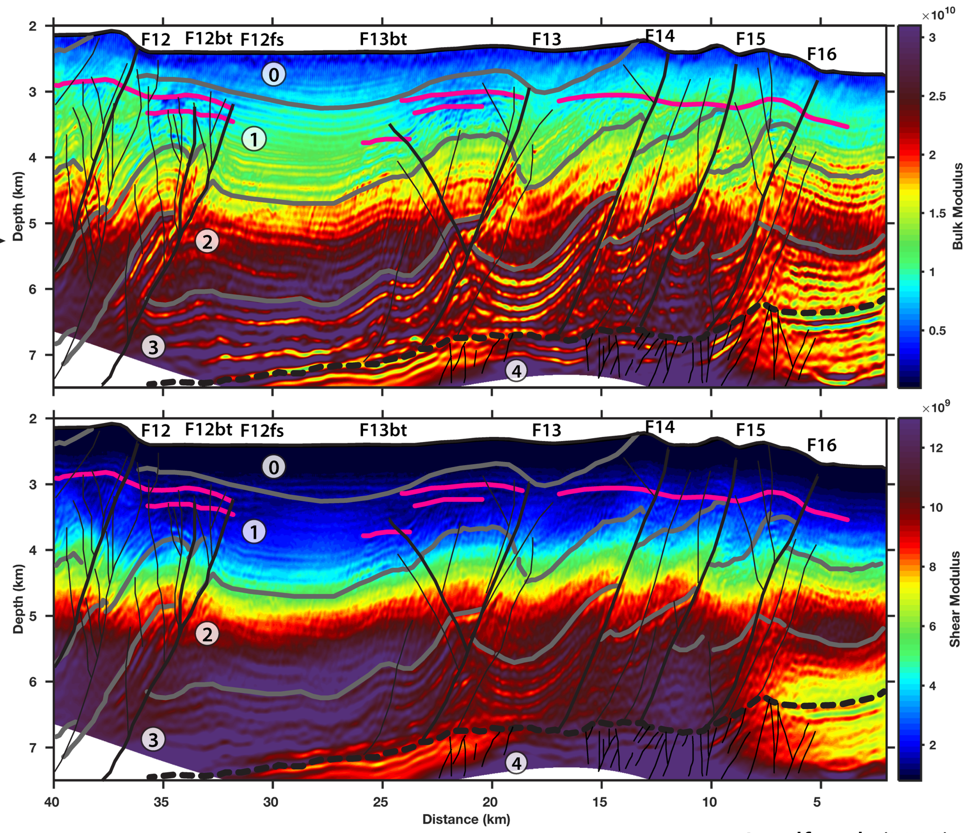
2006, 2011, 2016 (triggered by Kaikoura EQ)

~1-3 cm slip over 1-3 week duration

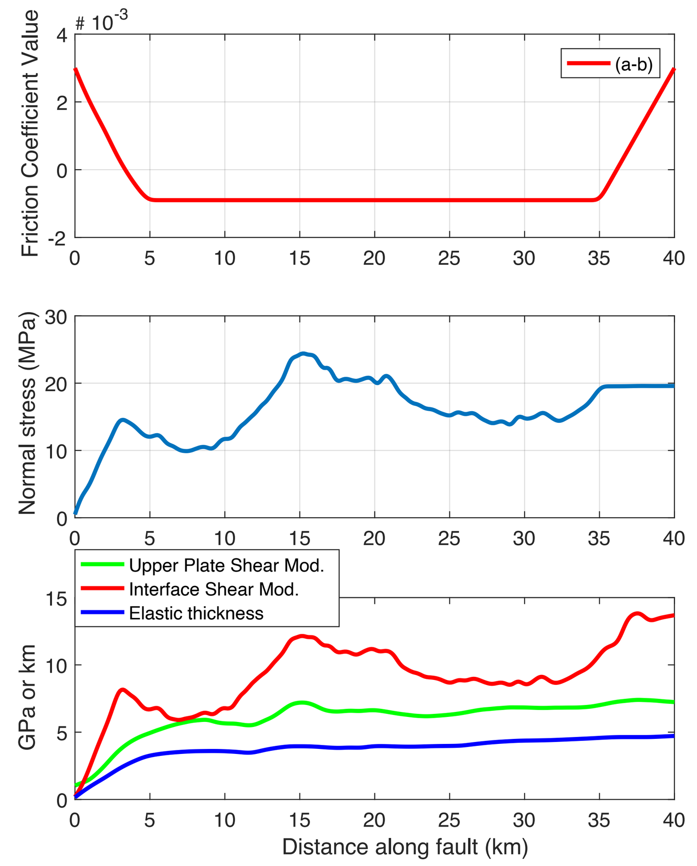
Transition from locked to creeping regions



