The onset of depletion-induced seismicity in slip-weakening faults characterized by interacting peaked shear stresses

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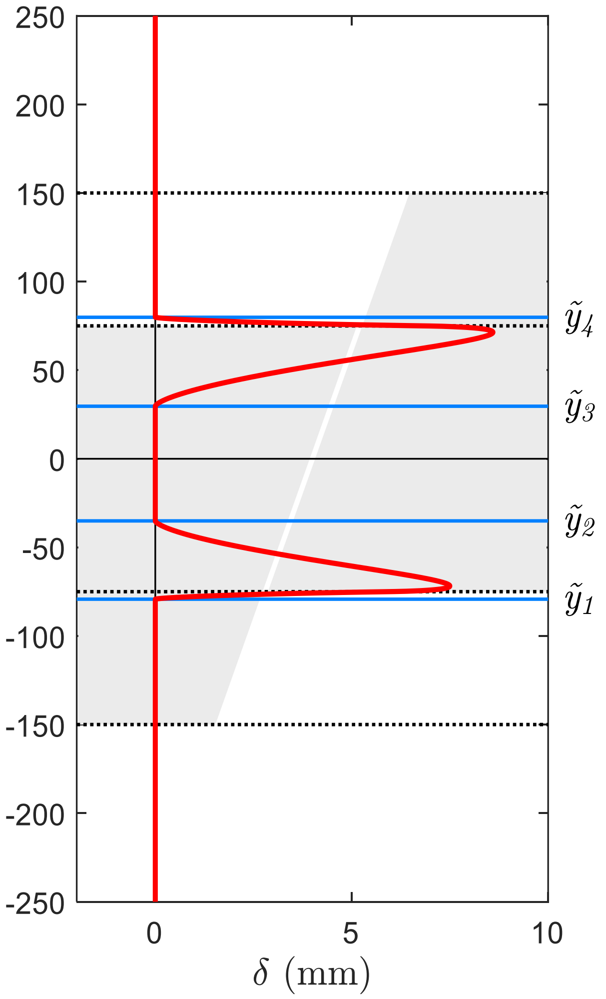
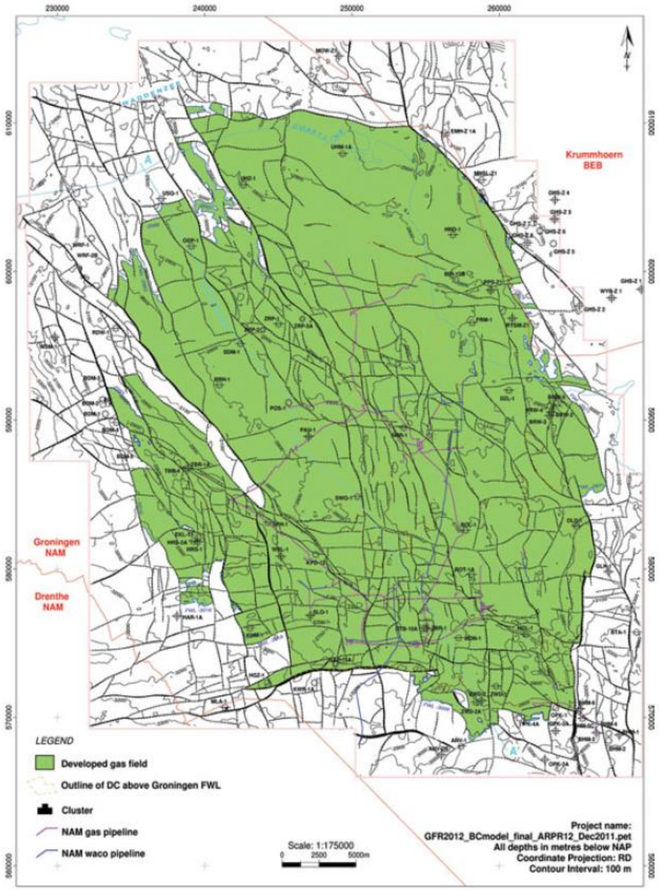
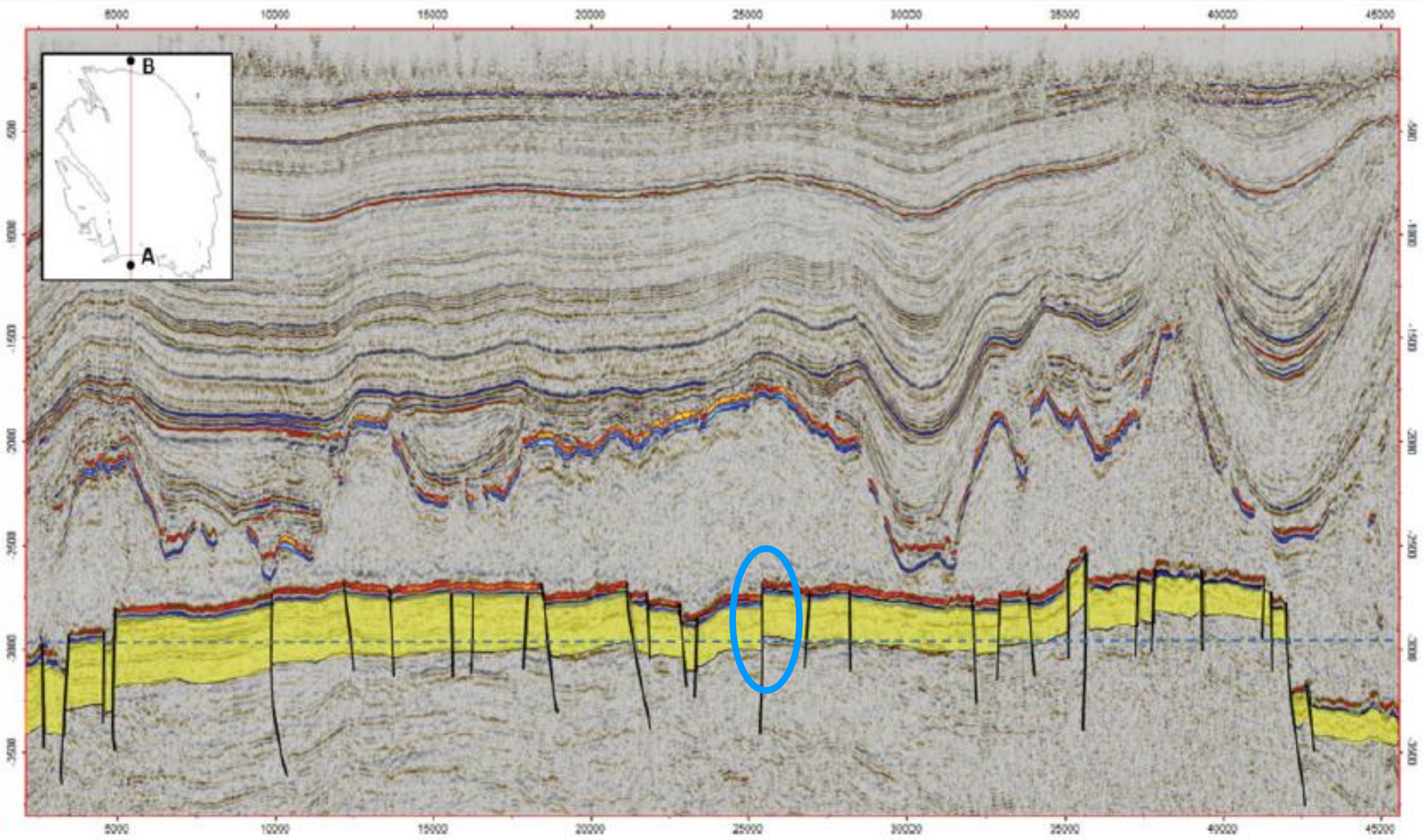


