Average prestress conditions for earthquake rupture in numerical models of low-stress faults with enhanced weakening:

Relation to earthquake statistics and apparent quiescence of mature faults

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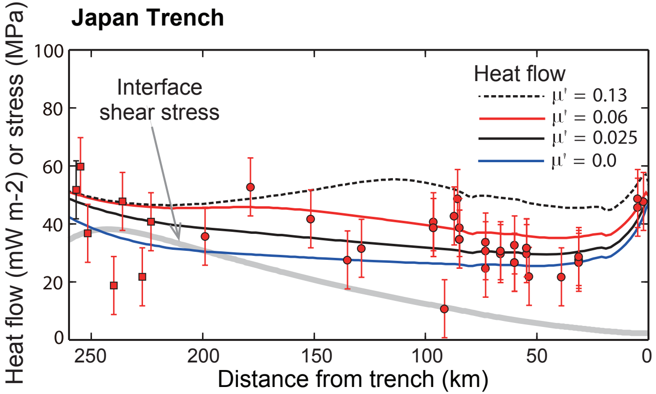
A number of lines of evidence for mature faults in both subduction and crustal plate boundary settings being "weak", with average shear stresses below 20 MPa (e.g. Brodsky et al., 2020 and references therein)



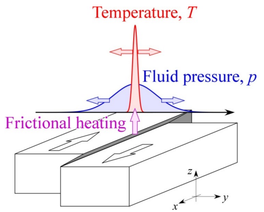
Gao & Wang, Science 2014

Mature faults could be:

1) **Persistently weak,**
e.g. due to chronic fluid overpressurization or low quasi-static friction

Or,

2) **Dynamically weak,**
due to enhanced dynamic weakening, such as from the thermal pressurization of pore fluids

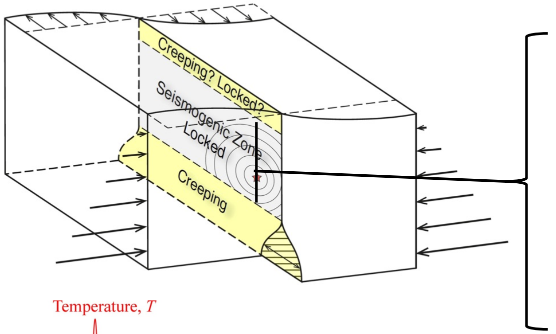


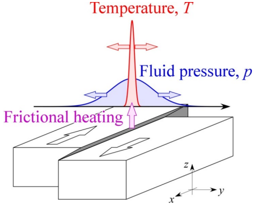
Spatially varying shear stress in numerical fault models with uniform frictional properties and normal stress

Local shear stress evolves due to **loading from slow and fast slip** in other parts of the fault and **stress release during local slip**

$$\tau(V,\theta) = (\sigma - p)\left[f_* + a\ln\frac{V}{V_*} + b\ln\frac{\theta V_*}{D_{\mathrm{RS}}}\right]$$

Local shear resistance depends on **current motion** and **history of previous motion,** as well as **changes in pore fluid pressure**

