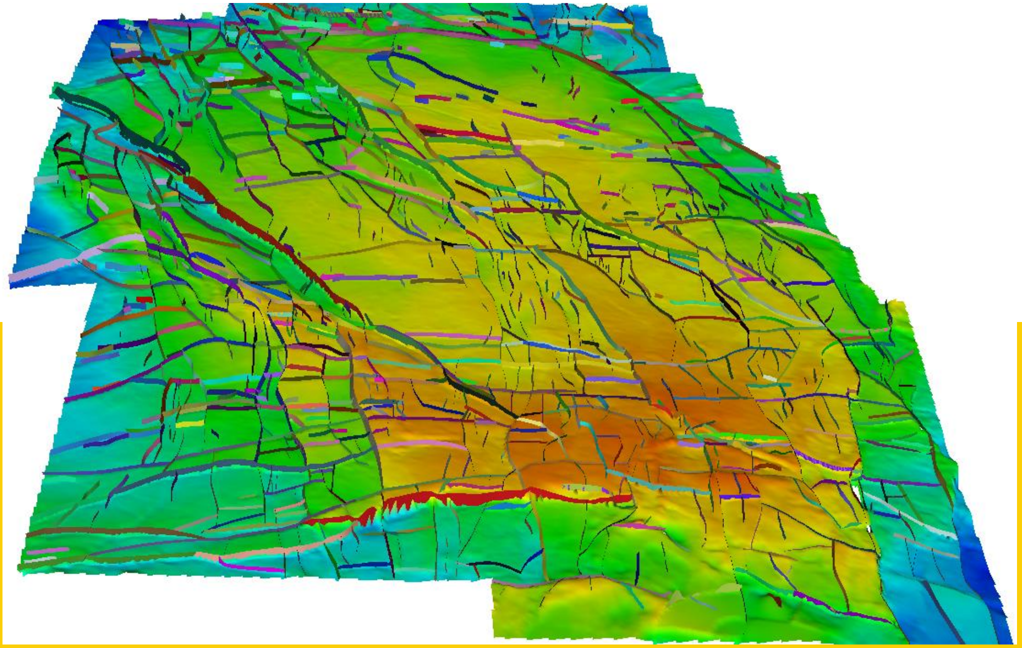
An analytical approach to fault rupturing in depleting gas reservoirs