Motivation

- Depletion-induced seismicity in Groningen natural gas reservoir
- Huge reservoir, 200-300 m thick, 1000+ mapped (normal) faults, 70-90 dip



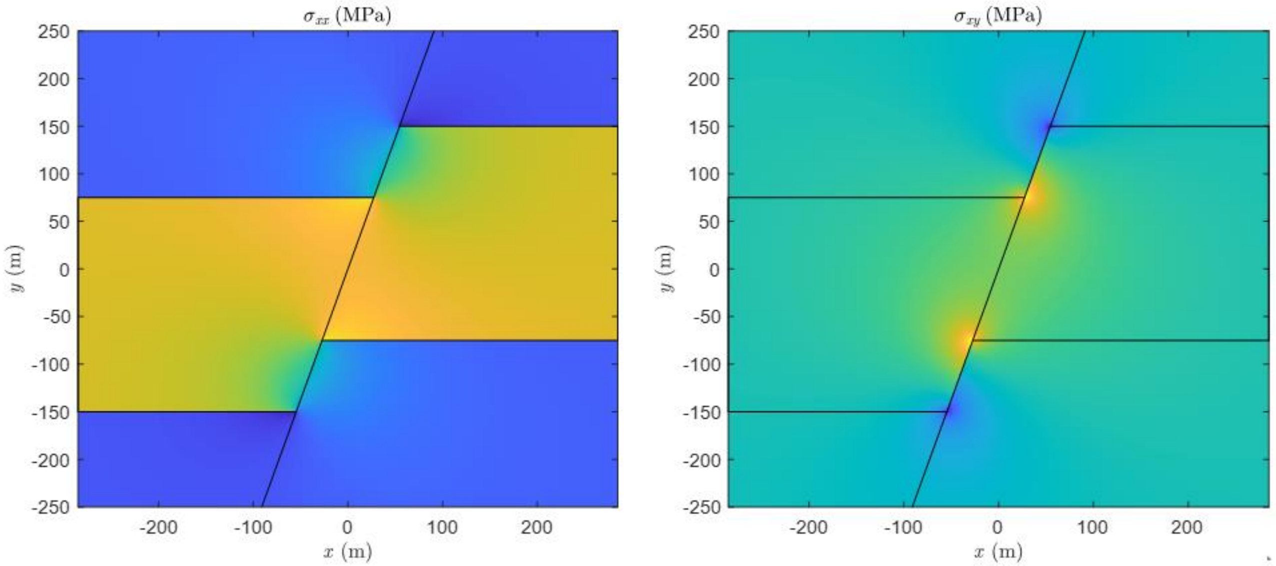


Source: De Jager & Visser (2017)

Depletion-induces stresses (analytical or numerical solution)