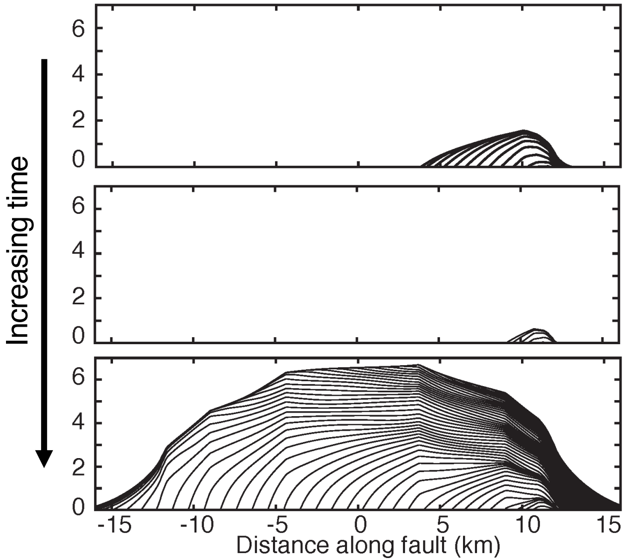




Thermal pressurization of pore fluids

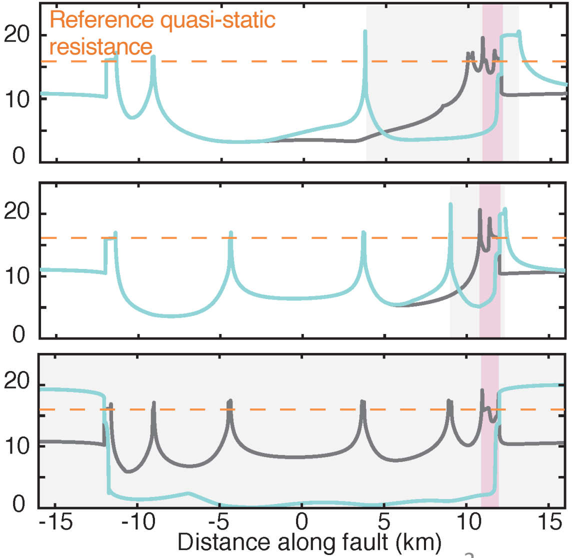
Reference quasi − static resistance
$f_* = 0.6;\ \sigma - p = 25$ MPa

Evolution of slip during ruptures (m)

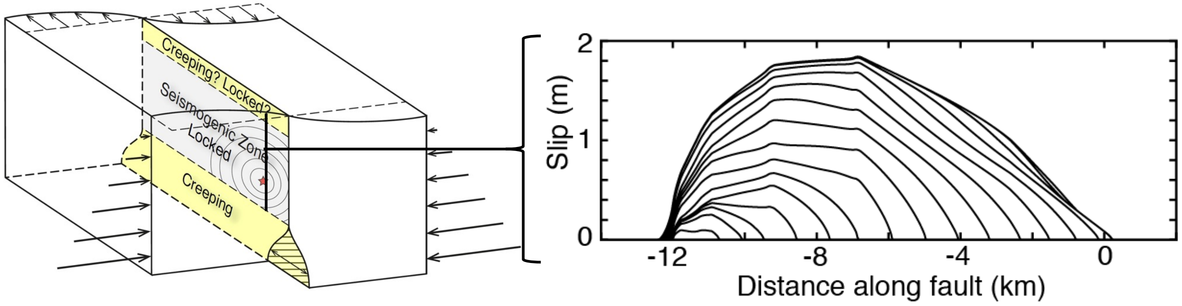


Stress before rupture
Stress after rupture
Nucleation region

Shear stress along the fault (MPa)



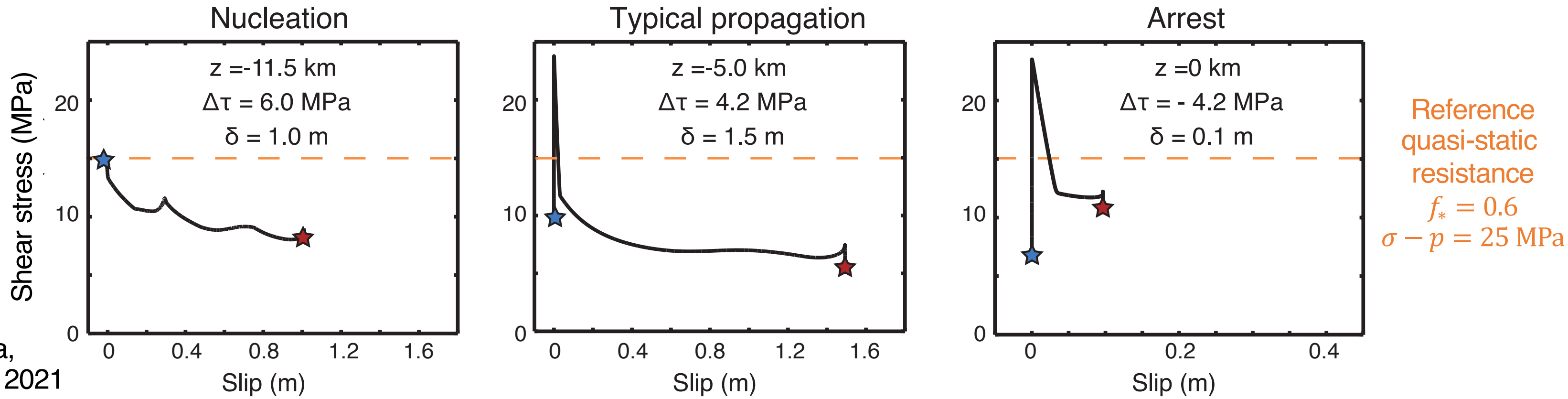
Heterogeneity in shear stress and resistance is important for determining how earthquake ruptures start, grow and stop



