Model for permeability enhancement from yielding in a fault damage zone during passage of a rupture

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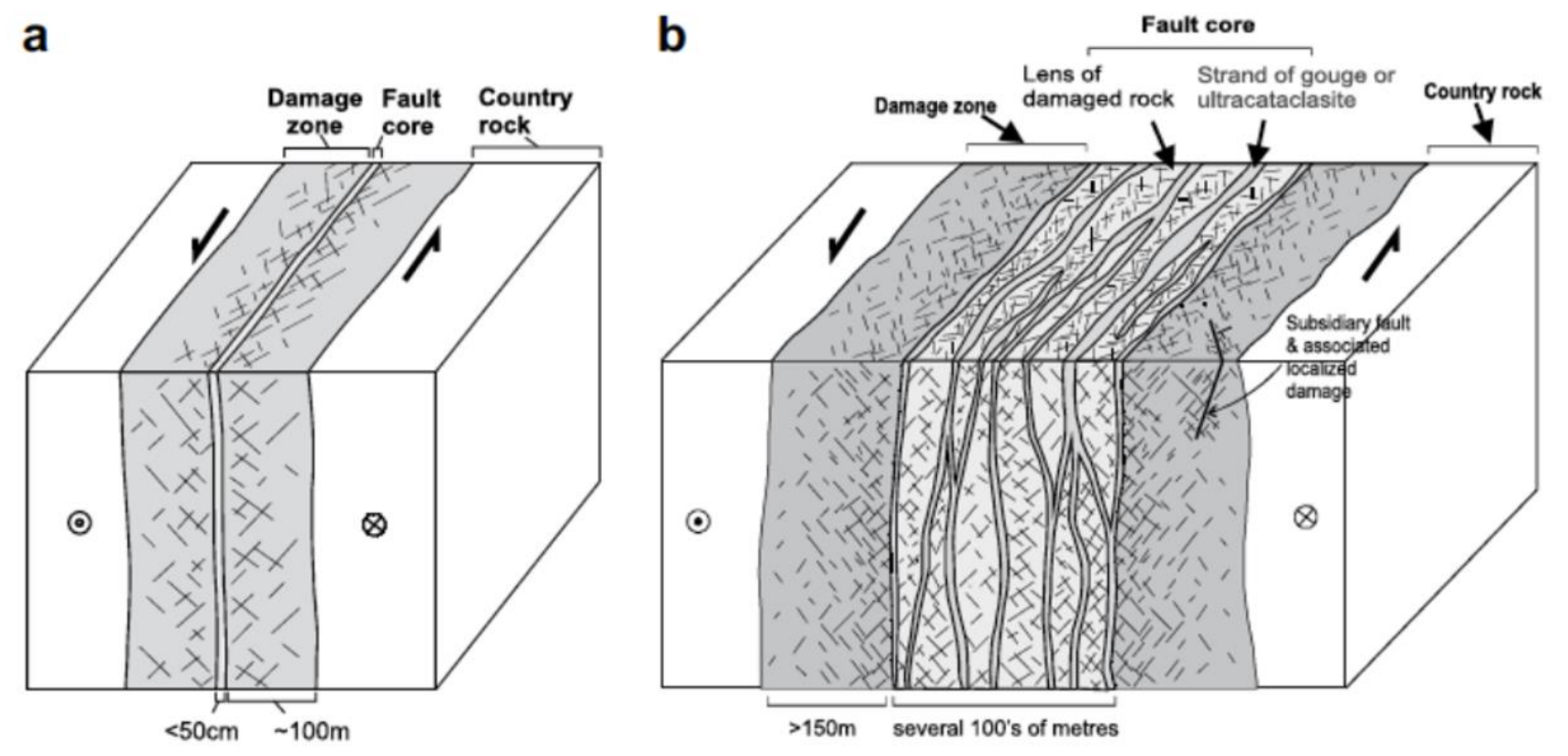
Background

- The stress concentration around a propagating rupture front creates and/or activates secondary fractures (tensile and shear) in the fault damage zone. Permeability is thus increased within the damage zone.
- Increased permeability enhances the transport of fluid and fluid pressure diffusion along the fault, which affects rupture nucleation, propagation, and arrest.
- Despite the importance of permeability enhancement for induced seismicity, swarm seismicity, and similar phenomena, **there are few models to describe permeability evolution with slip and rupture that are appropriate for mature faults with well-developed damage zones.**

Fig. 1



Two examples of damage zones around a fault core. From Mitchell and Faulkner (2009)

Introduction

Our goal is to connect the simple but ad hoc Model A with the more complex but physically motivated Model B. Is the ad hoc model appropriate? How should its model parameters be chosen?