Full-wave-form inversion



Extract relevant mechanical properties

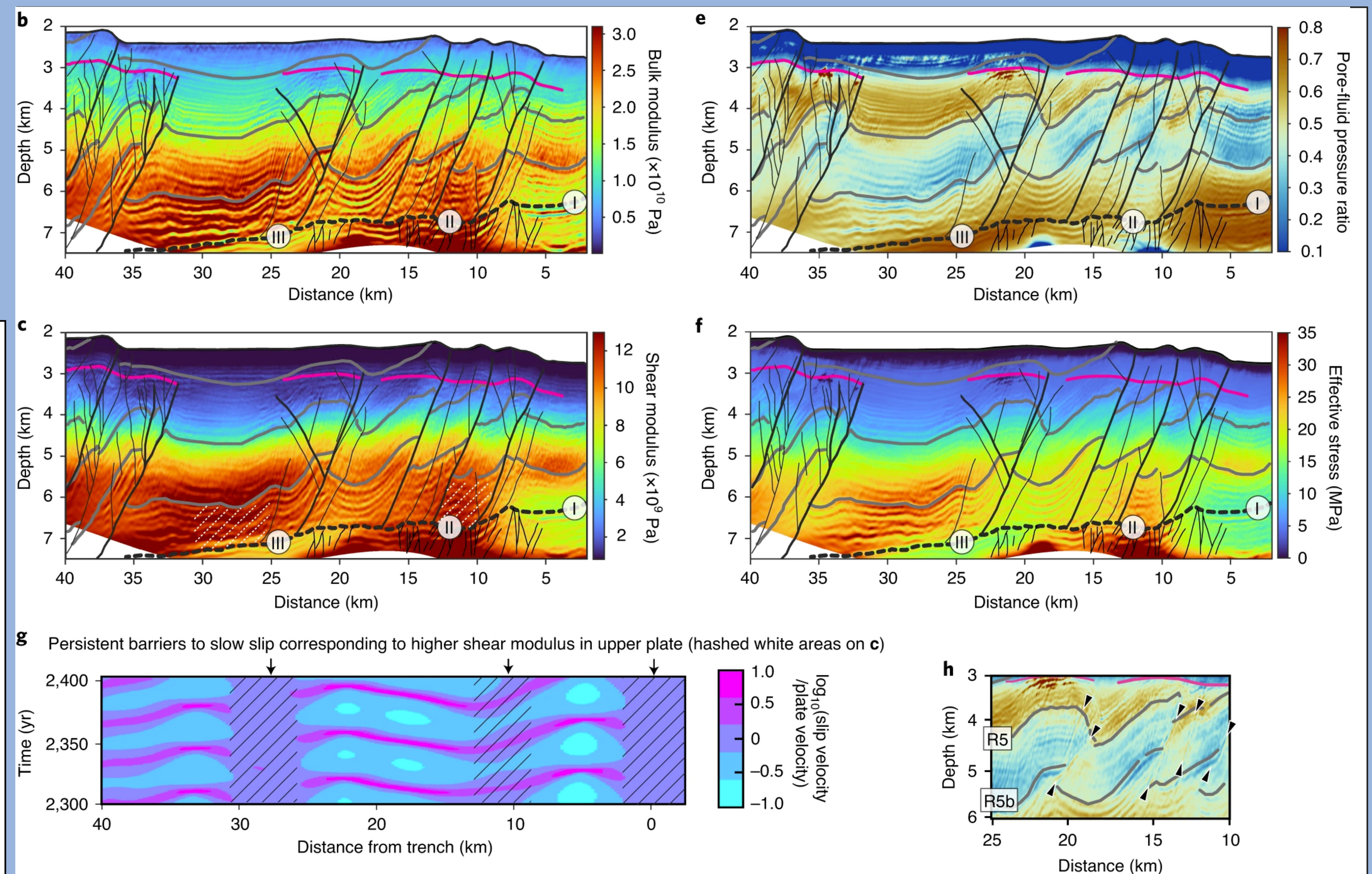


Arnulf et al., (2018)