Average slip δ = 1.2 m

Average stress drop $\Delta\tau$ = 2.8 MPa

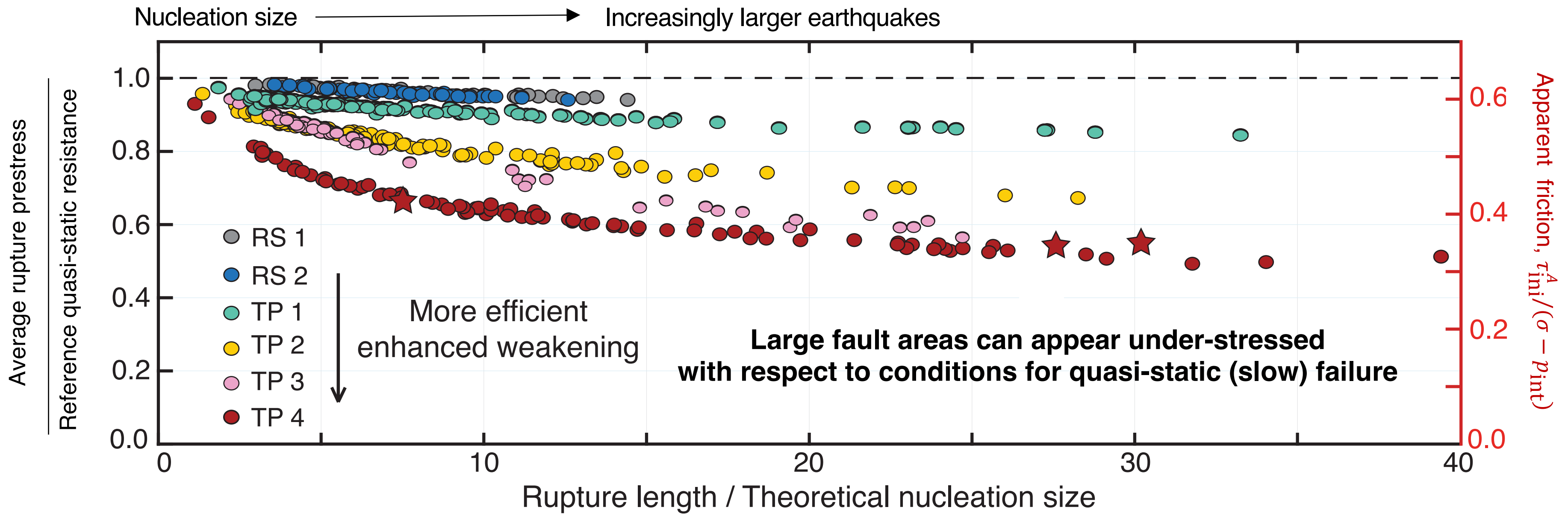
Conditions required for rupture nucleation are not the same as those required for rupture propagation