Model A
(e.g., Zhu et al. 2020)

$$\frac{\mathrm{d}k}{\mathrm{d}t} = v_{slip}\frac{k - k_{max}}{L}$$

$k \equiv$ permeability
$\phi \equiv$ porosity
$L \equiv$ critical slip distance for permeability enhancement
$\delta_c \equiv$ slip at end of cohesive zone
$v_{slip} \equiv$ slip velocity
$\Delta^p \equiv$ volumetric plastic strain

Model B
(e.g., Yang and Dunham 2023)

$$k = k_0\frac{(\phi_0 - \Delta^p)^3}{\phi_0^3}$$

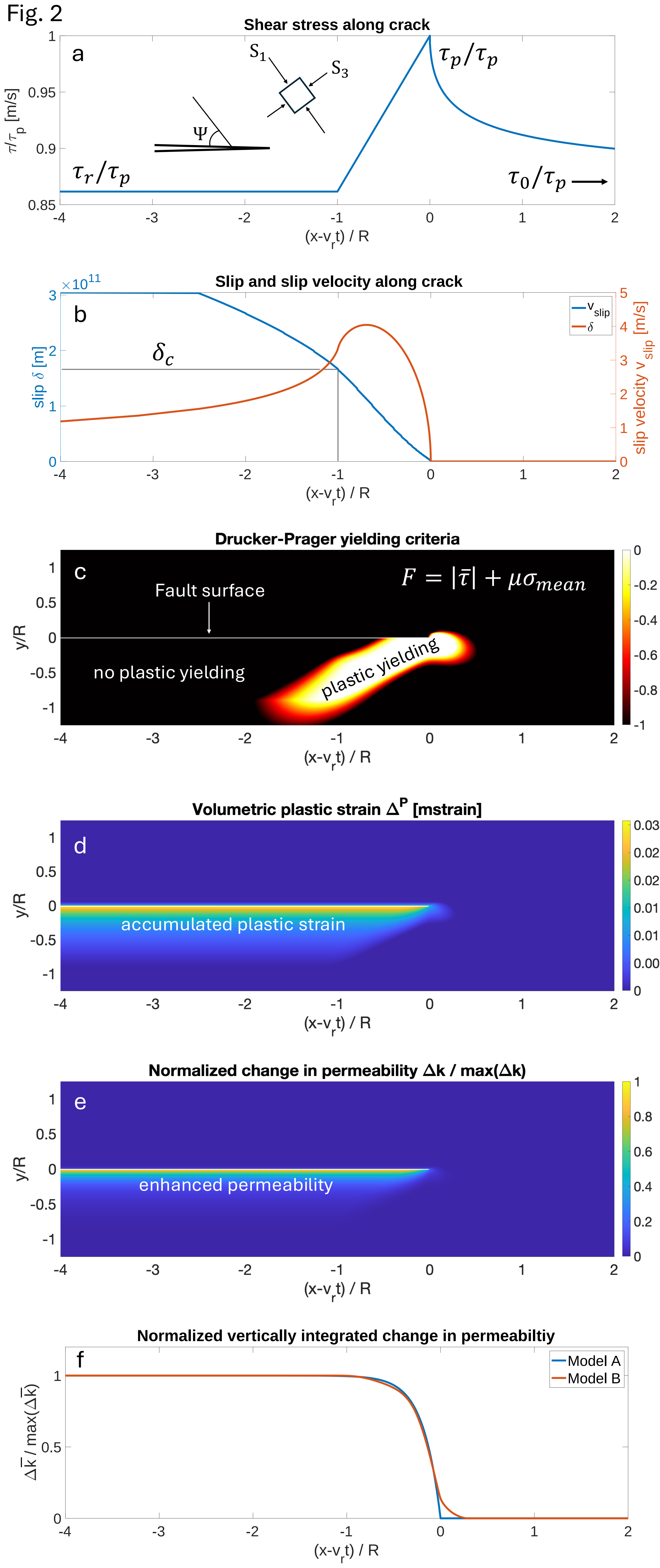
$$\bar{k} = \frac{1}{w}\int_{-\frac{w}{2}}^{\frac{w}{2}} k(x,y,t)\,dy$$

$$\beta\phi\frac{\partial P}{\partial t} = \frac{\partial}{\partial x}\left(\frac{\bar{k}}{\eta}\frac{\partial P}{\partial x}\right)$$

*Similar results obtained for $k \propto \Delta^p$, and for $k \propto$ plastic strain generally

Results for a “Typical Case”