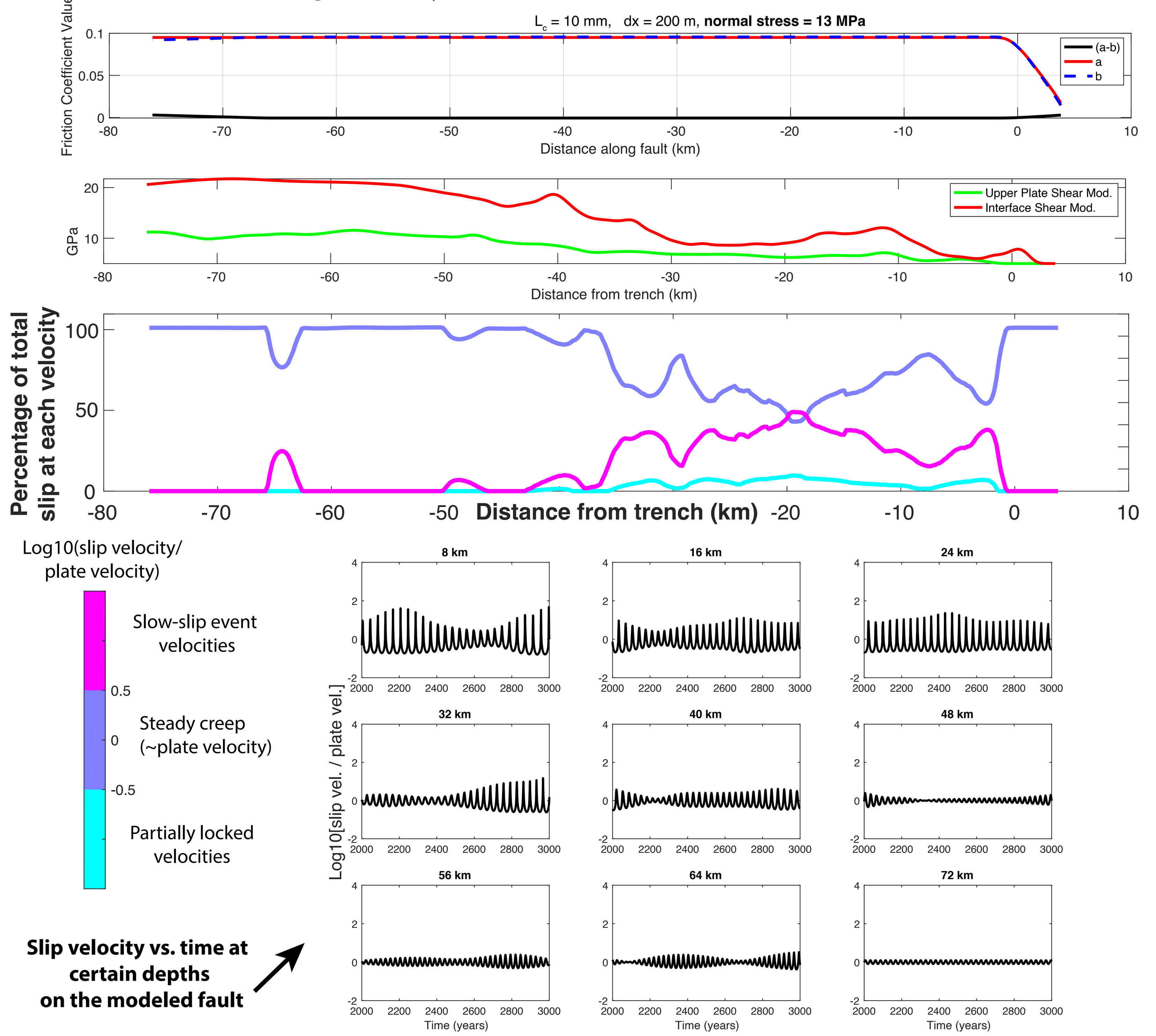
Models with homogeneous elastic properties and typical a-b values can produce periodic slow-slip events with recurrence intervals of ~2 years by lowering the effective normal stress (highly overpressured pore fluids)

Models with seismically constrained elastic moduli and effective stress require near-velocity-neutral conditions for slow-slip, and overestimate the duration and recurrence interval relative to slow-slip events observed in Hikurangi