Lambert, Lapusta, & Faulkner, JGR 2021

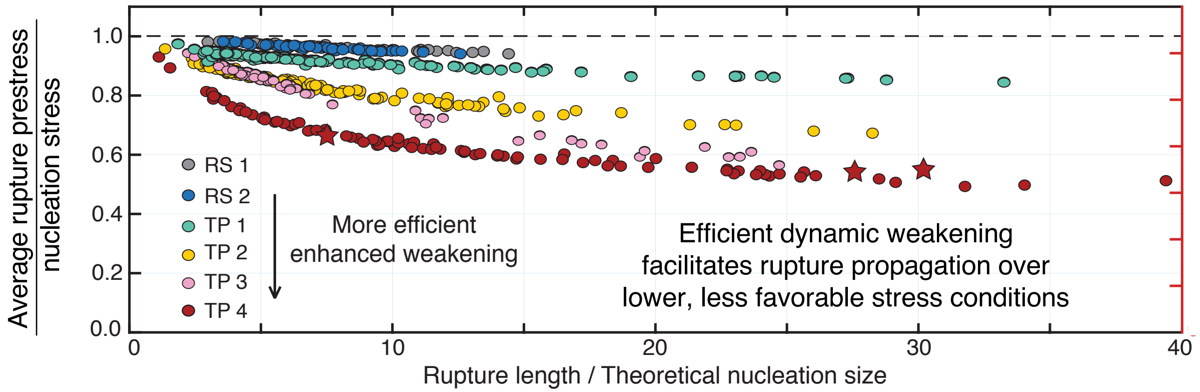
Larger ruptures with more efficient weakening propagate under lower stress conditions

Critical prestress conditions for rupture occurrence depend on the size of the rupture and efficiency of weakening

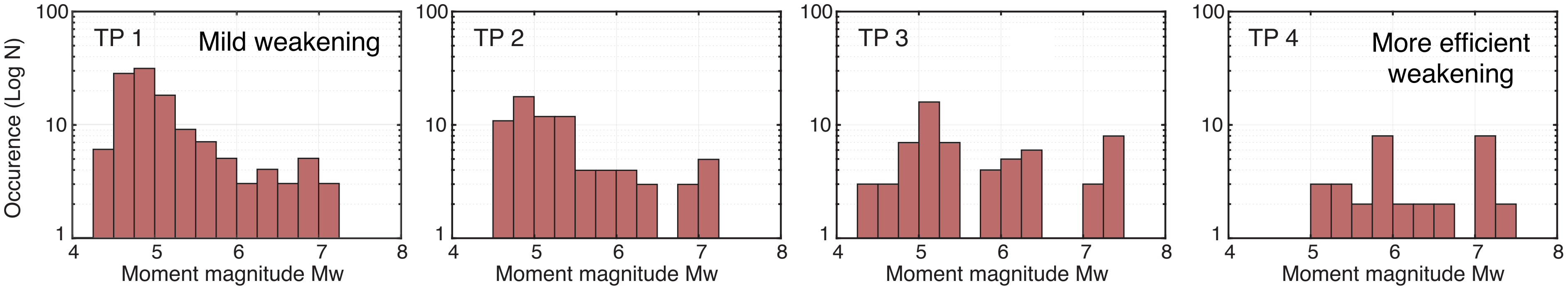


Lambert, Lapusta & Faulkner, JGR 2021

Efficient weakening draws average fault stress state below stress conditions required for rupture nucleation



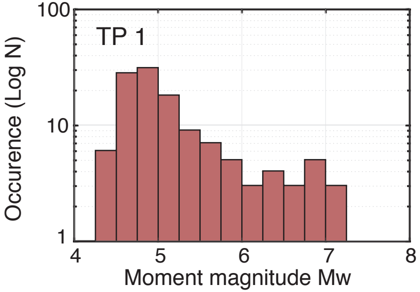
Fault models with more efficient weakening produce predominantly large earthquakes at the expense of small ones



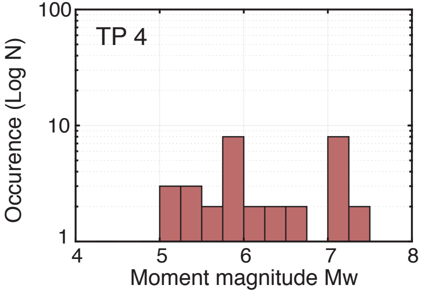
Lambert, Lapusta & Faulkner, JGR 2021

Fault models with efficient dynamic weakening show diminished microseismicity

Mild weakening
More smaller events

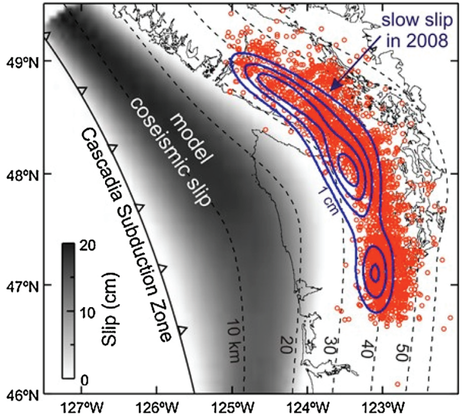


More efficient weakening
Predominantly larger events
fewer smaller events



Lambert, Lapusta & Faulkner, JGR 2021

Potential consideration for apparent quiescence along parts of the Cascadia subduction zone?