Horizontal stress

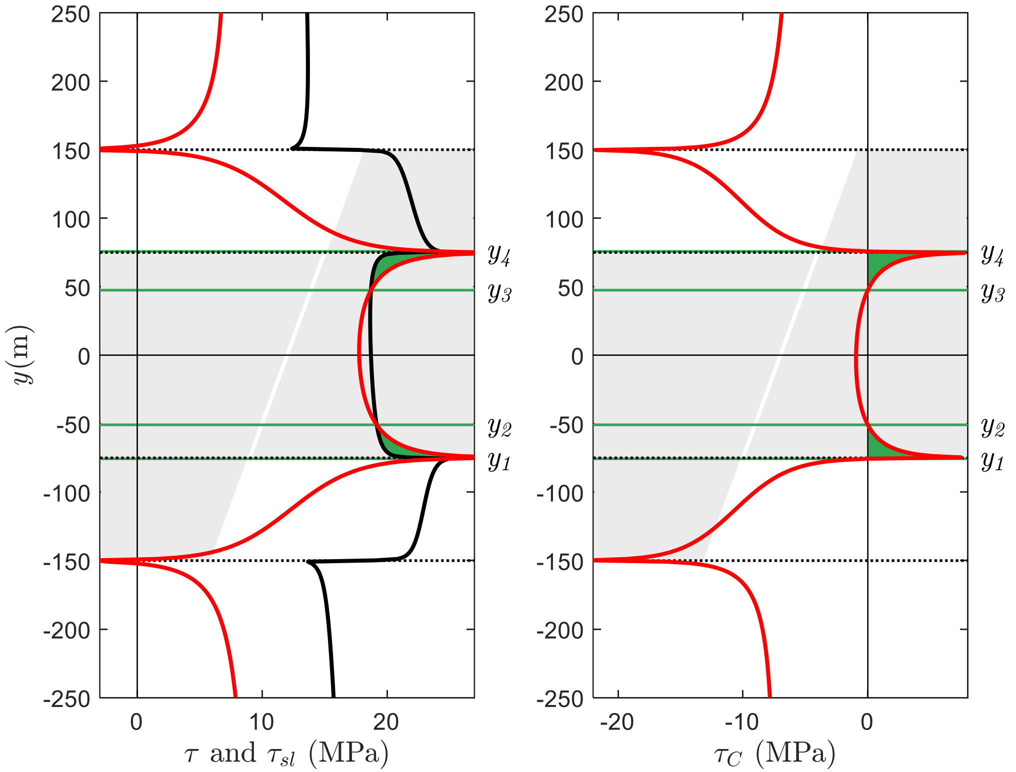
Shear stress



Shear stress τ

Slip boundary τ_{sl}

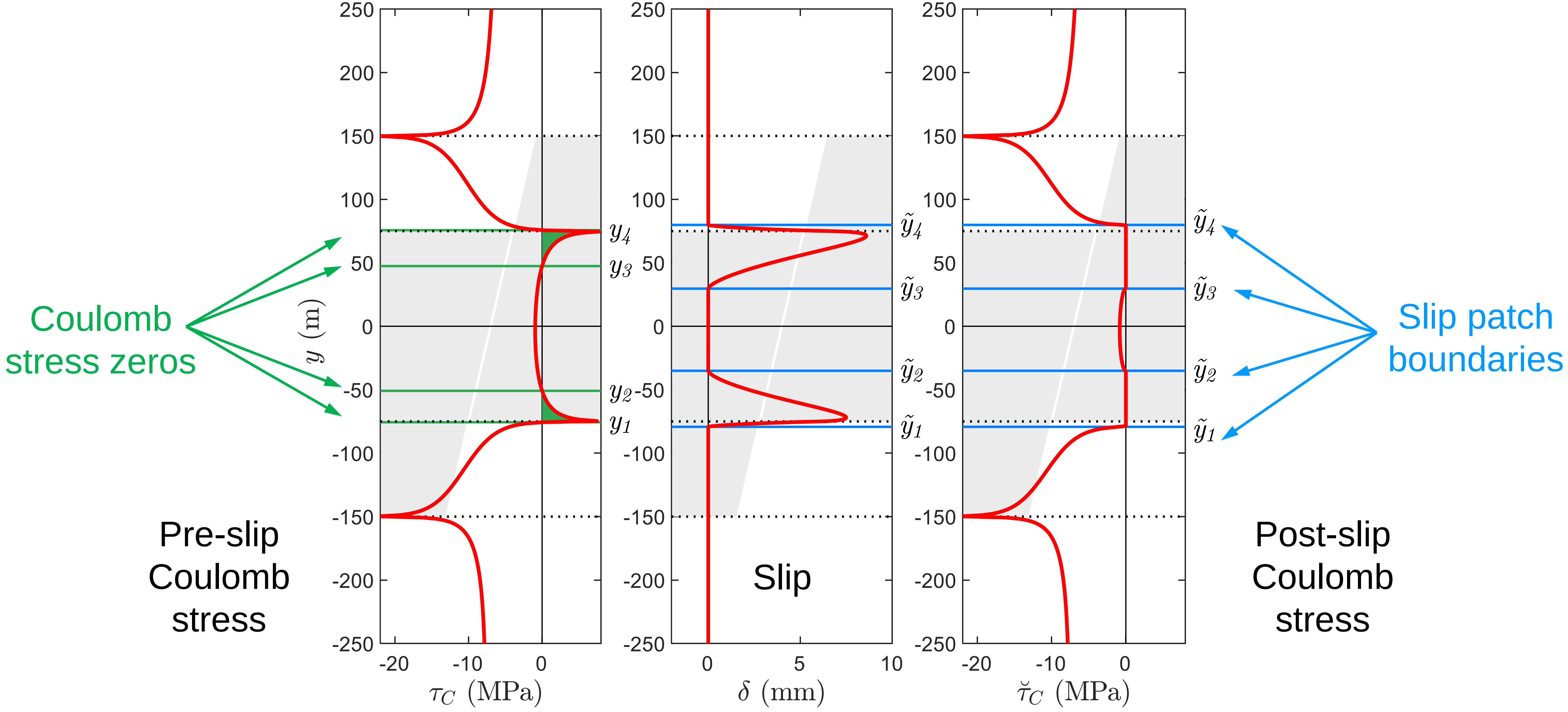
Pre-slip Coulomb stress τ_C



$$\tau_{sl} = -\mu\,\sigma'$$

$$\tau_C = \tau - \tau_{sl}$$

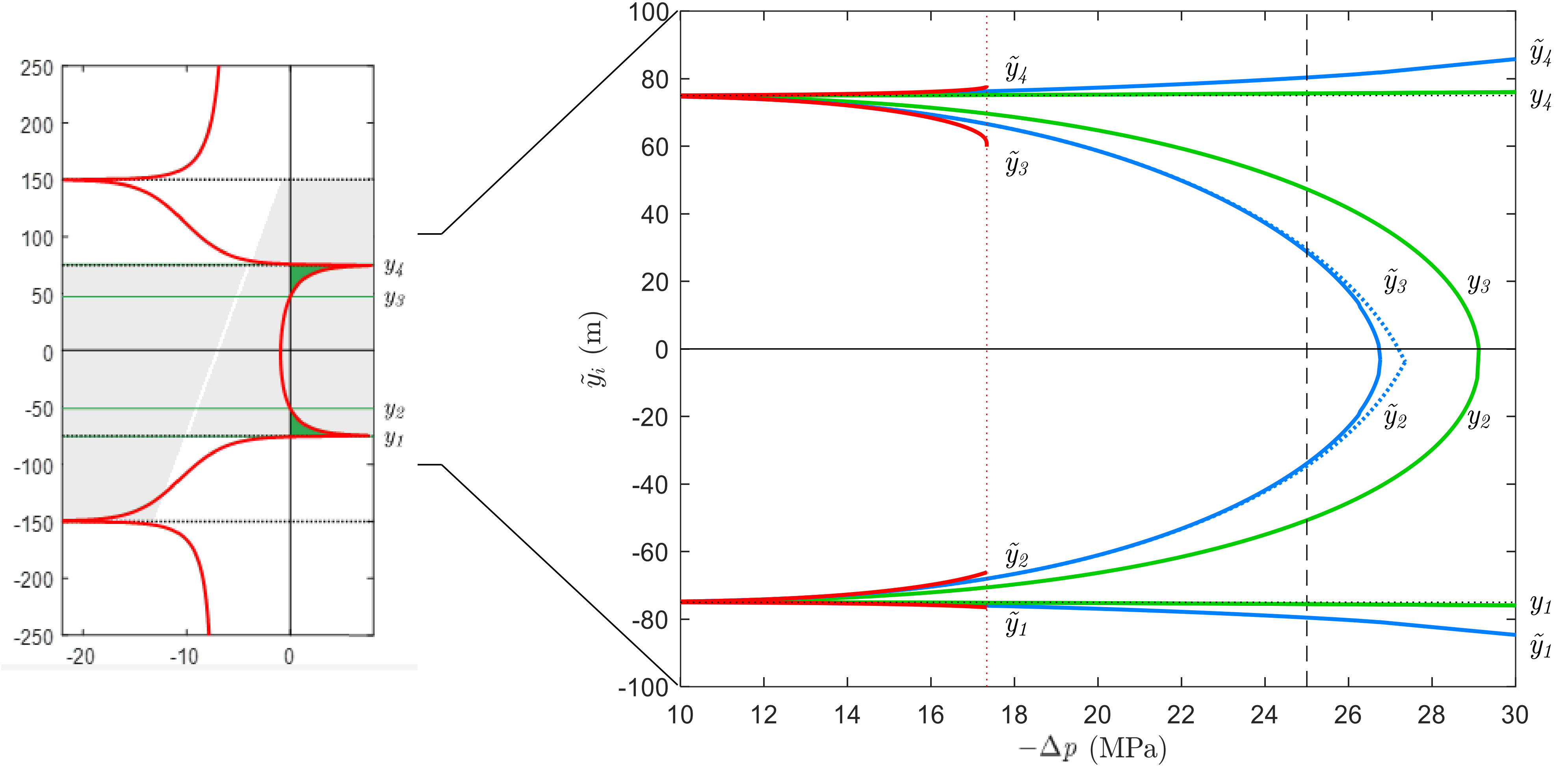
Effect of double-peaked stresses: double slip patch



Semi-analytical results: Meulenbroek & Jansen (2024)

