Plasticity in rupture dynamics: what role does pore fluid play?

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NMCDEF, Golden, CO

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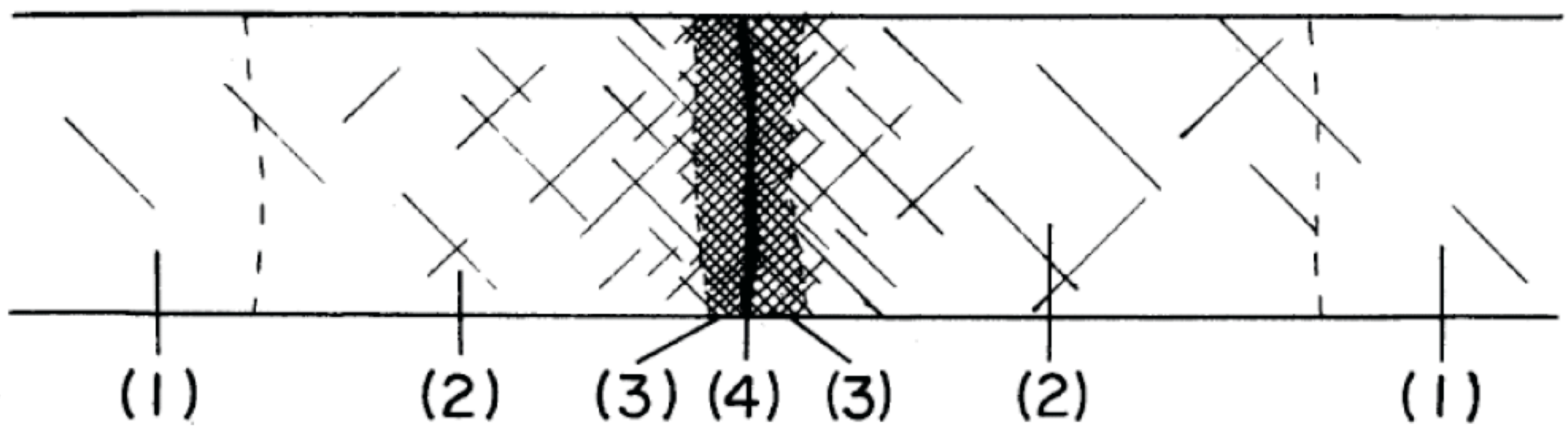
(Harvard University)

Now at : [1] Exxon-Mobil Research

[2] Stanford University

Typical structure of a mature fault

Internal Structure of Principal Faults of the North Branch San Gabriel Fault



1) Undeformed Host Rock

fault zone:

2) Damaged Host Rock (*highly cracked, 10-100 m*)
3) Foliated Zone (*granulated fault zone, 1-10 m*) — fault core
4) Central ultracataclasite layer (*10-100 mm*) — fault core

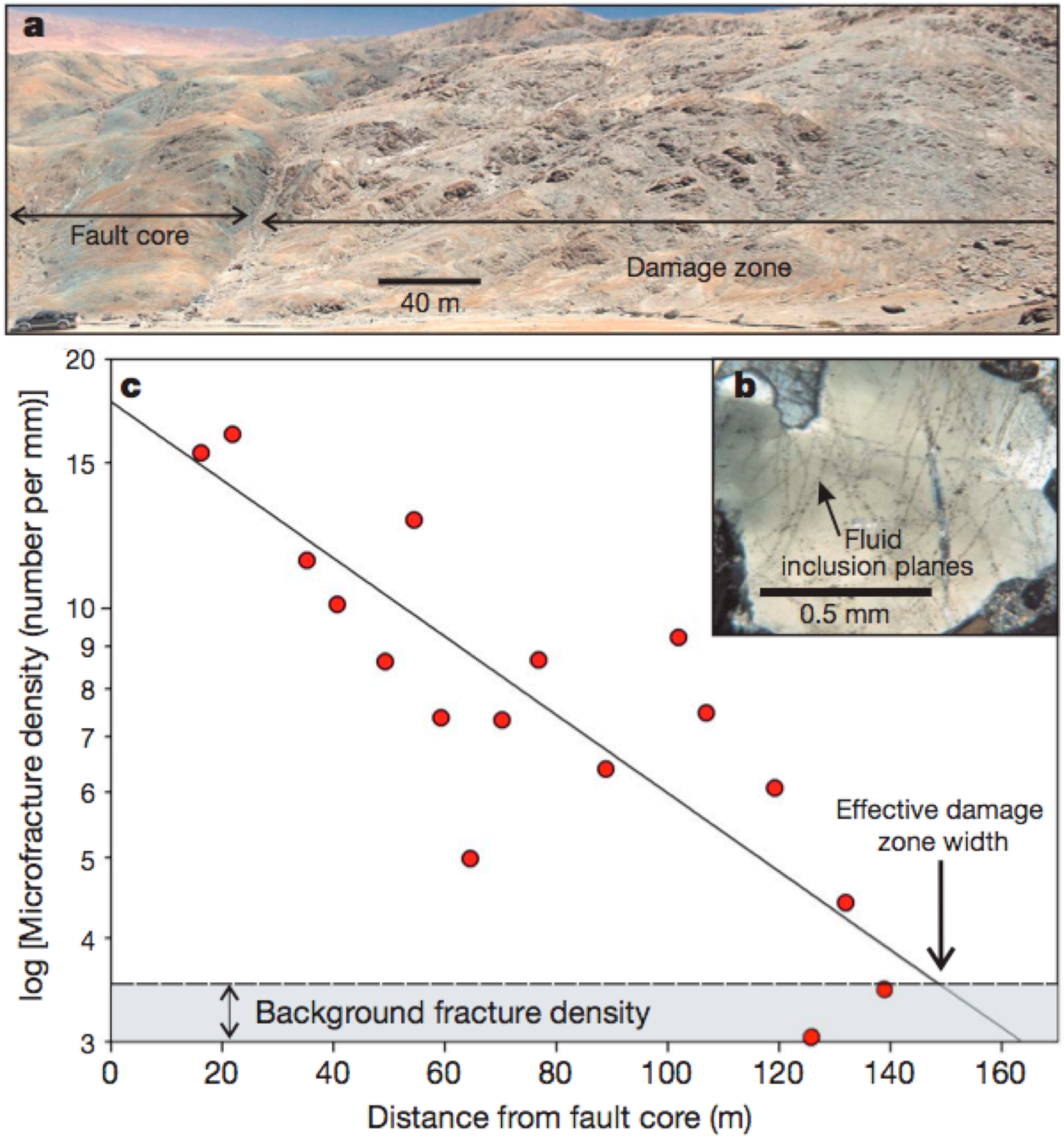
F. Chester, J. Evans and R. Biegel, *J. Geoph. Res.*, **98** (B1), 771-786 (1993)

Damage zone observations

Caleta Coloso fault, Atacama Desert, Chile

>5km offset

Exhumed from 4–10km

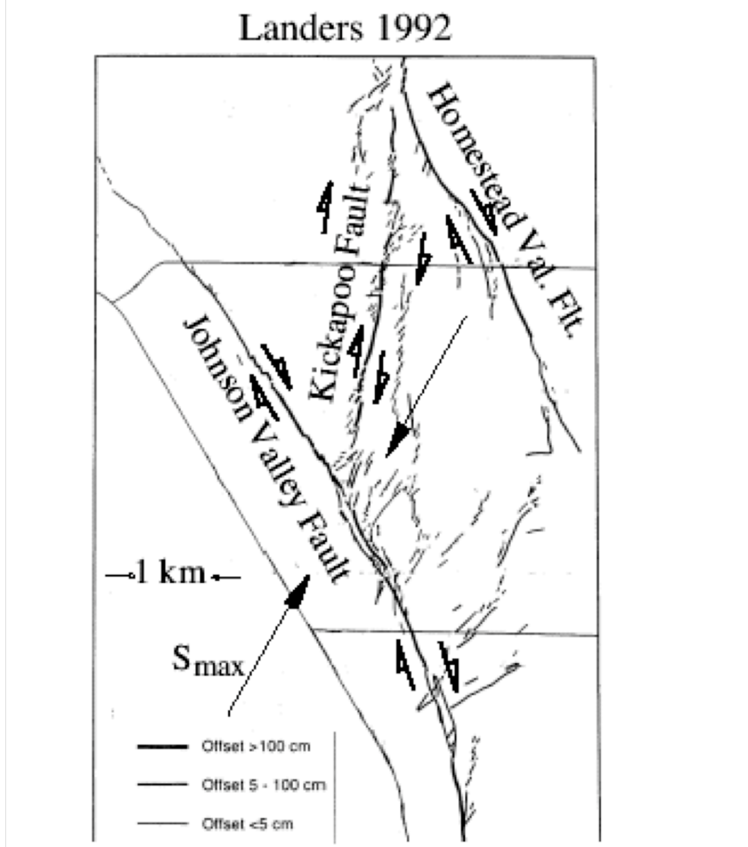


Faulkner et al. (2006)

Damage zone observations

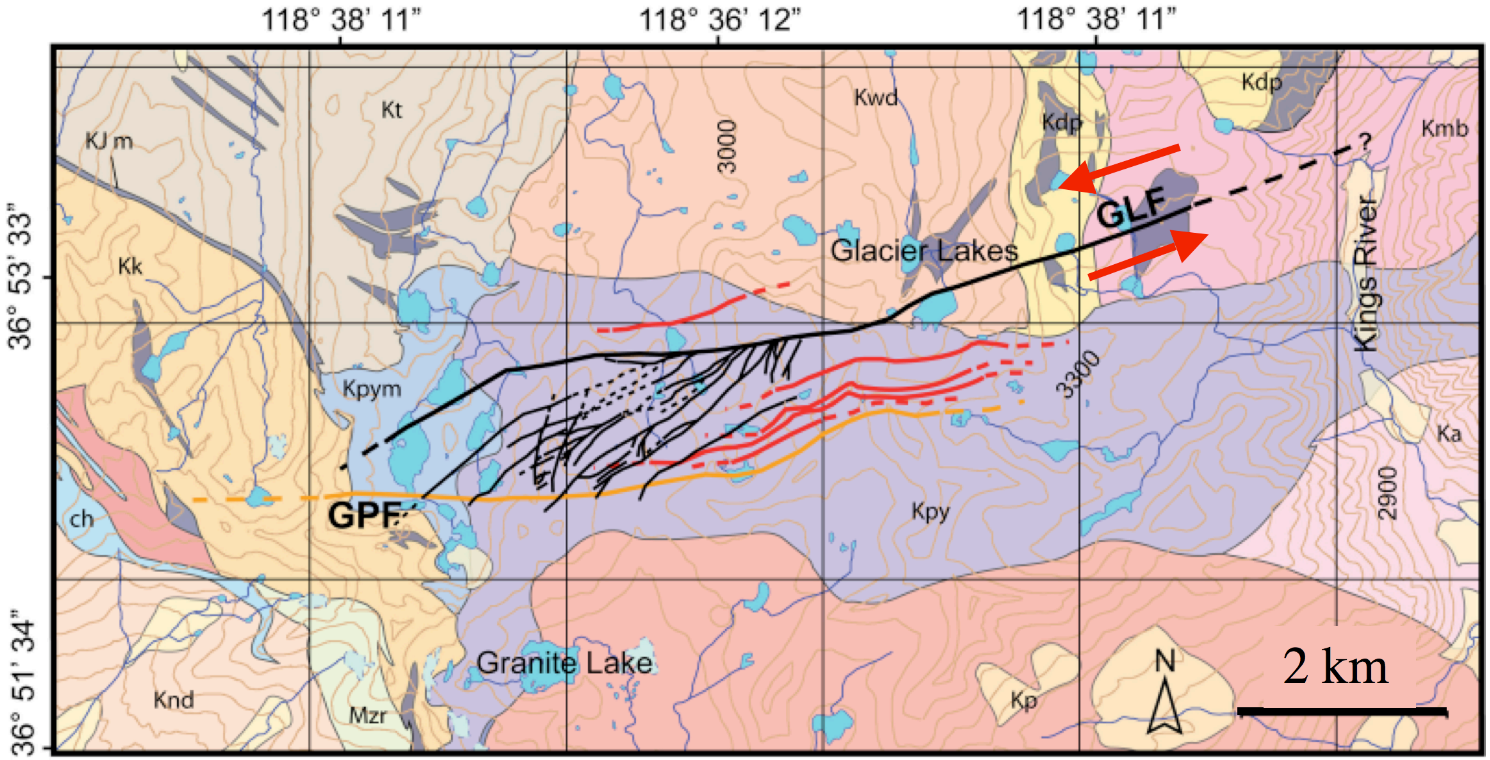
[Poliakov, Dmowska and Rice, *JGR*, 2002]

Map view: Steep S_{max} direction, $\Psi \approx 60^o$;
secondary failures on *extensional* side:



(fault map from Sowers et al., 1994;
stress from Hardebeck and Hauksson, 2001)

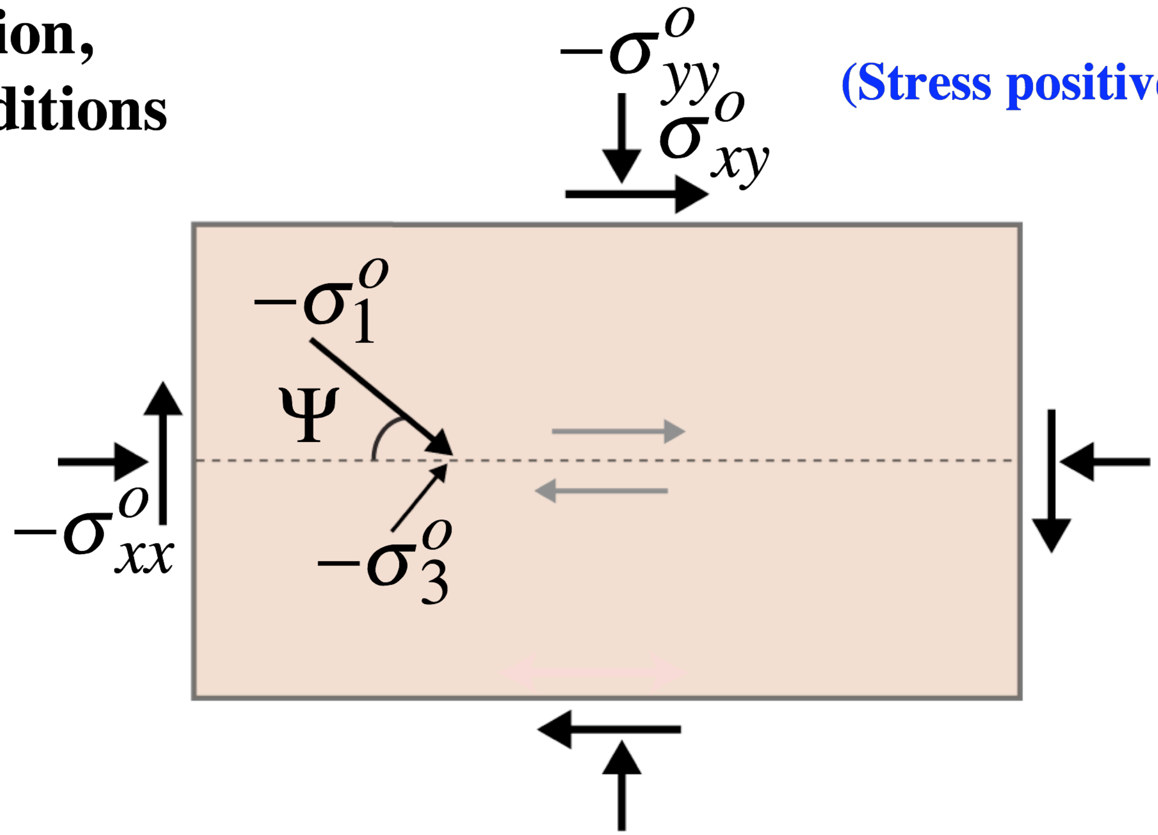
Damage zone observations



J. D. Kirkpatrick, Z. K. Shipton, J. P. Evans, S. Micklethwaite, S. J. Lim, and P. McKillop, *J. Geophys. Res.*, **113**, B04304, (2008).