With application to the Groningen field
The Netherlands



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with contributions from many colleagues in NAM and Shell
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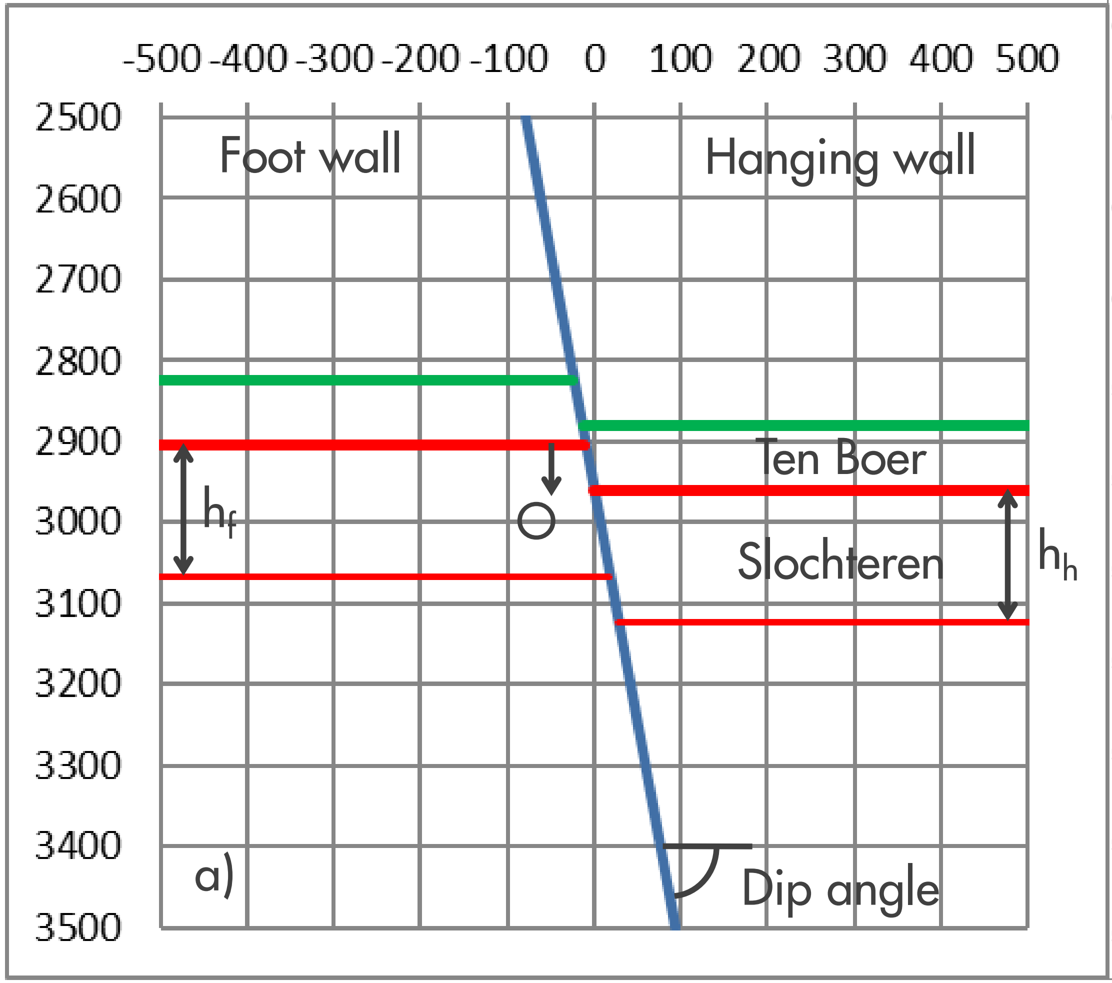
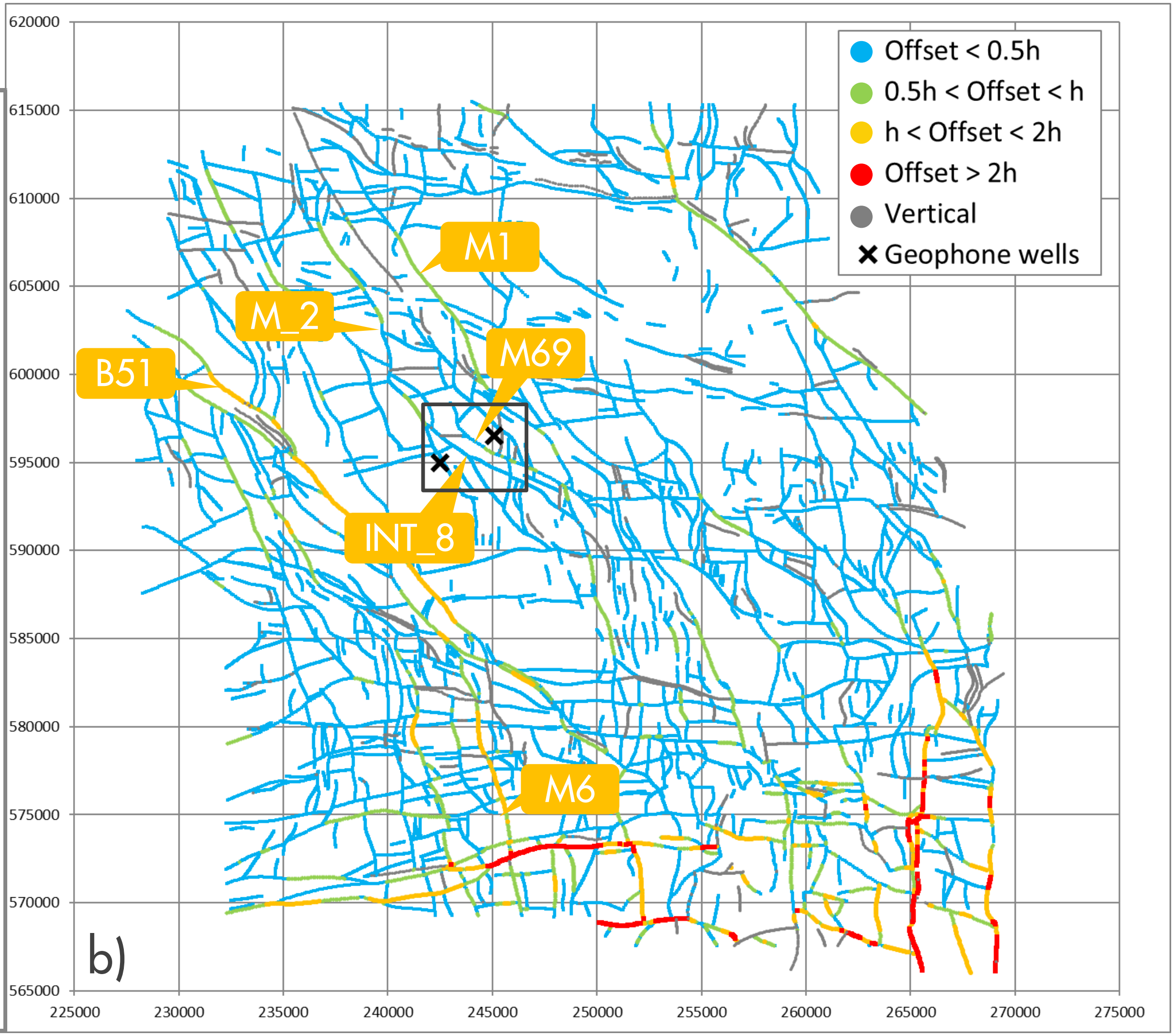
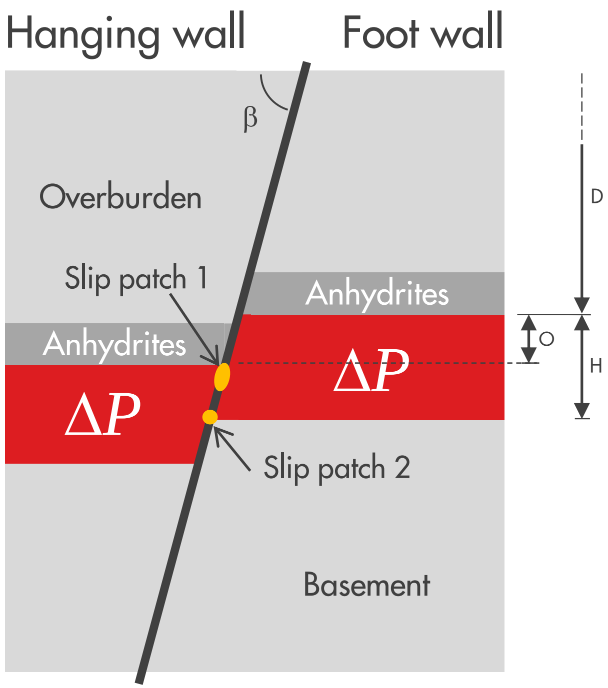
- Groningen fault model
  - Tectonic setting, geometry and key modelling parameters
- Mechanism of nucleation and arrest of seismic rupture
  - Linear slip-weakening relationship
  - Poroelastic modelling of depletion-induced stress changes
- Lehner's analytical solution of Goodier's problem (Lehner, 2019)
  - Application to faults with offset
- Conclusions