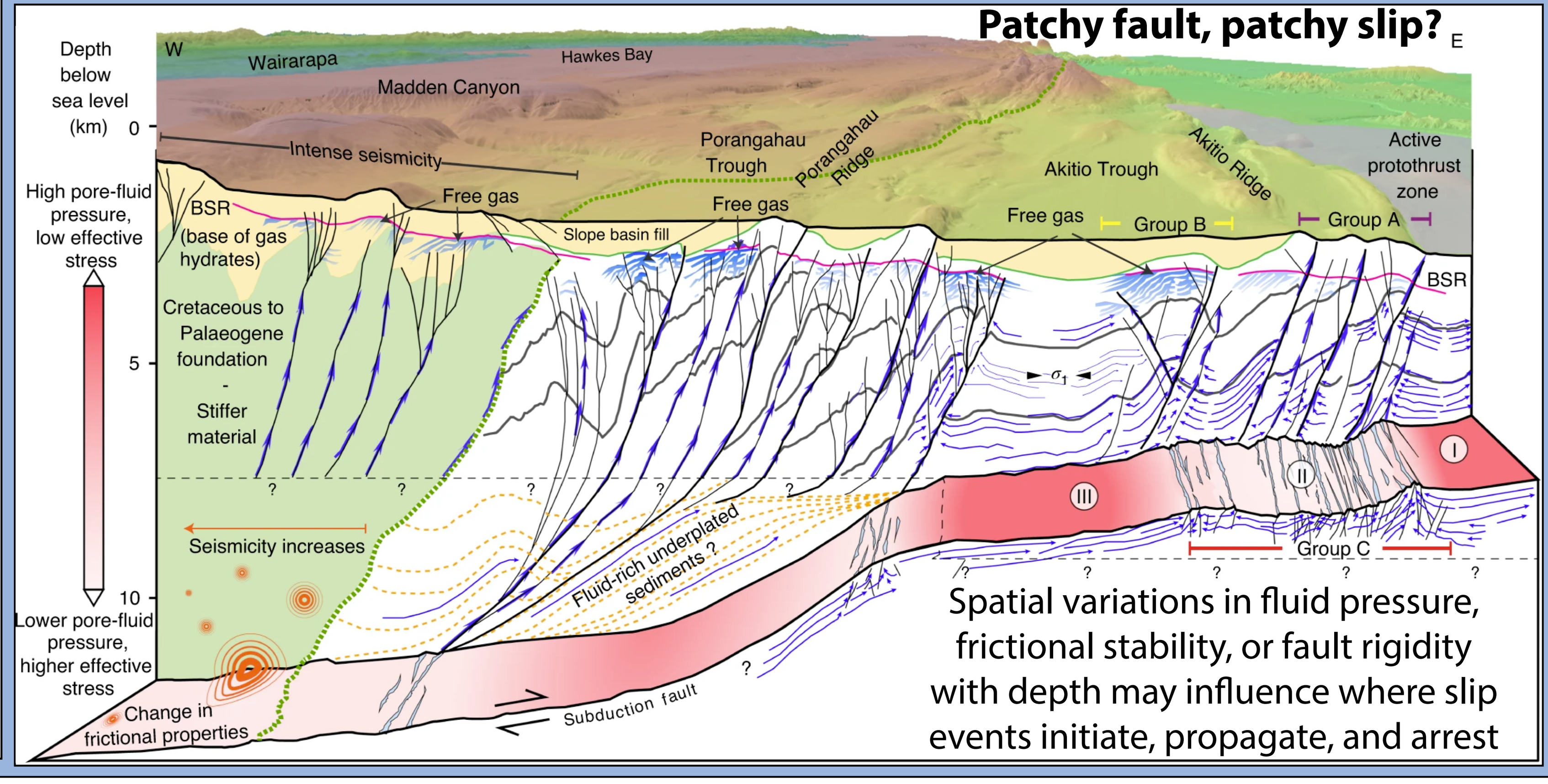
Realistic distribution of effective stress and shear modulus with depth enhance slow-slip segmentation along the fault



Model using seismically observed elastic moduli and effective normal stress



Patchy fault, patchy slip?



Spatial variations in fluid pressure, frictional stability, or fault rigidity with depth may influence where slip events initiate, propagate, and arrest

Do models with seismically constrained mechanical properties produce slow-slip events?

Yes, but only under near-velocity-neutral a-b conditions, or by drastically increasing pore fluid pressure (decreasing effective stress)

