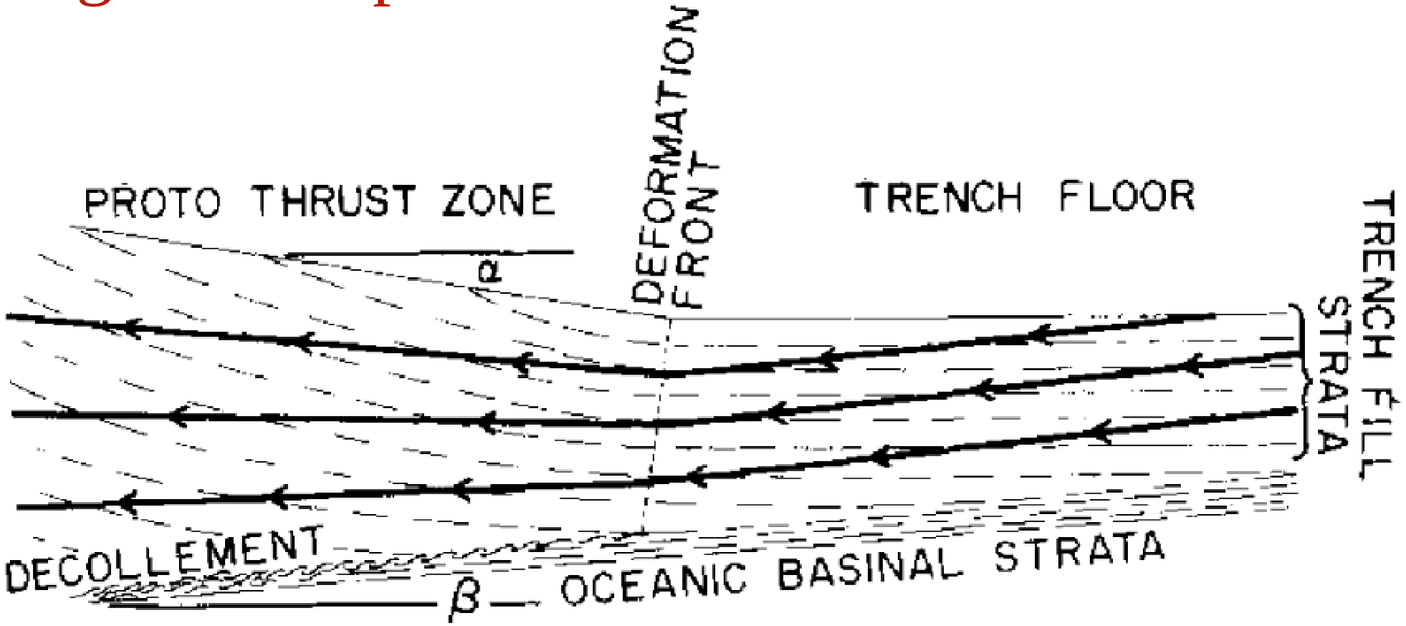
Mechanisms generating fluid overpressure at the trench of subduction zones and implications for megathrust weakening

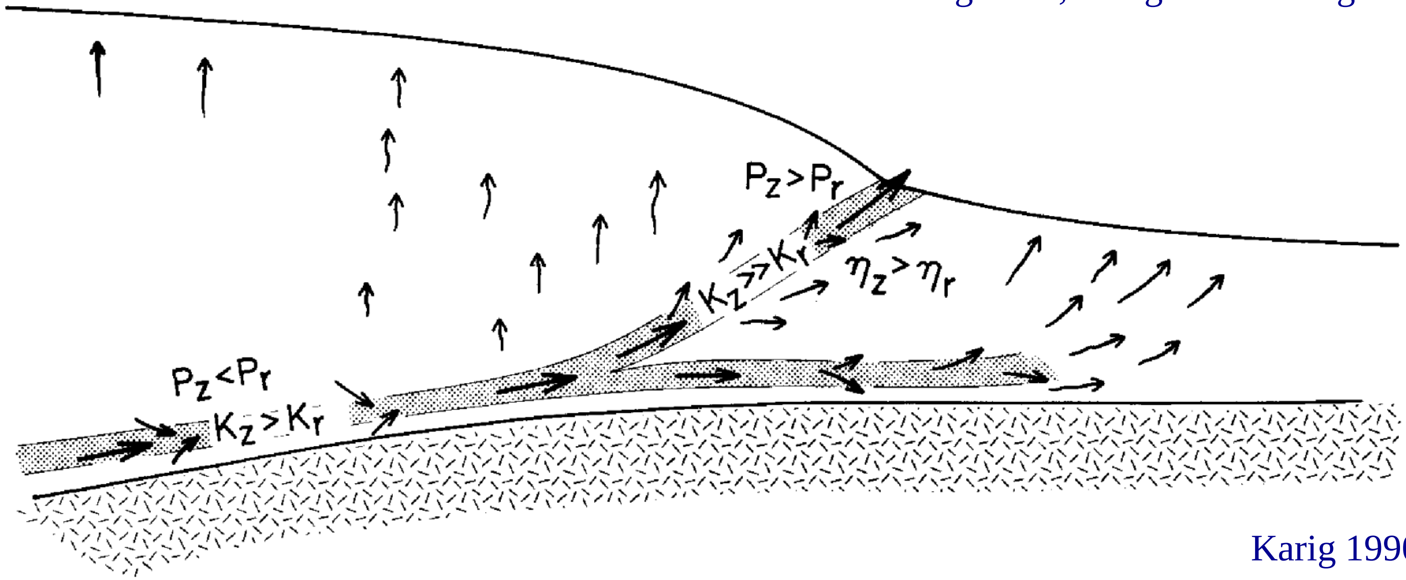
Maria Nikolinakou

The University of Texas at Austin

Long-studied problem



Karig 1990; Karig & Lundberg 1990

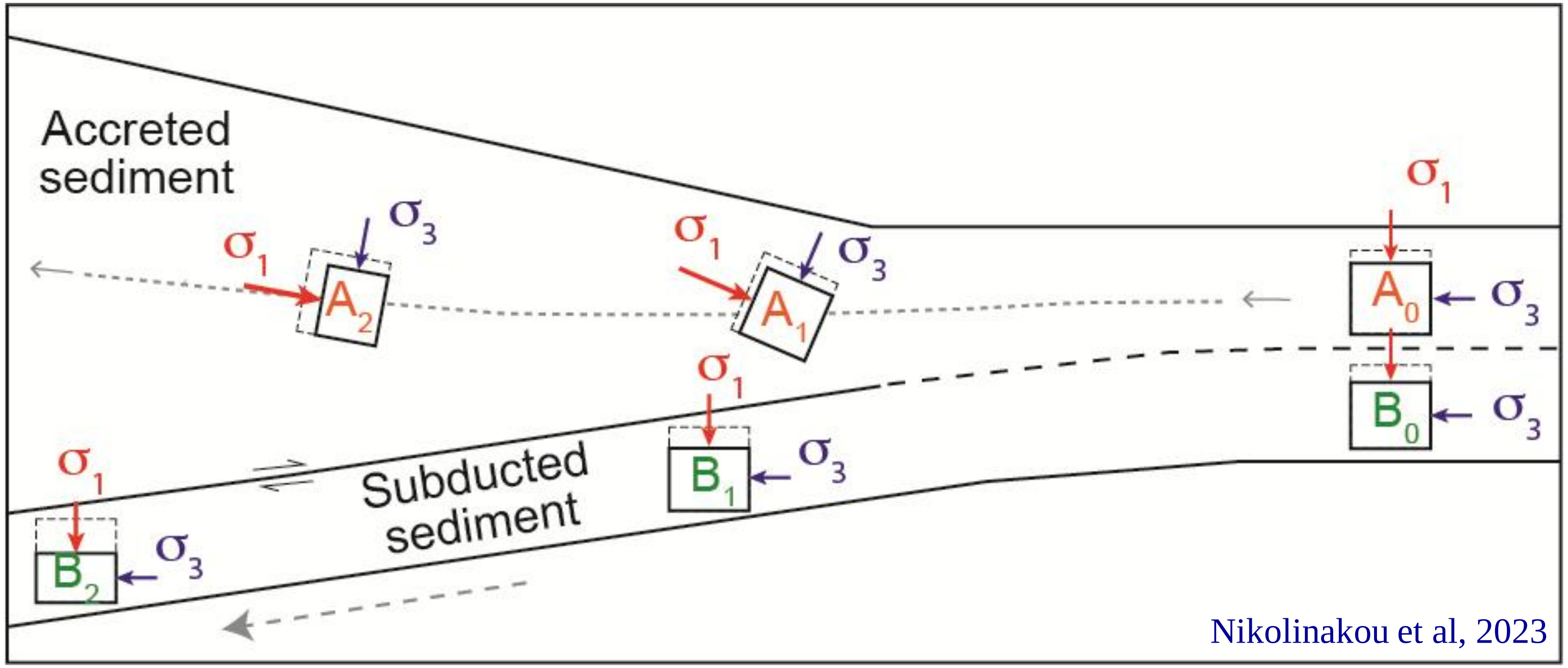


Karig 1990

- Evolving system where material is entering the thrust zone

- Generation and dissipation of overpressures

Evolution of stress state

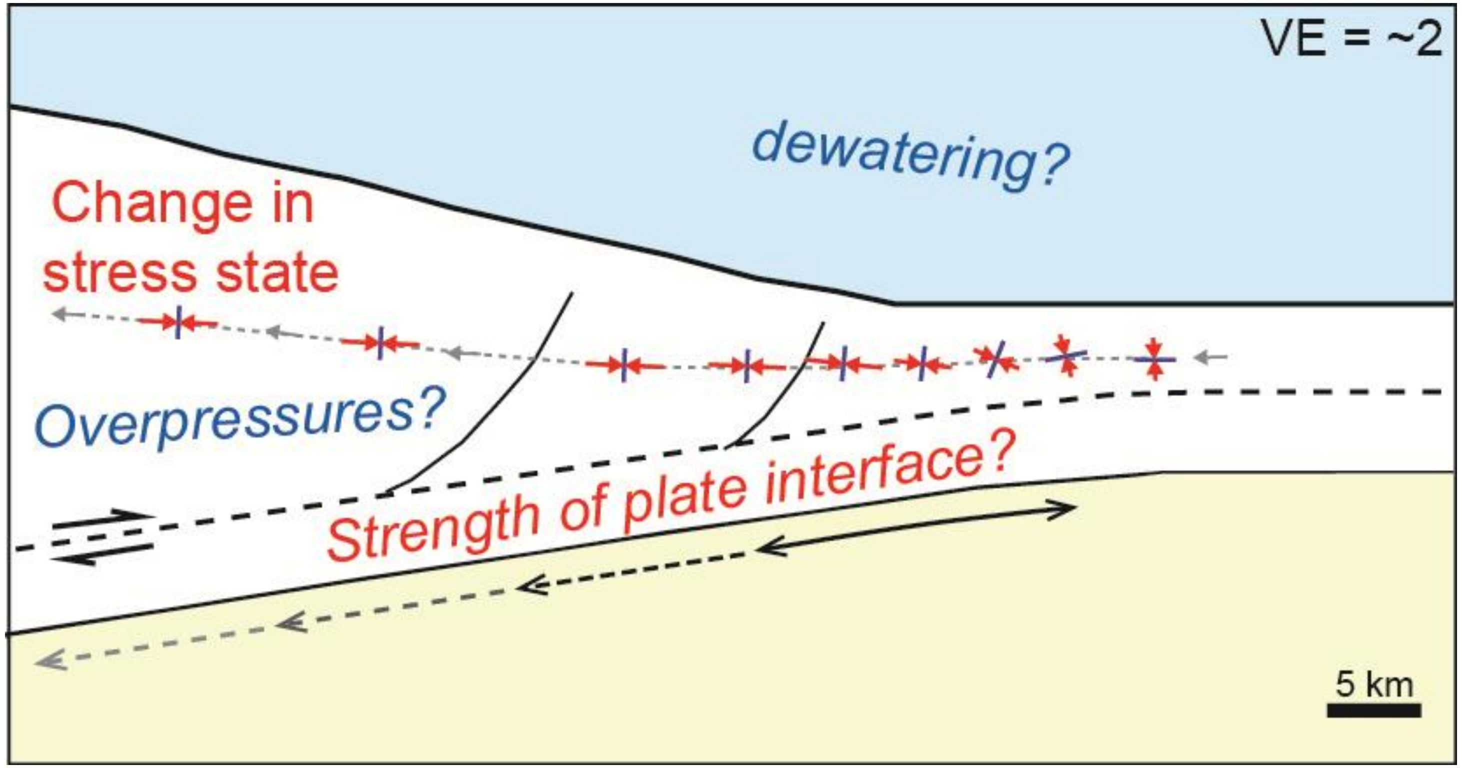


Komatsu D65PX-15 (youtube)

- Hanging wall: change in loading from vertical burial to lateral compression

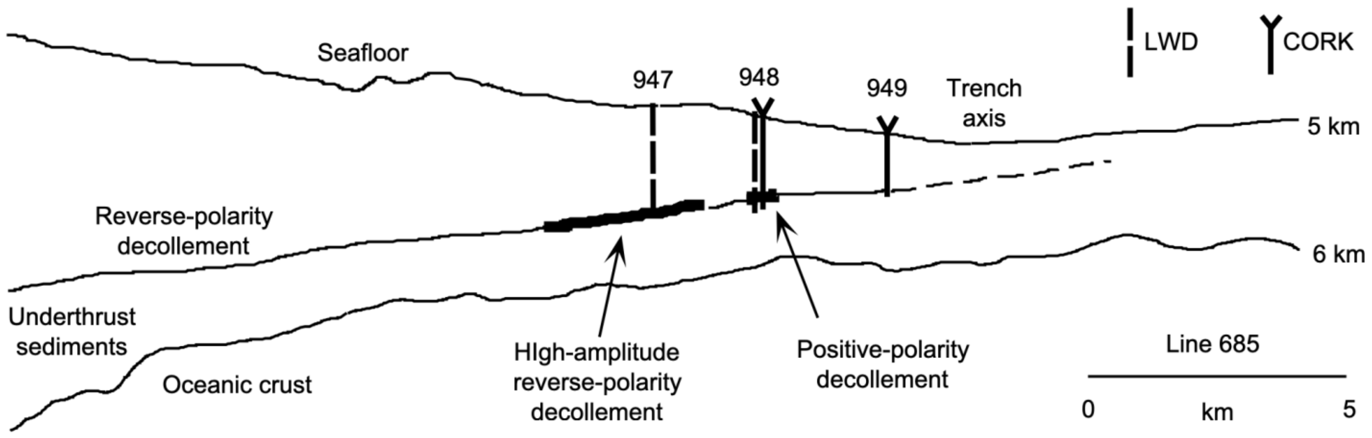
    e.g., Hubbert & Rubey (1959), Davis et al (1983), Karig (1986)

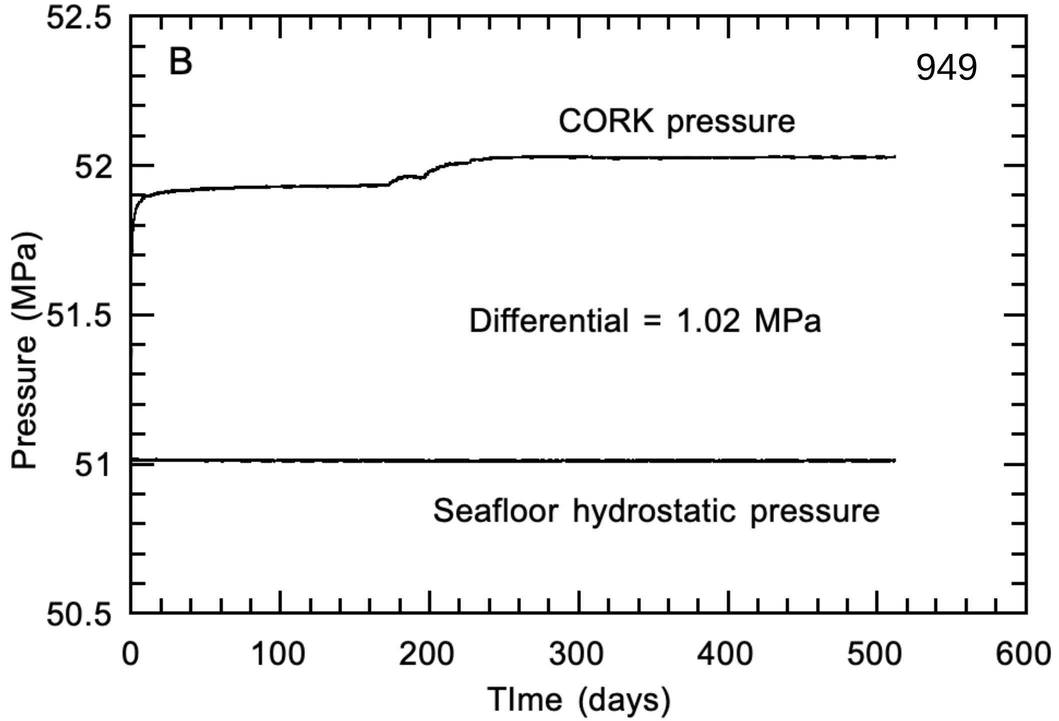
Long-standing question



How does the change in mechanical loading and stress state affect porosity, overpressures, and décollement strength?