Fault friction, initial conditions

(Stress positive in tension)



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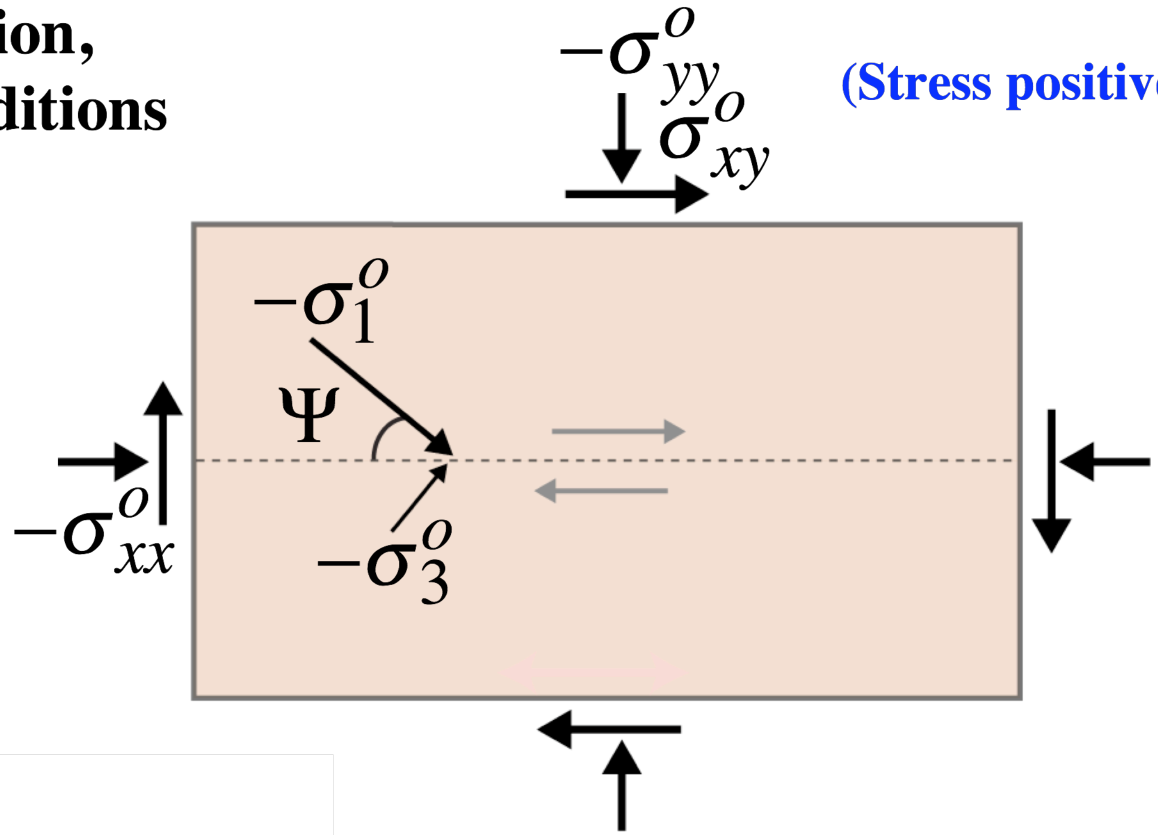

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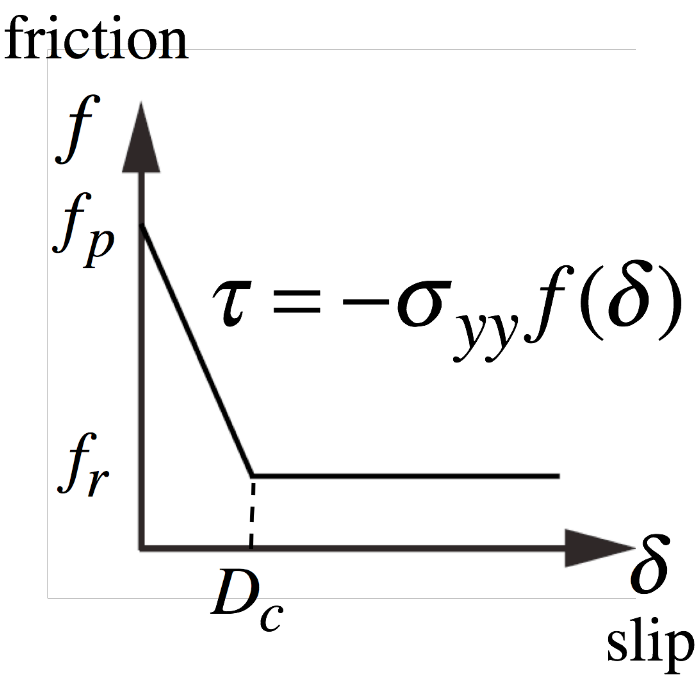

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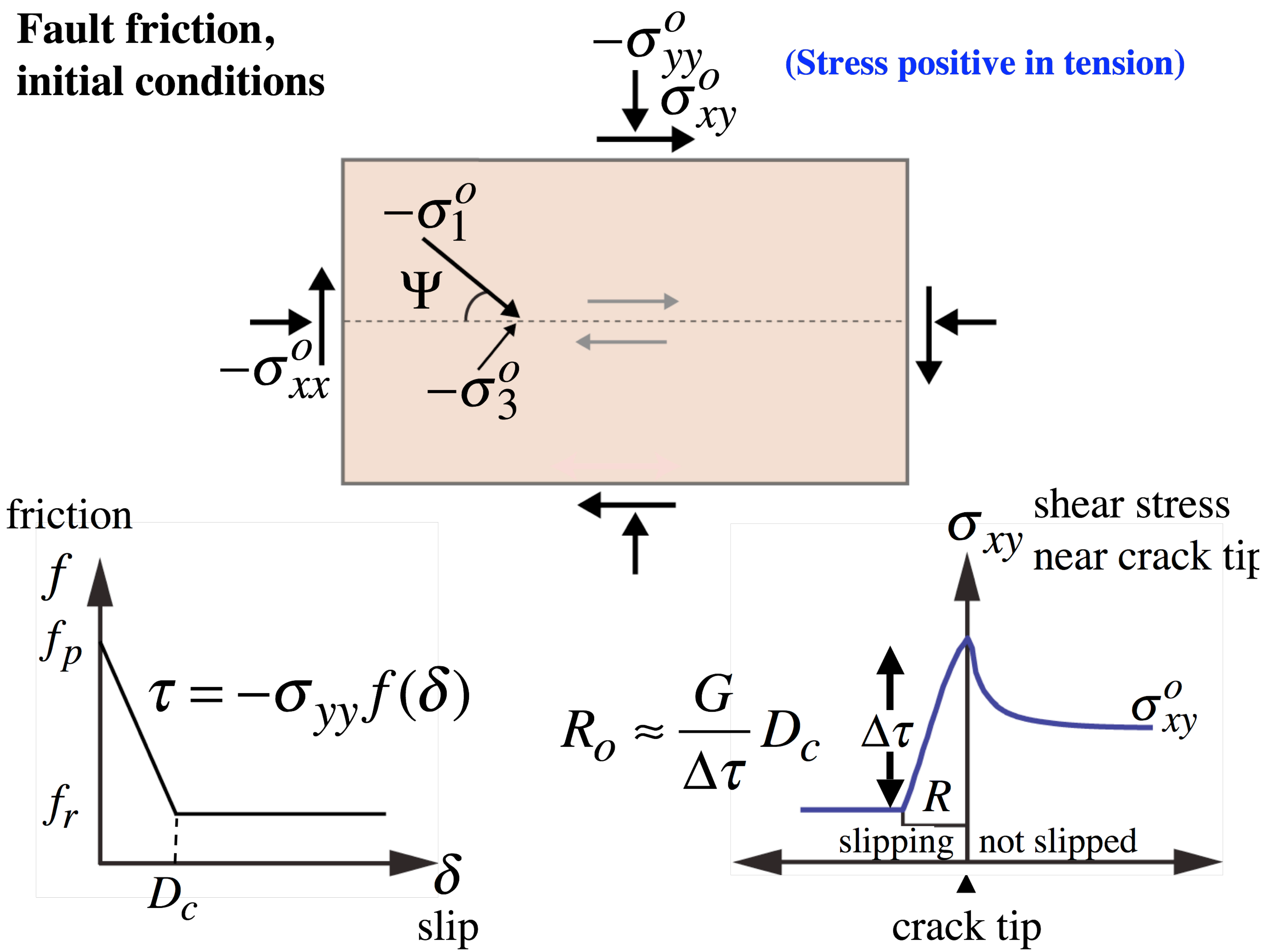
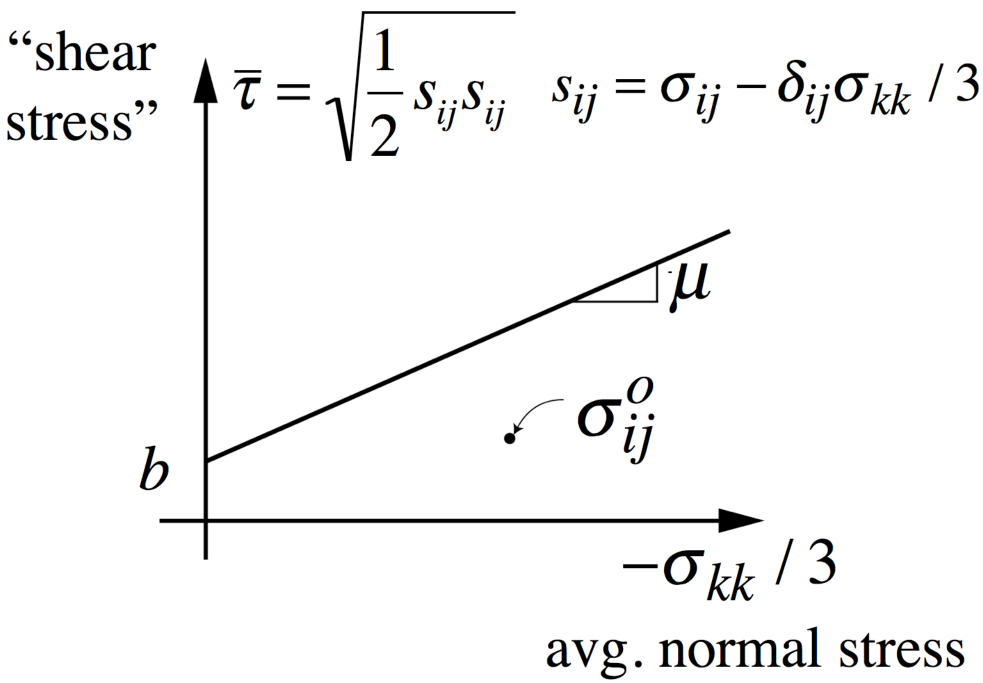
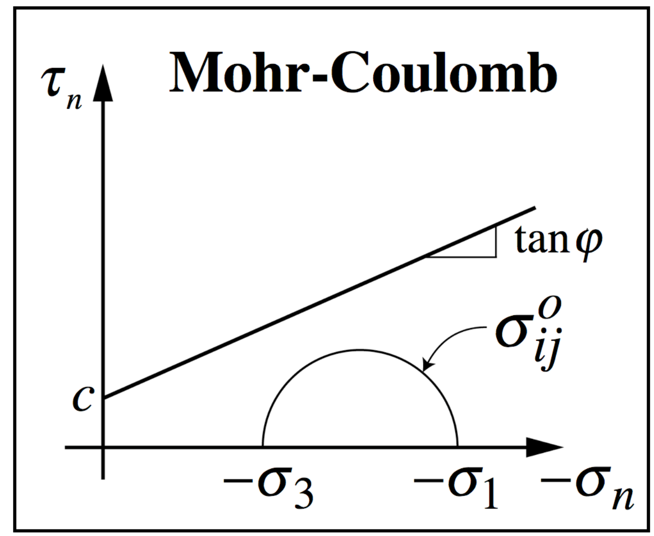


Off-fault material description Linear elasticity with Drucker-Prager plastic yield criterion:

Drucker-Prager

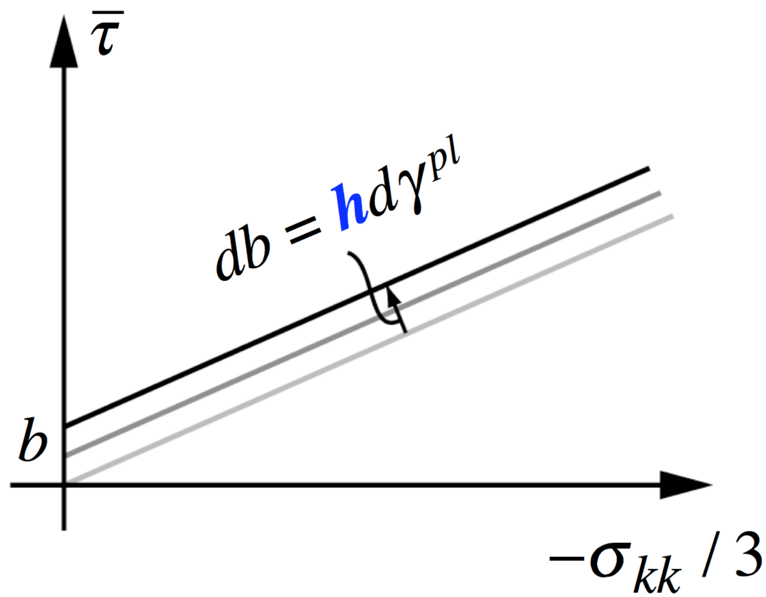


compare to:



Off-fault material description Linear elasticity with Drucker-Prager plastic yield criterion:

Hardening of yield surface, h



Plastic dilatancy, β

$$d\epsilon_{kk}^{pl} = \beta d\gamma^{pl}$$

increment of plastic volumetric strain

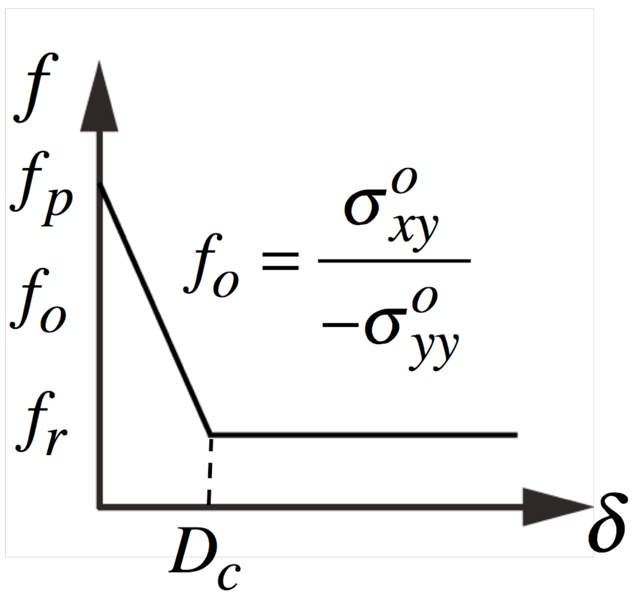
increment of plastic "shear strain"

$h = 0$: no plastic hardening (perfectly plastic)

$\beta = 0$: no plastic dilation

Measures of proximity to failure of initial stress state

On fault



$$S = \frac{f_p - f_o}{f_o - f_r}$$

Measures of proximity to failure of initial stress state

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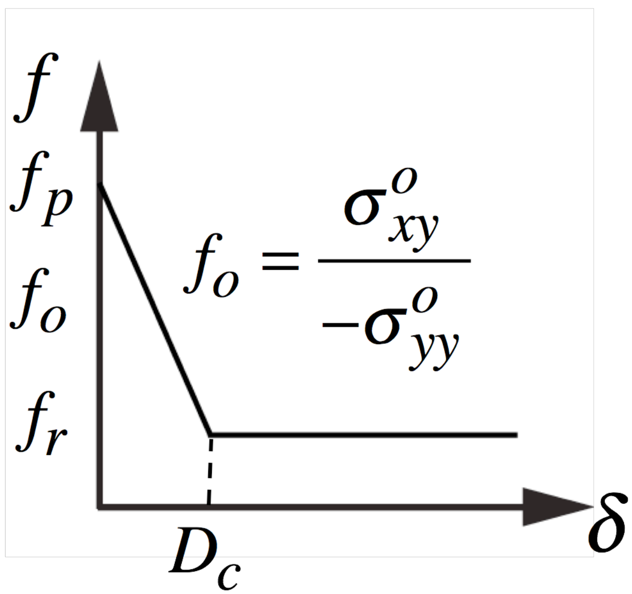