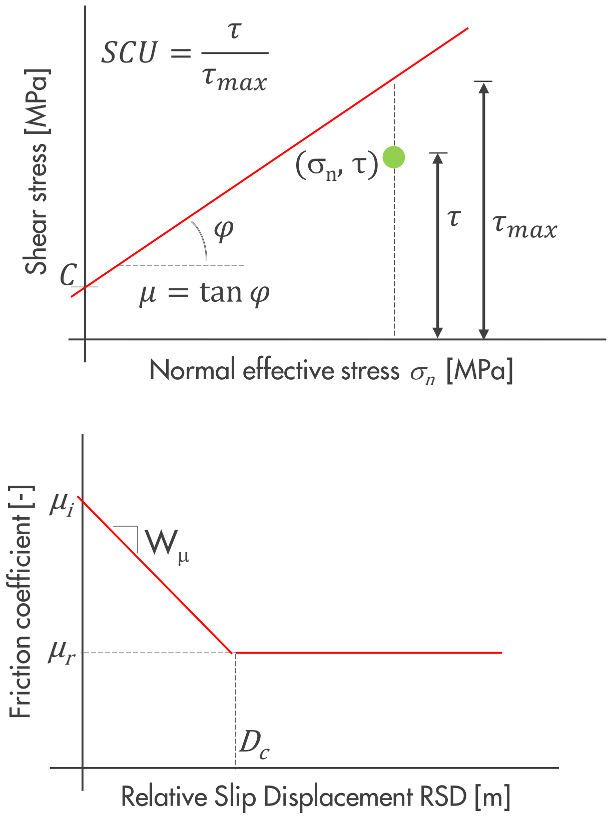
Normalised reservoir offset

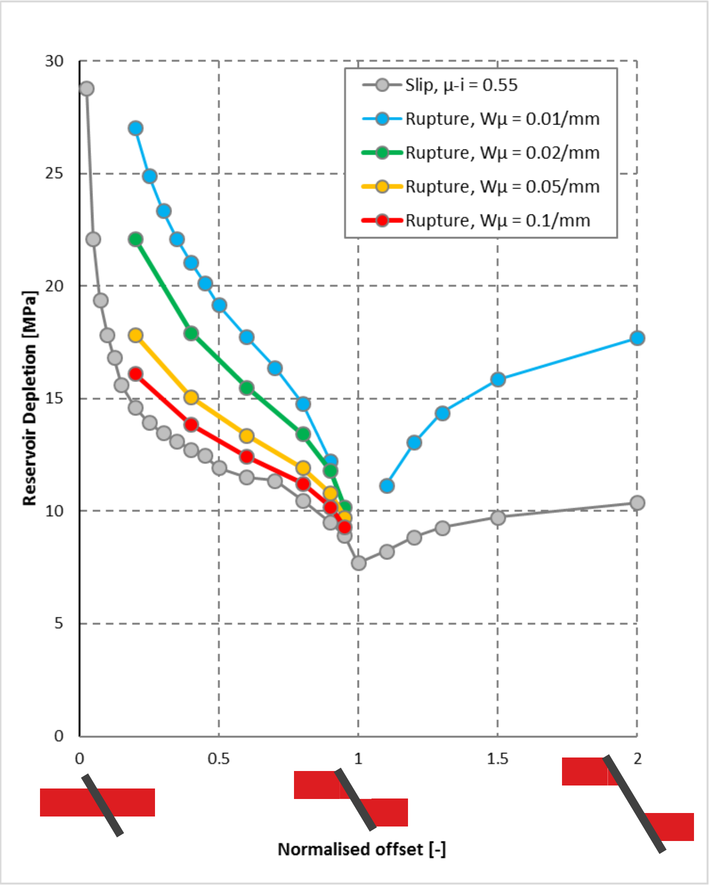




Seismic Rupture is dependent on normalised offset and slope W_μ







- Reservoir offset in a normal faulting stress regime
- Linear elastic subsurface