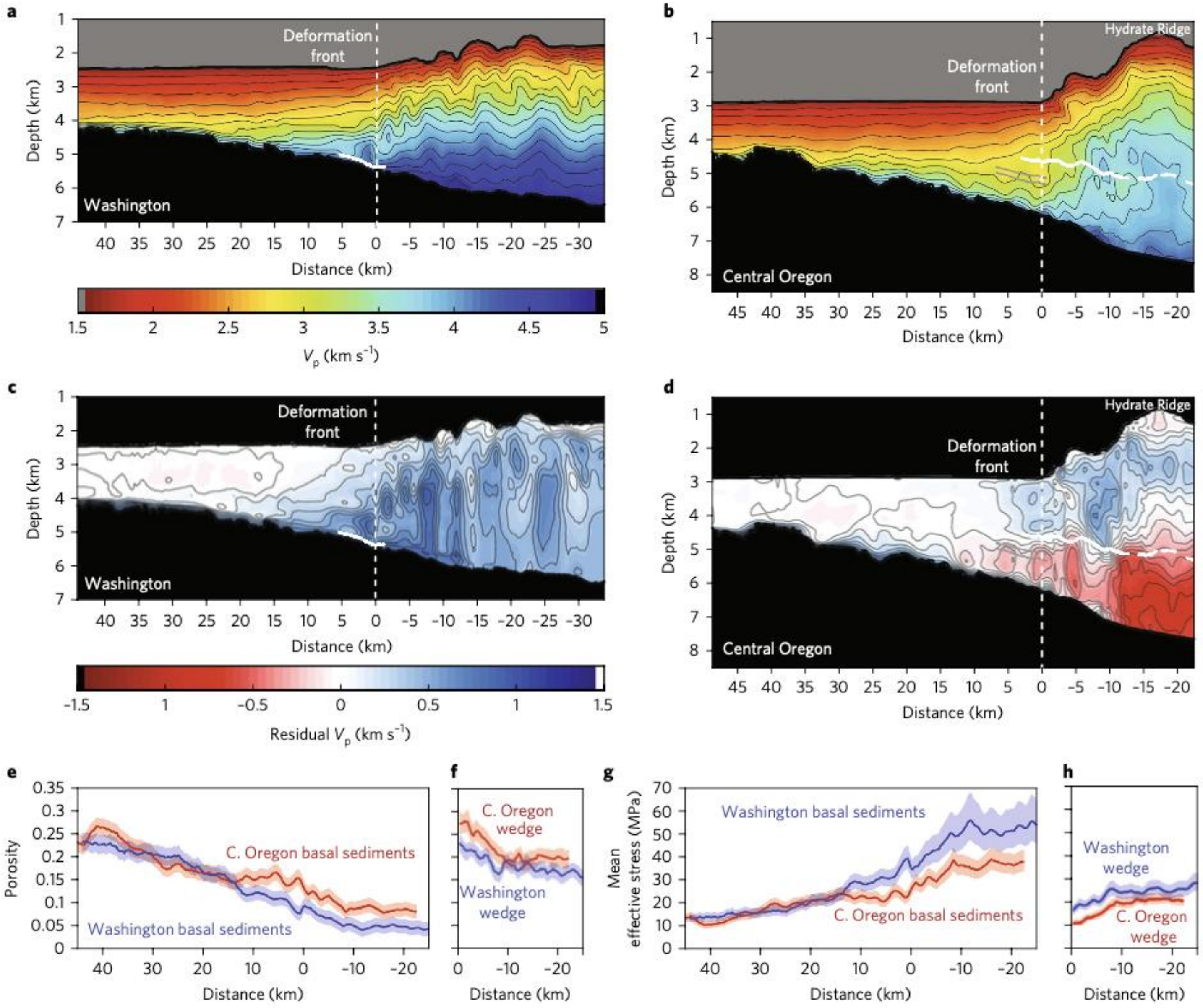
Very limited data from direct measurements





Barbados – Becker et al; 1997

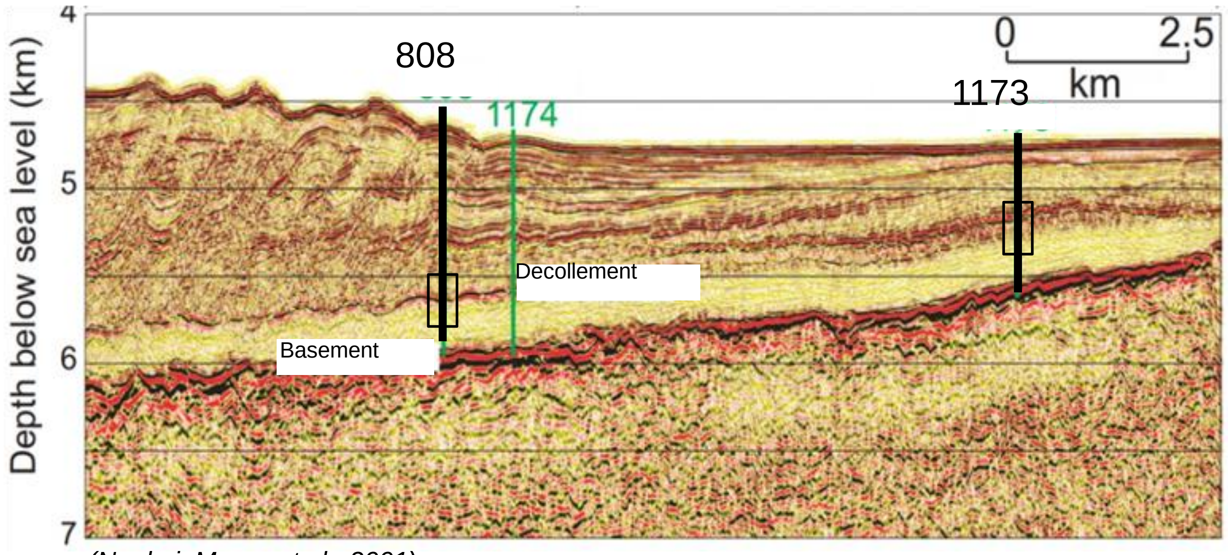
Long-standing question studied using a) seismic/geophysical data



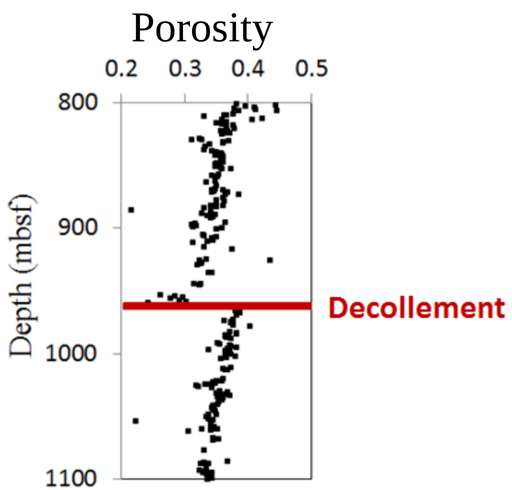
Han et al., 2017

- Low velocity zones interpreted to reflect high pore pressure in basal sediments below the décollement

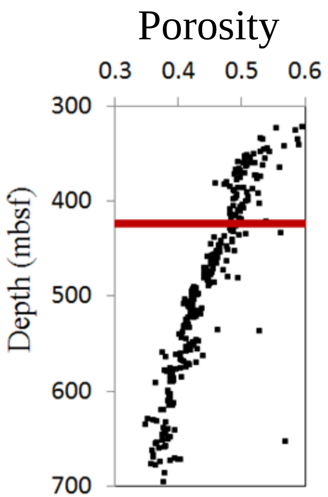
Long-standing question studied using b) field measurements



(Nankai; Moore et al., 2001)



Site 808

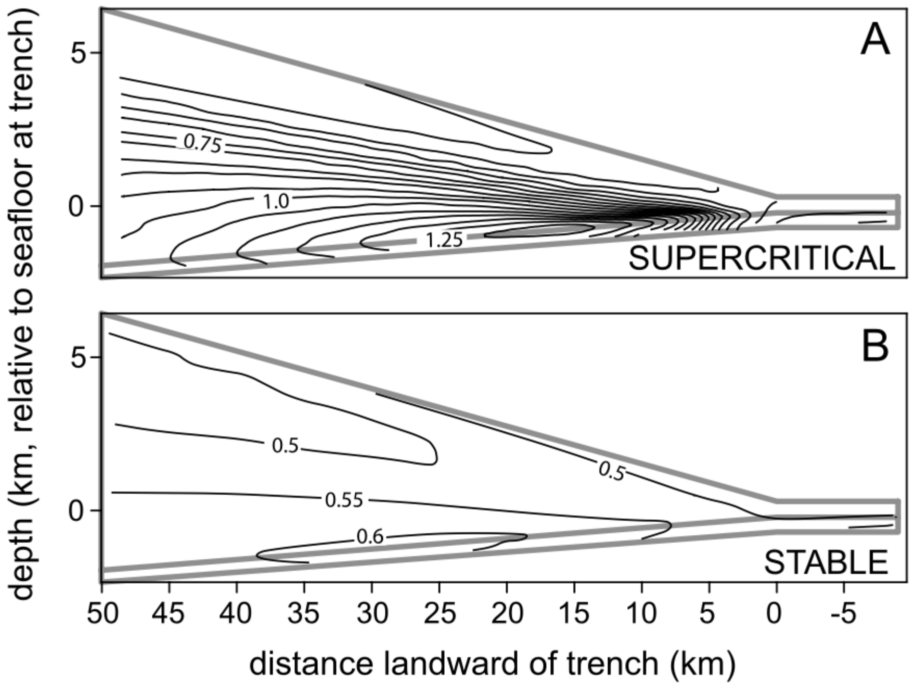


Site 1173

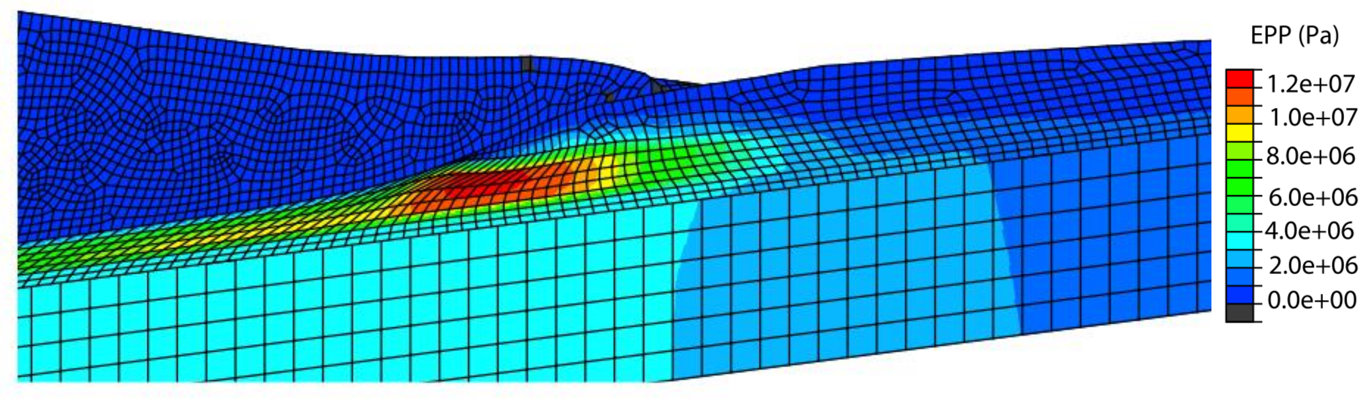
(Shipboard Scientific Party, 1991)

- Accretionary prism sediments are more compacted despite the presence of overpressures
- Contrast in physical properties between hanging wall and footwall sediments

Long-standing question studied using c) numerical models



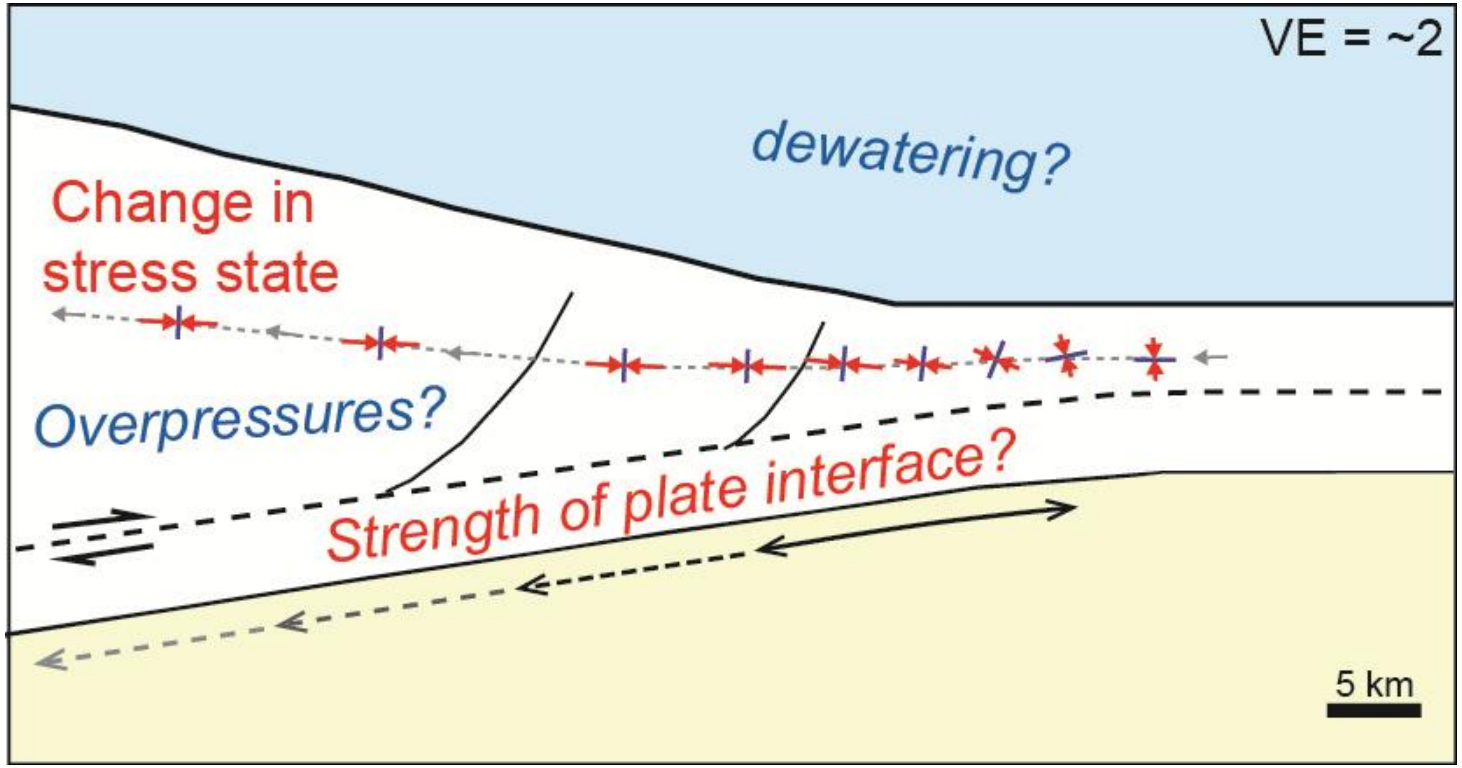
Saffer & Bekins, 2006



Rowe et al (2012)