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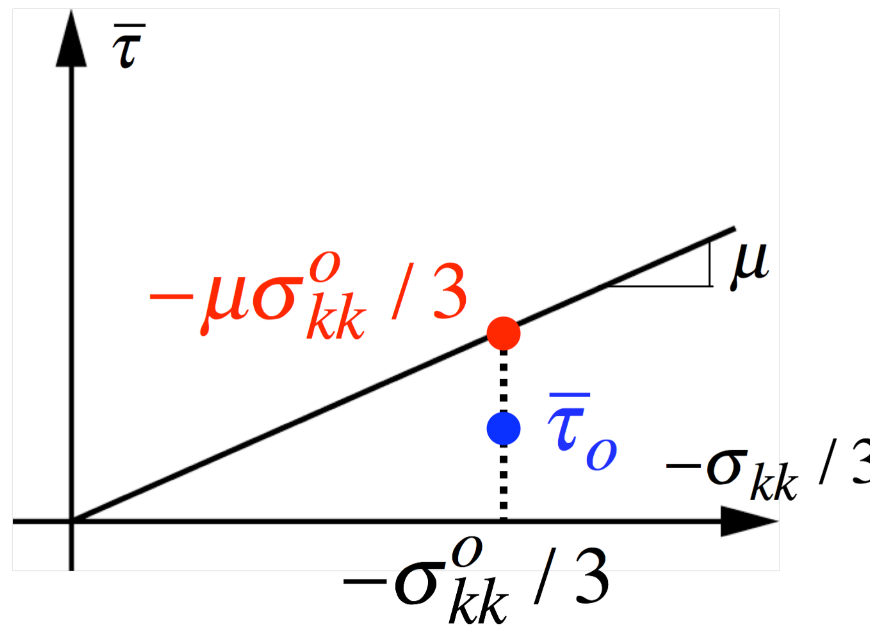
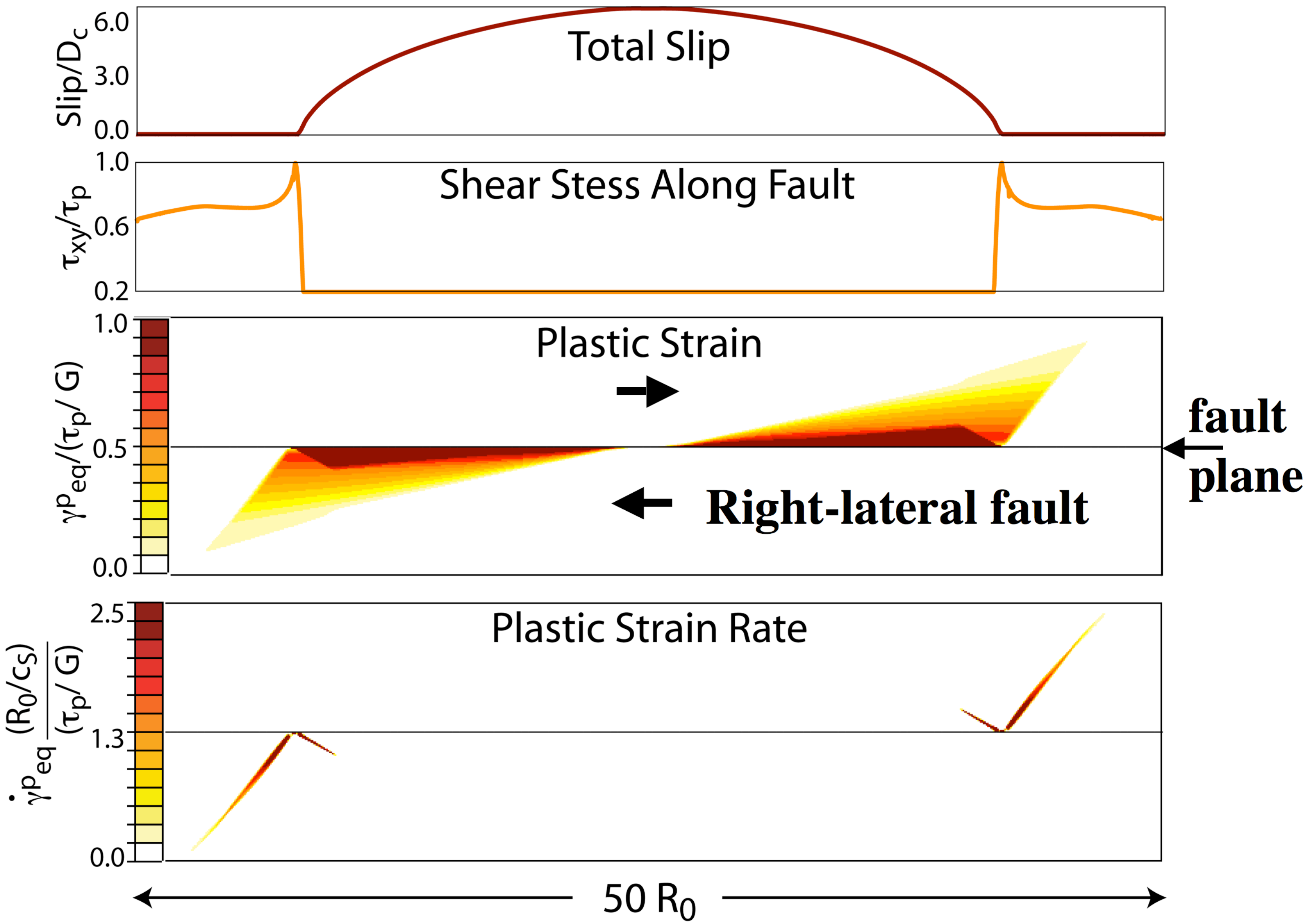


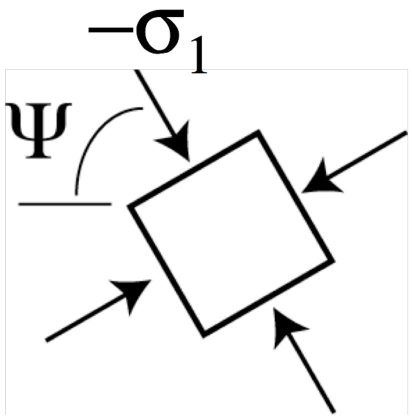
$$CF = \frac{\bar{\tau}_o}{-\mu\sigma_{kk}/3}$$

(S, *CF*, and Ψ are interdependent)

Evolution of plastic strain during rupture



Locations of plastic strain: Effect of pre-stress angle (Ψ)



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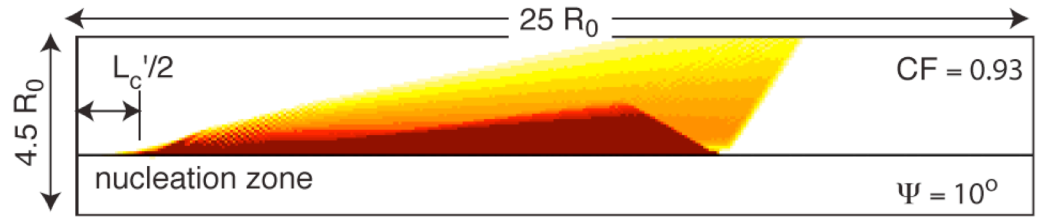

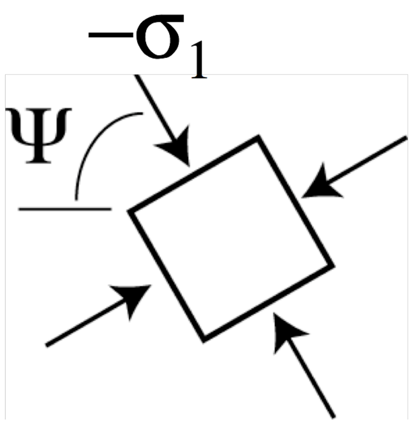

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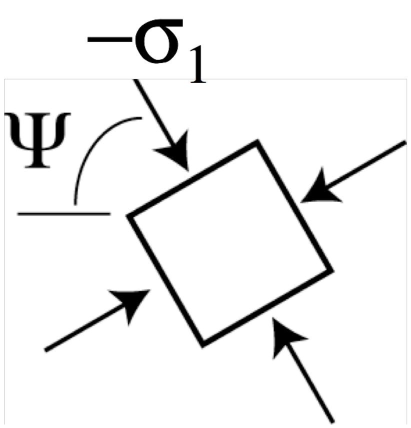
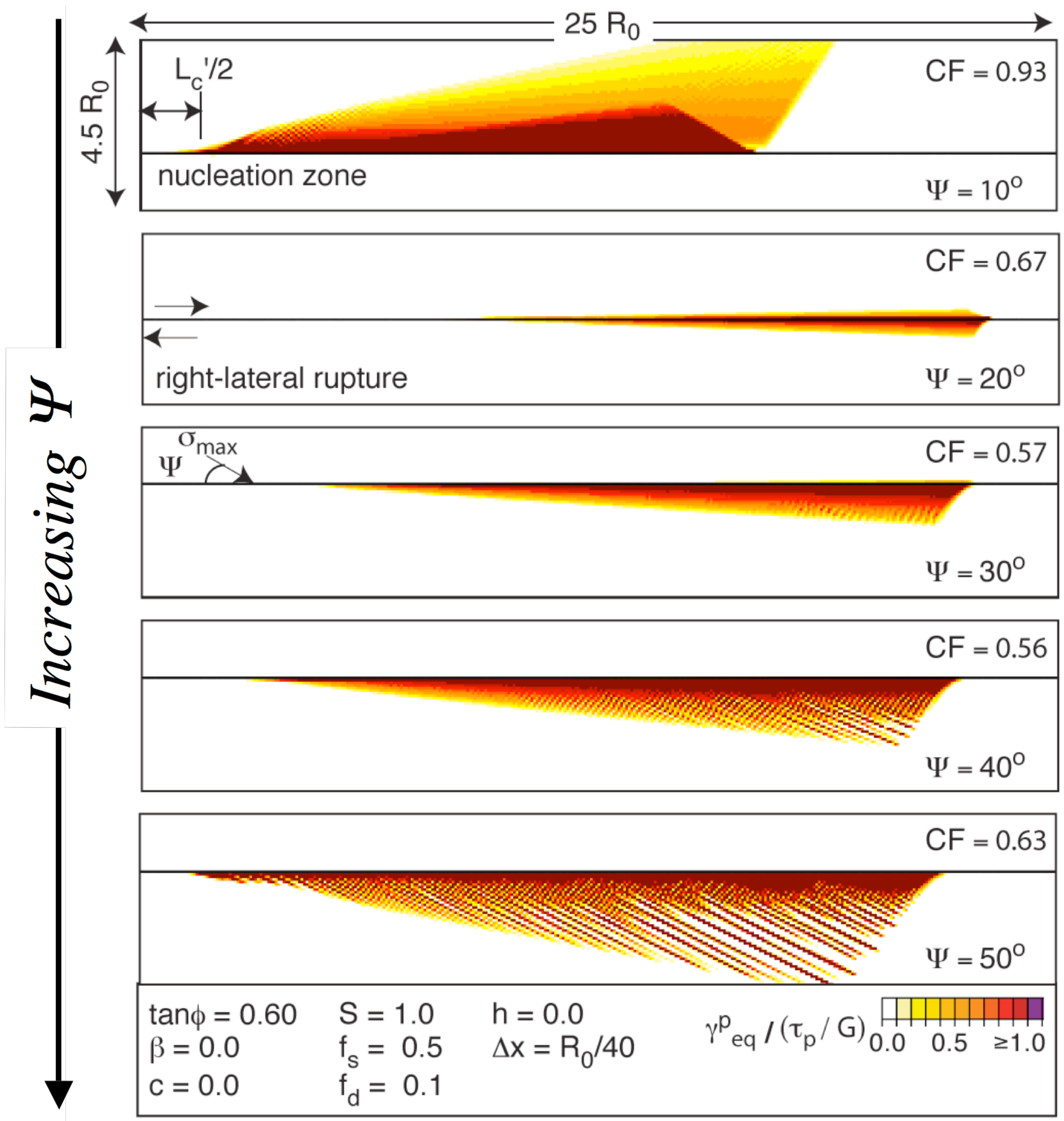
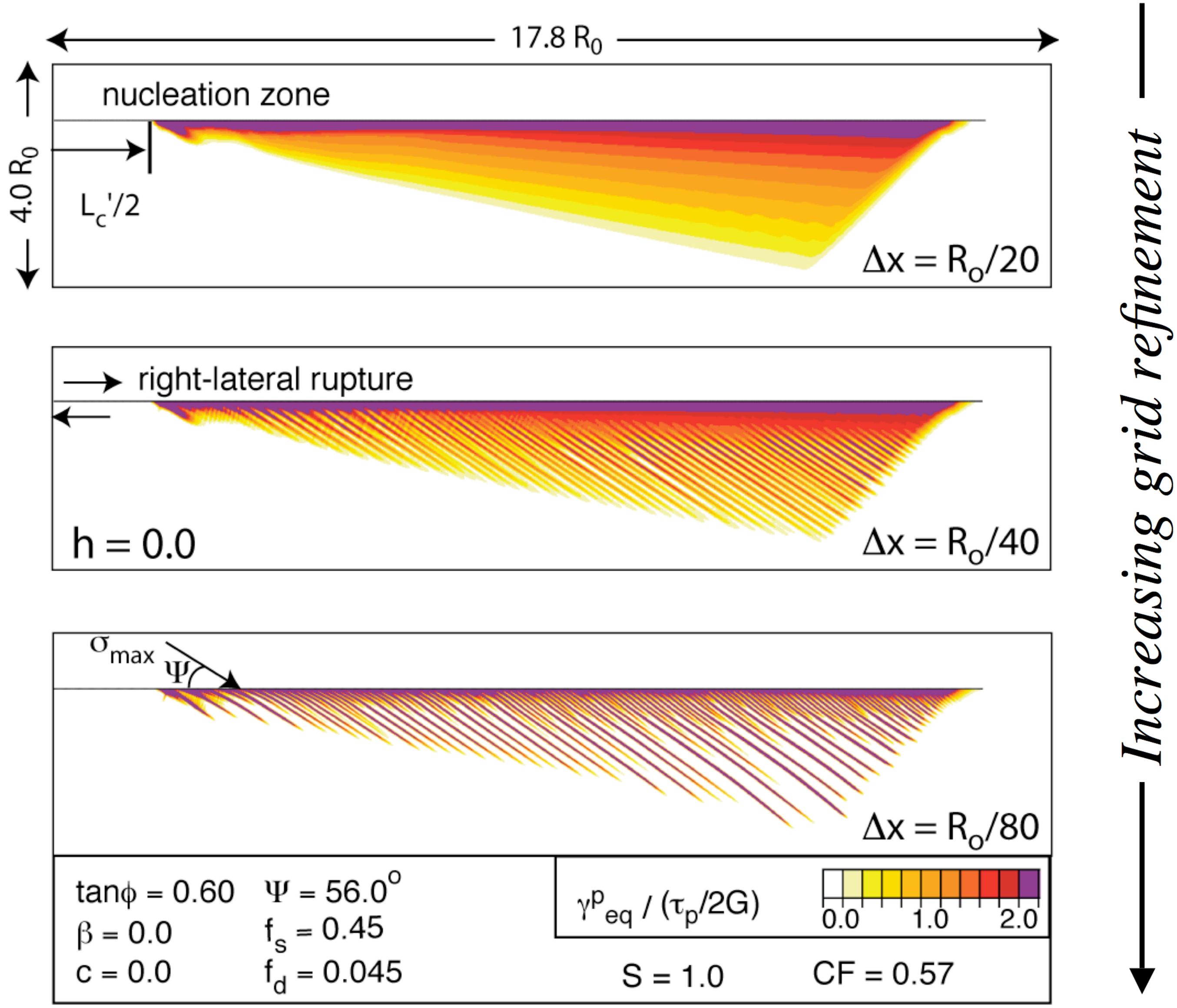




Templeton & Rice (2008)

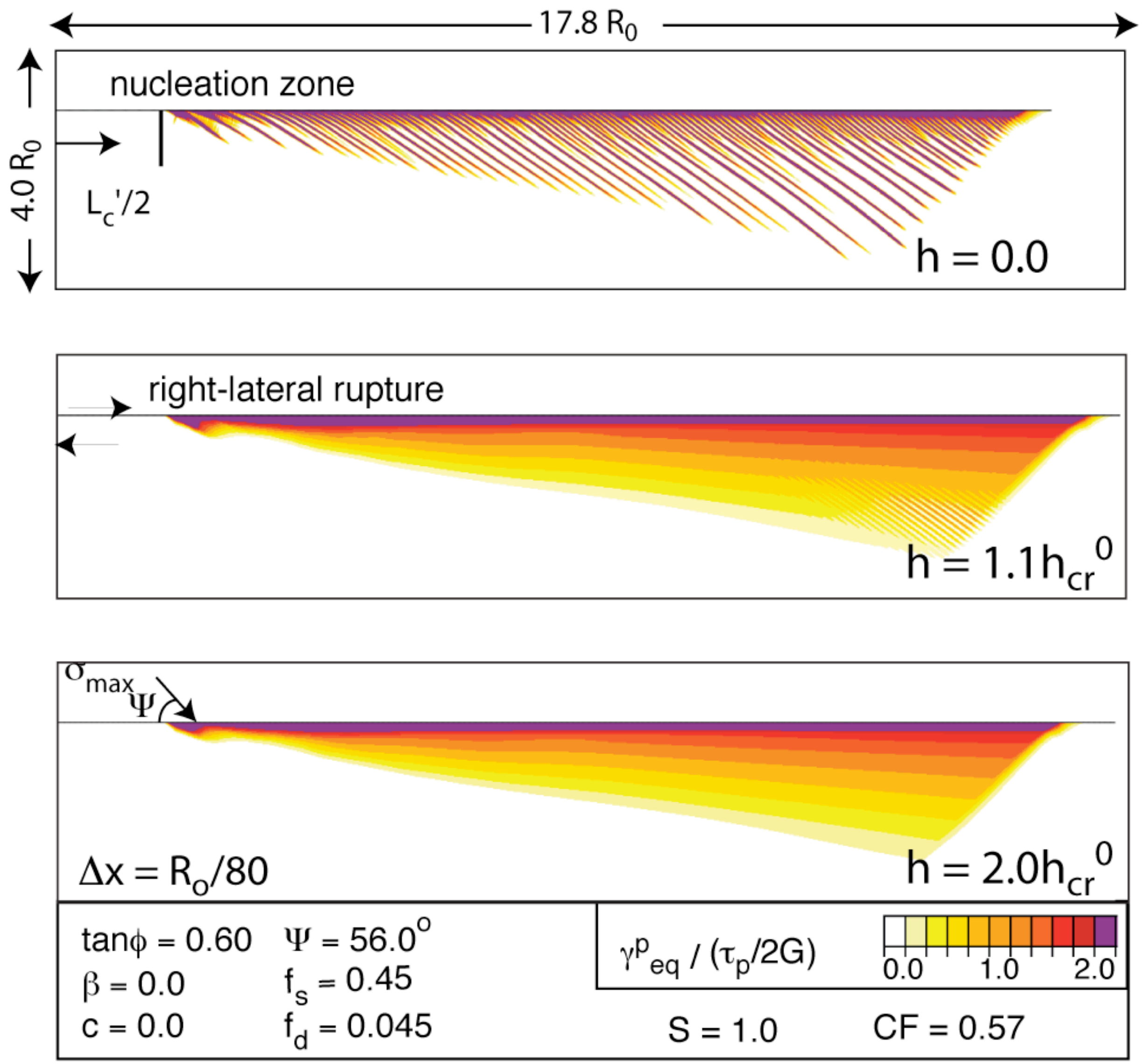
Localizations: effect of grid refinement



Templeton & Rice (2008)

Localizations: hardening eliminates features

Effects of increasing
$h > h_{cr}^{0}$
for fixed grid refinement
$\Delta x = R_0 / 80$



Increasing hardening

Templeton & Rice (2008)

How do we account for fluid saturation?