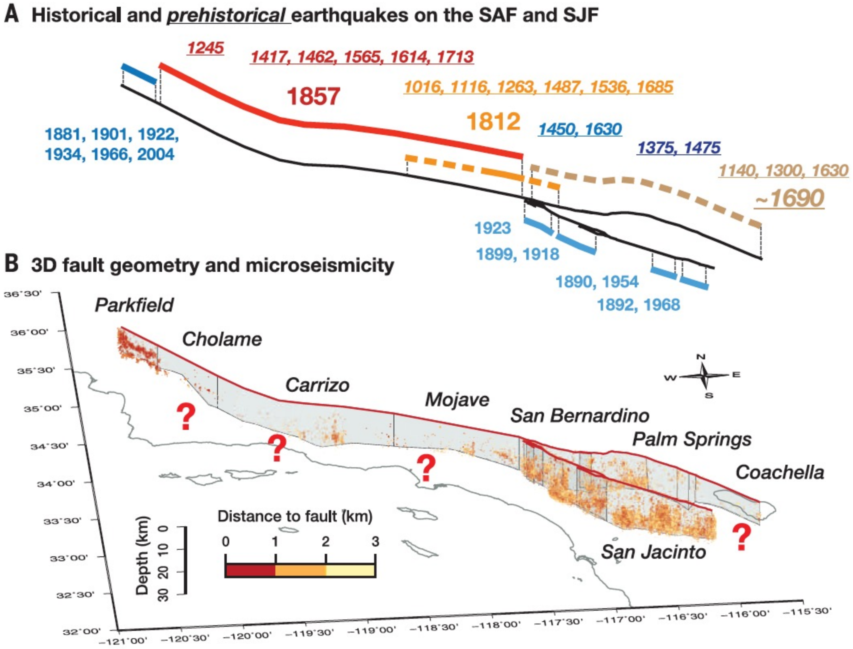


Wang & Tréhu, J. Geodyn. 2016

Physical explanation for deviations from Gutenberg-Richter statistics?

Paucity of small events on some mature faults may be observational indication of efficient dynamic weakening,

such as along some San Andreas Fault segments



Jiang & Lapusta, Science 2016

Summary

1. Heterogeneity in fault behavior plays an important role in how frictional ruptures start, grow and stop

Important to account for aspects of finite rupture evolution when interpreting laboratory and field observations

2. Critical conditions for rupture occurrence depend on the size of the rupture and weakening behavior

Large ruptures on faults with efficient dynamic weakening can propagate under less favorable, low-stress conditions

⇒ Large fault areas can appear under-stressed but be sufficiently stressed to propagate large dynamic ruptures

3. Fault models with efficient dynamic weakening produce more large events at the expense of smaller events

Paucity of smaller events may suggest some mature faults undergo substantial dynamic weakening during earthquakes

(e.g. Cholame and Carrizo segments of the San Andreas Fault, California and Alpine Fault, New Zealand)

⇒ **Potentially relevant for apparent quiescence of the Cascadia subduction zone (?)**

⇒ Probability of an earthquake on such faults becoming much larger may be greater than expectations based on Gutenberg-Richter scaling

Lambert, V., Lapusta, N. and D. R. Faulkner (2021). Scale dependence of earthquake rupture prestress in models with enhanced weakening: Implications for event statistics and inferences of fault stress. *J. Geophys. Res. Solid Earth* 126, doi:10.1029/2021JB021886