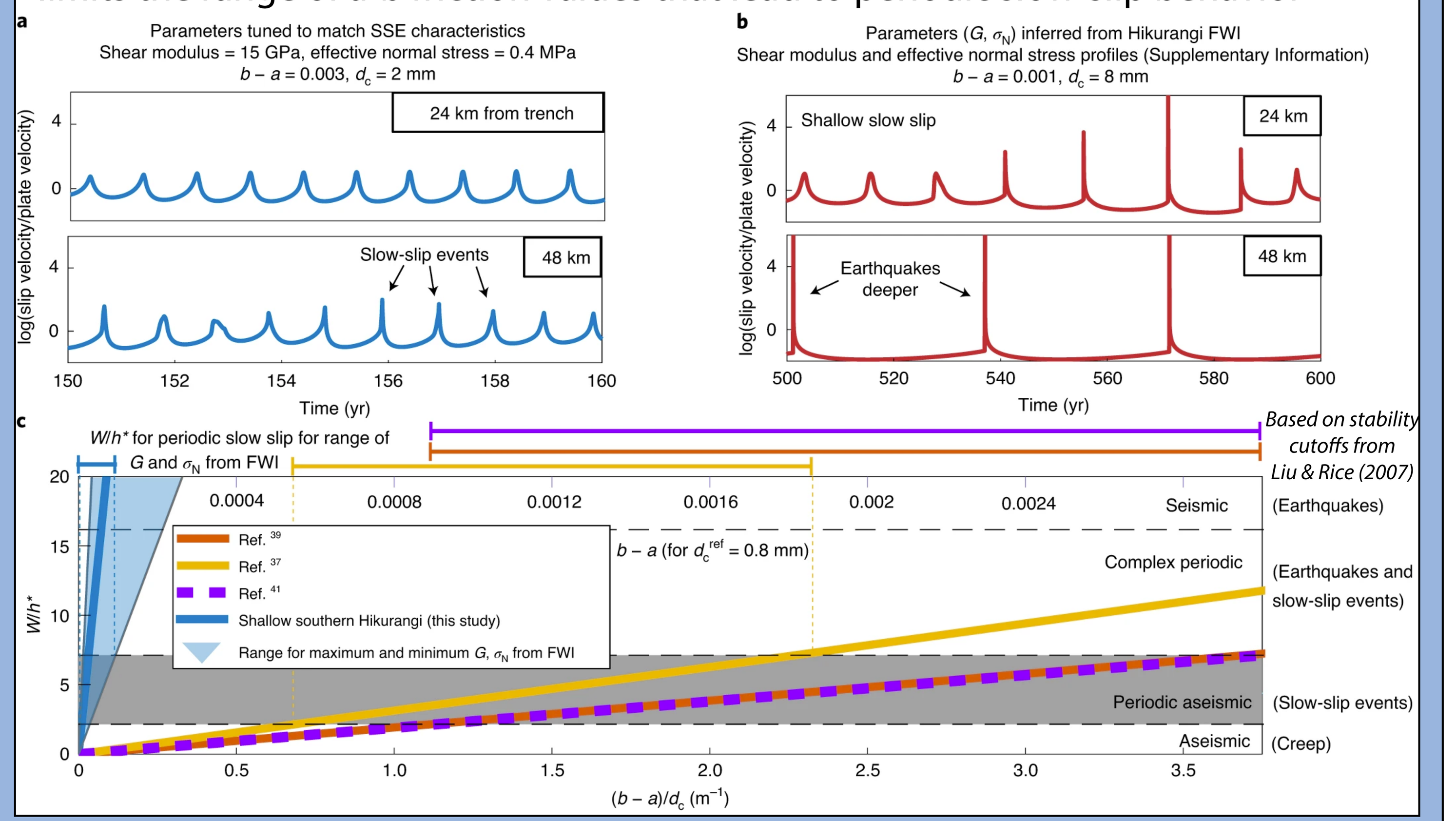
Rate-state fault stability can be predicted by W/h*, which accounts for the stiffness and size of the velocity-weakening patch:

$$\frac{W}{h*} = \frac{\pi W(1-\nu)(b-a)\tilde{\sigma}_n^*}{2G d_c}$$

Liu & Rice (2007)

Large W/h* corresponds to period earthquake slip, small values leads to steady aseismic creep, and intermediate values yield transitional seismic and aseismic slip (including periodic slow-slip events)

Using seismically constrained elastic moduli and effective normal stress severely limits the range of a-b friction values that lead to periodic slow-slip behavior



Conclusions

- High-resolution (18 Hz) FWI models of Hikurangi reveal strong lateral and downdip variations in rigidity, pore fluid pressure, and upper plate faulting
- Upper-plate faults appear to modulate pore pressure on the subduction interface by acting as pathways for fluid escape to the surface
- Data-constrained numerical models struggle to reproduce observed slow-slip event characteristics using standard 'ageing law' rate-state friction, suggesting one or more other mechanisms for shallow slow-slip, such as:
  - Cyclic fluid pressurization and release (e.g., Warren-Smith et al., 2019)
  - Effective near-velocity-neutral frictional behavior of shallow fault materials at plate-tectonic loading rates (e.g., Rabinowitz et al., 2018)
  - Modified slip-rate-dependent friction law, as in Im et al., 2020

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