How does it affect deformation patterns?

Undrained deformation

when $\left.\dfrac{\text{stressing timescale}}{\text{diffusive timescale}}\right|_{\text{over lengthscale of interest}} << 1$

For rapid stressing of dynamic rupture, pore fluid diffusion is negligible ("undrained") down to lengths of O(mm-cm)

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Undrained *poroelastic* response:

$$\Delta p_u = -B \frac{\Delta \sigma_{kk}}{3}$$

Skempton coefficient (B), typ. 0.5–0.9

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Undrained *poroelastic* response:

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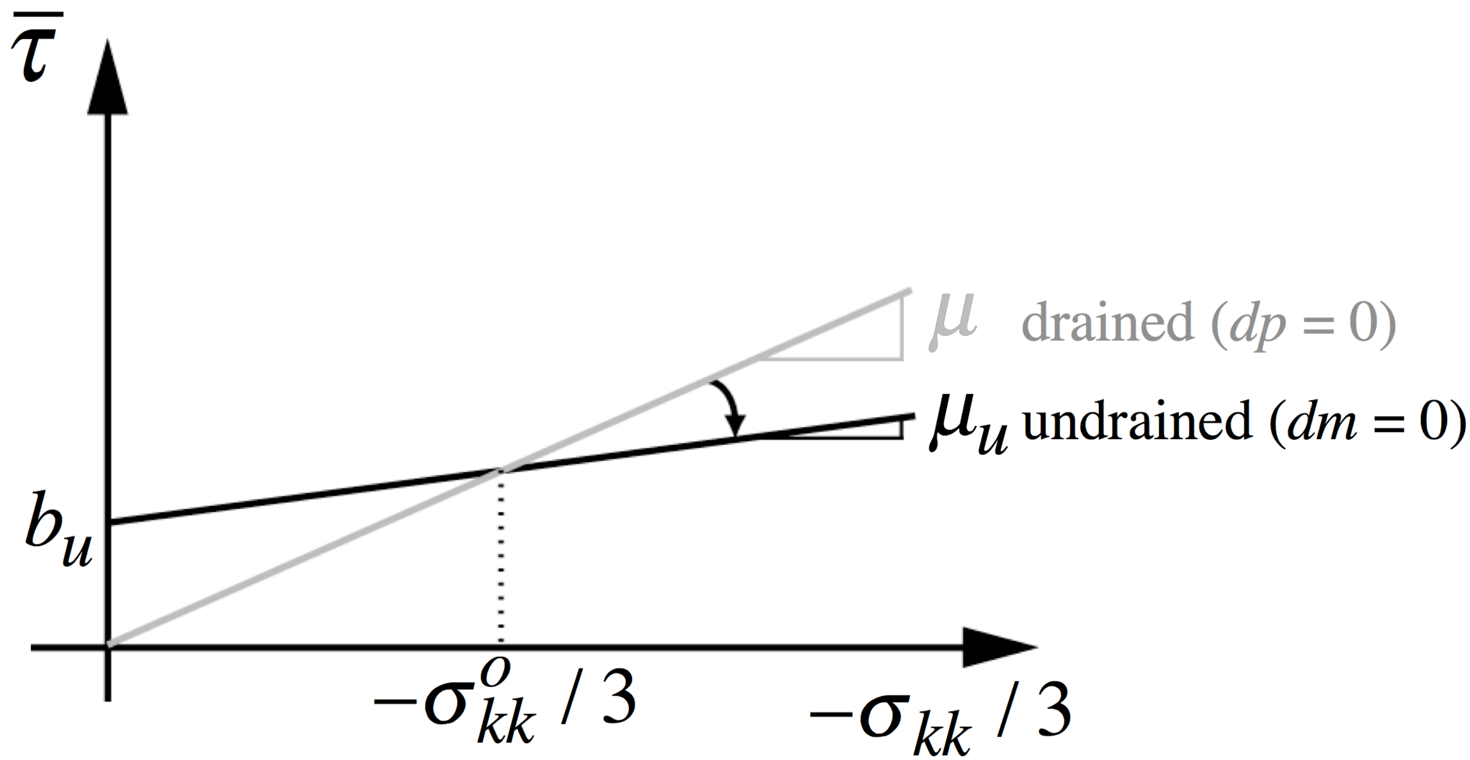
Material strength depends on effective stress

$$\bar{\sigma}_{ij} = \sigma_{ij} + p\delta_{ij}$$

Undrained deformation: Transformation of yield criterion

[e.g., Rudnicki, 2000; Viesca et al., 2008]



Undrained behavior can be characterized by

$$b \rightarrow b_u$$
$$\mu \rightarrow \mu_u$$
$$K \rightarrow K_u$$

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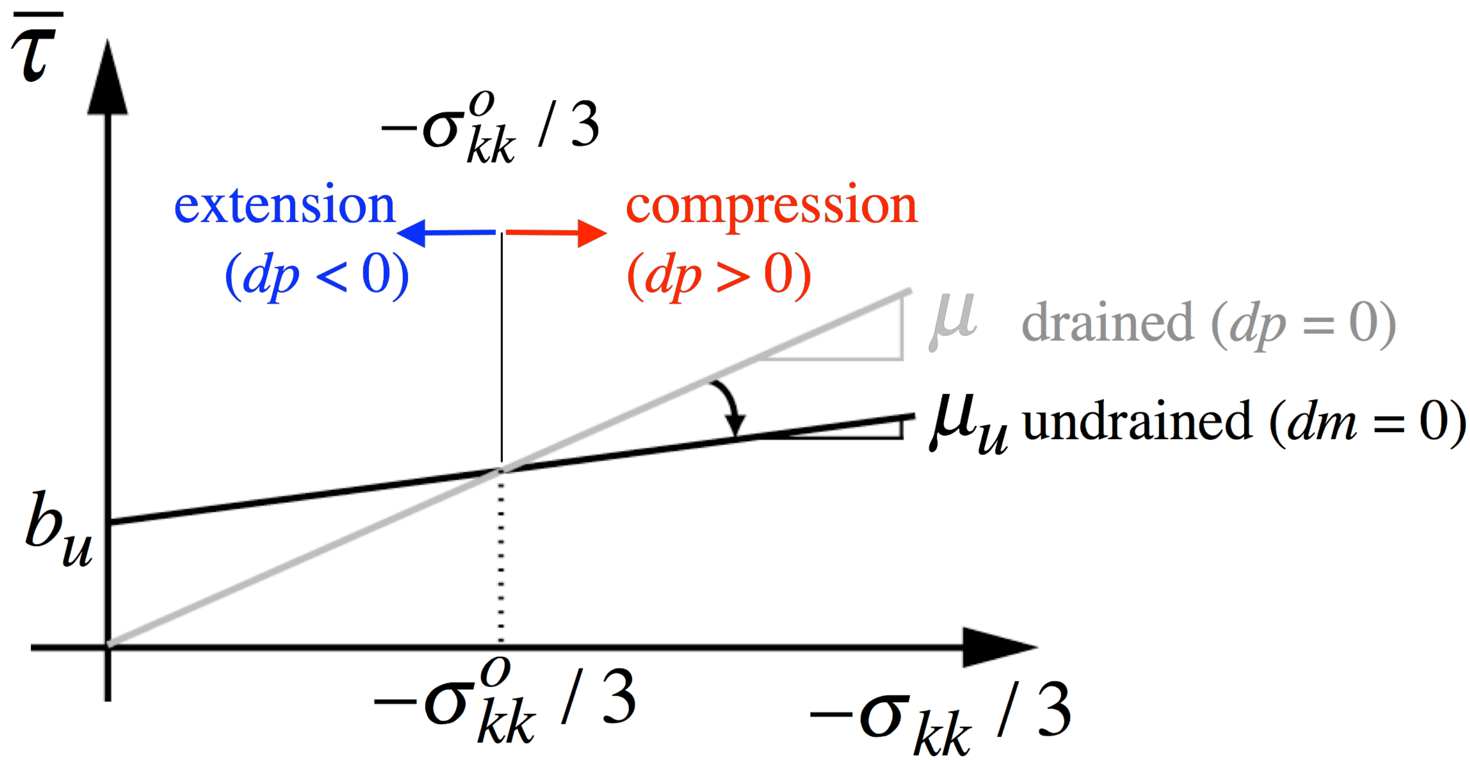

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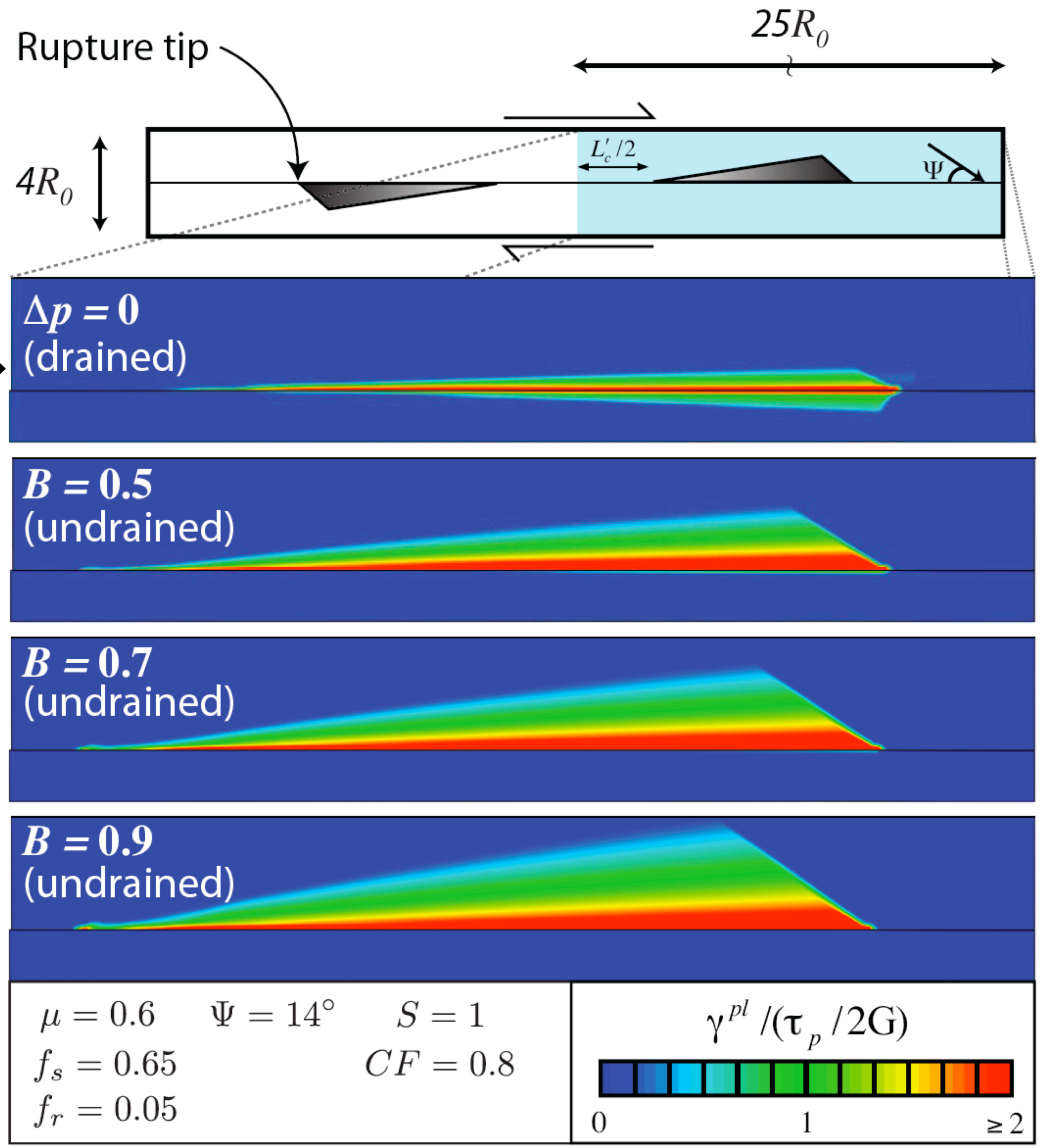
Effect of Skempton coefficient B (h = 0)



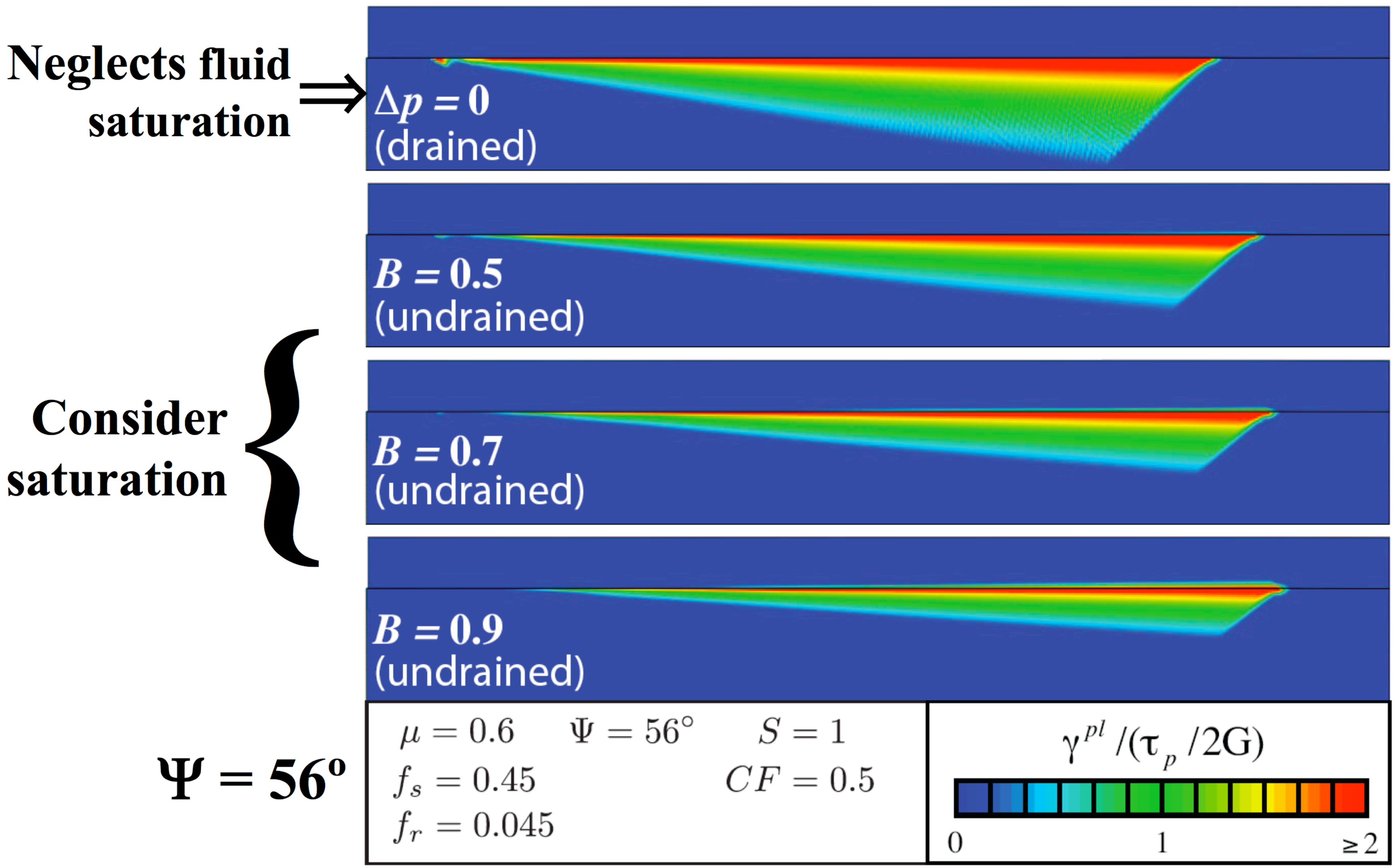
Neglects fluid saturation ⇒

Consider saturation

Ψ = 14º

Viesca et al. (2008)

Effect of Skempton coefficient B (h = 0)