Effect of depletion

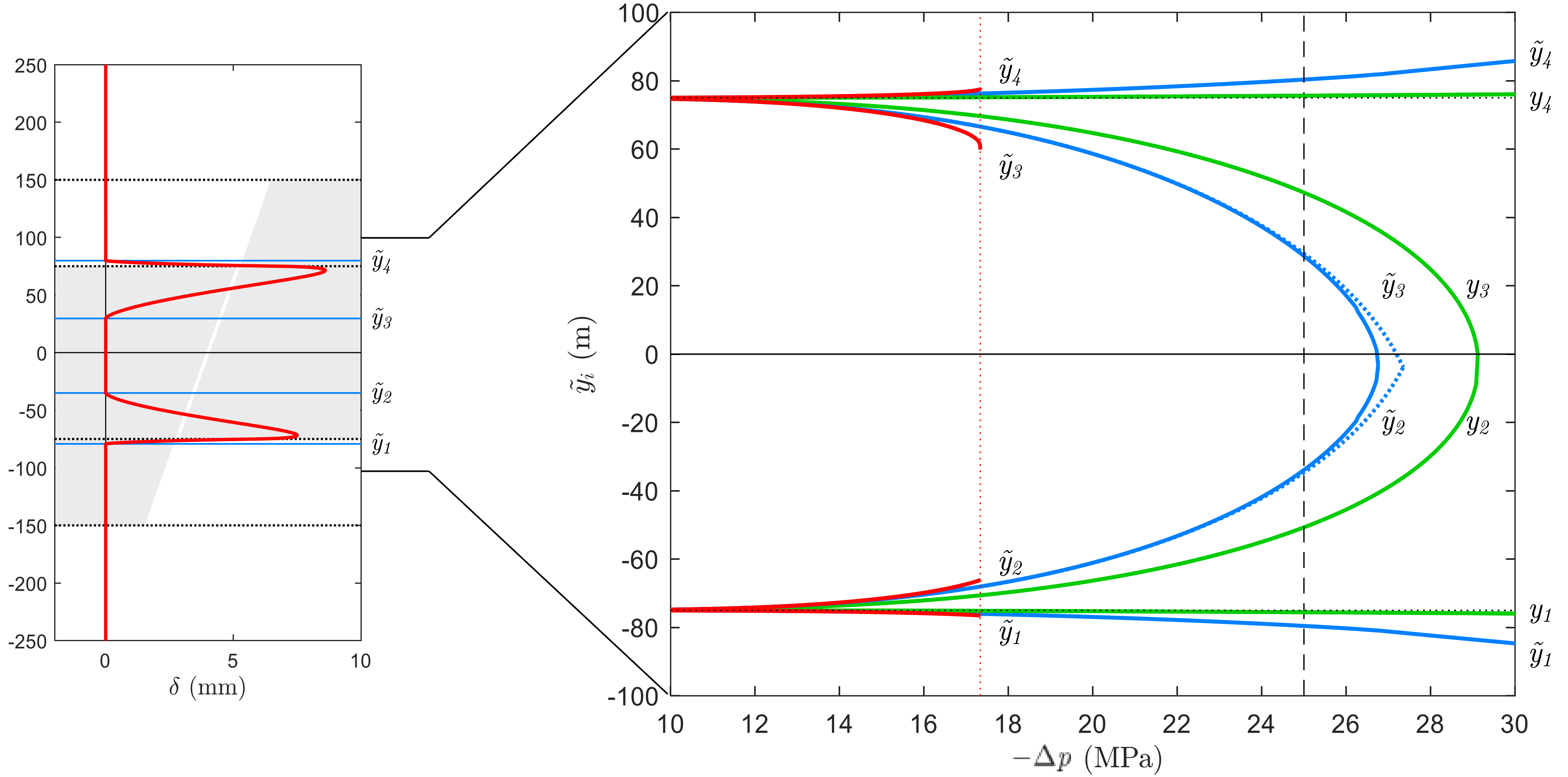
Coulomb stress zeros



Effect of depletion

Coulomb stress zeros

Slip patch boundaries - constant friction

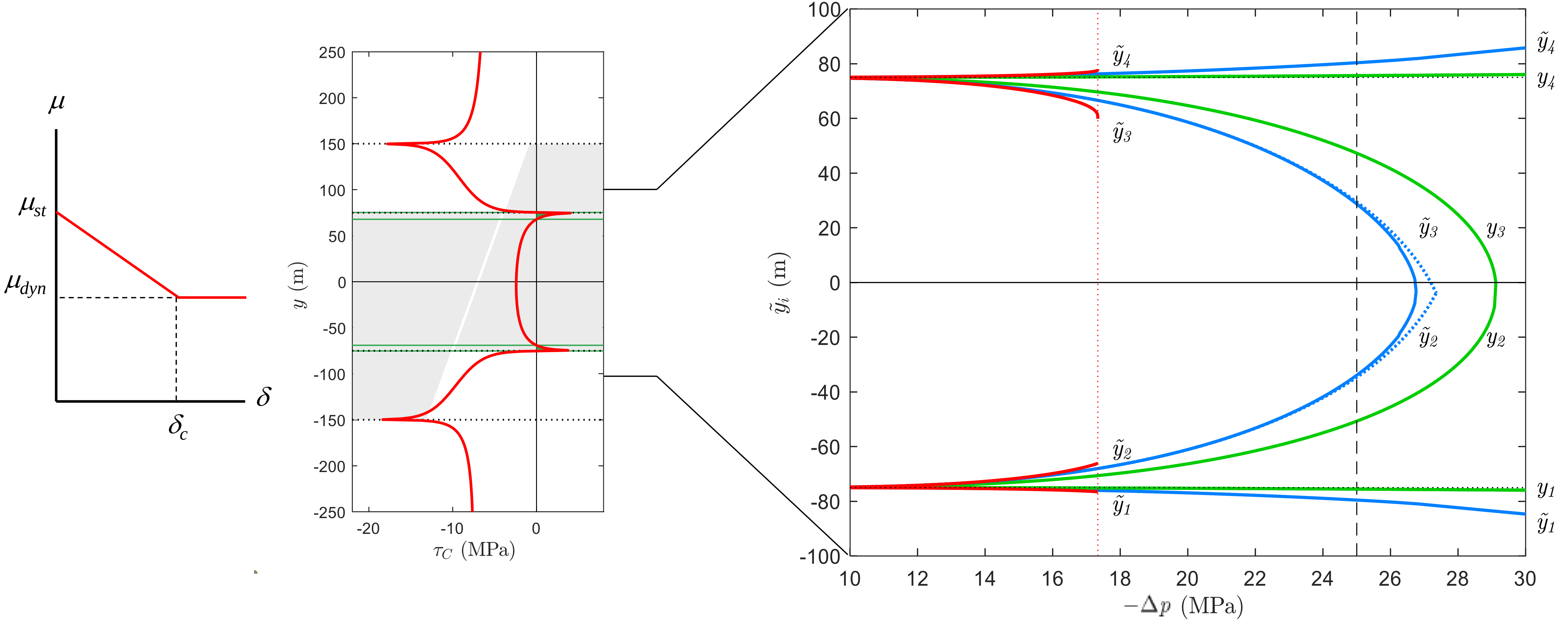


Effect of depletion

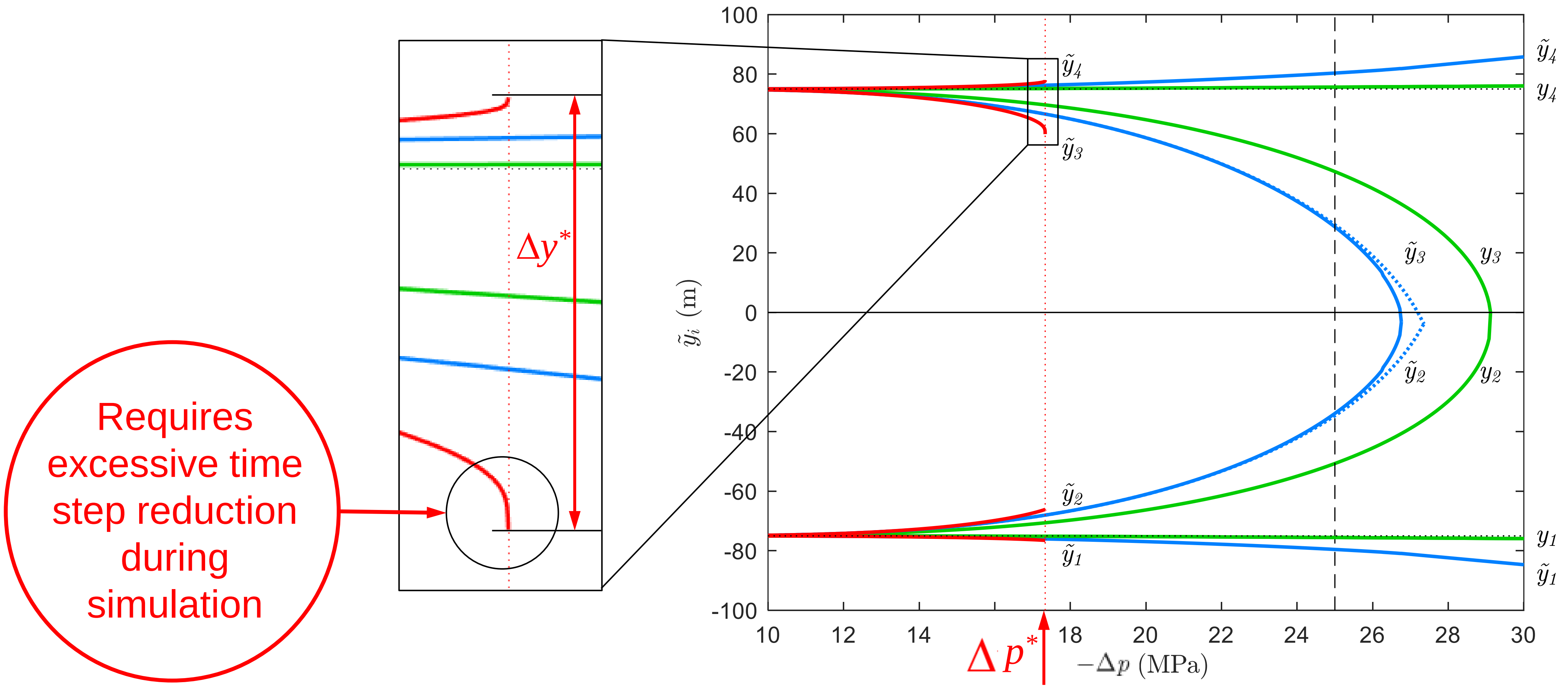
Coulomb stress zeros

Slip patch boundaries - constant friction

Slip patch boundaries - slip-weakening friction



Effect of depletion for slip-weakening friction



Nucleation: eigenvalue/vector problem (Uenishi and Rice 2003)

Forward and eigen problems

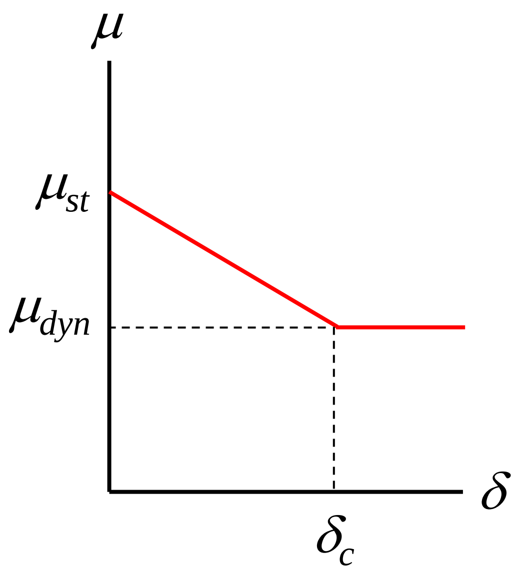
- Forward problem: Various approaches: Chebyshev polynomials, Gauss-Chebyshev quadrature, matrix inversion, analytical inversion, boundary elements

$$-\tau_C(y) = A\left(\int_{\tilde{y}_1}^{\tilde{y}_2} \frac{\nabla\delta(\xi)}{\xi - y} d\xi + \int_{\tilde{y}_3}^{\tilde{y}_4} \frac{\nabla\delta(\xi)}{\xi - y} d\xi\right)$$