- Mohr-Coulomb friction law
- Linear slip-weakening relationship

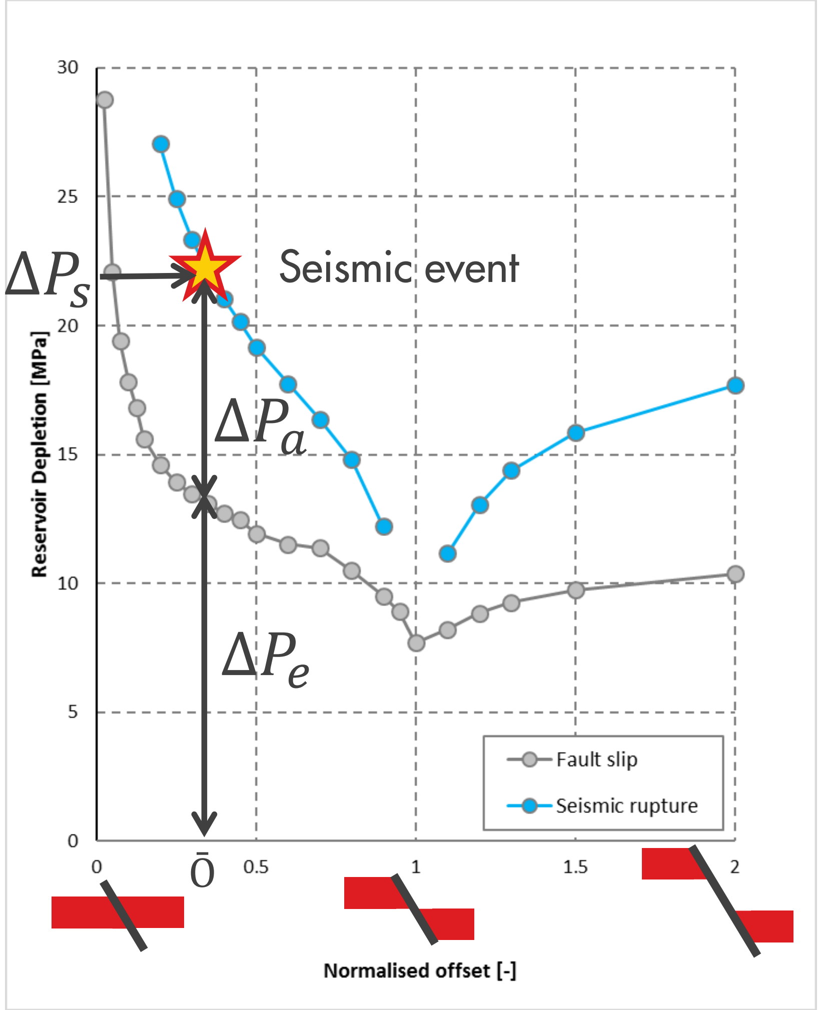
- Fault reactivation and seismic rupture strongly dependent on normalised reservoir offset

Reservoir depletion at which seismic rupture nucleates

$$\Delta P_s = \Delta P_e + \Delta P_a$$

- ΔP_e reversible (elastic) fault deformation, leading to fault slip
  - Poisson's ratio of the reservoir (lab data)
  - Fault orientation (geological interpretation)
  - Initial stress condition (limited data)
  - Fault initial friction coefficient (experimental data)
- ΔP_a induces a-seismic fault slip, leading to seismic rupture
  - Slope W_μ (unknown)
  - Consistent with L_c derived by Uenishi & Rice (2003)

$$\Delta P_s = \Delta P_e(\underline{S}_0, \mu_i) + \Delta P_a(W_\mu)$$



Uenishi, K. and Rice, J. R. (2003), Universal nucleation length for slip-weakening rupture instability under nonuniform fault loading, J. Geophys. Res., 108(B1), 2042, doi:10.1029/2001JB00168.

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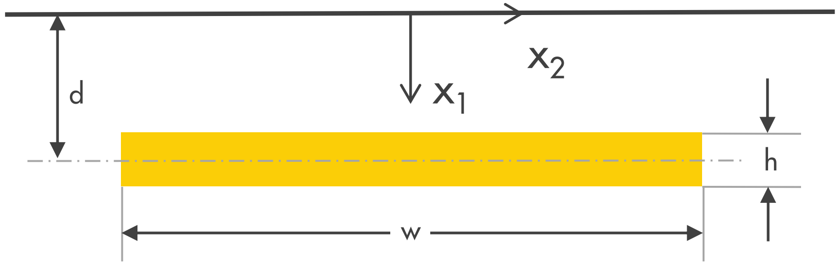
Analytical Solutions