Undrained deformation: Transformation of yield criterion

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Undrained poro-elastic-plastic response:

$$dp_u = -B\frac{d\sigma_{kk}}{3} - \beta\cdot(\ldots)$$

dilatancy coefficient

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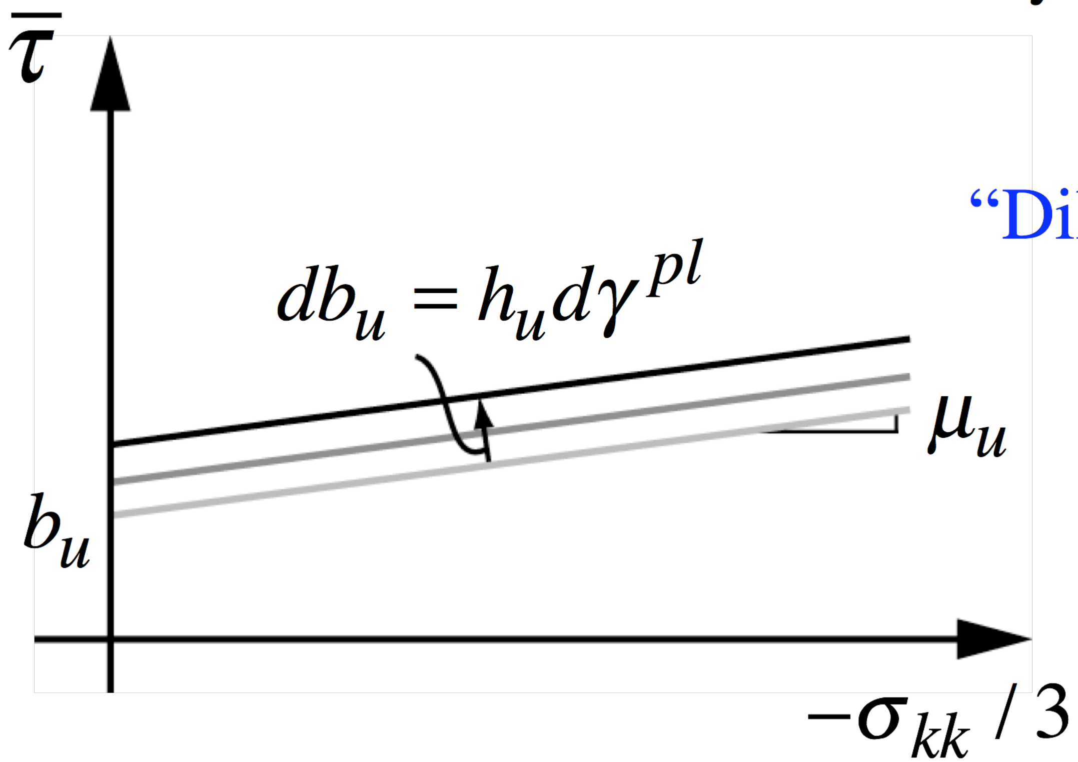
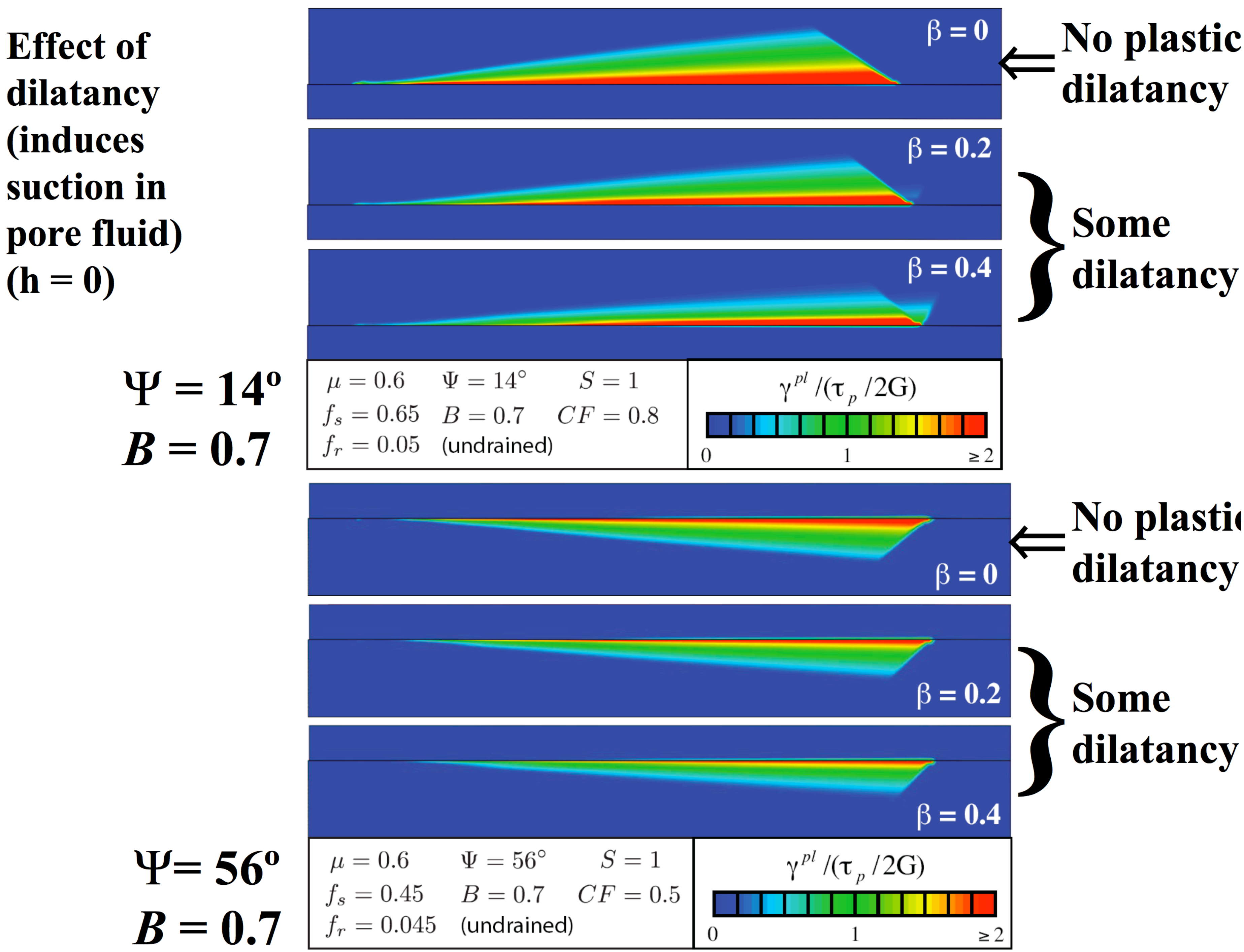


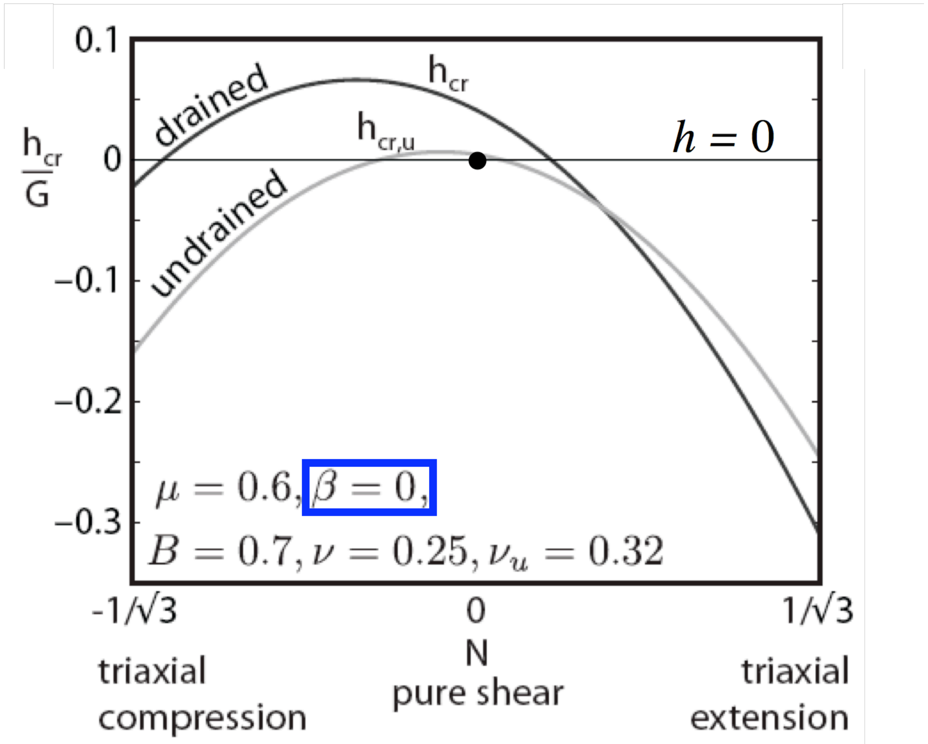
"Dilatant hardening effect"

$$h_u > h$$

for $\beta > 0$


Effect of dilatancy (induces suction in pore fluid) (h = 0)
β = 0
No plastic dilatancy
β = 0.2
β = 0.4
Some dilatancy
Ψ = 14°
B = 0.7
μ = 0.6 Ψ = 14° S = 1
f_s = 0.65 B = 0.7 CF = 0.8
f_r = 0.05 (undrained)
γ^pl /(τ_p /2G)
0 1 ≥ 2
β = 0
No plastic dilatancy
β = 0.2
β = 0.4
Some dilatancy
Ψ= 56°
B = 0.7
μ = 0.6 Ψ = 56° S = 1
f_s = 0.45 B = 0.7 CF = 0.5
f_r = 0.045 (undrained)
γ^pl /(τ_p /2G)
0 1 ≥ 2

Suppression of localization



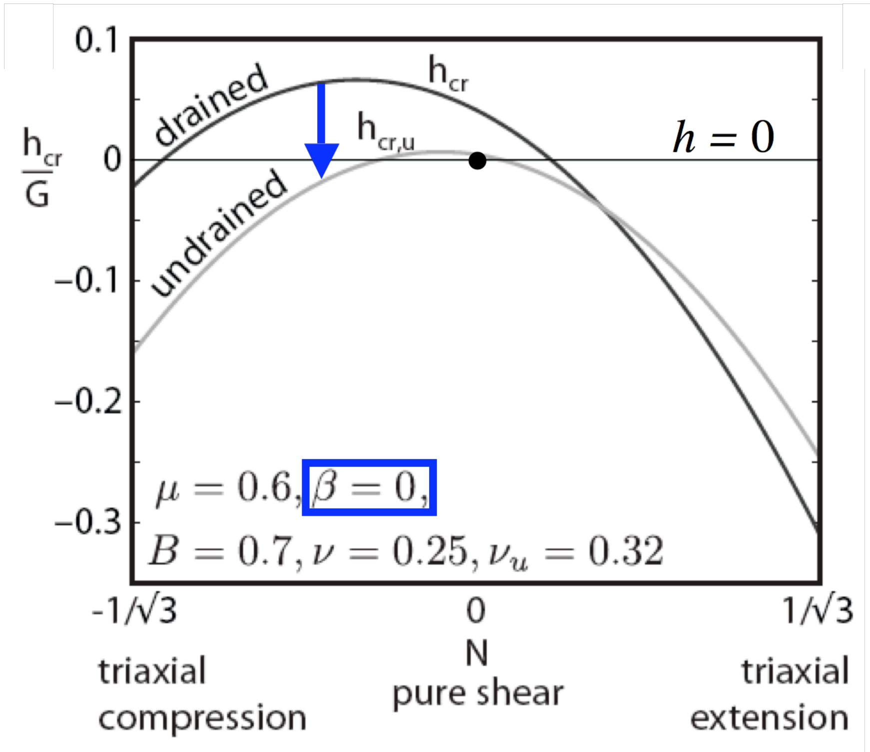
No plastic dilatancy

Rudnicki and Rice (1975): **A critical hardening h_{cr} exists below which localization is expected to occur**.

In our simulations: ***h* = 0**

Viesca et al. (2008)

Suppression of localization



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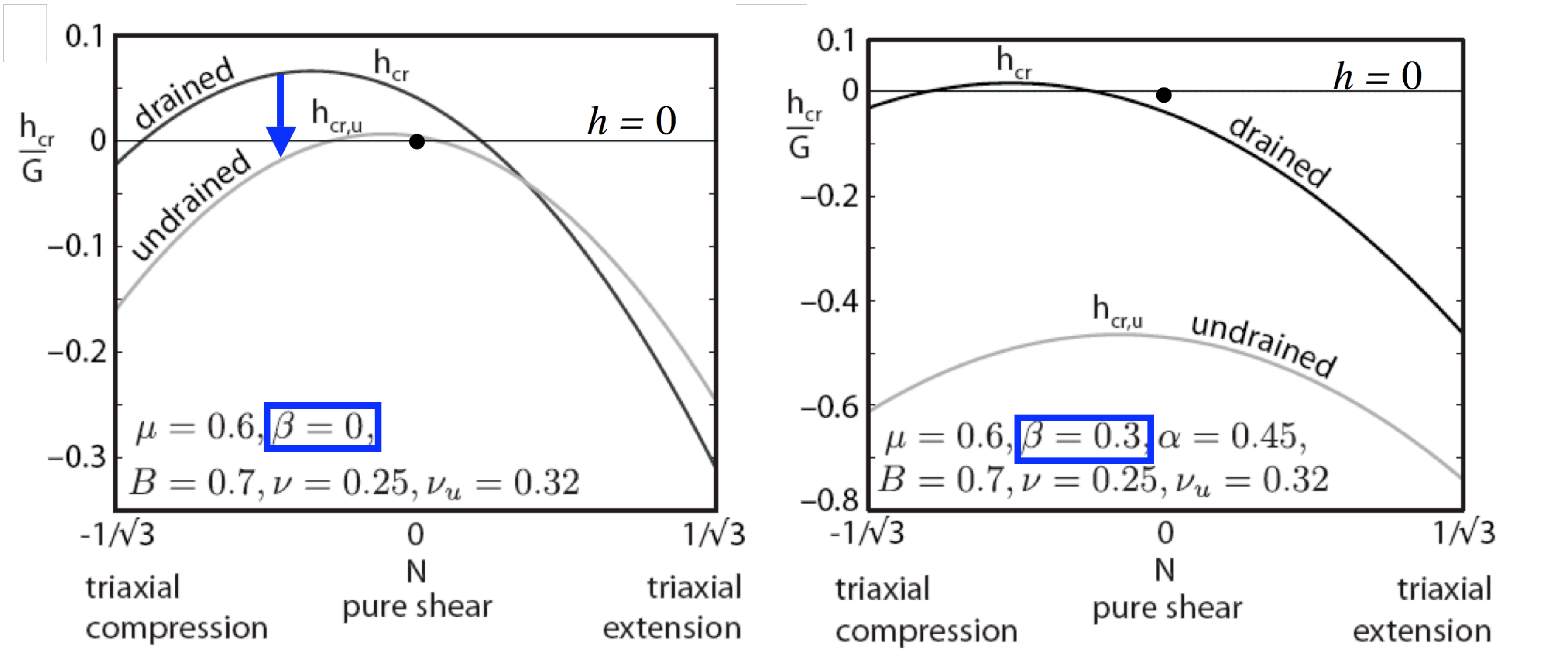
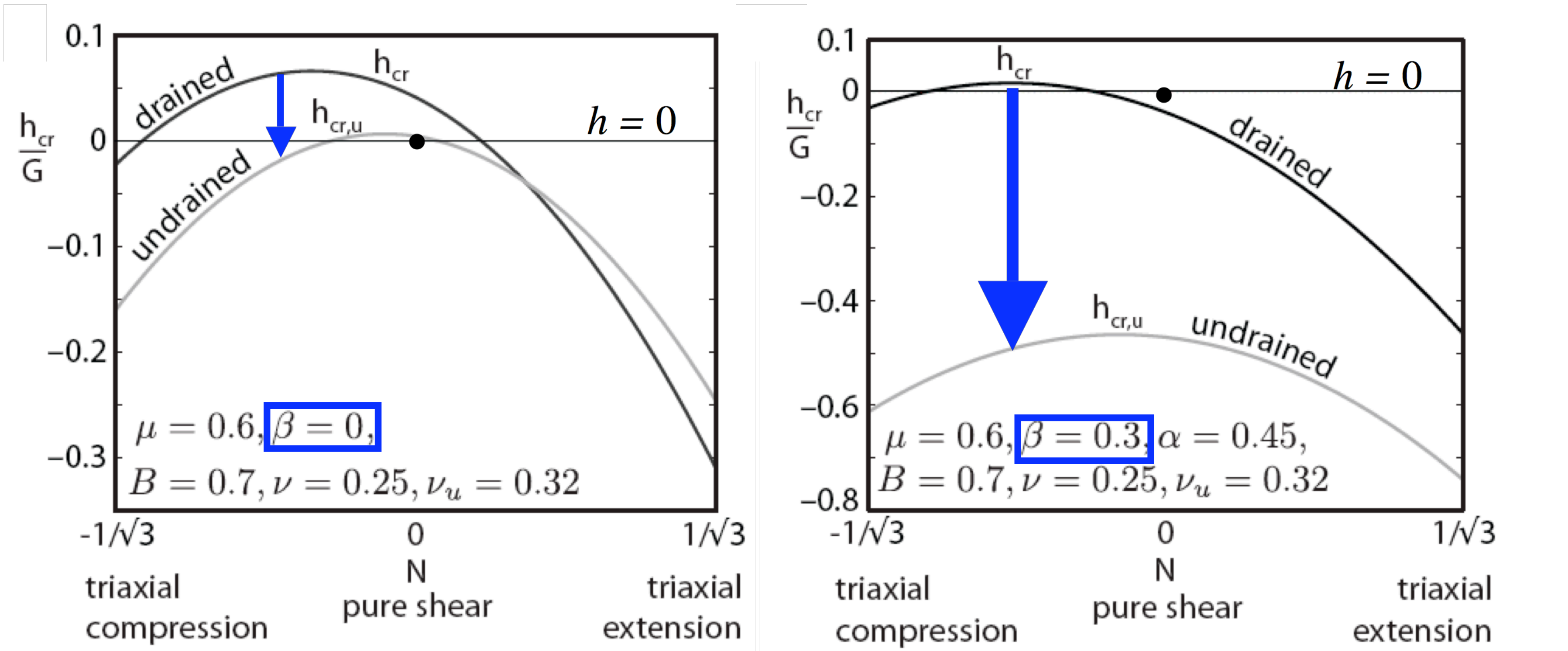


Viesca et al. (2008)

No plastic dilatancy **With plastic dilatancy**

Dilatancy limits localization.