- Decades of numerical simulations addressing large deformations, change in stress state, porous fluid flow

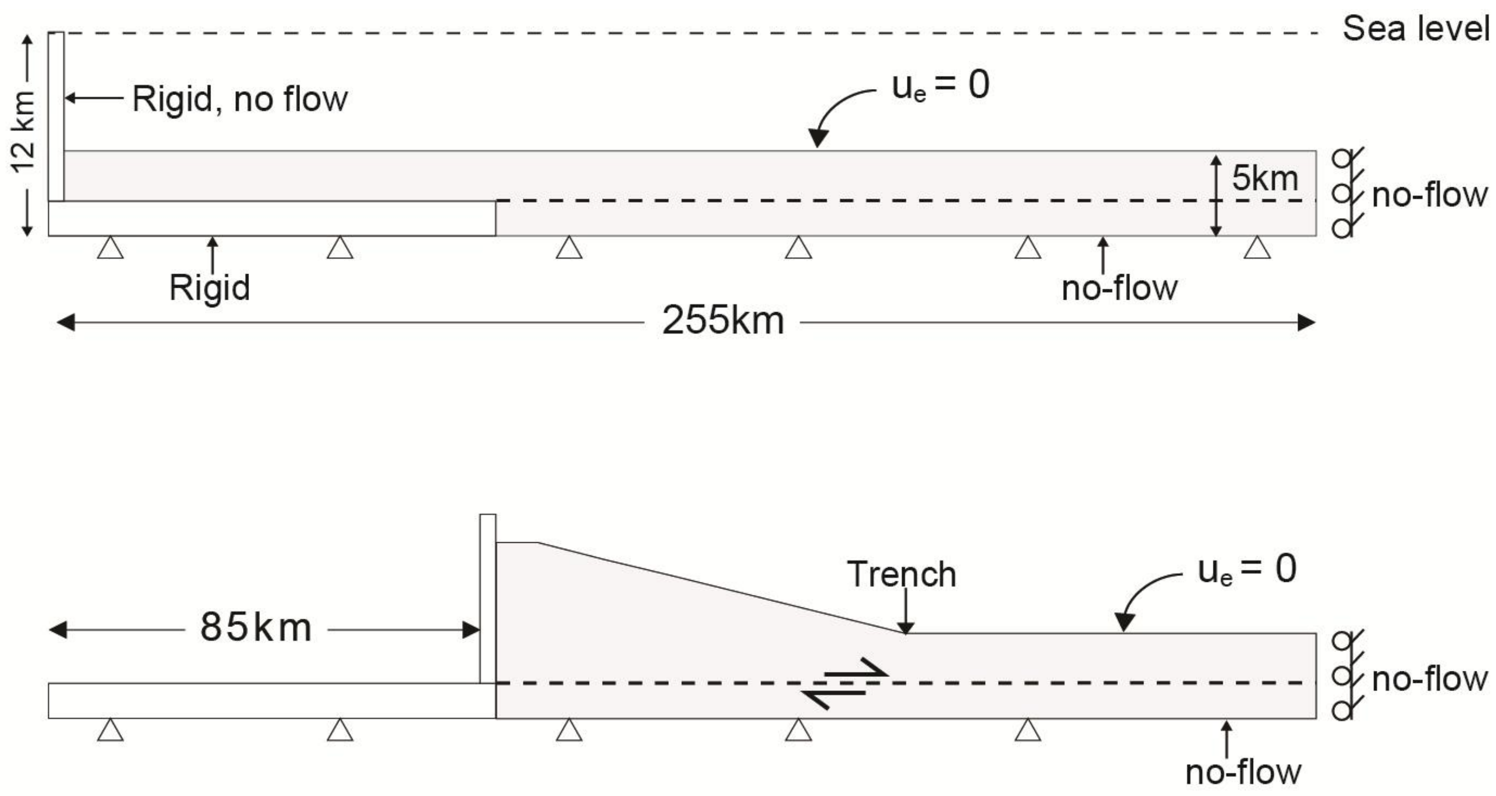
Our geomechanical study



Nikolinakou, Flemings, Gao, Saffer; JGR 2023

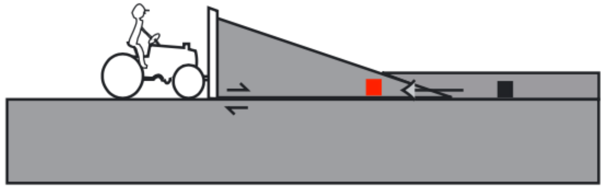
- Realistic sediment rheology that captures the poro-plastic behavior of marine sediments
  - Contribution of both mean and shear stress to compaction and overpressure generation
- Large-strain evolutionary geomechanical models
- Fully coupled (transient) deformation and porous fluid flow

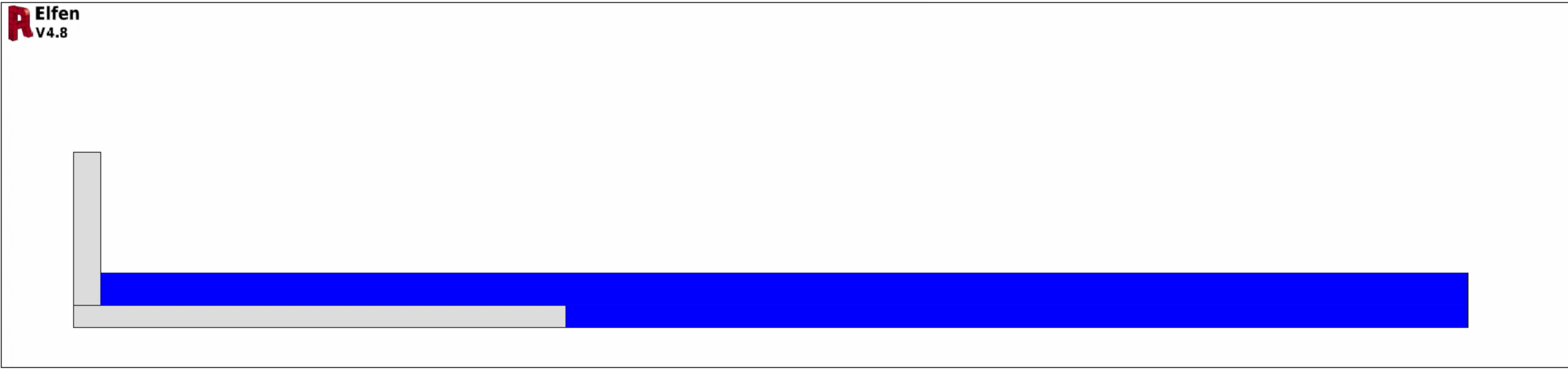
Evolutionary geomechanical model

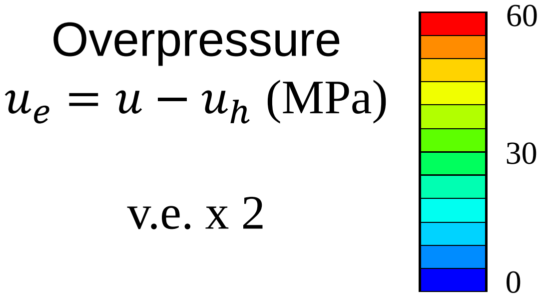


- Finite element model (Rockfield Elfen)
- 2D plane strain
- Transient analyses: couple loading, drainage, and sediment compression
- Poro-elastoplastic material (Critical state; SR3)

Evolutionary geomechanical model

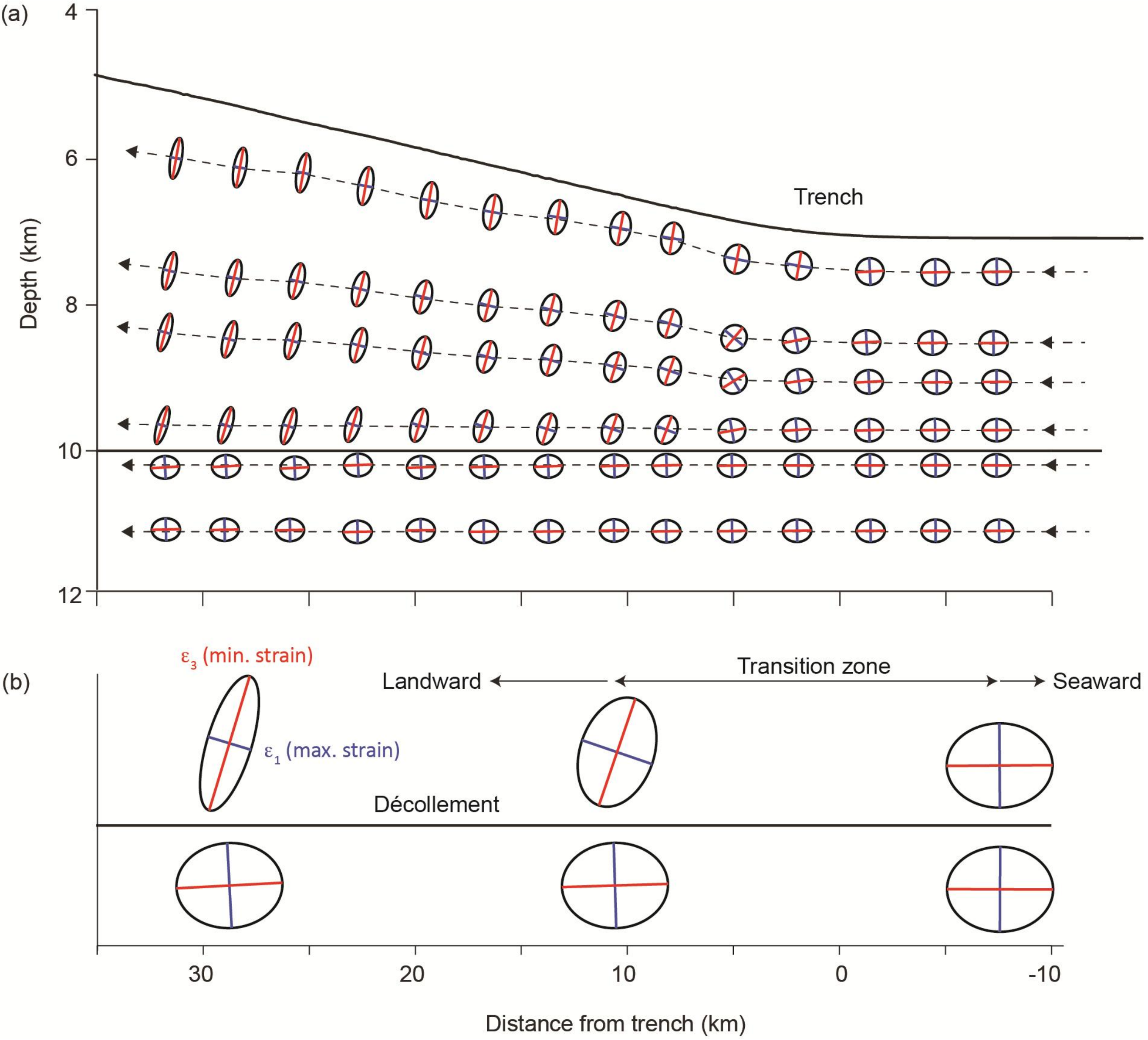


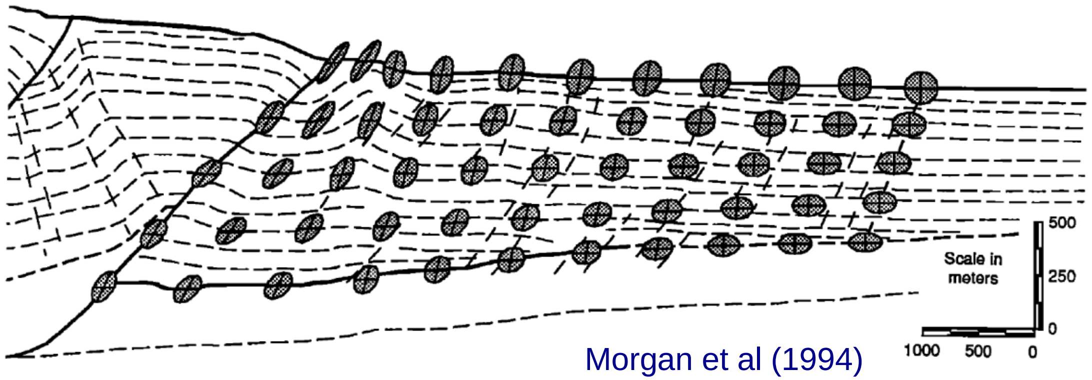




- Transient analysis couples tectonic loading, drainage, and sediment compression

Strain evolution

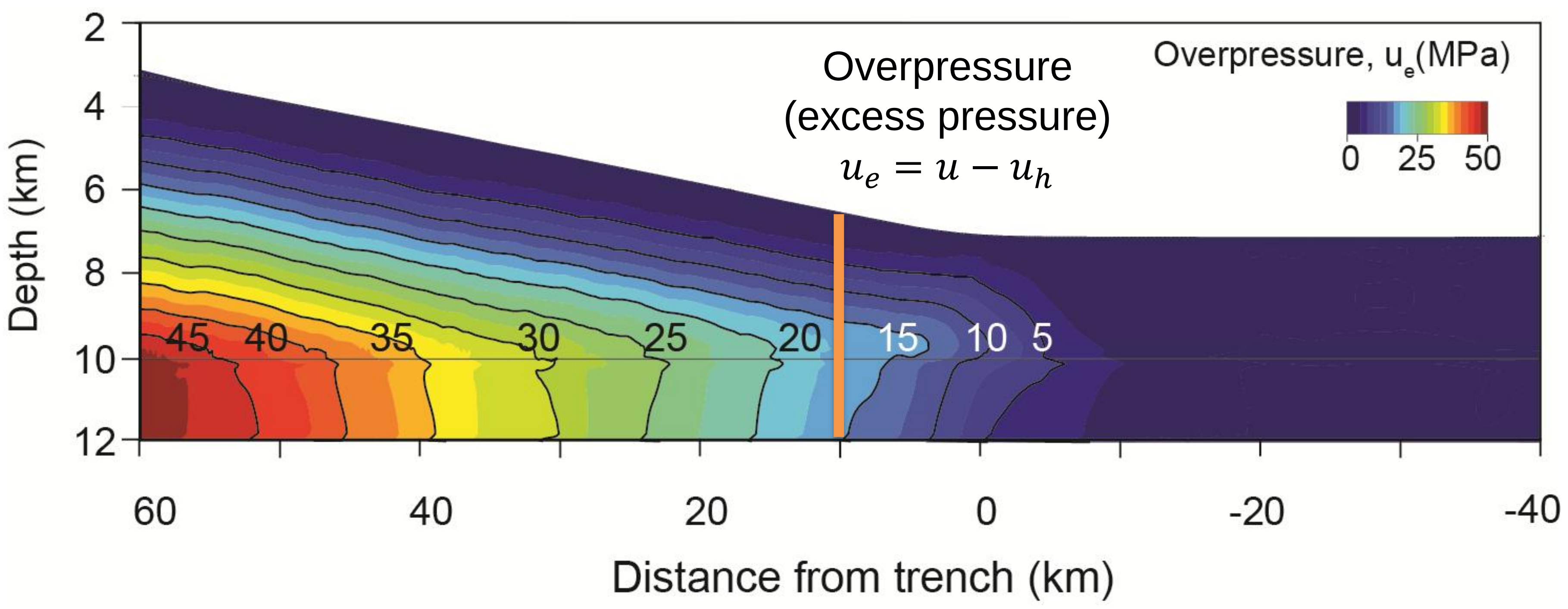


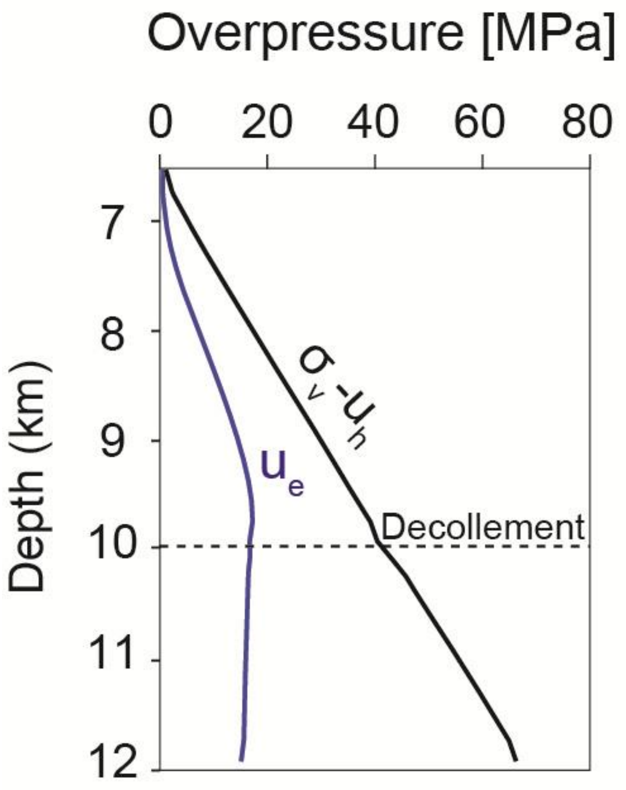


Morgan et al (1994)