- Eigen problem: Single-patch problem tackled by Uenishi & Rice (2003), extension to double patch not trivial

$$-W(y)\dot{\delta} = A\left(\int_{\tilde{y}_1}^{\tilde{y}_2} \frac{\nabla\dot{\delta}(\xi)}{\xi - y} d\xi + \int_{\tilde{y}_3}^{\tilde{y}_4} \frac{\nabla\dot{\delta}(\xi)}{\xi - y} d\xi\right)$$

$$W(y) = \sigma'(y)\,\frac{\mu_{st} - \mu_{dyn}}{\delta_c}$$



Eigen problem – Uenishi & Rice (2003)

- Eigen problem with constant normal stress for single patch:

$$-W\dot{\delta}(y) = A \int_{\tilde{y}_-}^{\tilde{y}_+} \frac{\nabla\dot{\delta}(\xi)}{\xi - y} d\xi, \quad \tilde{y}_- < y < \tilde{y}_+$$

$$W = \sigma' \frac{\mu_{st} - \mu_{dyn}}{\delta_c}$$

$$\Delta_{U\&R} \approx 1.1577 \frac{G}{W(1-\nu)}$$

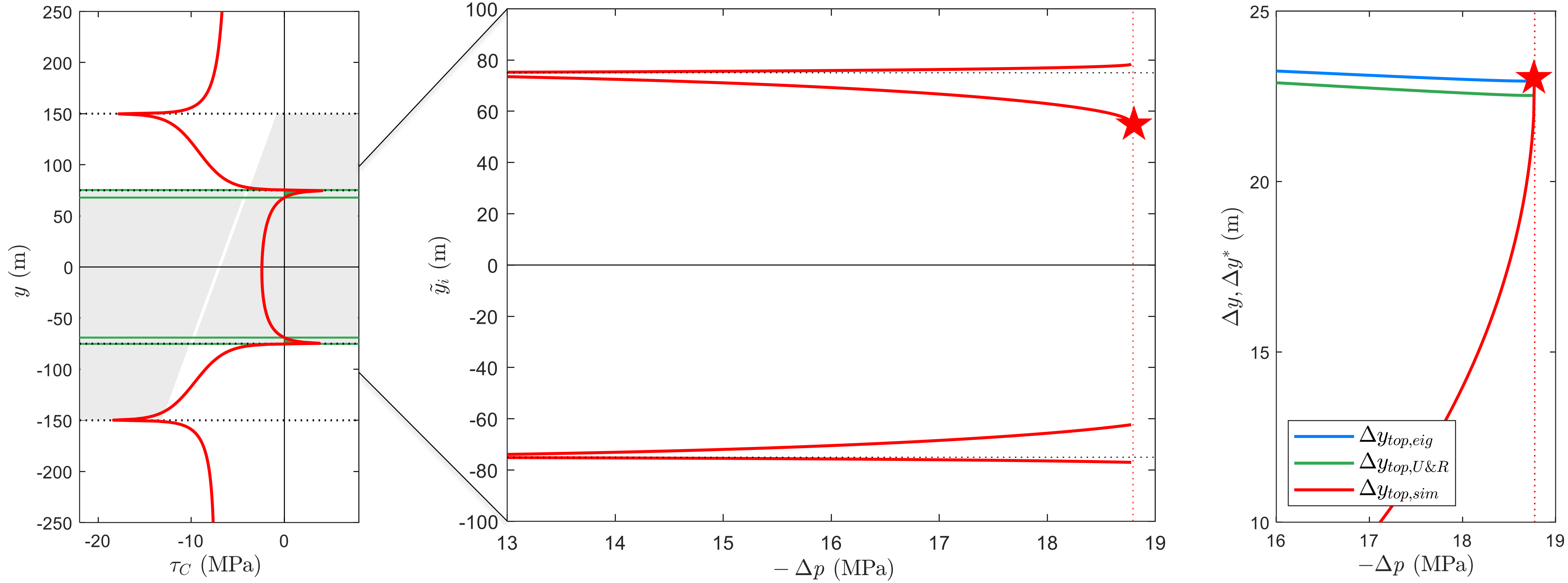
- Universal result: does not depend on shape of τ_C, as long as it is peaked
- Usefull result: does not require eigenvalue analysis; supports numerical simulation (van den Bogert, 2015,2018; Buijze 2017,2019)