Suppression of localization



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No plastic dilatancy **With plastic dilatancy**

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What happens at the slipping surface?

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Previously, we neglected pore pressure change on slip surface

$$\tau = -f(\delta)(\sigma_{yy} + p_s)$$

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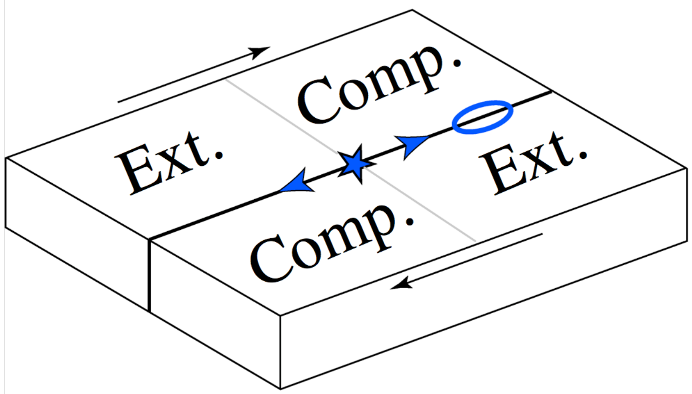
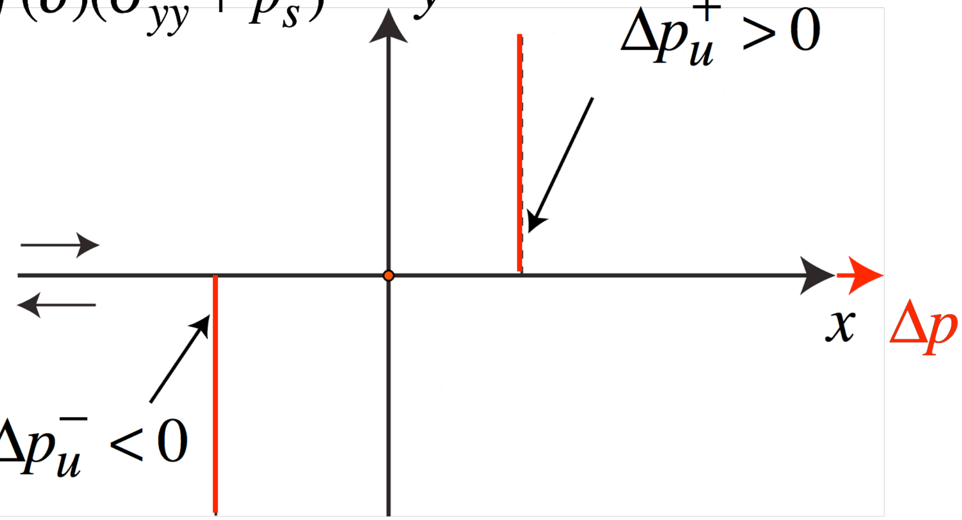
compression

$\varepsilon_{kk} < 0$





extension

$\varepsilon_{kk} > 0$

Undrained conditions → discontinuity in pore pressure at slip surface

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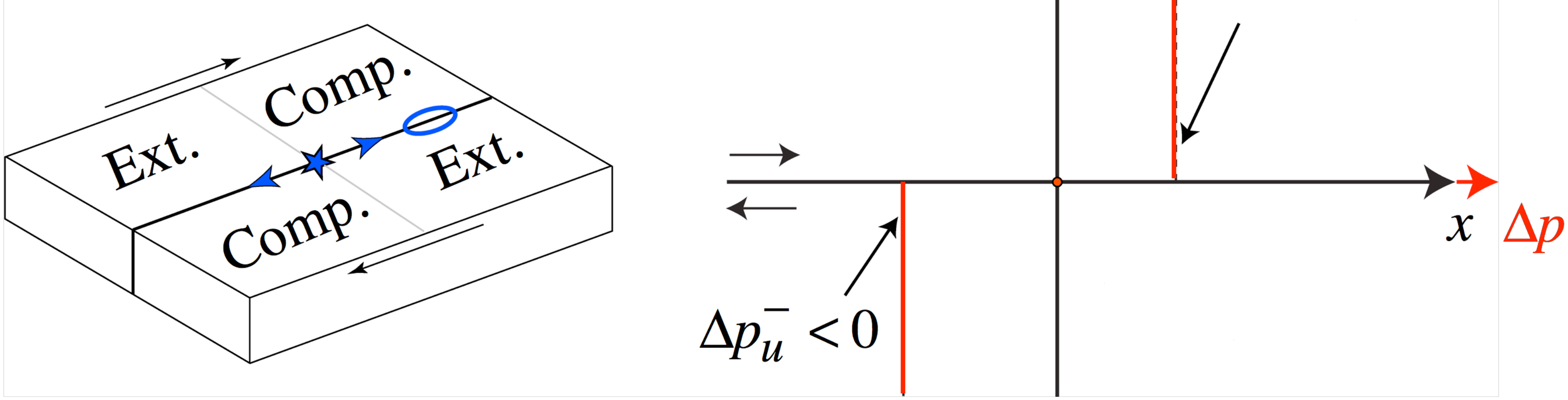
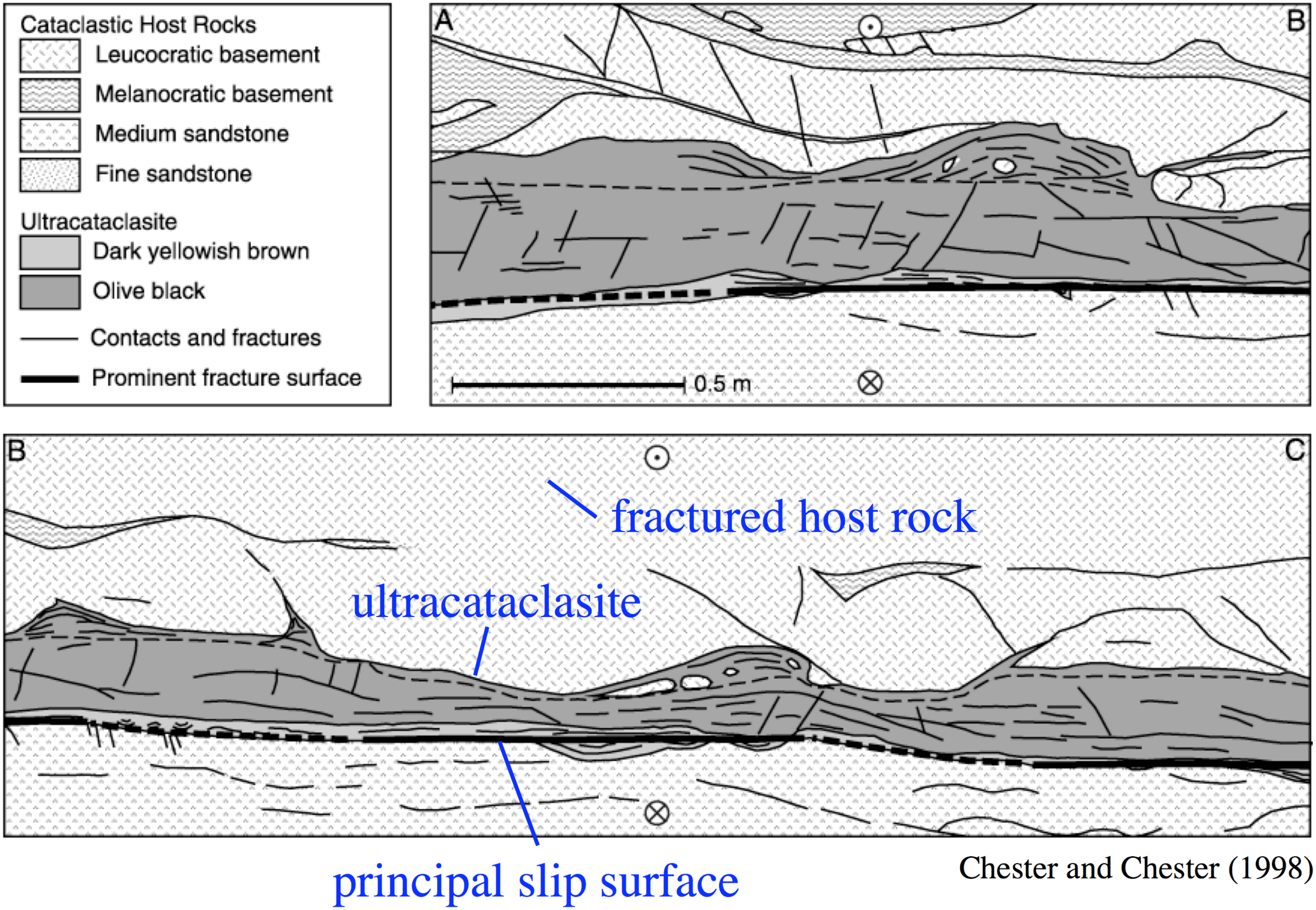


Undrained conditions → discontinuity in pore pressure at slip surface

However, pore pressure should be continuous.

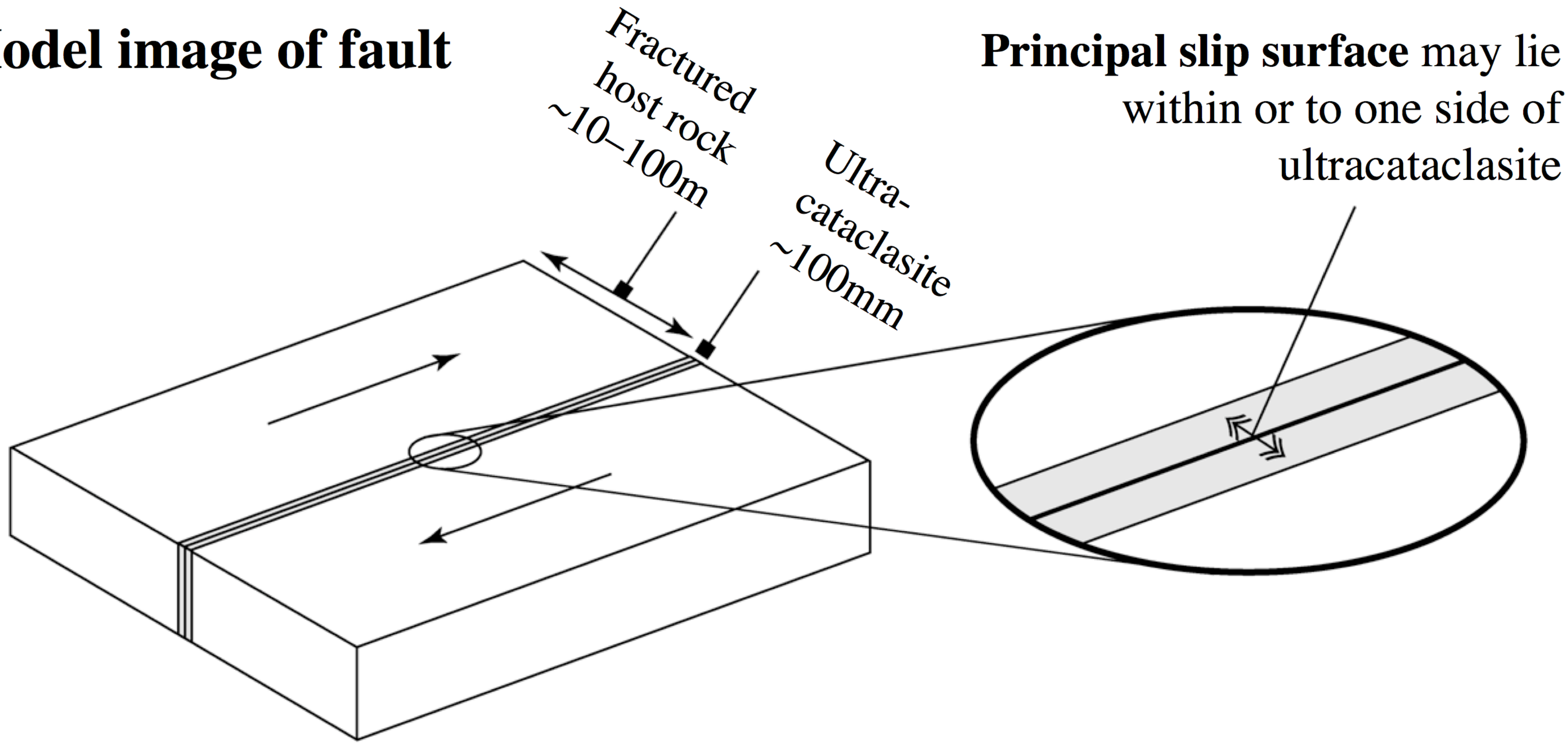
Will that lead to a pressure decrease or increase on the surface?
(strengthening) (weakening)

Fault observations: material surrounding principal slip surface



Chester and Chester (1998)

Model image of fault



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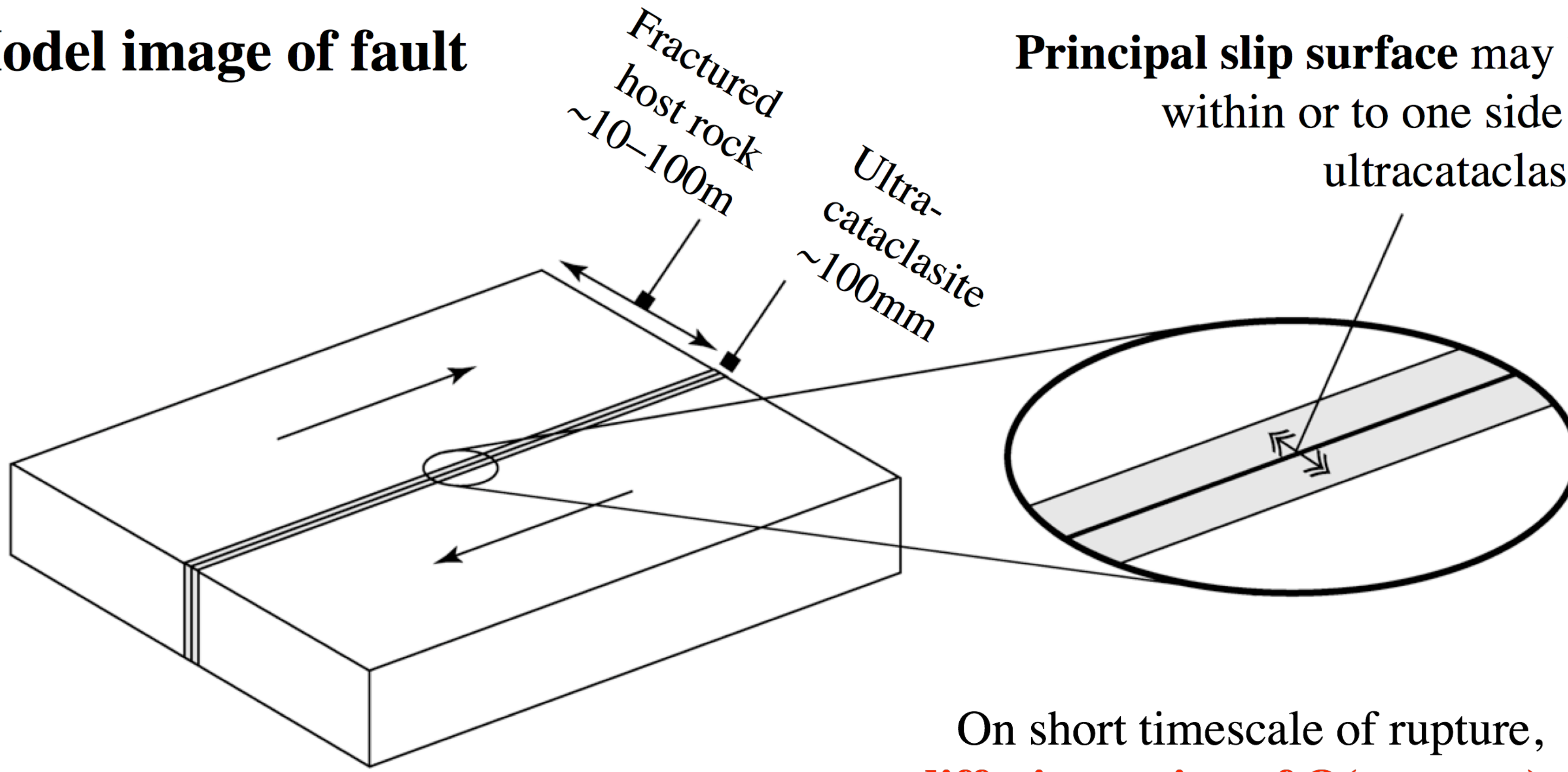
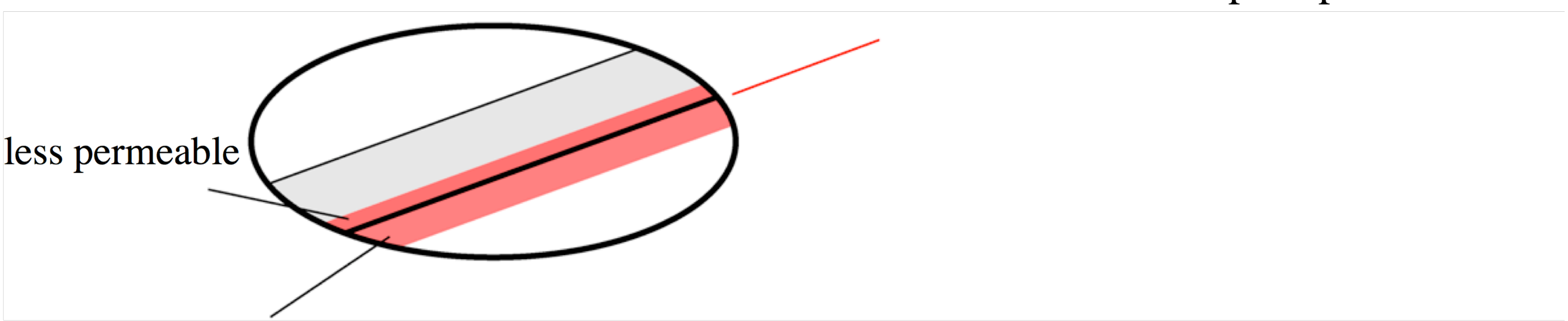