- Geomechanical results mechanically quantify strain evolution observed in the field
- Models now simulate observations at fabric scale

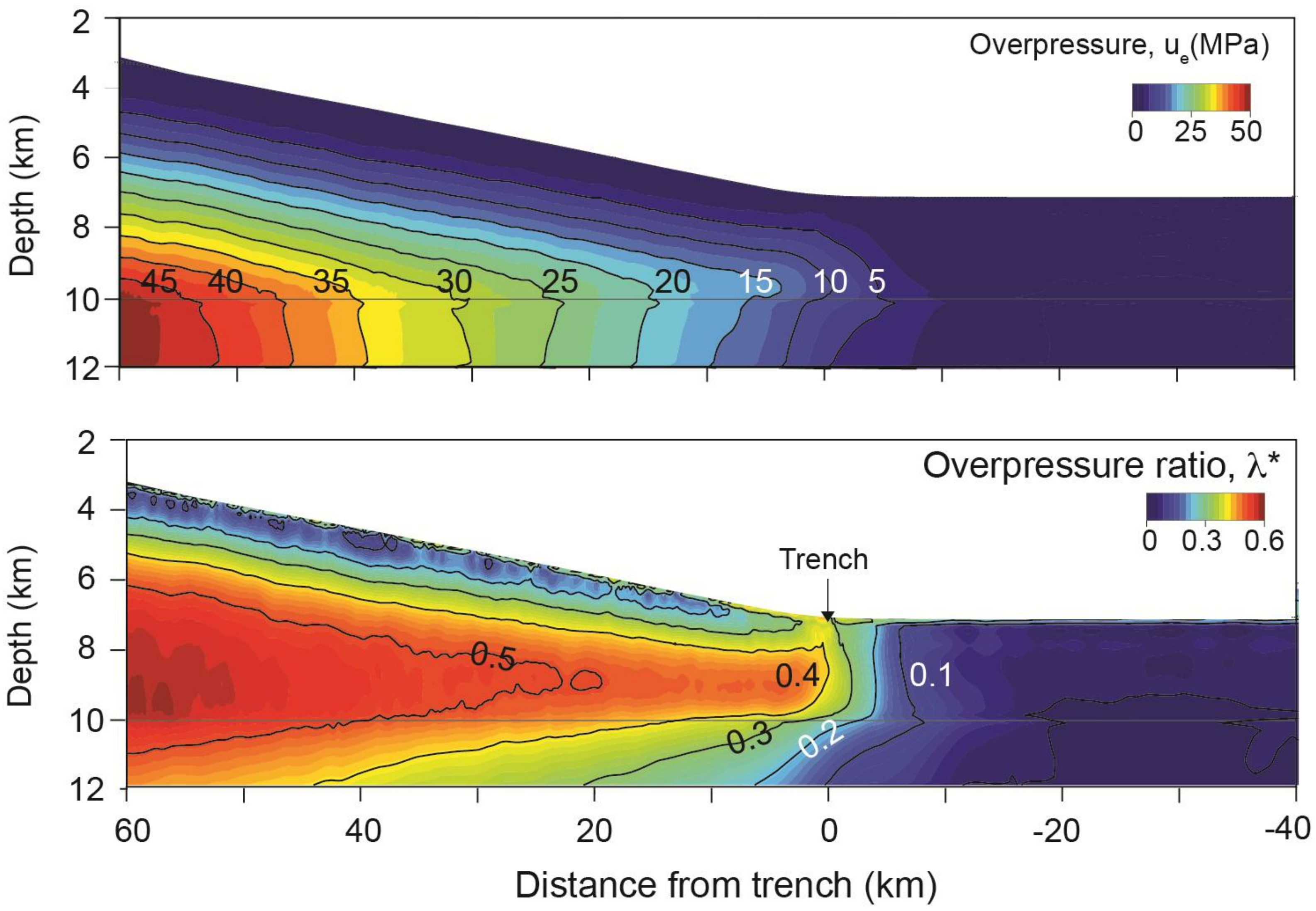
Overpressure

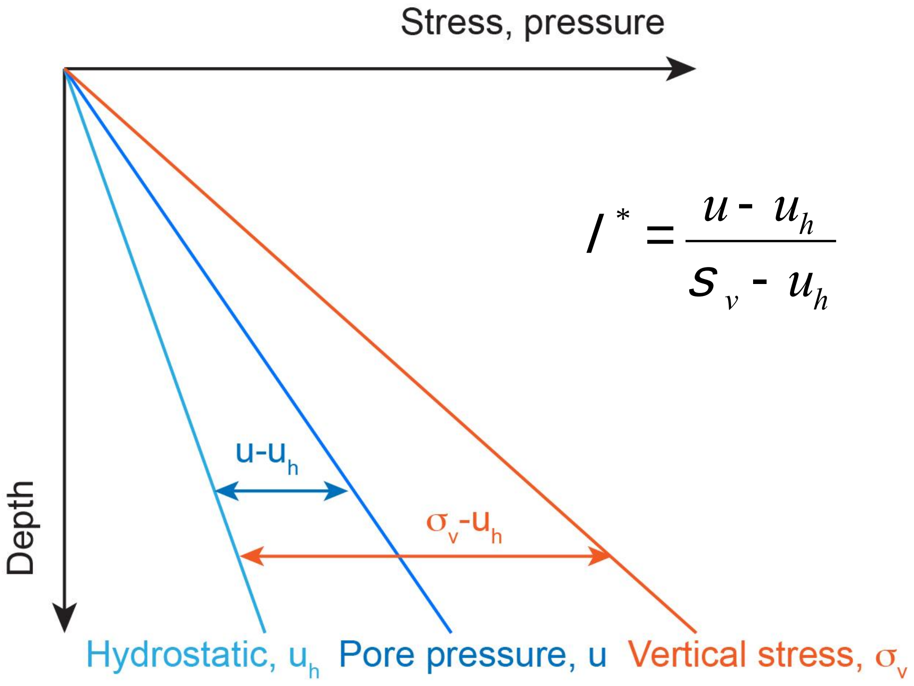




- Rapid increase of overpressure at trench
- Overpressure develops seaward of trench, despite constant overburden (flat sea floor)
- Near trench, pressure at hanging wall is much higher than in footwall

Overpressure ratio at trench

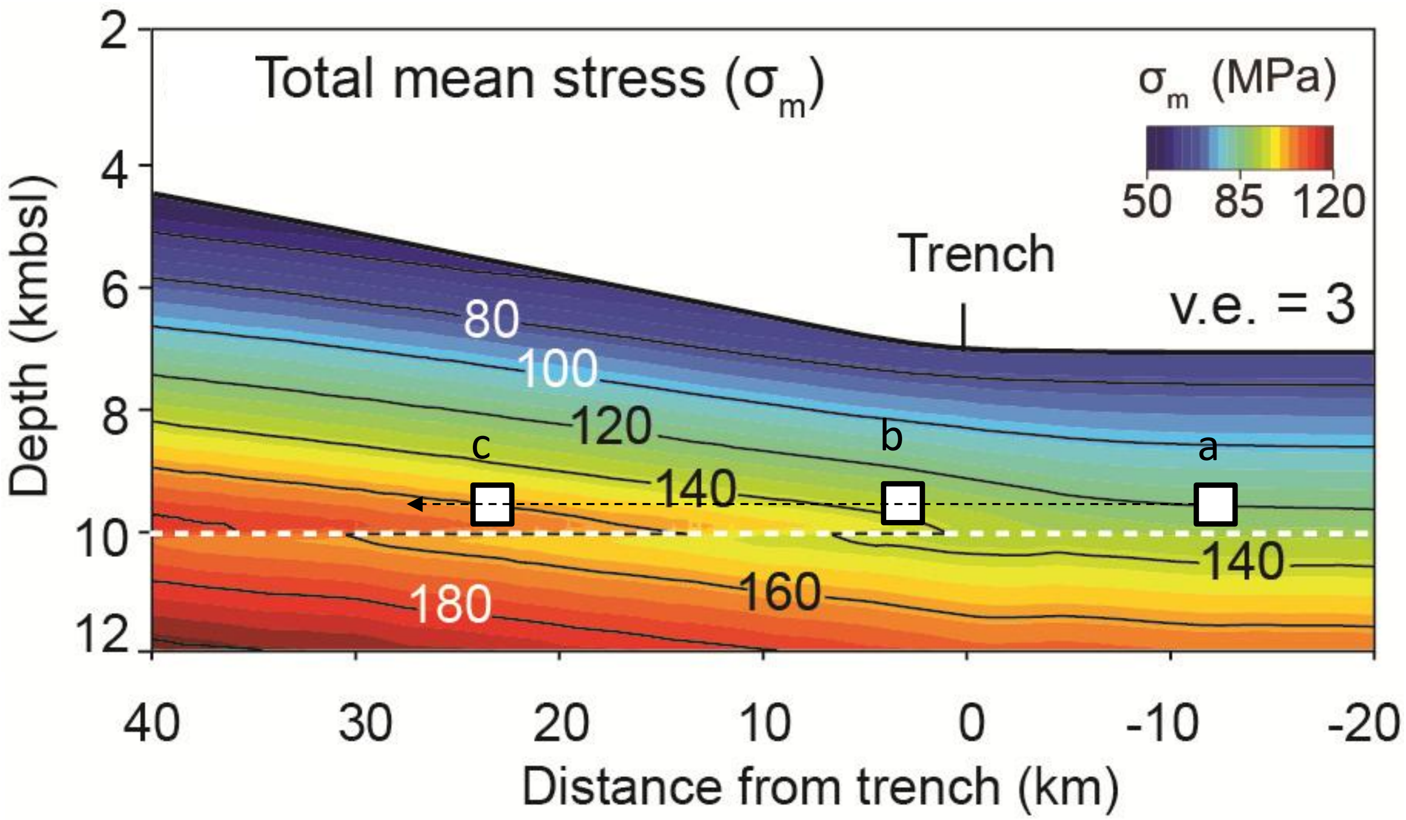


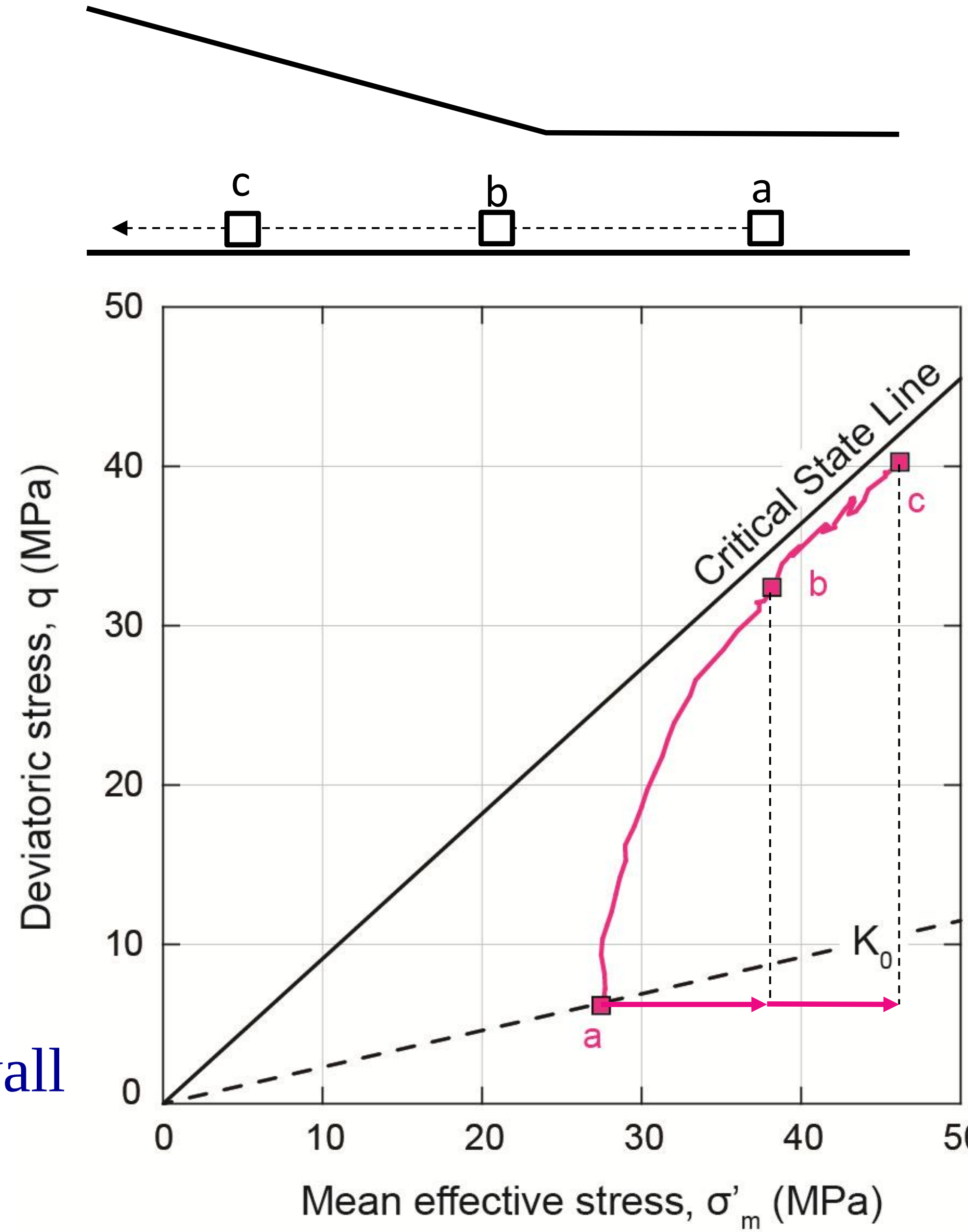


$$\lambda^* = \frac{u - u_h}{\sigma_v - u_h}$$

- Overpressure onsets ahead of the trench
- Overpressure increases faster than overburden at trench area