Example 1, modest offset: $\tilde{t}_f = t_f / h = 0.33$

Simulation

Eigen solution

U&R approximation

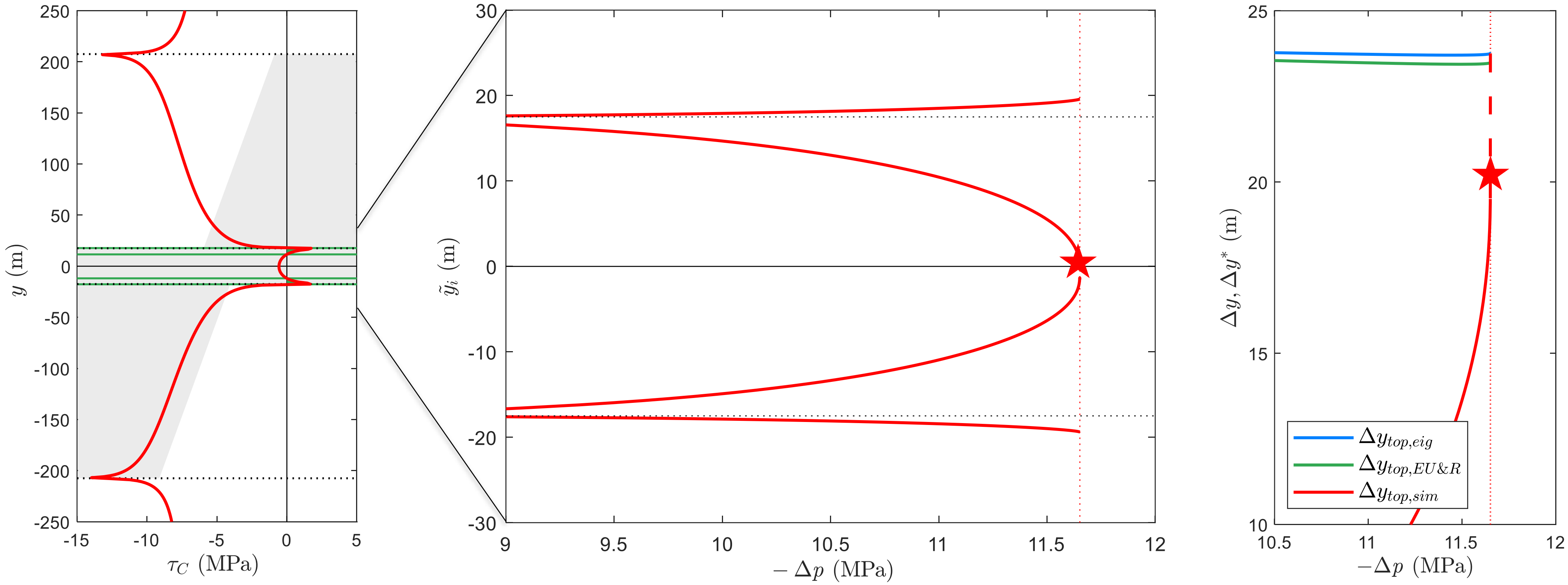


Example 2, large offset: $\tilde{t}_f = t_f / h = 0.83$

Simulation

Eigen solution

U&R approximation



Eigen problem – Extended Uenishi & Rice (EU&R)

- Eigen problem with constant normal stress for coupled patches:

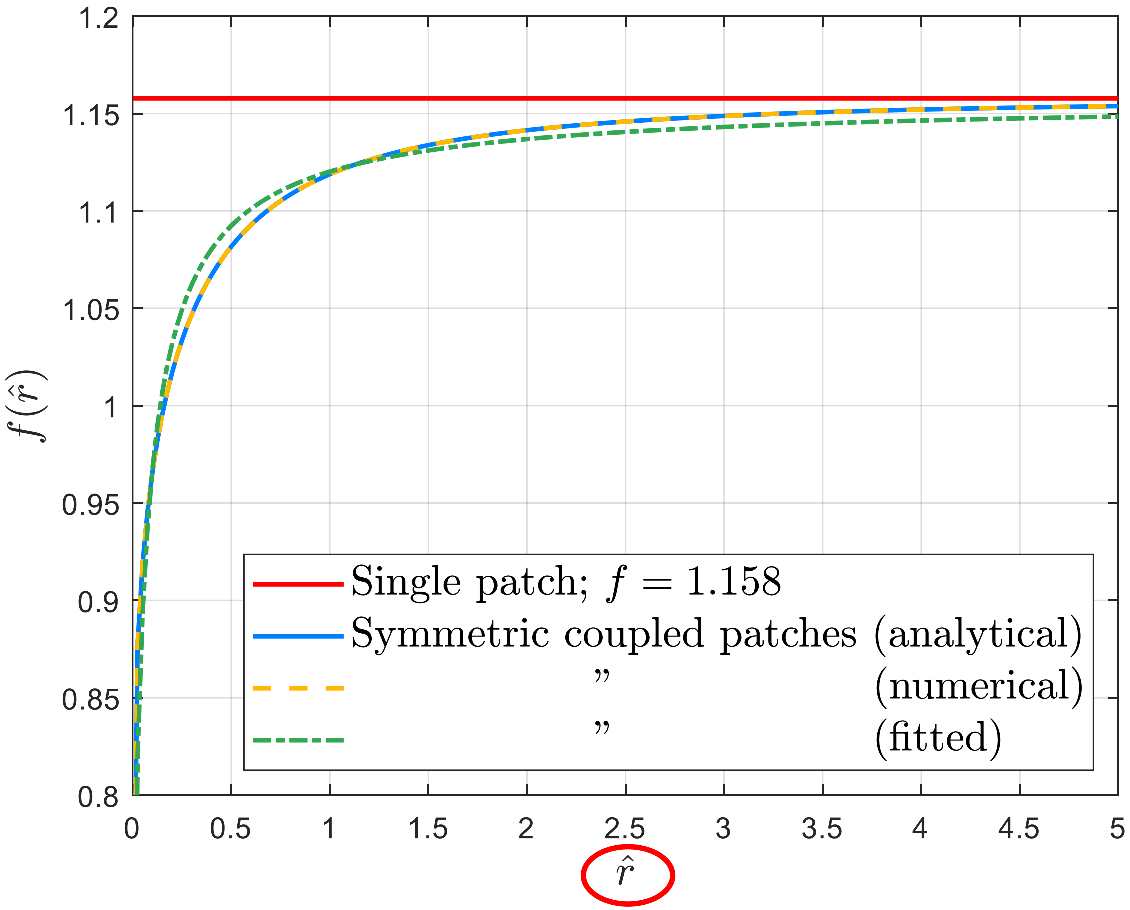
$$-W\dot{\delta}(y) = A\left(\int_{\tilde{y}_1}^{\tilde{y}_2} \frac{\nabla\dot{\delta}(\xi)}{\xi - y} d\xi + \int_{\tilde{y}_3}^{\tilde{y}_4} \frac{\nabla\dot{\delta}(\xi)}{\xi - y} d\xi\right)$$