On short timescale of rupture, **diffusive region of O(mm–cm)** contributes to surface pore pressure

Slip surface localized to one side:



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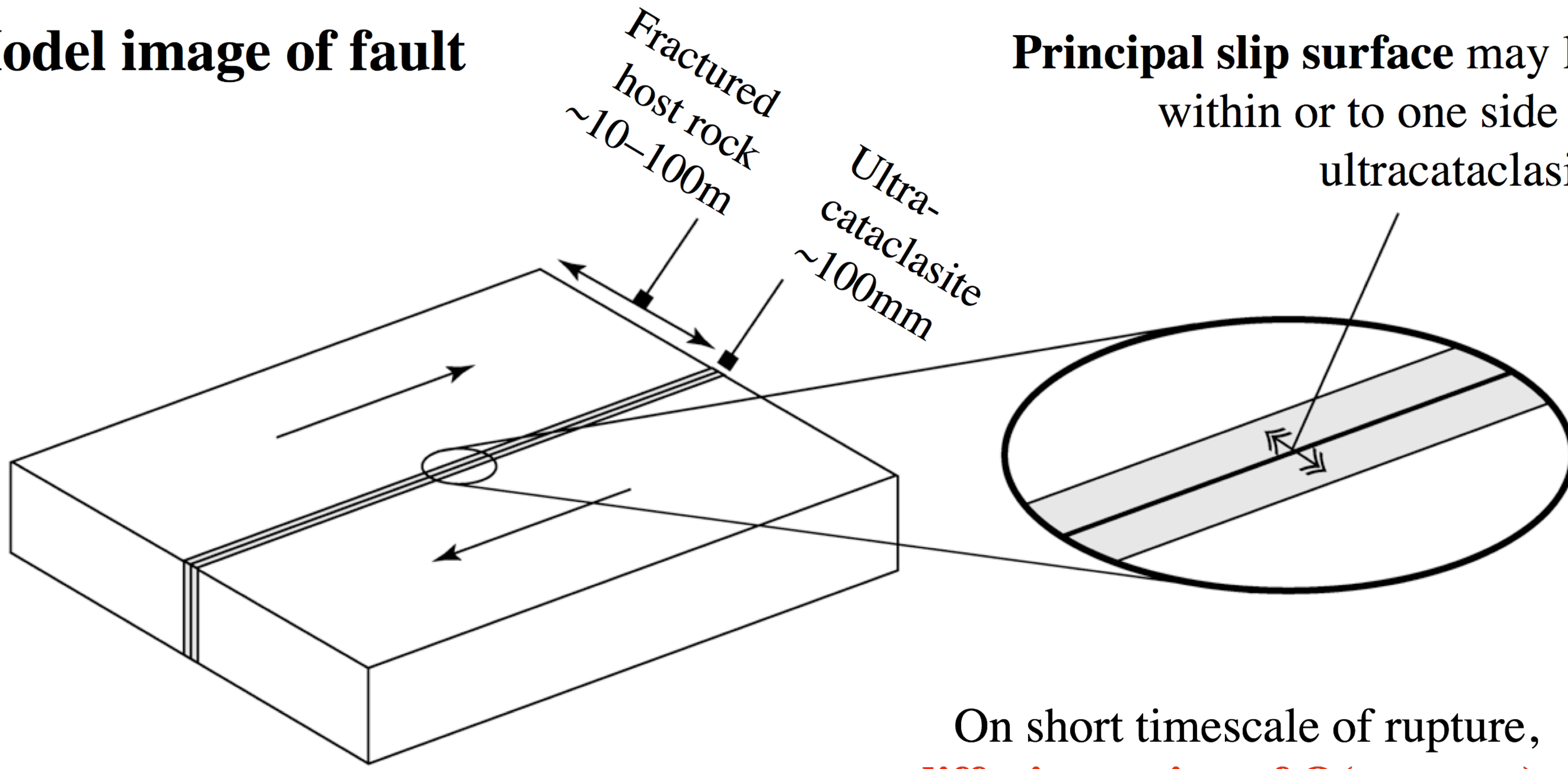

Principal slip surface may lie within or to one side of ultracataclasite

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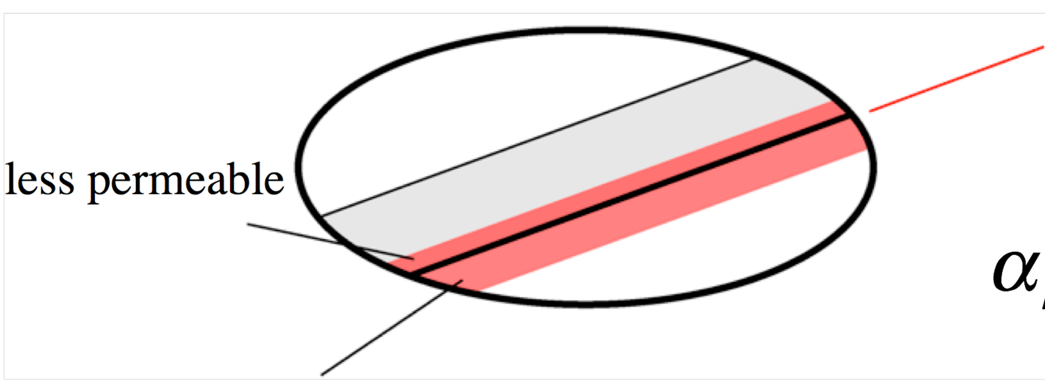


region size $\sim \sqrt{\alpha_{hy} t}$

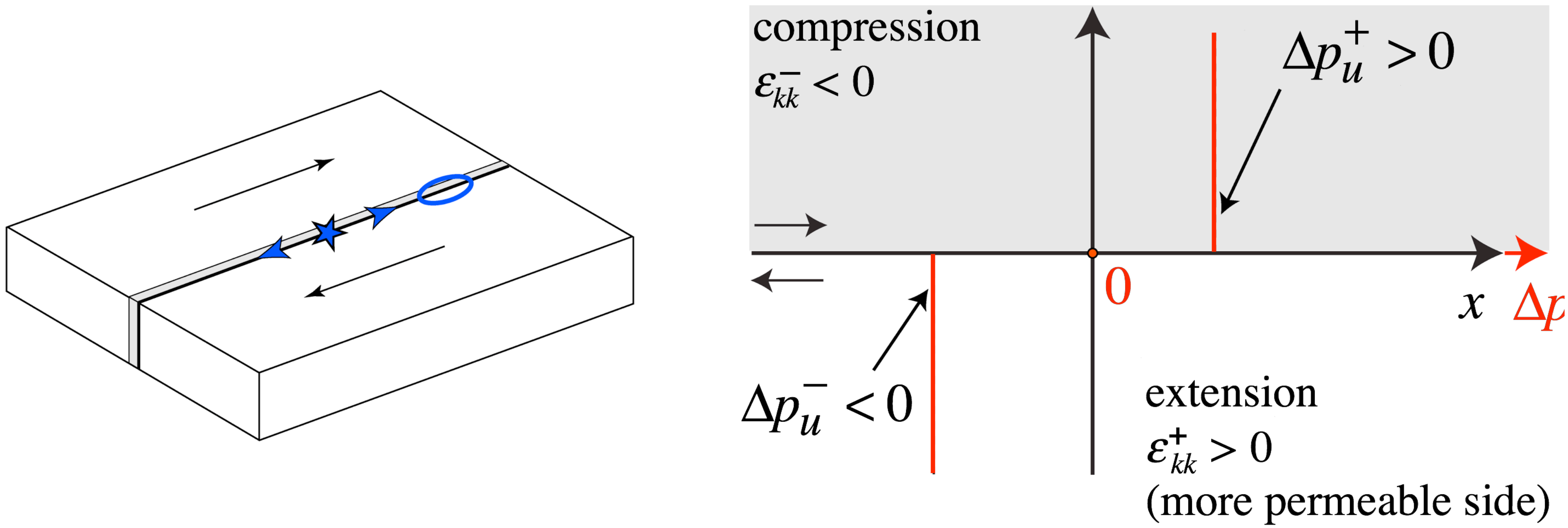
$$\alpha_{hy} = \frac{k}{\eta \beta_{stor}}$$

k — permeability

η — viscosity

β_{stor} — storage (compressibility)

Effects of near-fault fluid flow: poroelastic material



modified from Dunham and Rice (2008)

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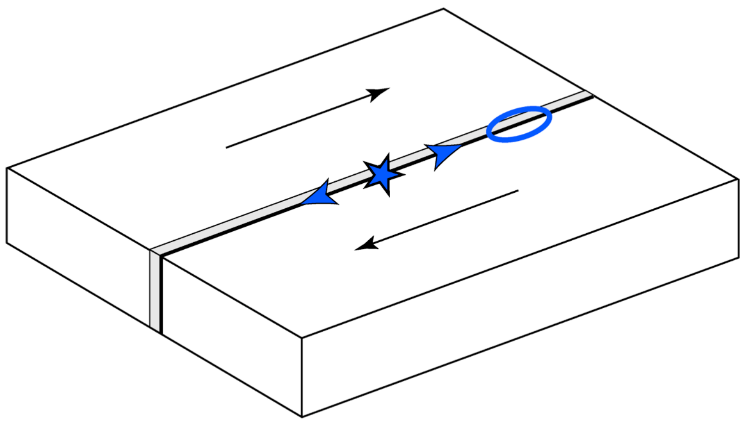
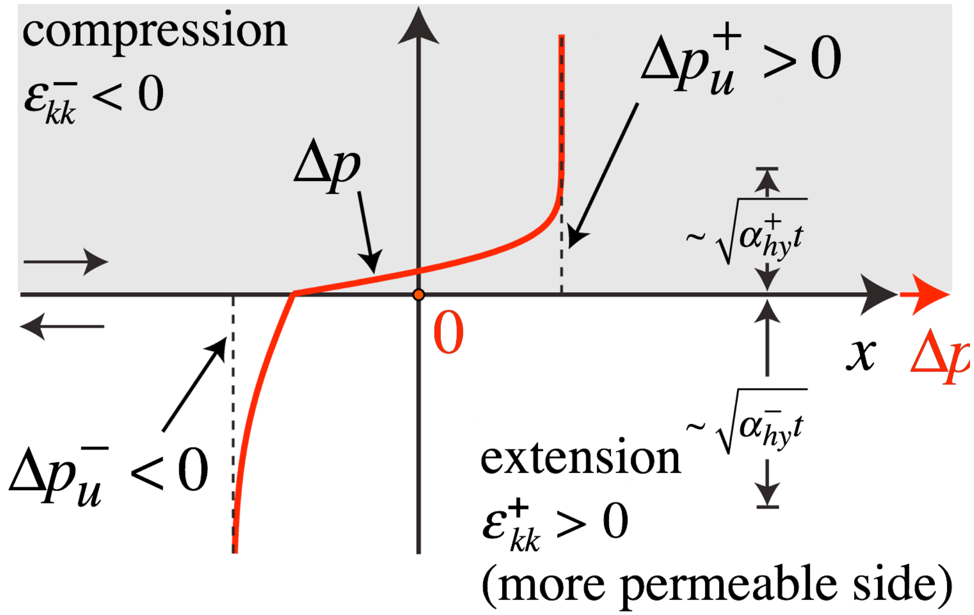


More permeable side wins:
its extension induces suction
(strengthening)



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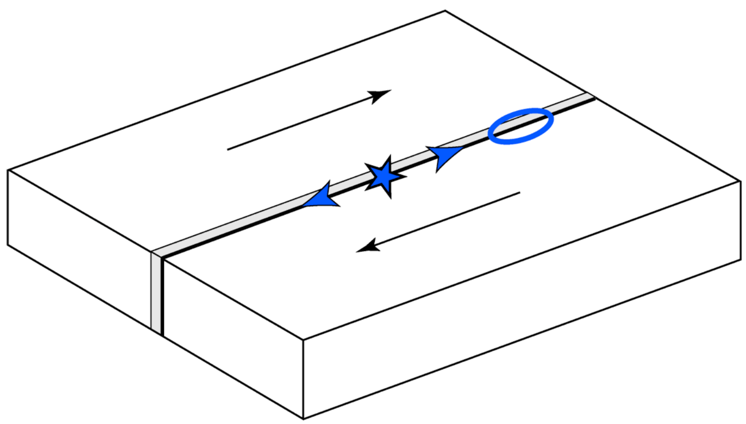

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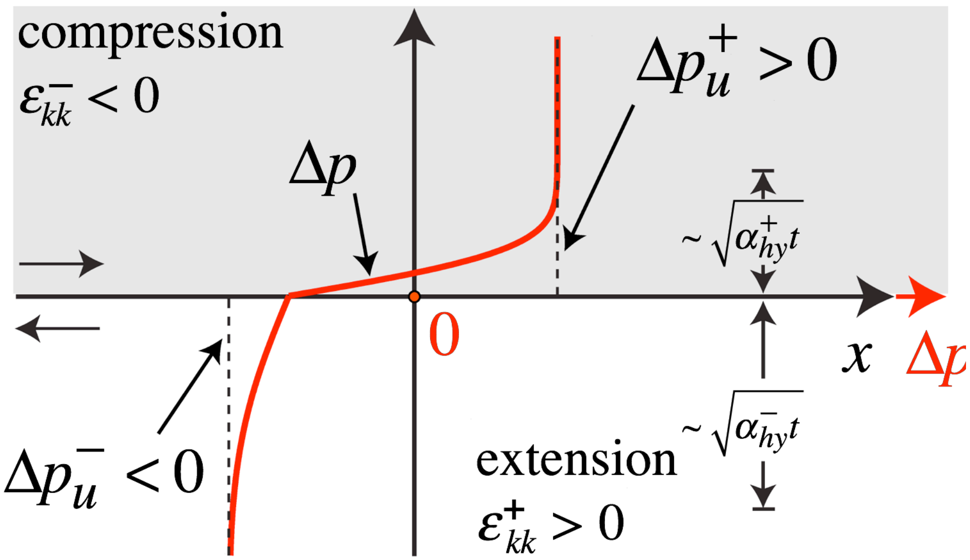


modified from Dunham and Rice (2008)

Pore pressure on the surface:

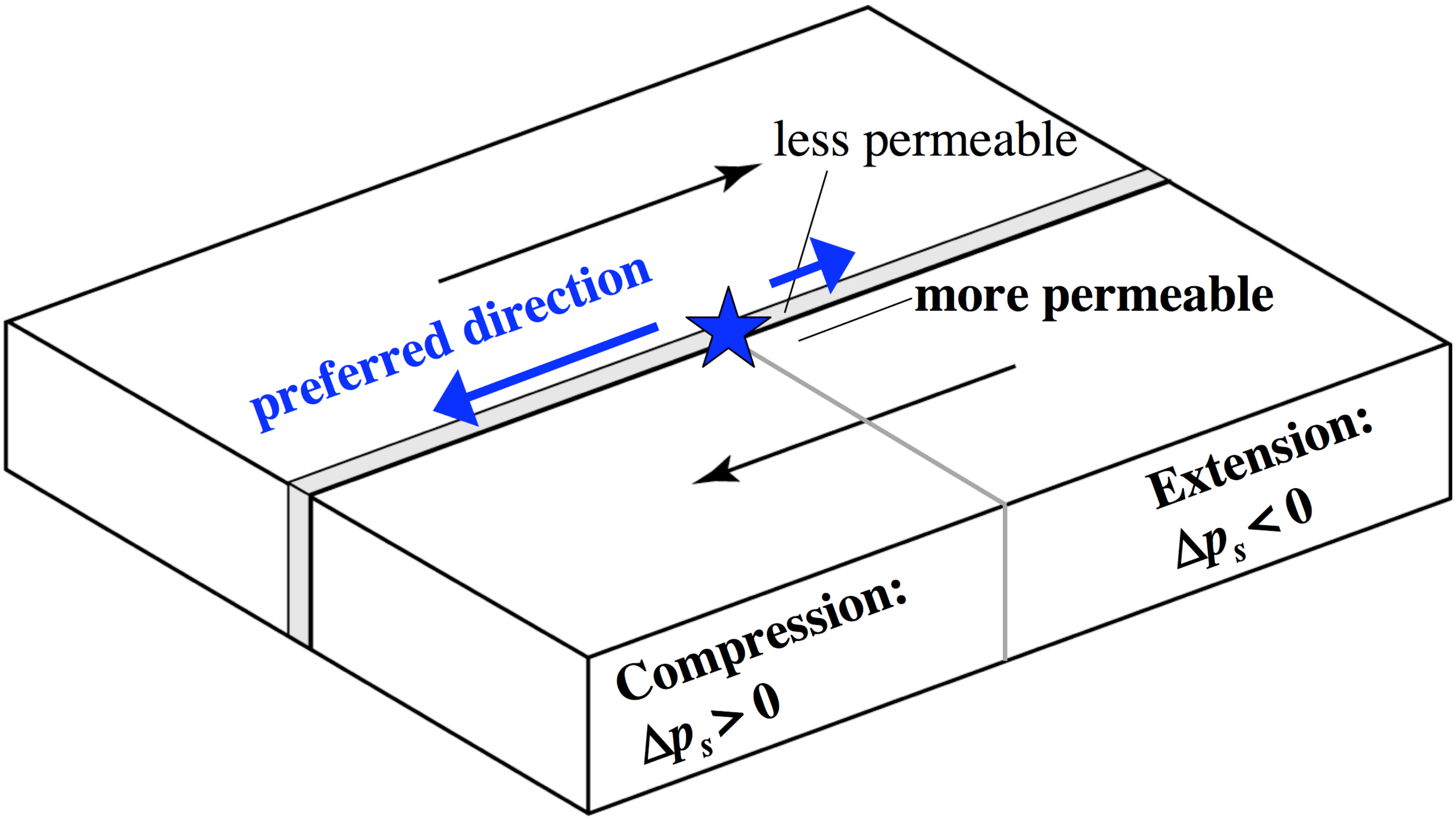
$$\Delta p_s = \zeta^{+} \Delta p_u^{+} + \zeta^{-} \Delta p_u^{-}$$

(Rudnicki and Rice 2006)

where $\Delta p_u^{\pm} = -B^{\pm} \dfrac{\Delta \sigma_{kk}^{\pm}}{3}$

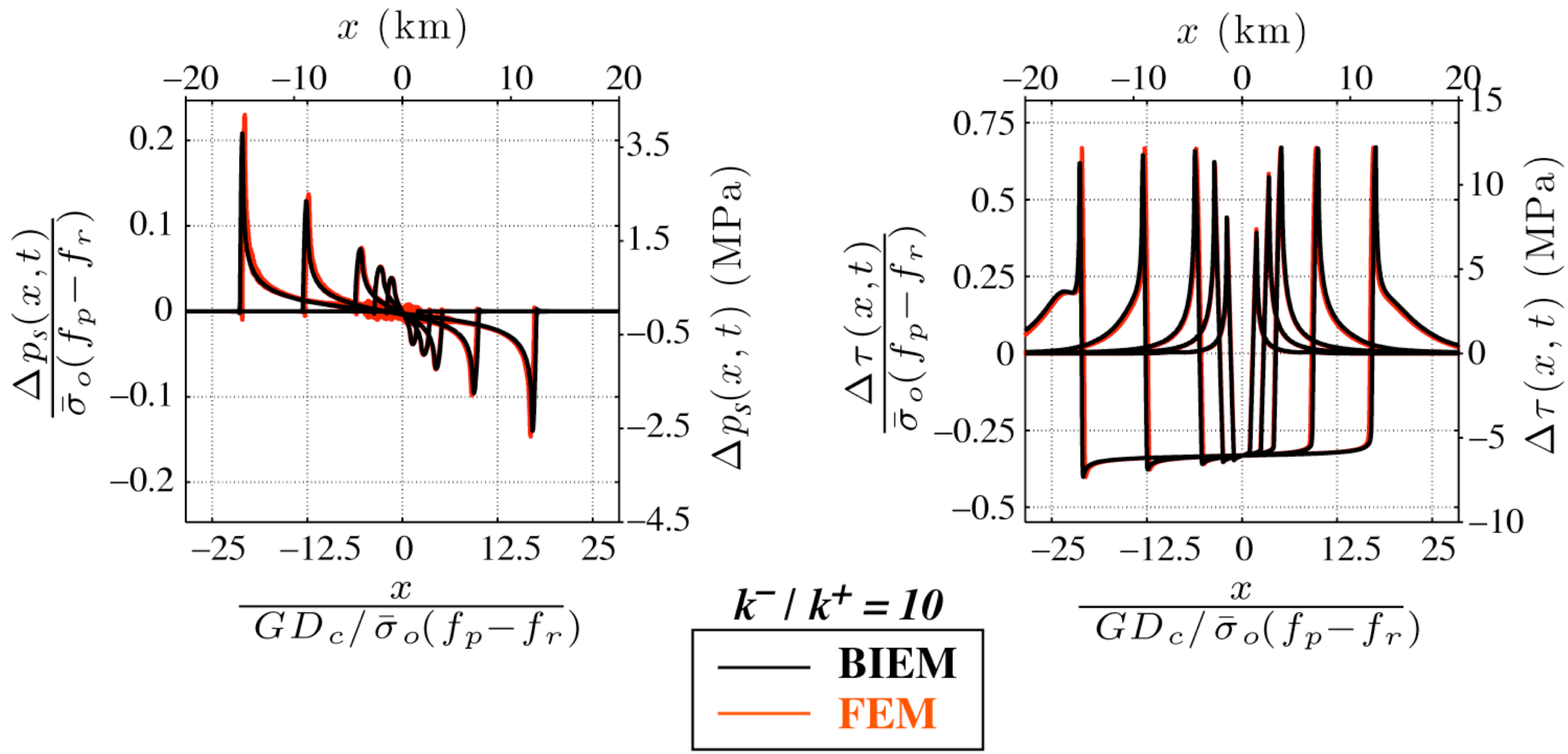
and $\zeta^{\pm}$ are weights determined by contrast in permeability, k, and storage coefficient β_{stor}^{el}

Permeability contrast induces preferred rupture direction



Dynamic plane-strain poroelastic rupture: snapshots in time

pore pressure change ***shear stress change***



BIEM from Dunham & Rice (2008)

Here, contrast in permeability leads to rupture direction preference.

Accounting for plastic deformation near slip surface

May increase permeability k by order(s) of magnitude:

e.g., Mitchell and Faulkner (2008): triaxial tests w/ variable confinement:

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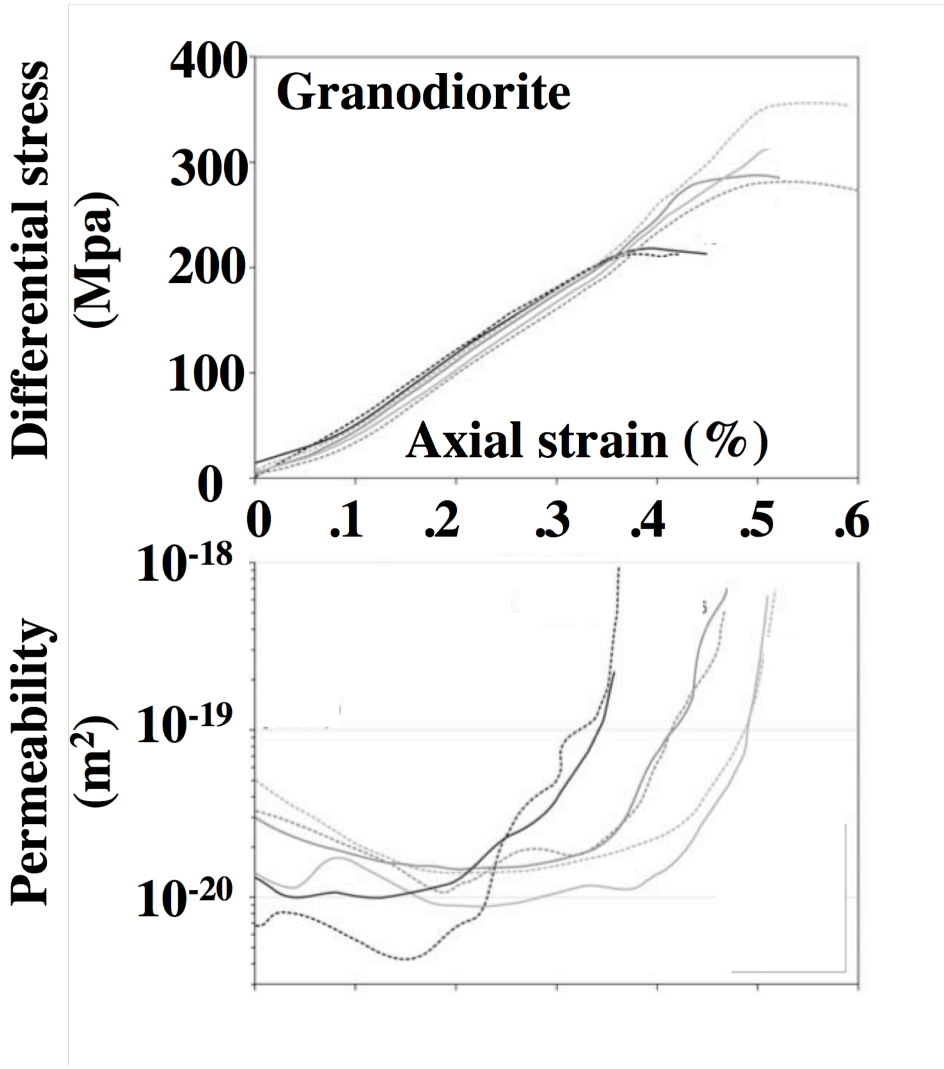

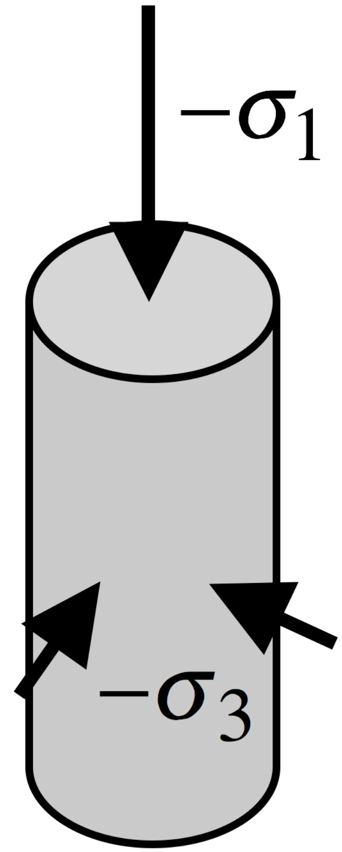

Differential stress:

$$-(\sigma_1 - \sigma_3)$$

Accounting for plastic deformation near slip surface

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Decreases undrained pore pressure increments:

$dp_u = - B d\sigma_{kk}/3$ – **effects of plastic dilatancy (β)**

Accounting for plastic deformation near slip surface

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With simplifications, find similarity to poroelastic case

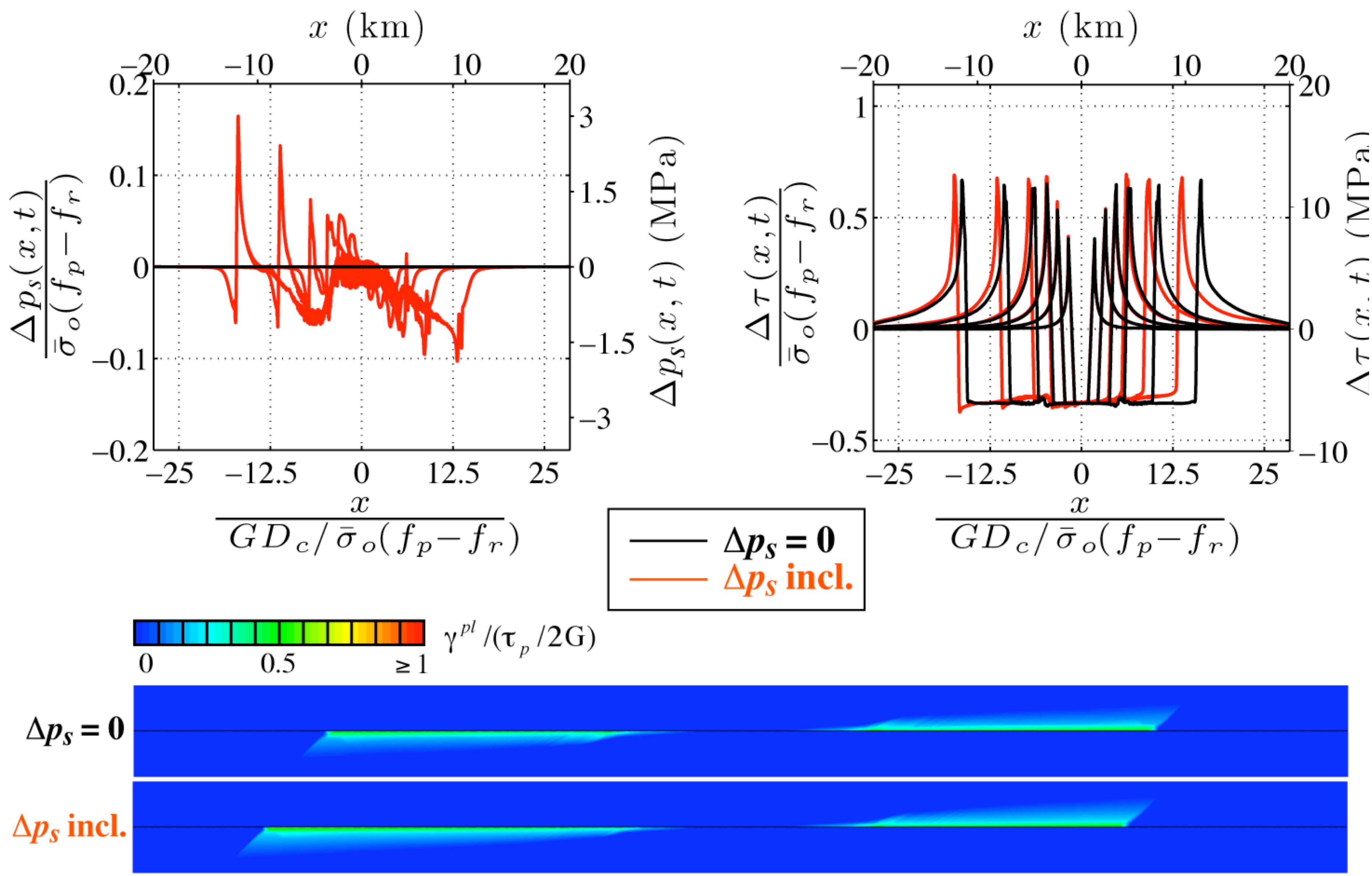
$$\alpha_{hy}^{pl}(t) = \frac{k(t)}{\eta \beta_{stor}^{pl}}$$

Viesca & Rice (2009, proceedings in press)

Next, approximate surface pore pressure accounting for some of the above (here neglect evolution of k)

using weighting similar to poroelastic case: $dp_s = \xi^+ dp_u^+ + \xi^- dp_u^-$

Does plastic deformation near the PSS affect rupture dynamics?



Poroelastic directivity preserved

Conclusions

- **Location** of plastic straining depends on angle, Ψ, of most compressive principal pre-stress:
  - For $\Psi < 10°$, plastic strain on **compressional** side
  - For $\Psi > 45°$, plastic strain on **extensional** side
- **Undrained pore fluid response:** $\Delta p = - B\, \Delta\sigma_{kk}/3$
  - increase plastic strain on compressional side
  - decrease plastic strain on extensional side
- **Undrained plastic dilatancy:** induces suction, decreases extent of plasticity
- For completely undrained deformation, fluid saturation **limits localization**.
- Poroelastic deformation can **change fault surface pore pressure** and propagation direction.
- Considering near-fault plastic deformation: **poroelastic directivity is preserved**.