Mean stress increase in hanging wall

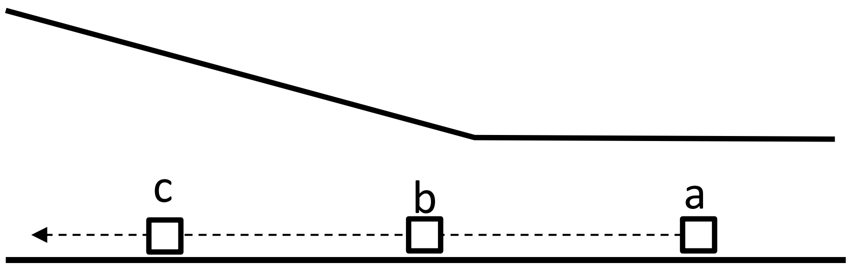


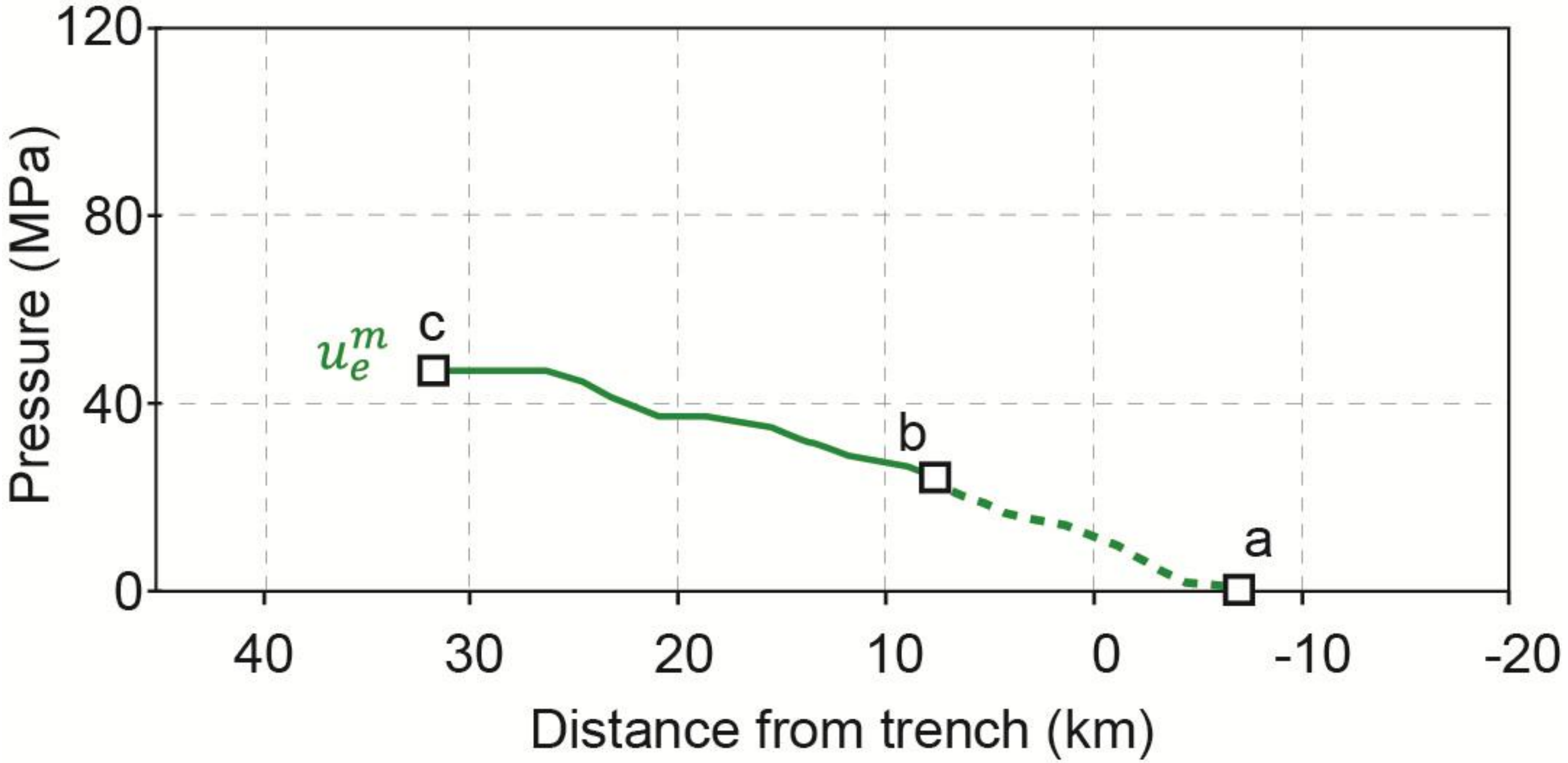


Lateral tectonic loading increases mean stress in hanging wall

Significant mean-stress increase in the trench area

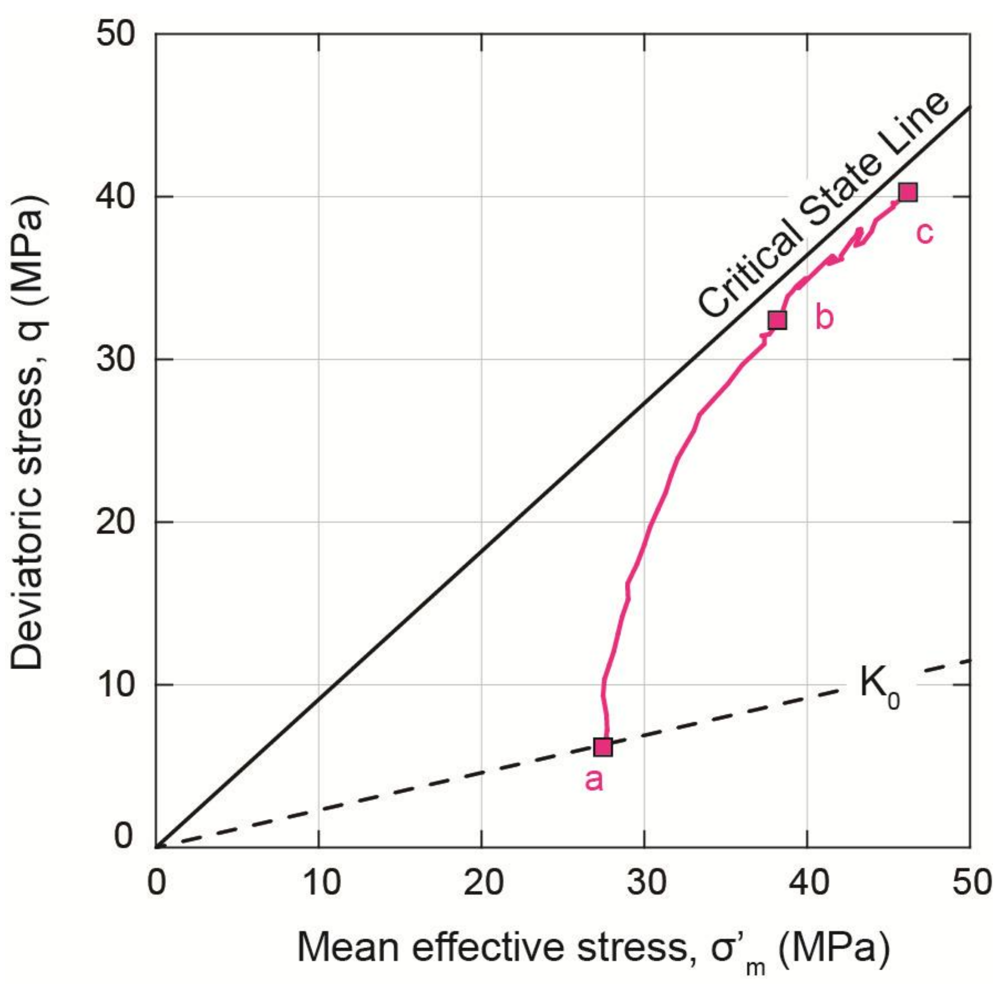
Mean-stress induced overpressures

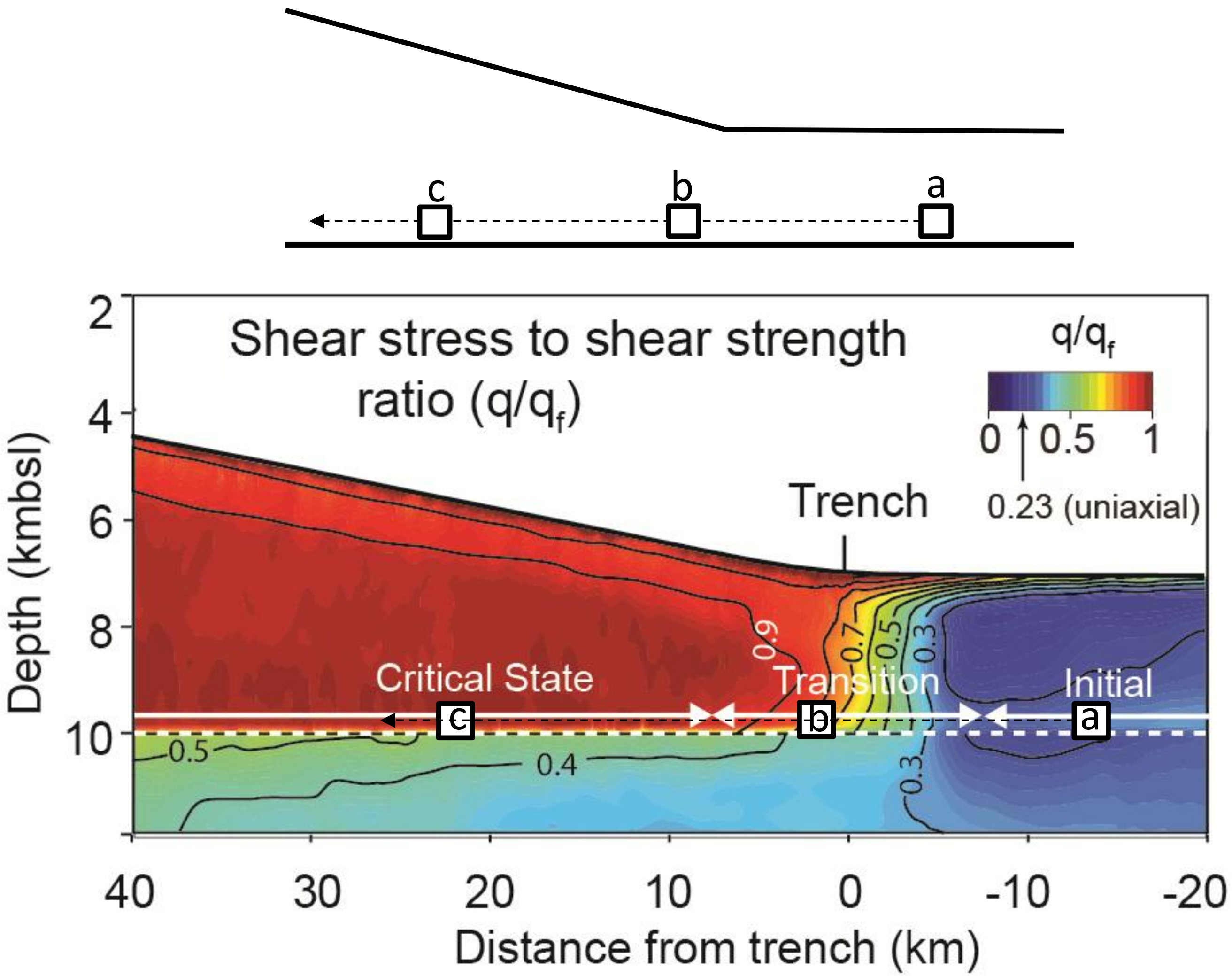




- Increase in mean stress leads to an increase in overpressure as sediment enters the wedge
- Overpressure increase ahead of the trench

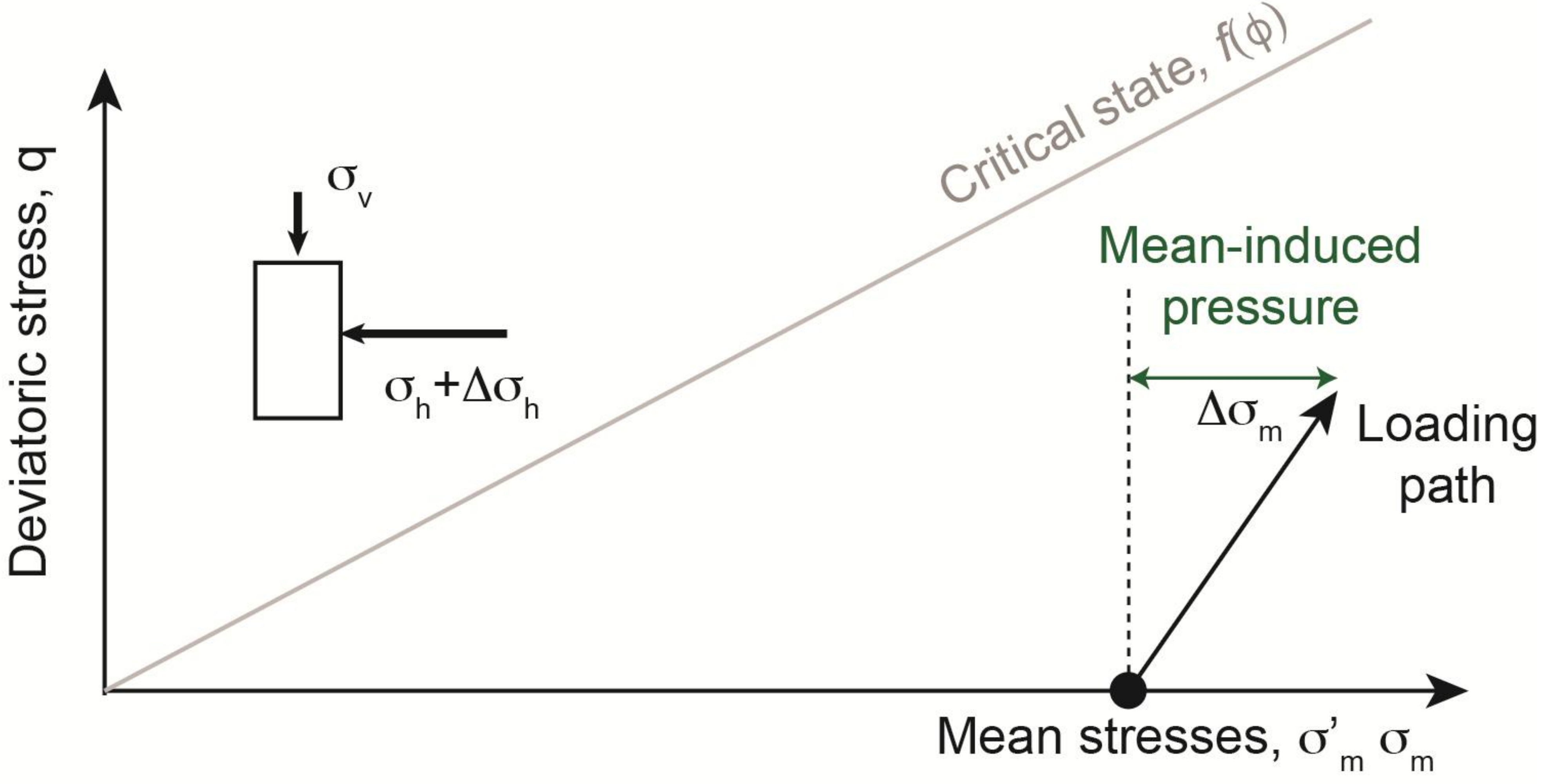
Differential stress in hanging wall





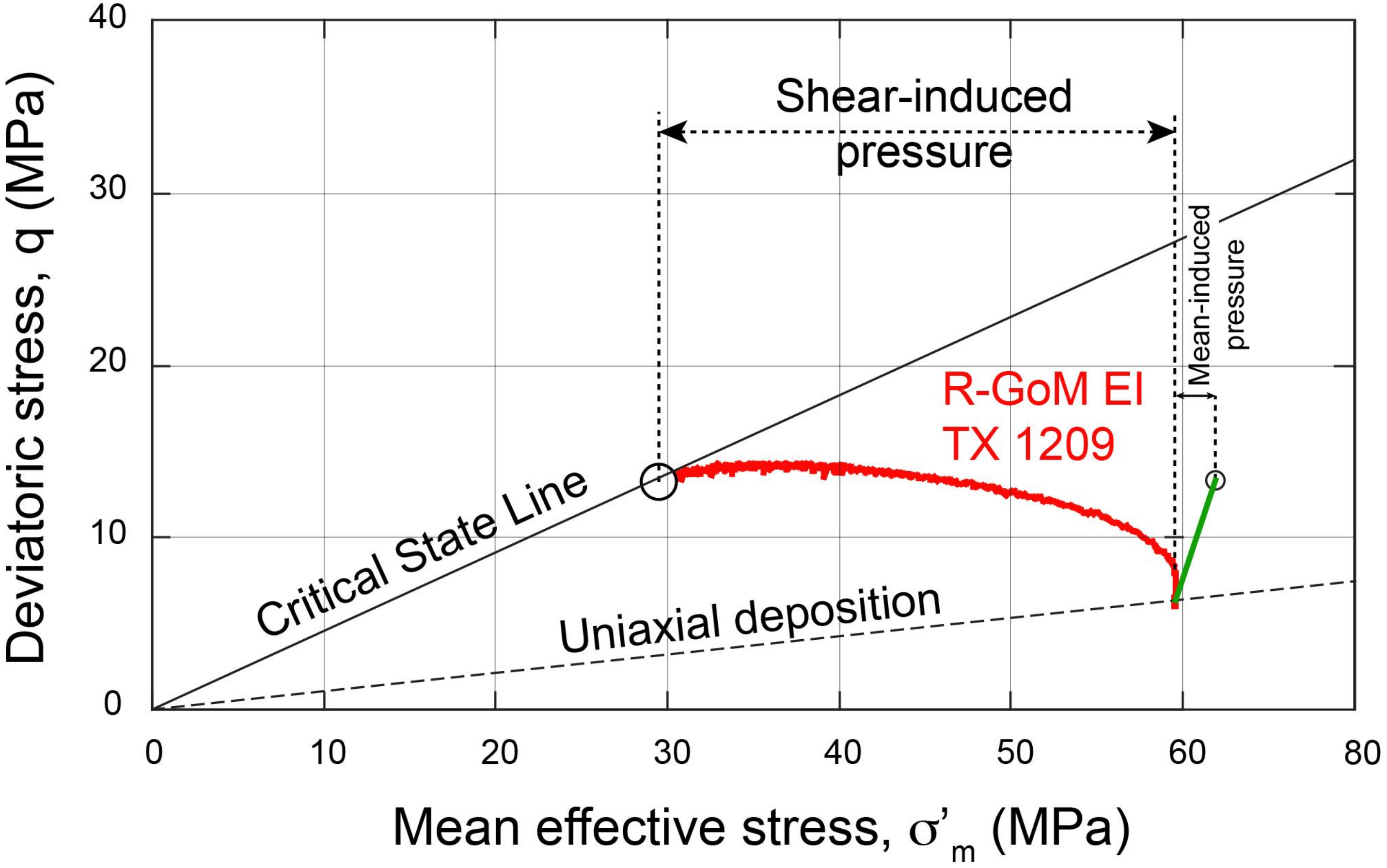
- Deviatoric stress increases faster than the mean effective stress
- Coulomb failure inside wedge