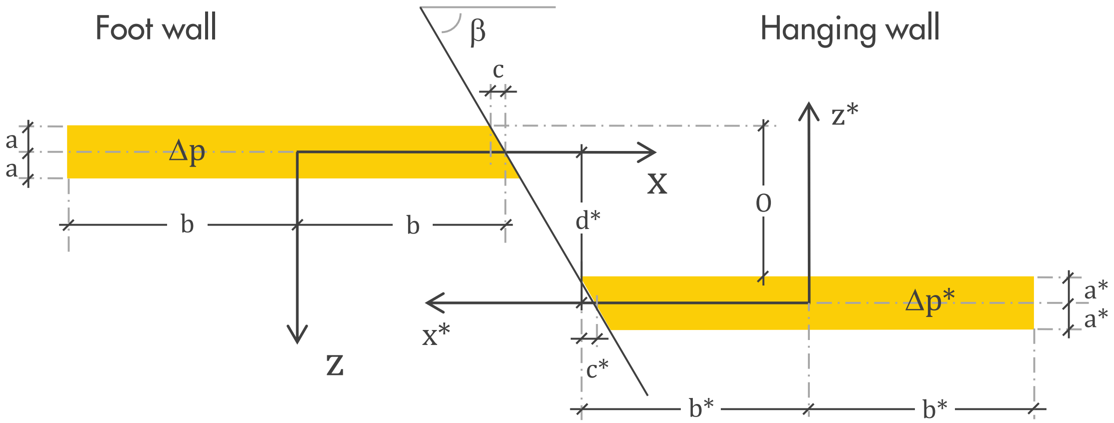
- Stress distribution around rectangular inclusion
  - Goodier (1935) for infinite plate
  - Nowacki (1956) for half space
- Stress distribution around trapeziod inclusion
  - Lehner (2019) for infinite plate
- Stress distribution along fault with throw
  - Superposition of stress induced by depletion of the foot wall reservoir and the hanging wall reservoir

Goodier (1935)

Nowacki (1956)

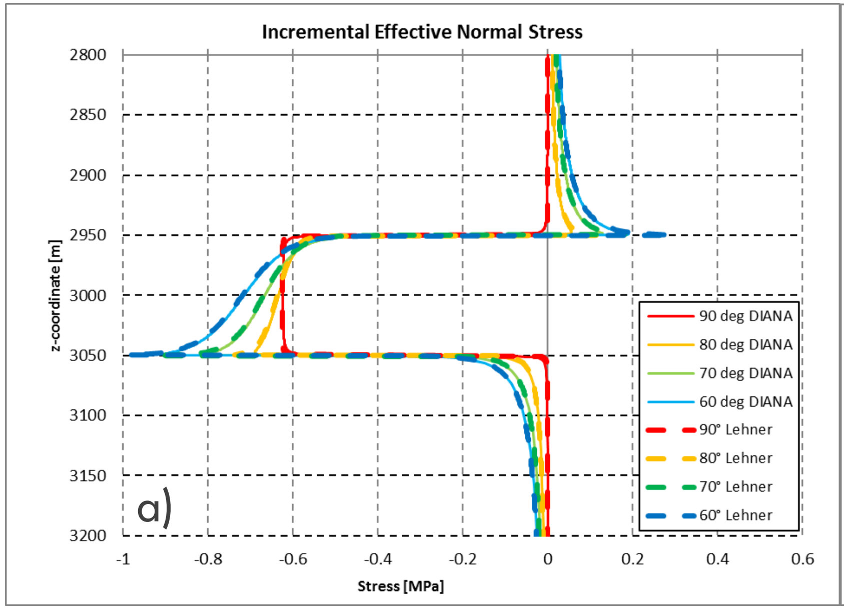


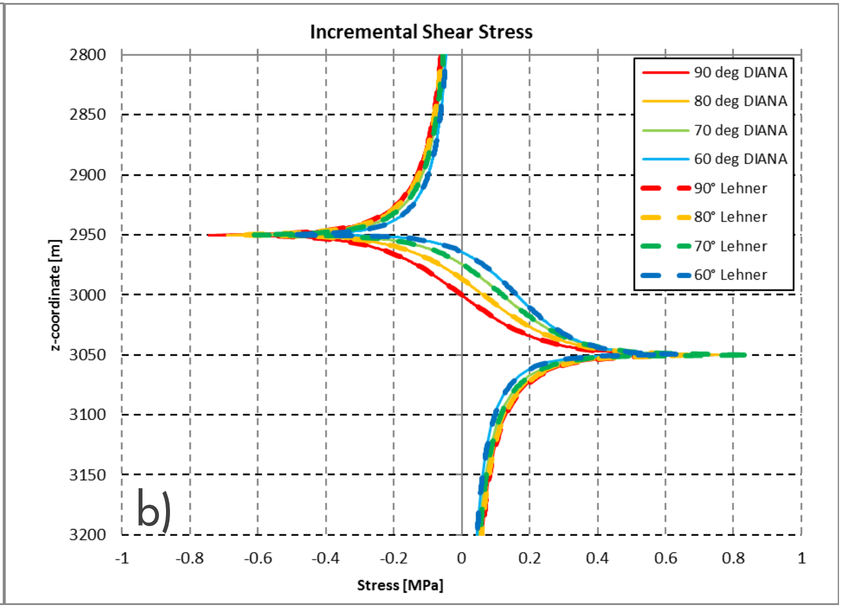
Lehner (2019)