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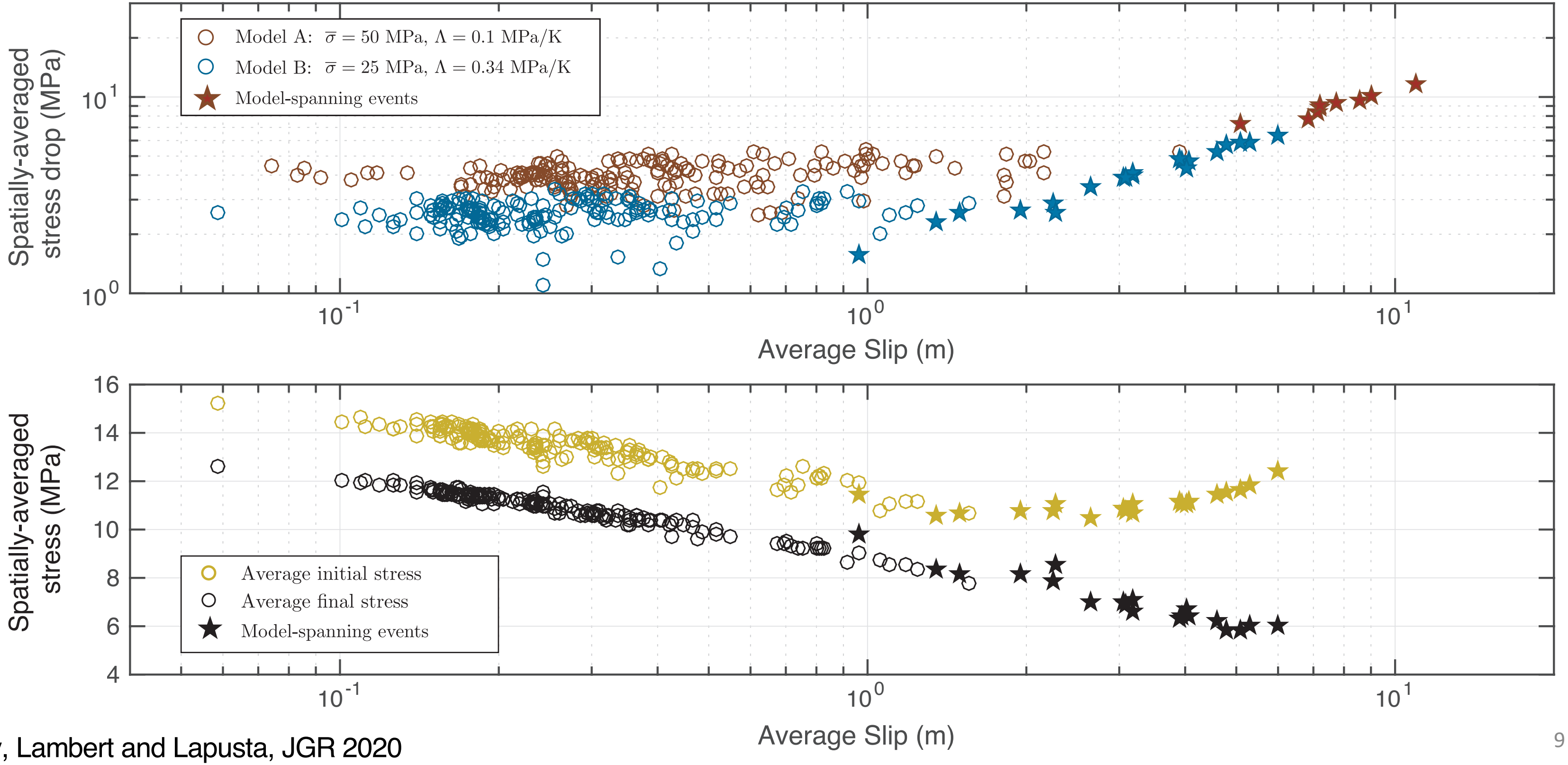
Additional Slides

Models with thermal pressurization produce nearly magnitude-invariant stress drops

Earthquakes nucleate in areas of relatively high stress but propagate and arrest over lower-prestressed regions

⇒ Finite-fault effects – how ruptures start, grow and stop – important for interpreting properties over larger fault areas



Perry, Lambert and Lapusta, JGR 2020