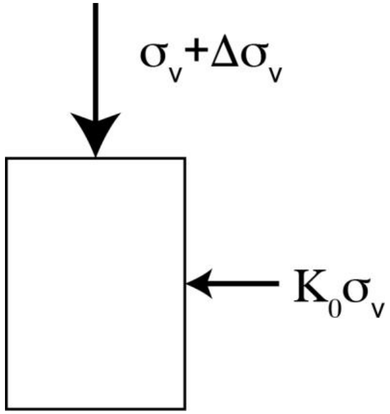
Undrained pore pressure response to mean stress increase



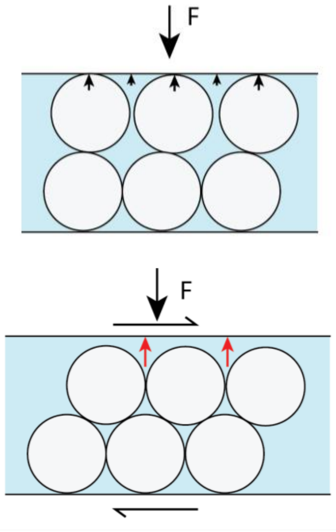
Total mean stress generates overpressure

Experimental measurement on offshore mudrocks





Triaxial frame; 40-100 MPa
Tufts University



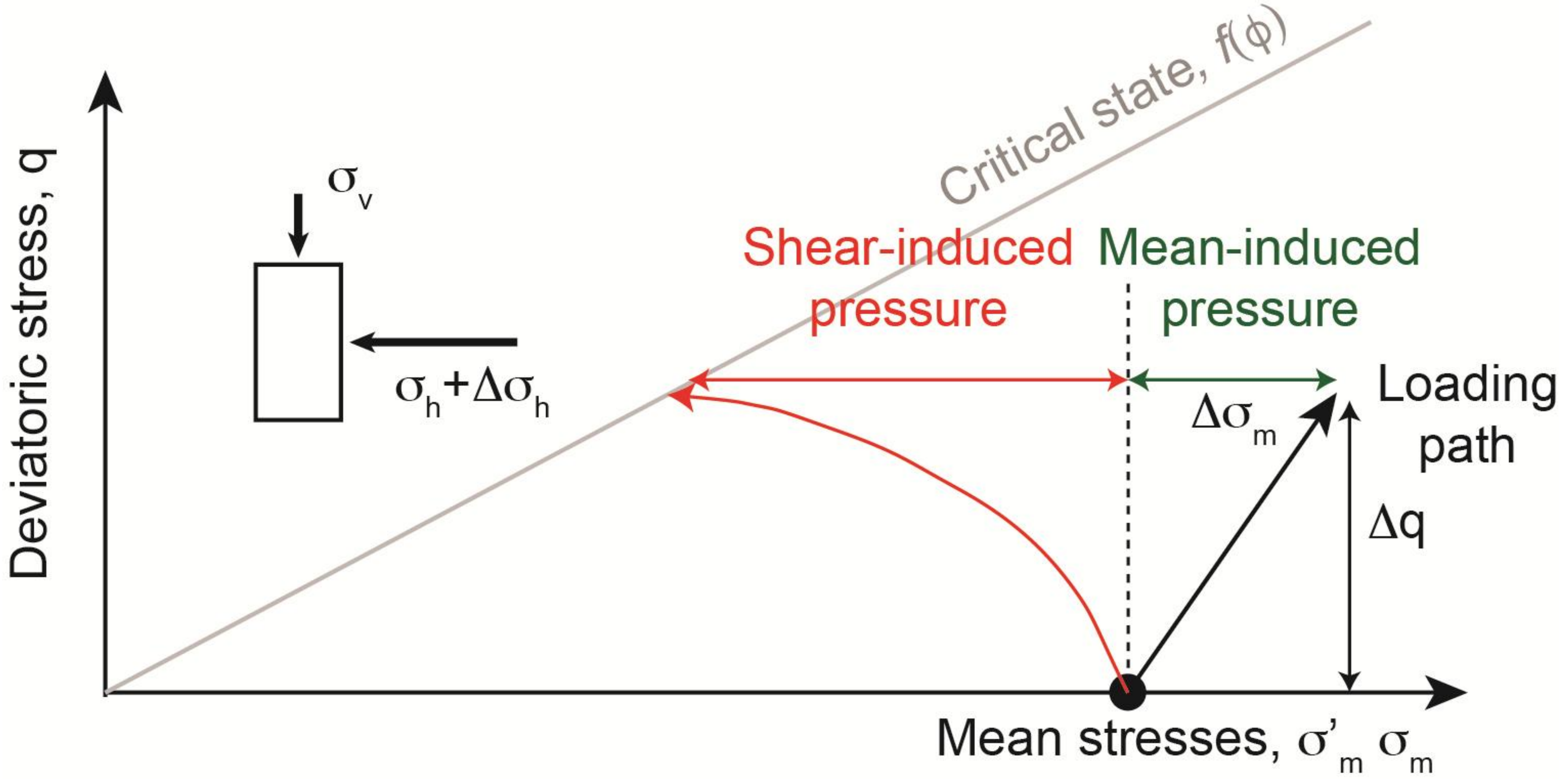
Effective stress decreases ➔ weaker material

Overpressure supports part of the load

Mudrocks can generate significant overpressure under differential loading

Flemings (2021)

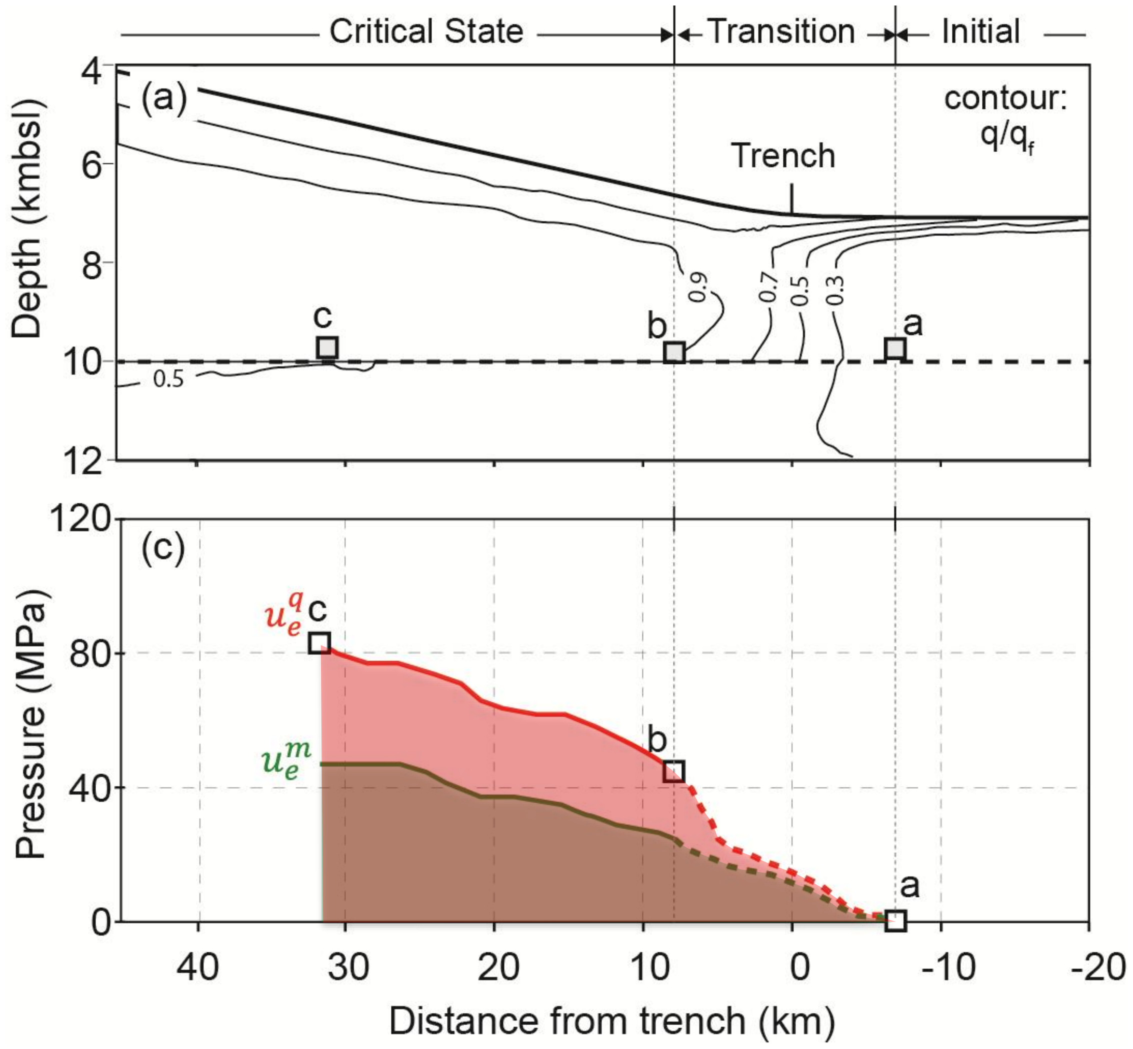
Undrained pore pressure response to mean and deviatoric stress increase



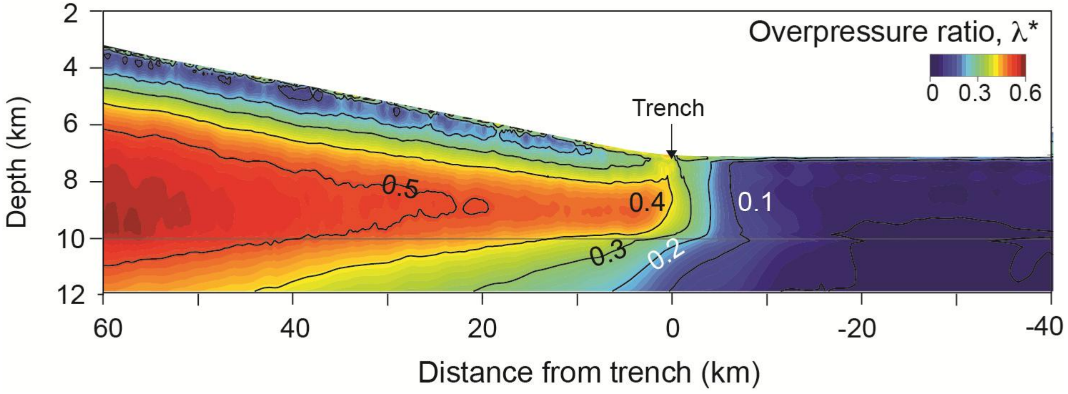
Both mean and deviatoric loading generate overpressure

Effective stress decreases ➔ weaker material, pore pressure supports part of the load

Shear-stress-induced overpressures



- Increase in differential stress generates significant overpressures
- Rapid increase of shear-induced pressures at the trench area, where relative shear increases



- Overpressure increases faster than overburden at trench area → decrease in effective stress

Components of overpressure generation

- Using conservation of fluid mass, Darcy's law, and poro-elastoplasticity:

Pressure | Mean-induced | Shear-induced | Pressure dissipation

$$\frac{Du}{Dt} = \frac{\xi_m}{S}\frac{D\sigma_m}{Dt} + \frac{\xi_q}{S}\frac{Dq}{Dt} + \frac{1}{S\rho_f}\nabla\cdot\left(\frac{\rho_f k}{\mu}\nabla\cdot u_e\right)$$

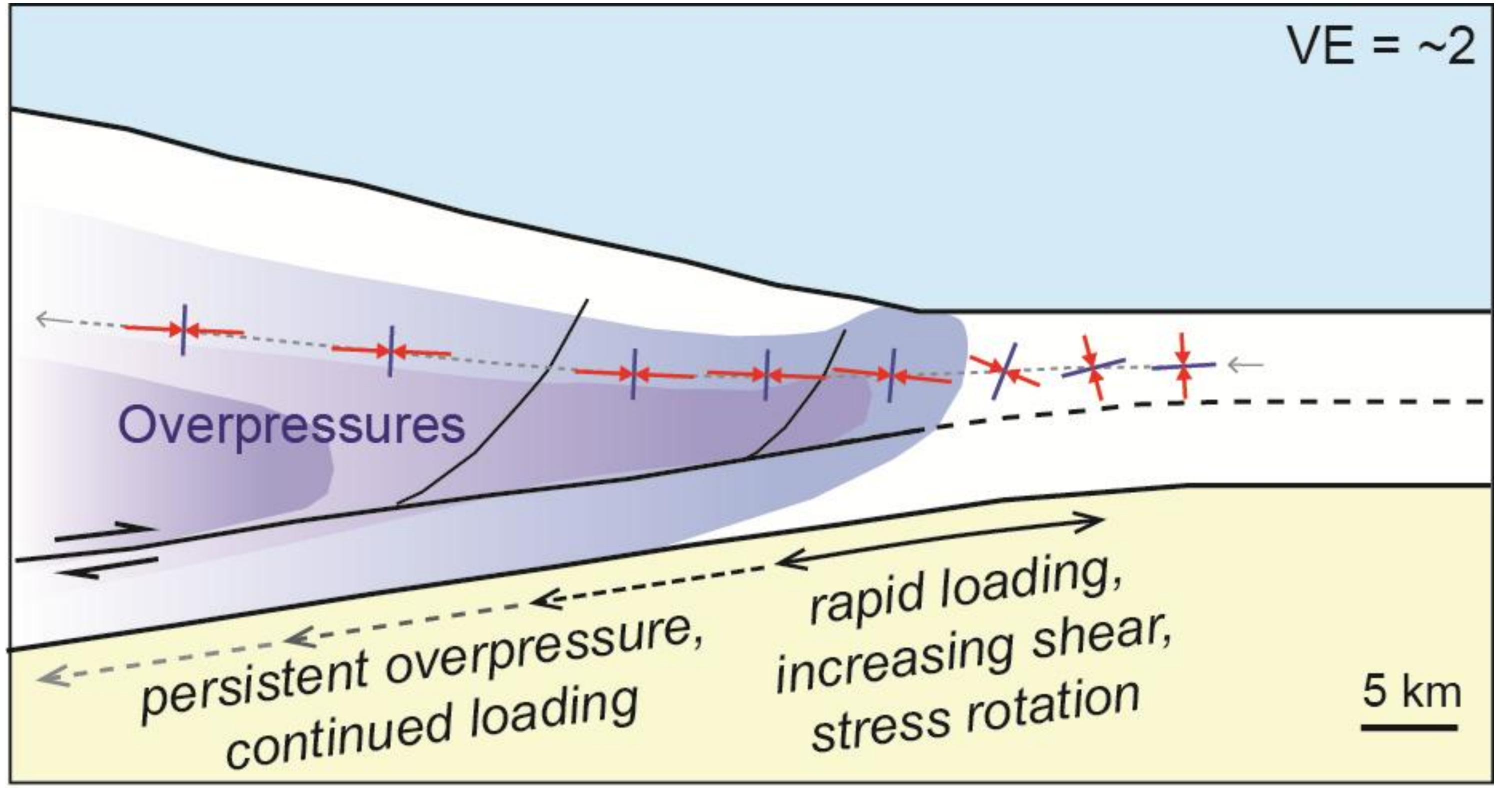
Nikolinakou, Flemings, Gao, Saffer; JGR 2023