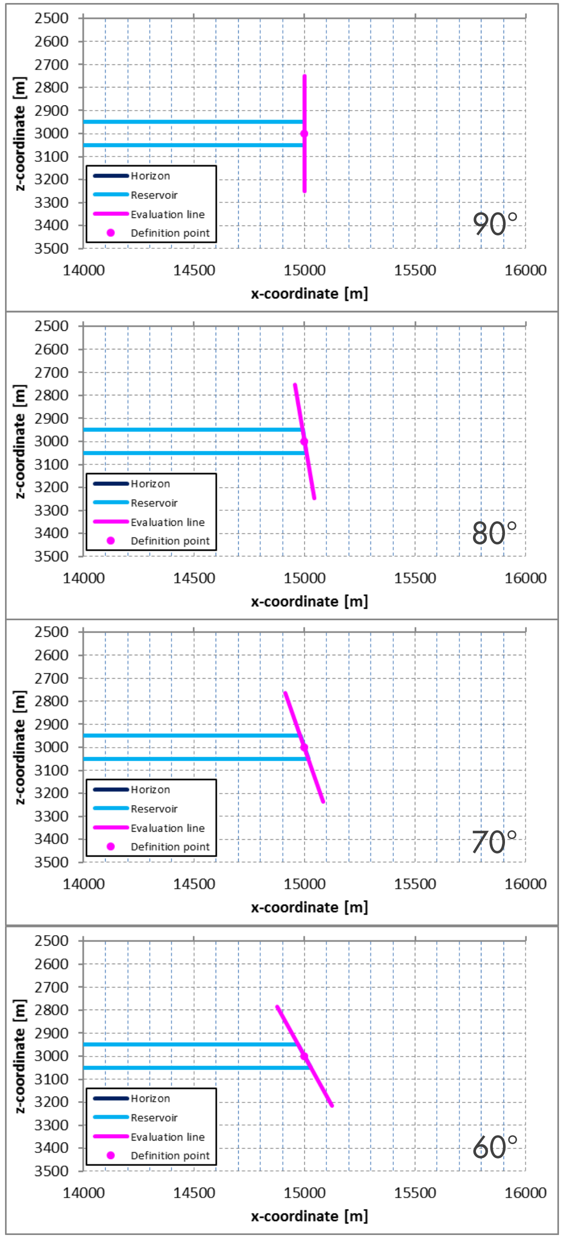


Lehner’s solution compared with FEM results

- Accurate description for the effective normal and shear stress distribution along a dipping fault plane
  - Under linear-elastic stress conditions