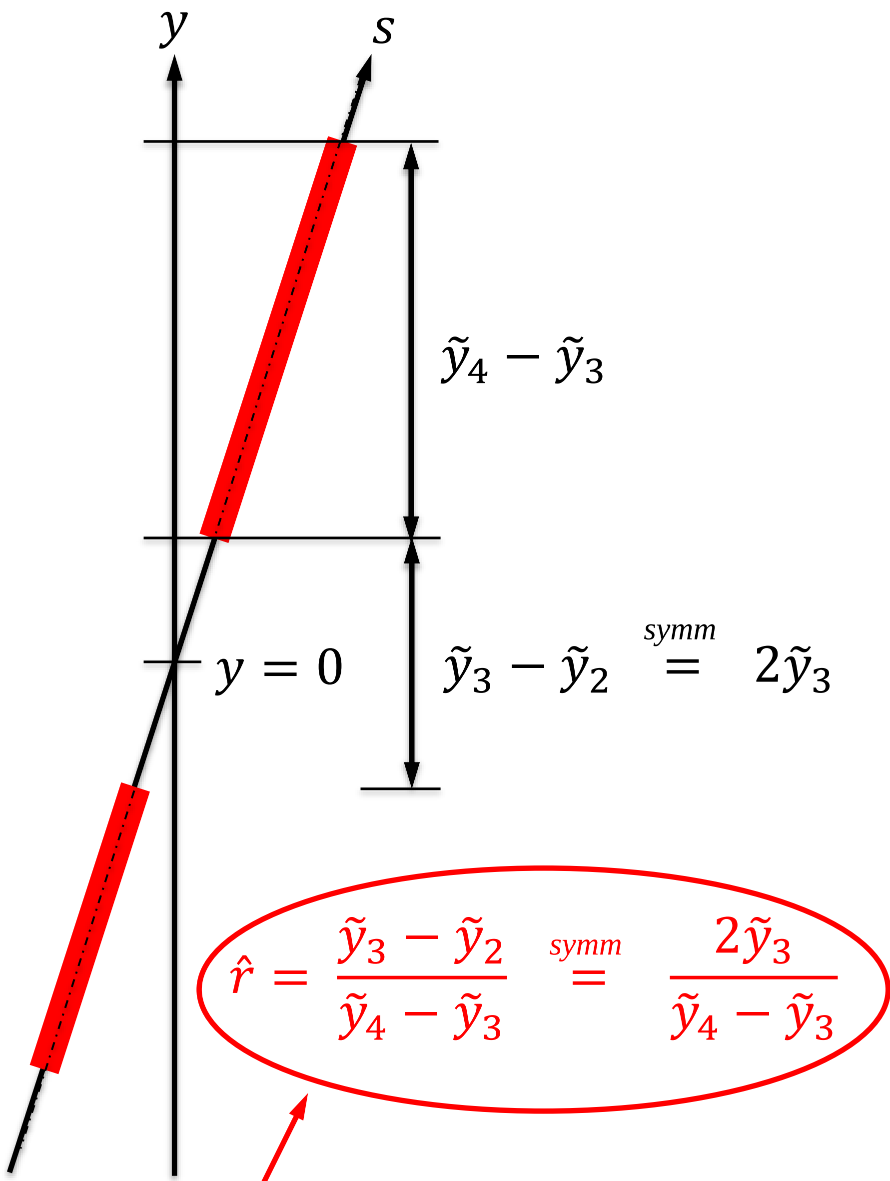
$$\Delta_{EU\&R} \approx f(\hat{r}) \frac{G}{W(1-\nu)}$$

$$f(\hat{r}) \approx \frac{1.158}{2}\left[1 - \frac{1}{\pi}\operatorname{arcsec}\left(17.872\,\hat{r}^{\,0.895} + 1\right)\right]^{-1}$$

- Depends on parameter $f(\hat{r})$ which depends on $p \Rightarrow$ no longer universal result
- Still useful to support numerical simulation