- Pore-pressure coefficients $\frac{\xi_m}{S}$, $\frac{\xi_q}{S}$ depend on constitutive model. They are function of:

  a) material parameters (friction angle and compressibility);

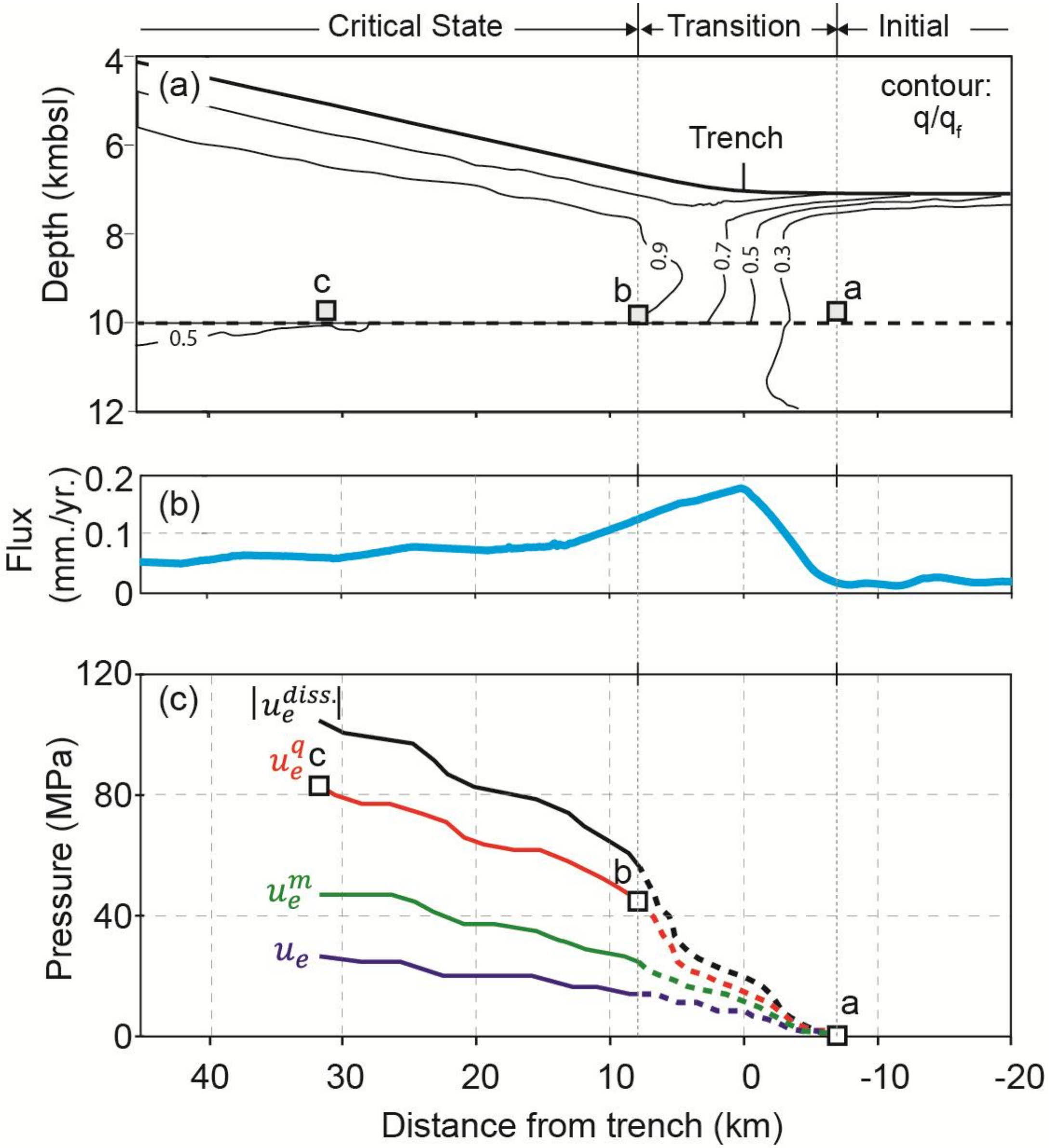
  b) the pre-loading state (porosity, shear-stress ratio).

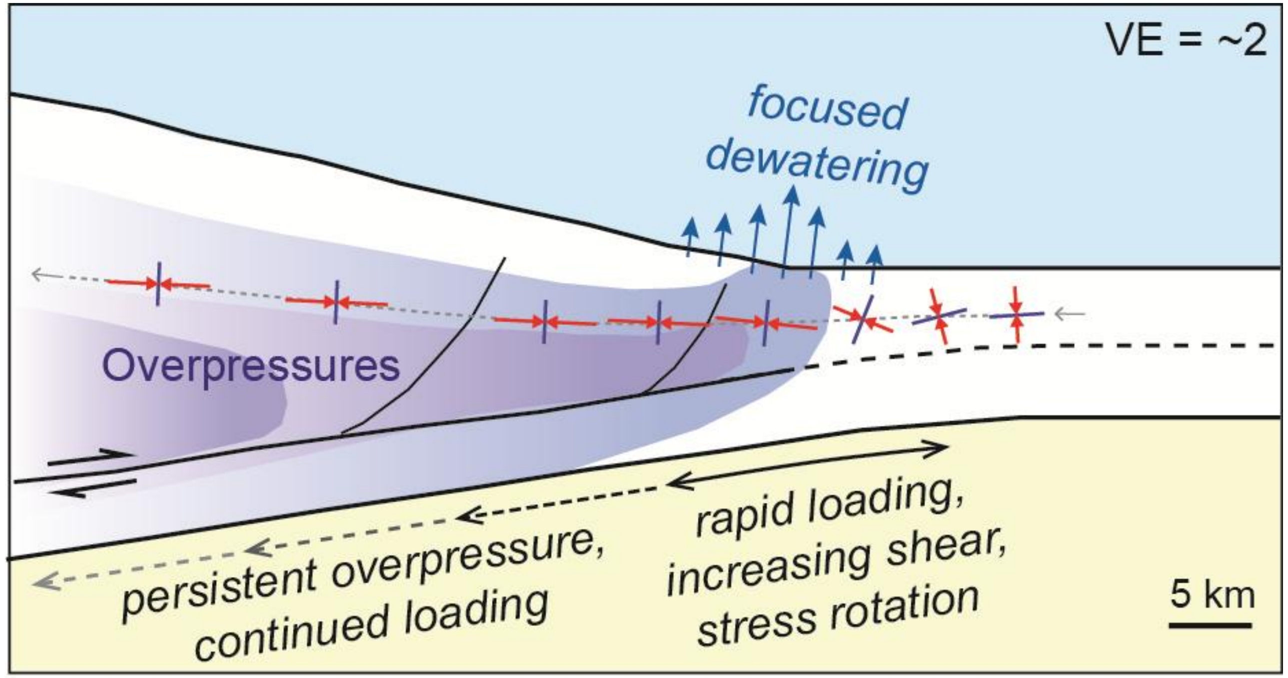
Summary: change in stress state and overpressures



- Evolution in stress state results in overpressures that onset seaward of the trench and increase rapidly in the trench area

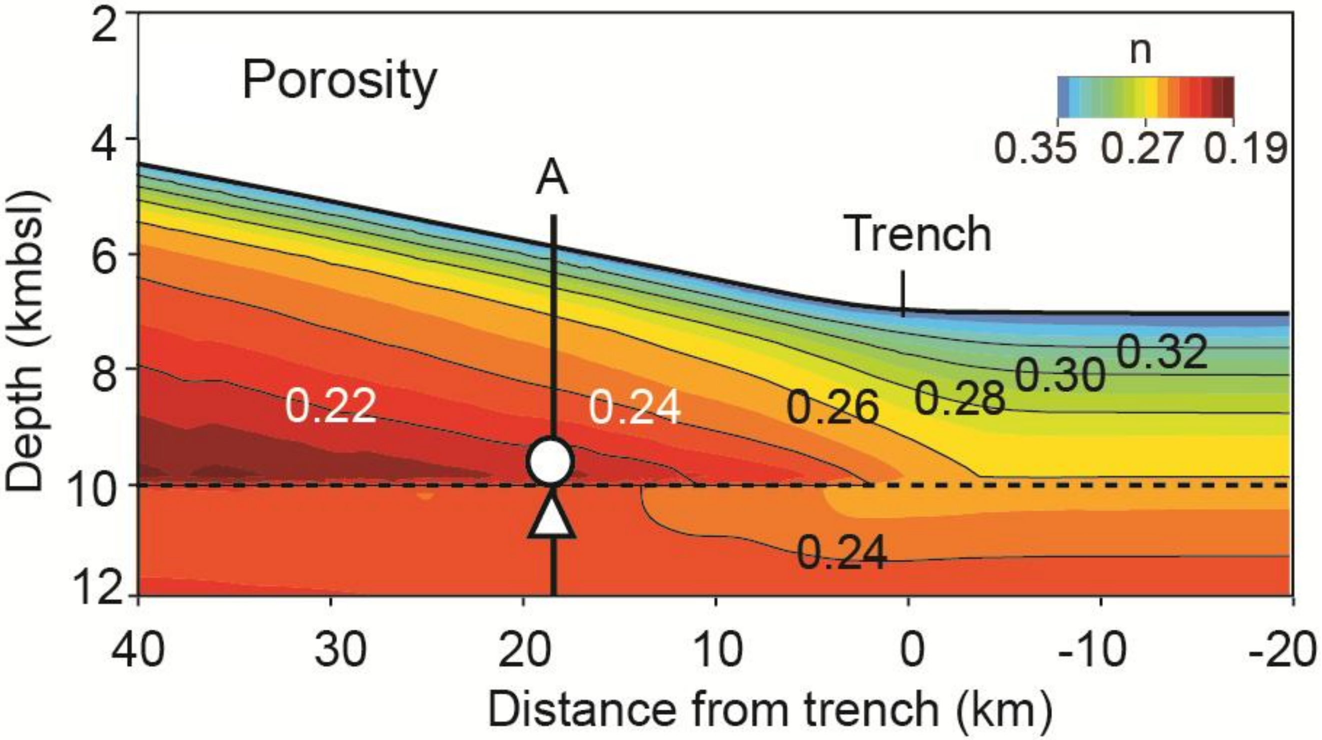
Implications: overpressure dissipation

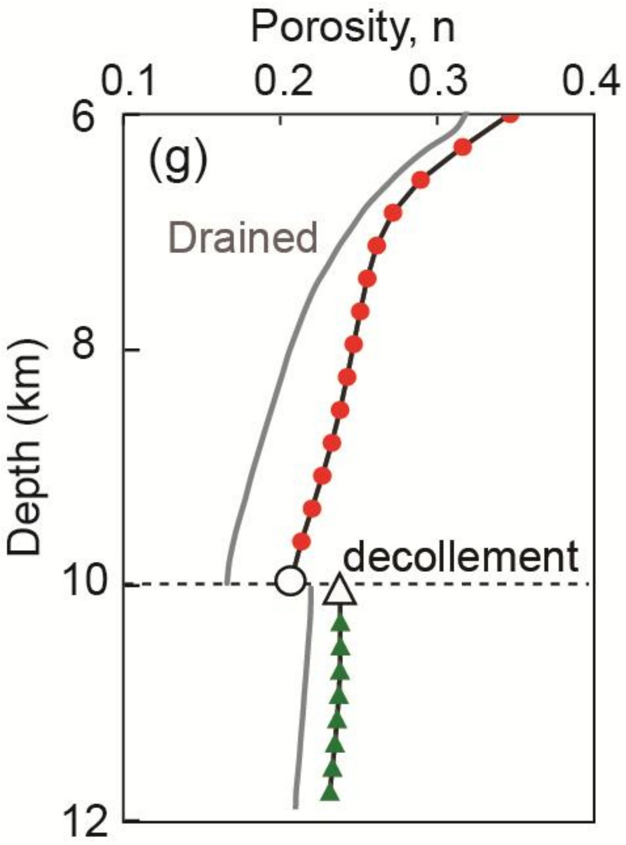




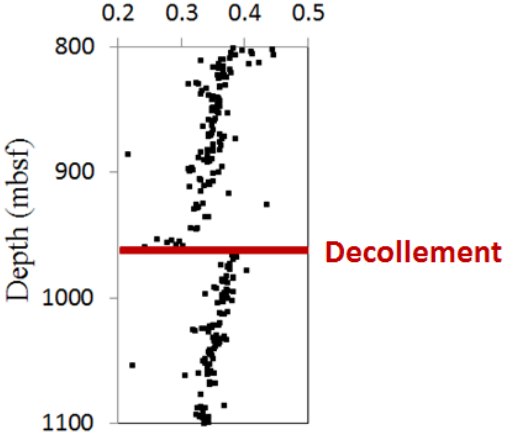
- Dissipation throughout the subduction path but focused at the trench

Implications: compression





Observed porosity
at Nankai

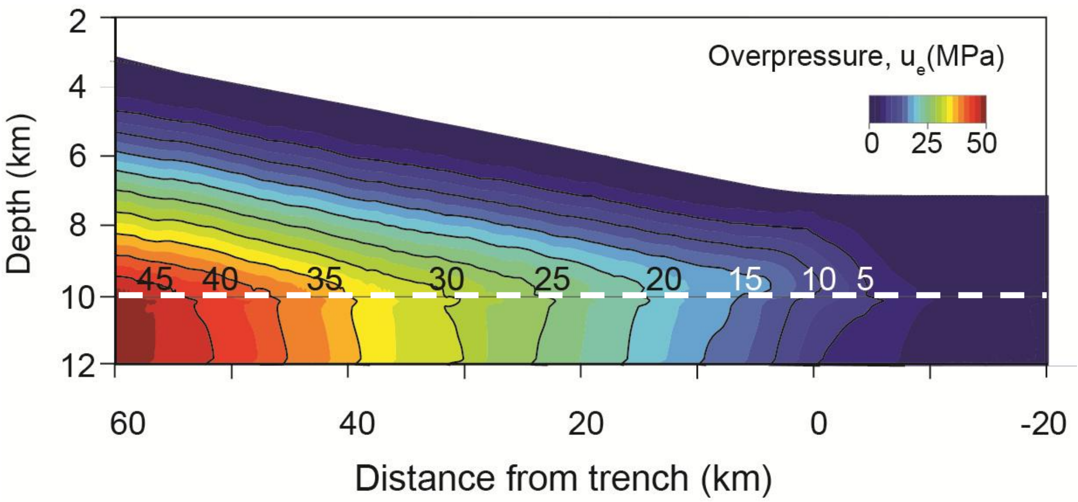


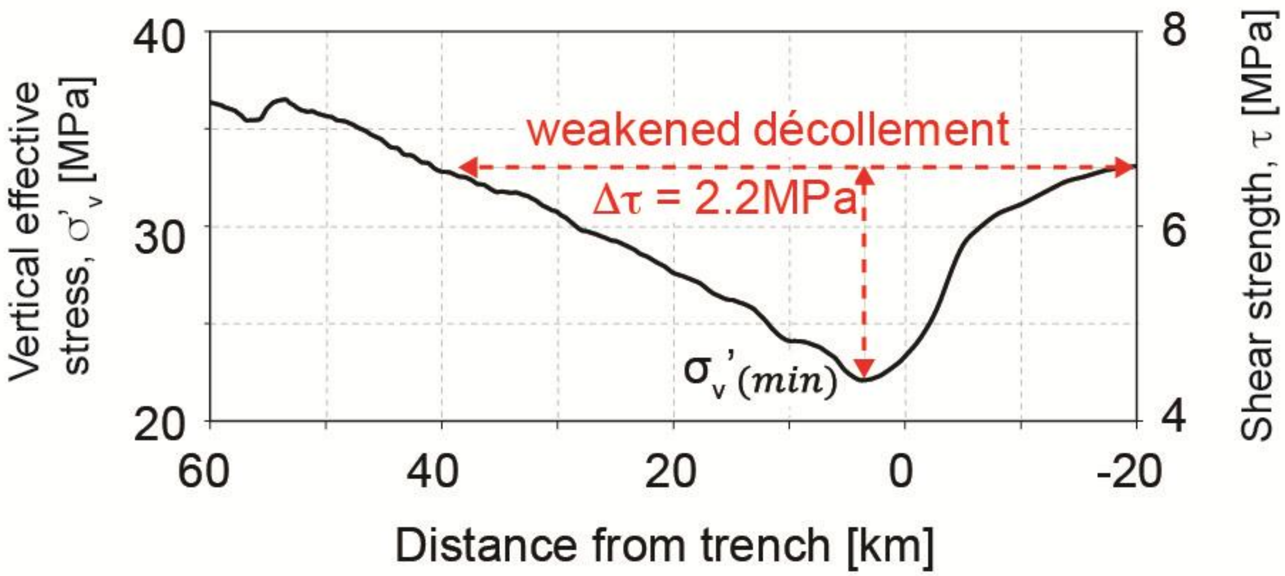
Site 808

(Shipboard Scientific Party, 1991)