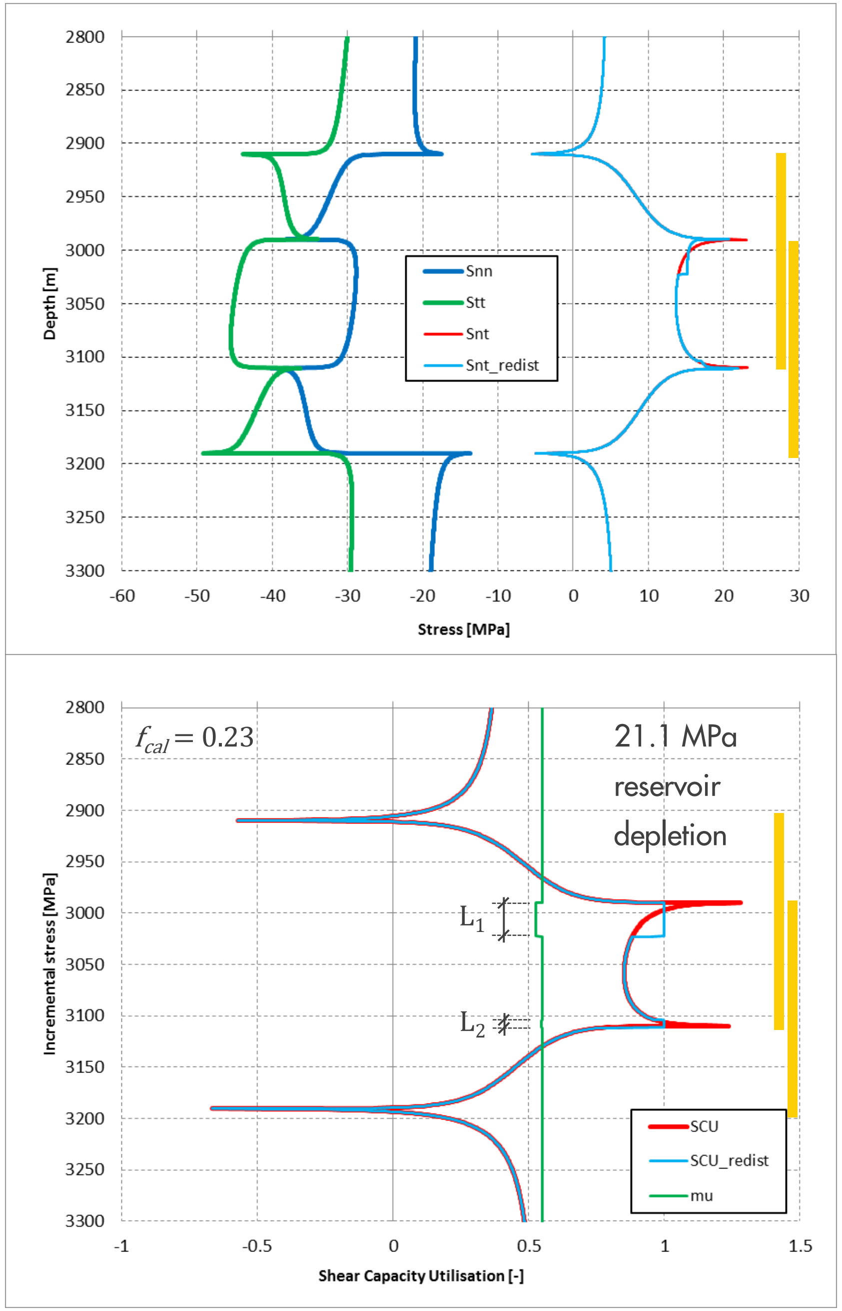


Nucleation of seismic rupture based on Lehner's analytical solution

- Iterative approach
  - Redistribute shear stress to ensure that SCU ≤ 1
  - Account for slip-weakening behaviour
  - Compute L_1 and L_2 for specified depletion pressure
- Seismic event occurs if slip patch reaches the critical size L_c Uenishi & Rice (2003)
  - Adjust depletion pressure such that $L_c \leq L_1, L_2 \leq L_c + \varepsilon$

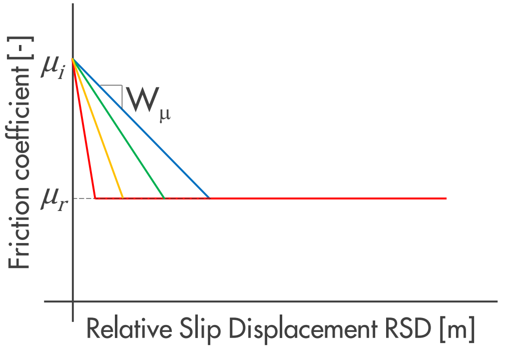
$$L_c = \frac{1.158}{(1-\nu)} \frac{G}{W} \qquad W = W_\mu \sigma_n$$

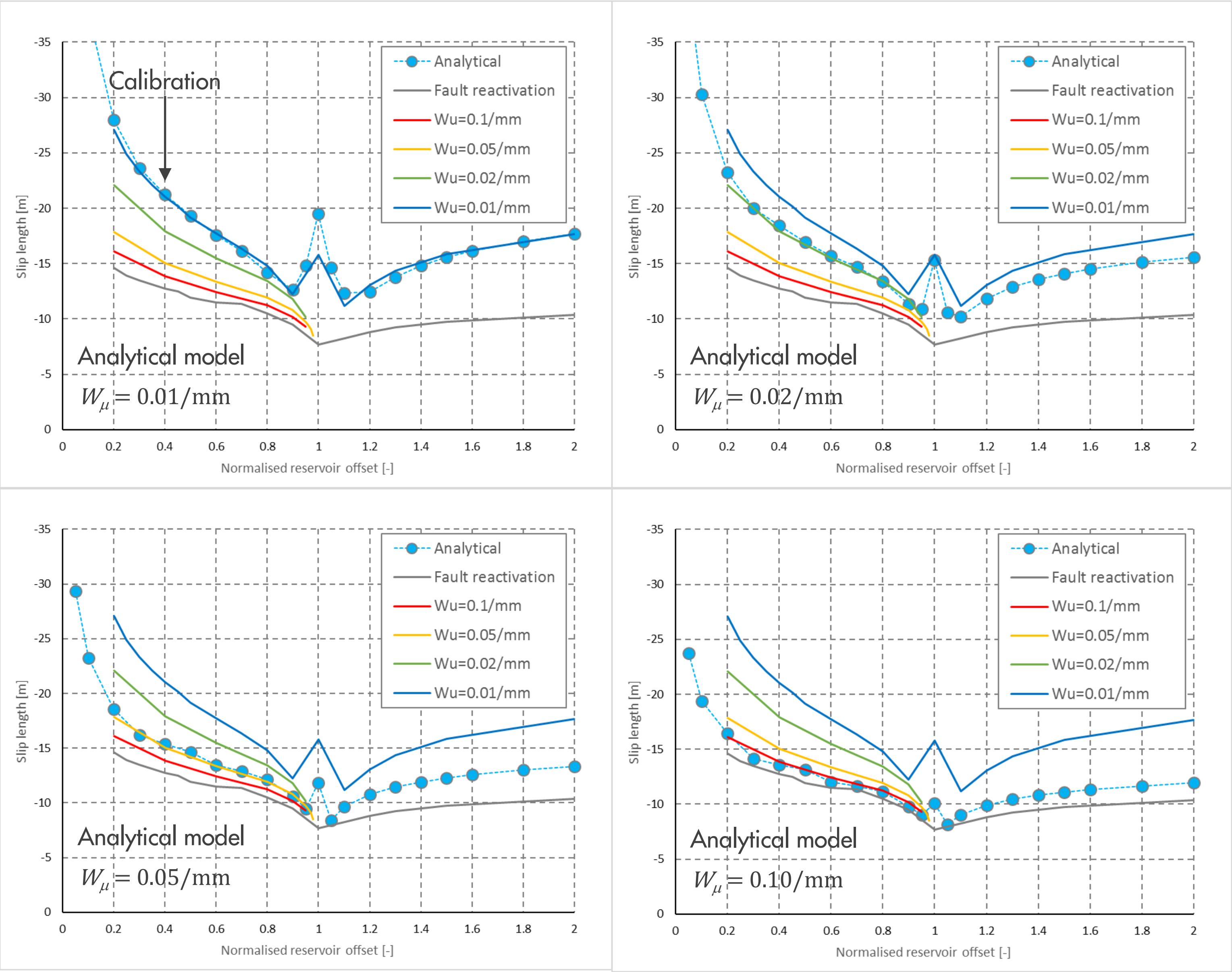
Uenishi, K. and Rice, J. R. (2003), Universal nucleation length for slip-weakening rupture instability under nonuniform fault loading, J. Geophys. Res., 108(B1), 2042, doi:10.1029/2001JB00168.