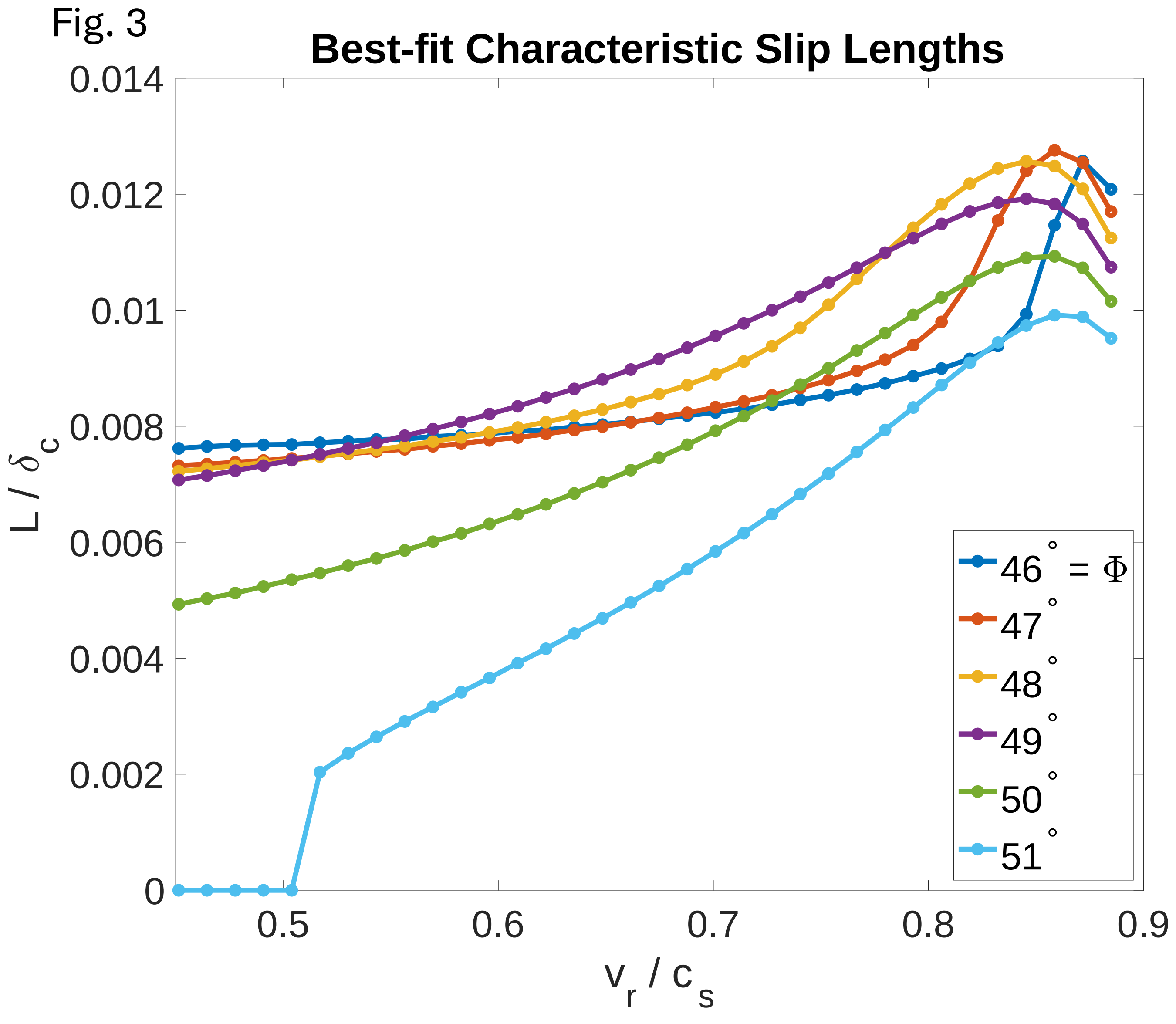
Fig. 2



In most relevant cases, Model A can well approximate Model B for some critical slip length L

Parameter Dependence

Fig. 3



The best-fit L depends on background stress angle Ψ, and on rupture velocity v_r

In general, $L \sim (0.002 \text{ to } 0.012) * \delta_c$, where $\delta_c \sim (\tau_p - \tau_r)R/G$

Conclusions

- Critical slip distance for permeability enhancement L scales with slip accrued within the process zone δ_c
- Critical slip distance L can be much larger than the slip-weakening or state evolution distance when off-fault yielding provides a significant contribution to total fracture energy
- Critical slip distance L increases with rupture velocity v_r
- Plastic yielding, and thus permeability enhancement, can occur ahead of the rupture front and prior to onset of slip, which is not captured in ad hoc permeability evolution model.

A note on edge cases

- Model B requires plastic deformation to occur to produce an increase in permeability, while Model A does not
- Low values of Ψ result in a significant fraction of the plastic deformation occurring ahead of the crack tip rather than behind it. Model A is not able to well approximate the prediction by Model B in such cases.

Acknowledgements

SCEC award number 24187

Code used to generate plots located at:
doi.org/10.5281/zenodo.13698504

References

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