Extended Uenishi & Rice coefficient





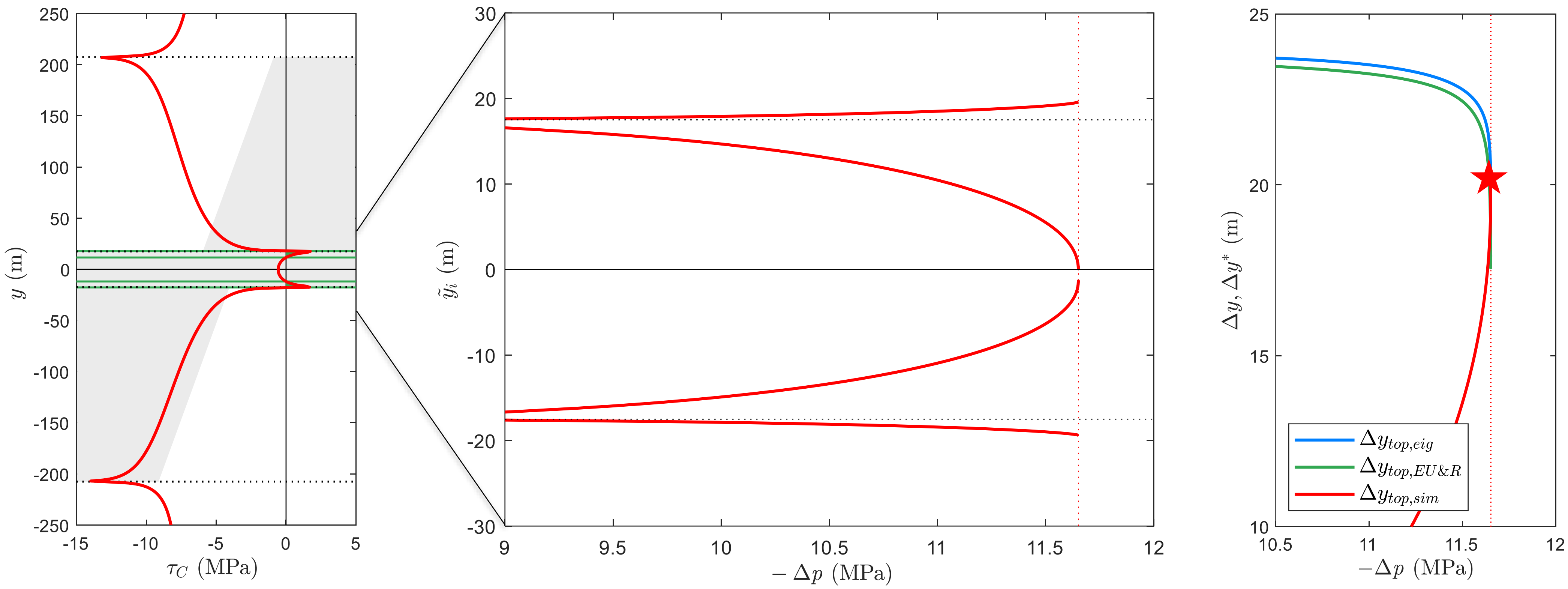
Scaled distance between patches

Example 2, large offset: $\tilde{t}_f = t_f / h = 0.83$

Simulation

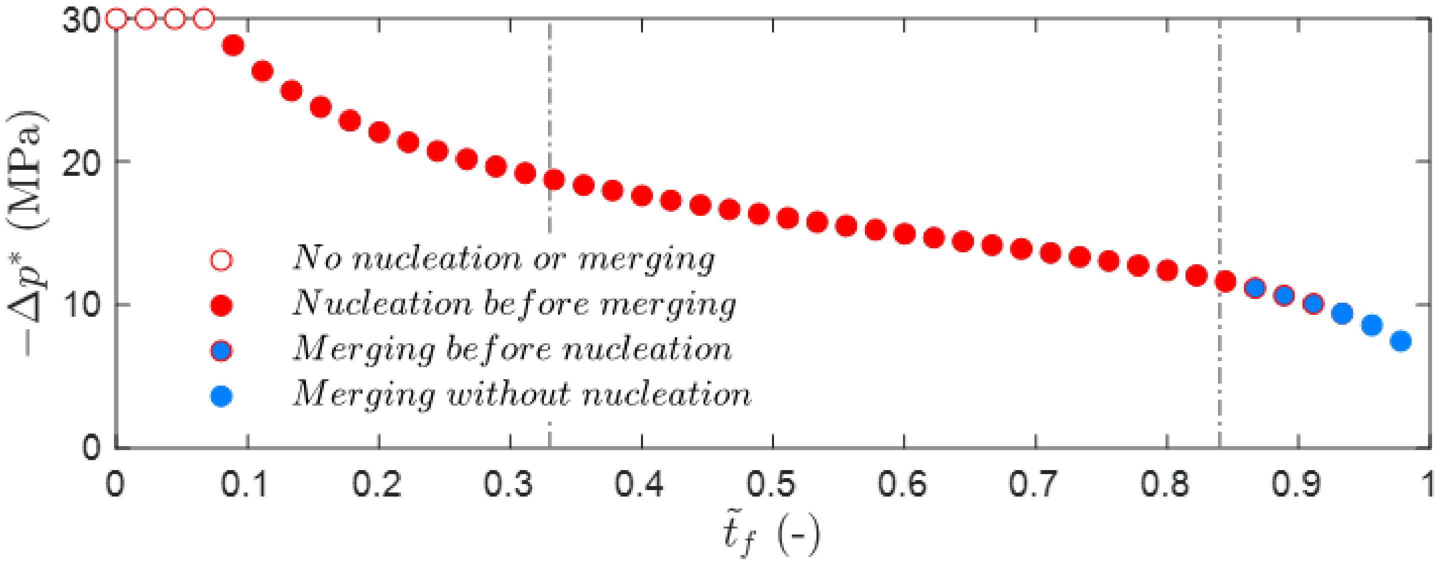
Eigen solution

U&R approximation

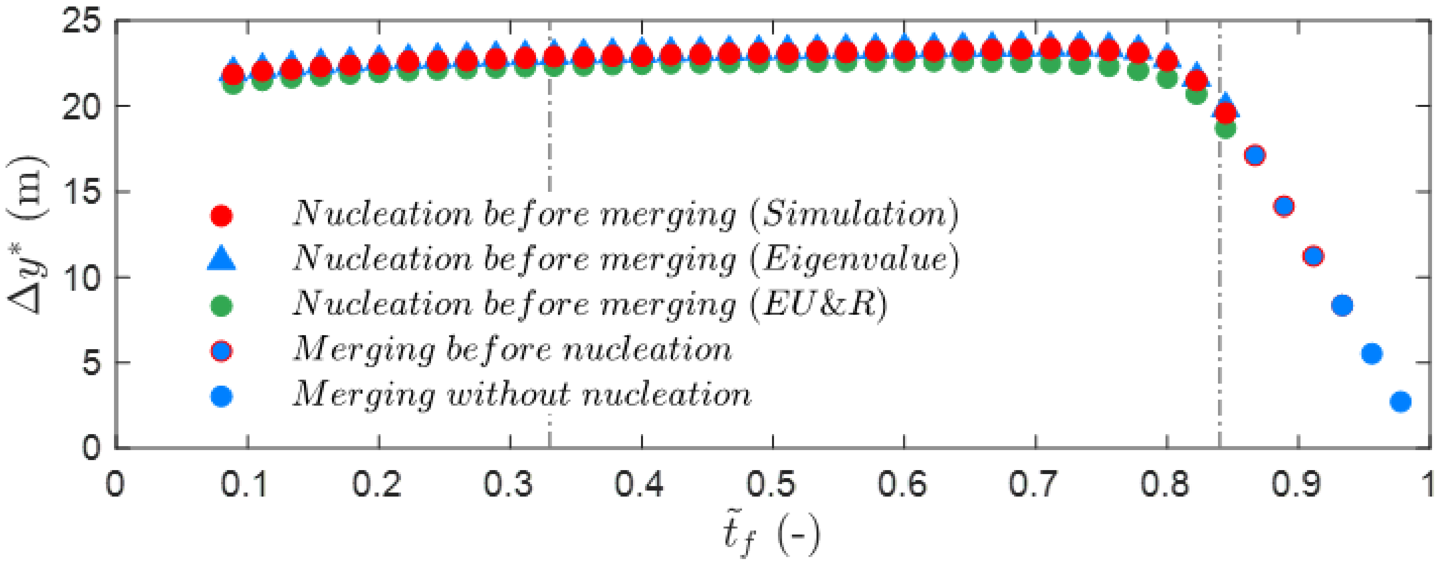


Effect of relative fault throw $\tilde{t}_f = t_f / h$

Nucleation pressure



Nucleation patch length



What we already knew

- Nucleation requires reduction in slip resistance with increasing slip (e.g. slip-weakening, velocity-weakening or rate and state)
- Can be computed exactly (eigen problem) or approximately (U&R criterion).
- Original U&R criterion only valid for constant normal stress and single patch.
- Simple averaging over slip patch usually sufficient to cope with varying stress.
- For high relative fault throws ($t_f/h > 0.70$), coupling between the patches becomes important, and the U&R criterion overestimates the nucleation length.

What's new

- Exact eigenvalue solution for coupled patches can now be computed.
- Solution dependent on relative distance between patches.
- Extended U&R criterion for symmetric coupled patches can also be computed.
- Useful to support numerical simulations. Explicit expression for nucleation length avoids need for excessive pressure step reduction close to nucleation.

- Mathematical innovation involves a singular functional form of the slip gradient which allows for the formulation of slip-patch end conditions that can be directly extended to multiple patches.
- Jansen, J.D. and Meulenbroek, B.J, 2025.: The onset of depletion-induced seismicity in slip-weakening faults with interacting peaked shear stresses: Uenishi and Rice Extended. *Submitted*

References

Related to this presentation.

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- Jansen, J.D. and Meulenbroek, B.J, 2025.: The onset of depletion-induced seismicity in slip-weakening faults with interacting peaked shear stresses: Uenishi and Rice Extended. *Submitted*.
- **Related further reading**
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