Calibration against FEM results

- Single calibration factor for all cases
- Analytical approach retrieves FE depletion pressure at which seismic rupture nucleates
  - Initial stress condition
  - Fault orientation
  - Normalised reservoir offset
  - Slope W_μ

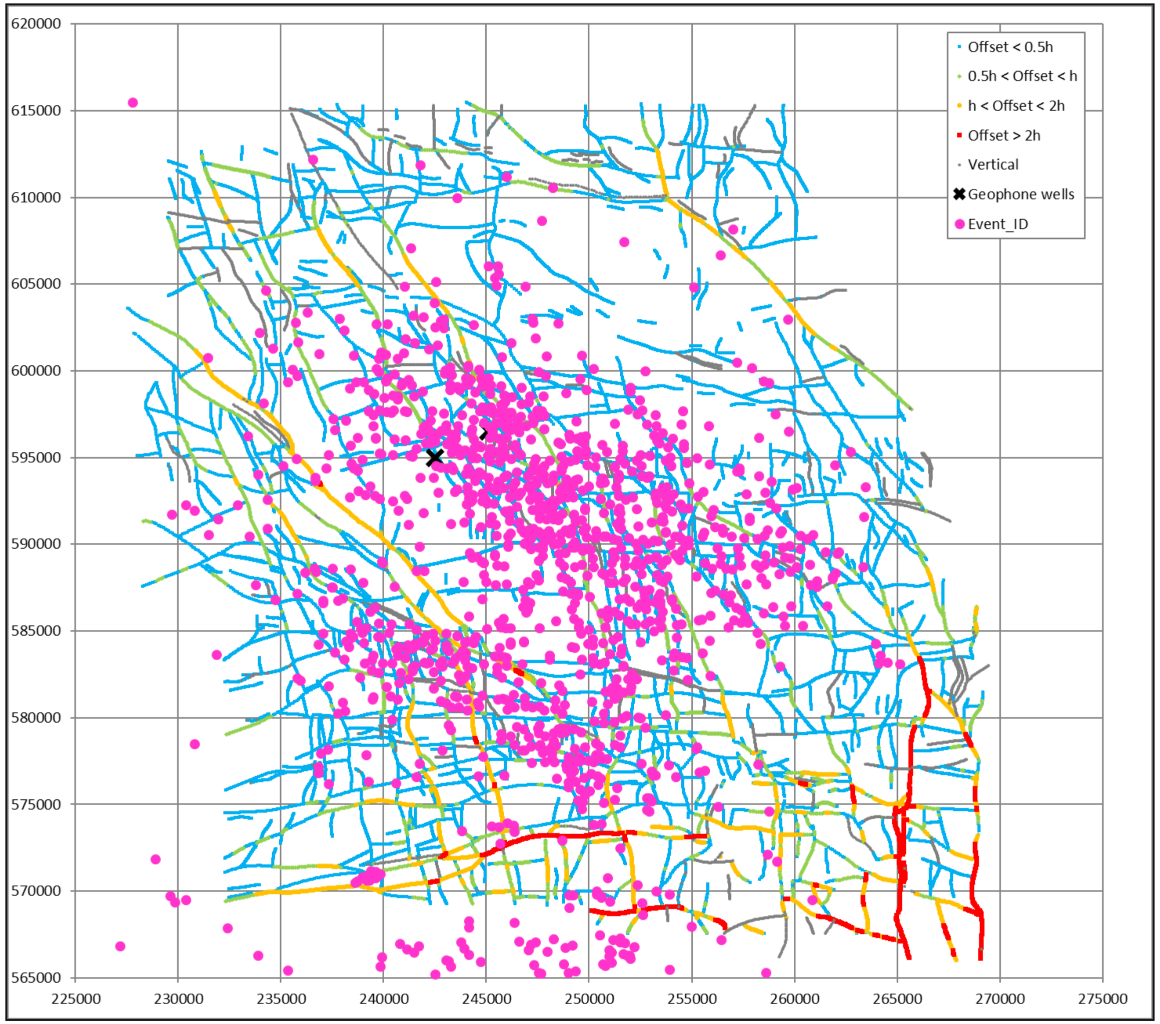




Conclusions

- Analytical approach accurately reproduces occurrence of seismic events in dynamic rupture simulations
  - Replicating the same physical response
  - Only a single calibration required to represent reservoir offset and slope W_μ

- Analytical solution provides the opportunity to improve a stochastic seismological model
  - Inversion for fault slip parameters W_μ, μ_i, μ_r from seismic events



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