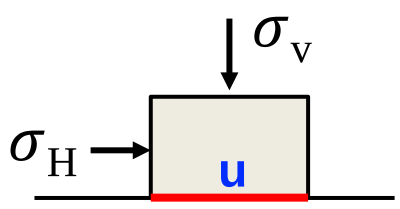
- Hanging-wall sediments are more compressed than footwall ones despite overpressure because of tectonic loading and dissipation

Implications for décollement strength



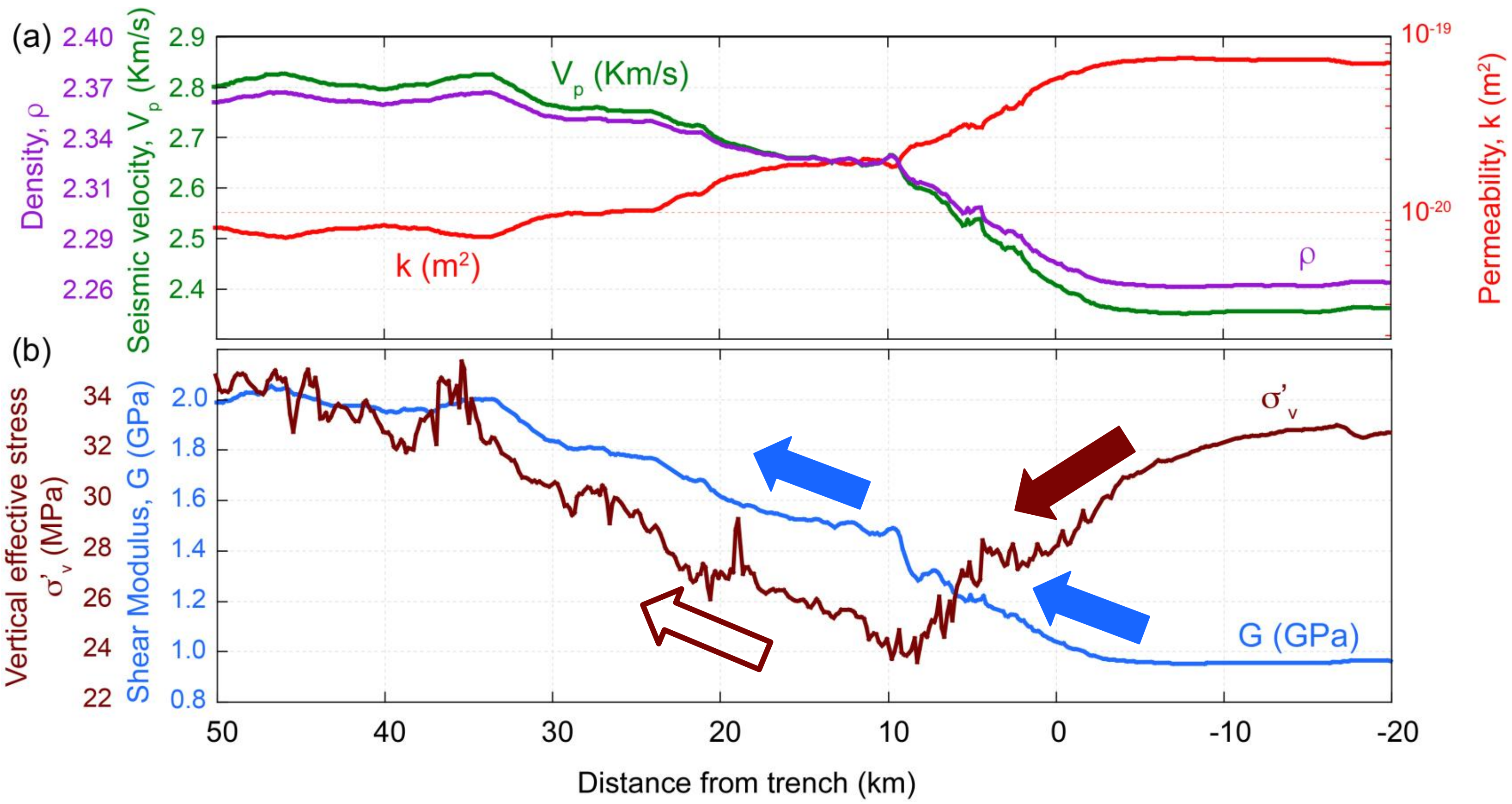


- Vertical effective stress lower than initial value seaward of trench
- 33 % decrease in décollement strength
- Weakened décollement for several km into the subduction zone, despite increase in overburden thickness



$$\tau = \mu\sigma_v' = \mu(\sigma_v - u)$$

Broader Implications for slip behavior



Stable slip:

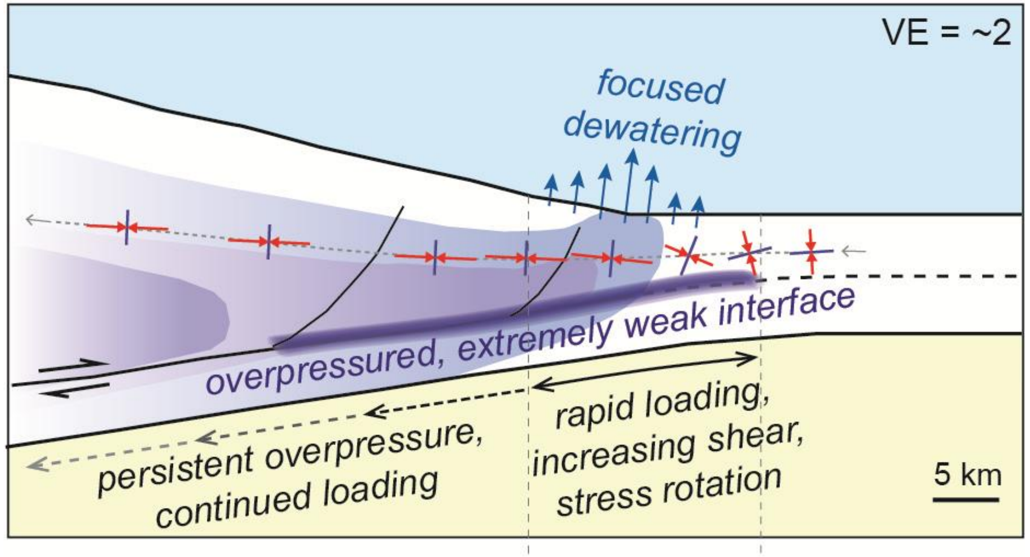
$$K > K_c = \sigma'_n \frac{b-a}{D_c}$$

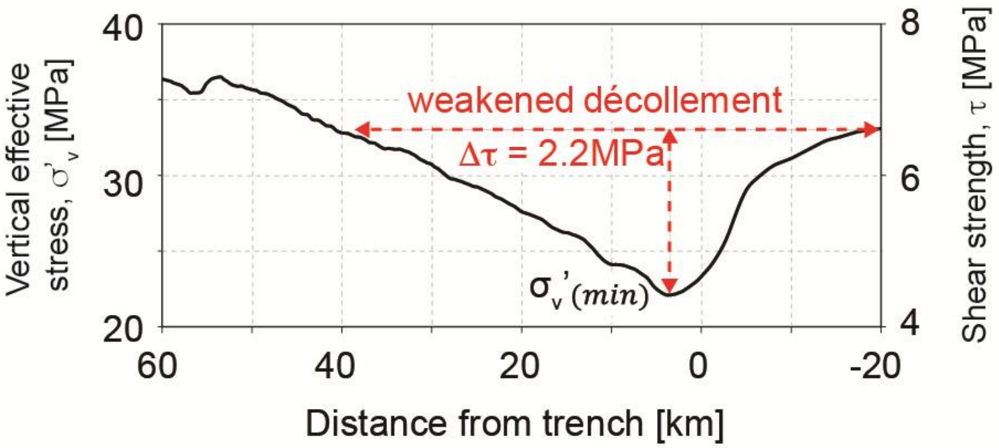
In the outer several tens of km of the subduction zone:

- Effective stress remains low
- Compaction increases the sediment elastic moduli

→ Stable slip

Broader Implications for earthquake behavior

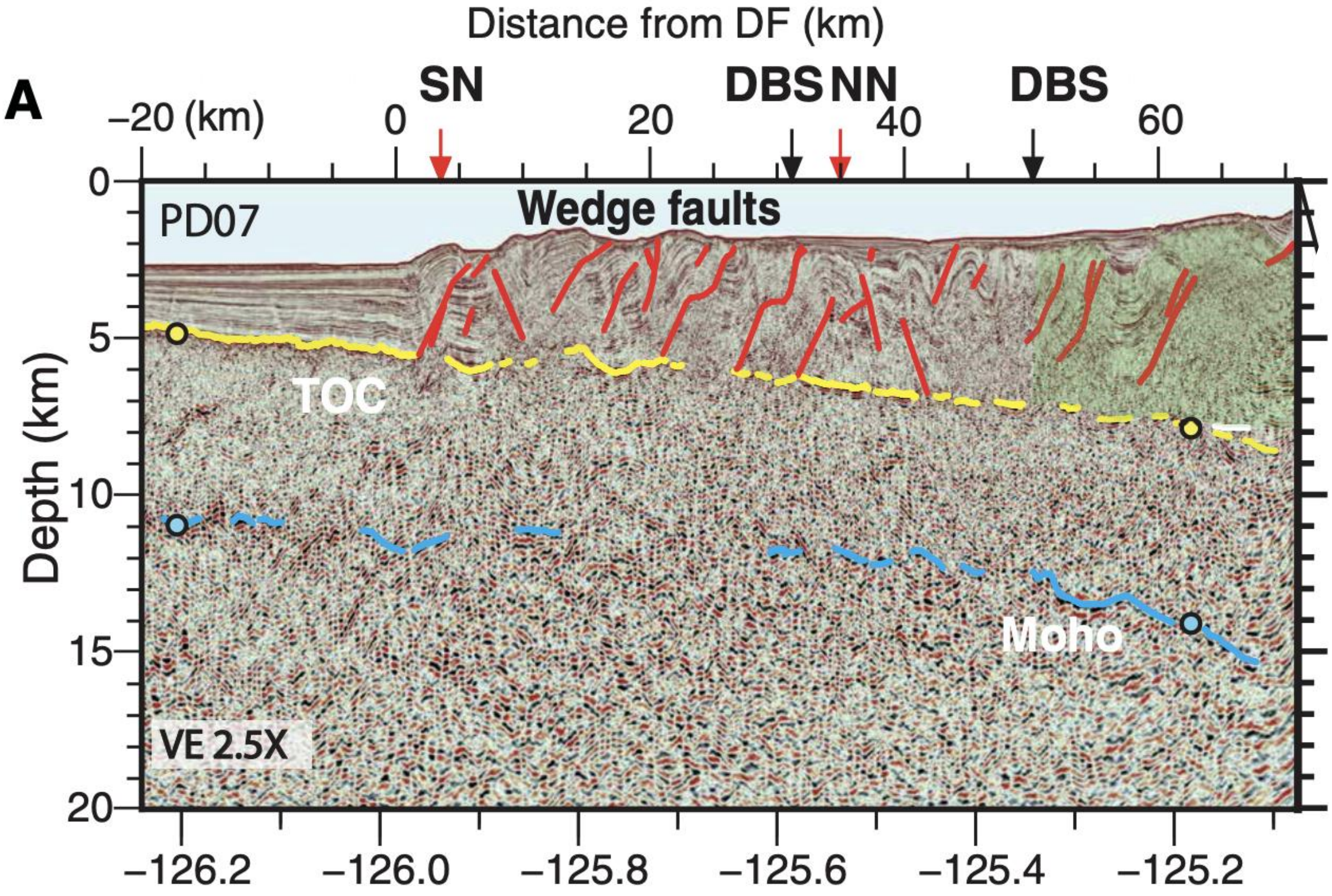




High overpressures, low megathrust strength are established outboard of trench and extend for tens of km downdip:

- development of protothrust zones seaward of trench
- creep, shallow slow earthquakes
- propagation of large shallow coseismic slip

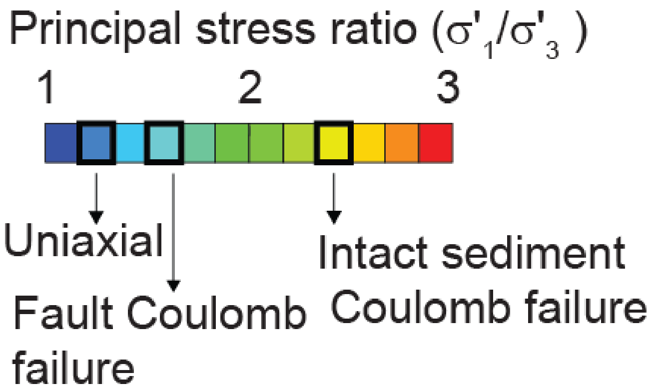
How do stresses change when faults develop?

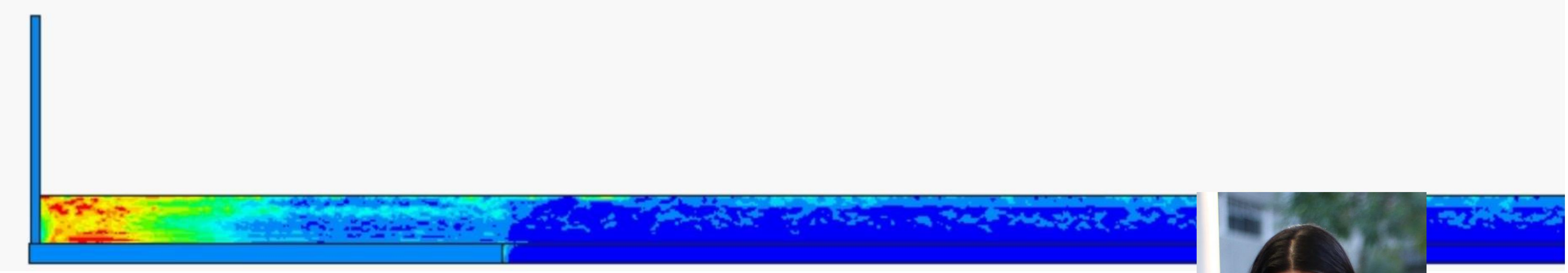


Carbotte et al (2024)

Evolutionary geomechanical models with spontaneous fault generation

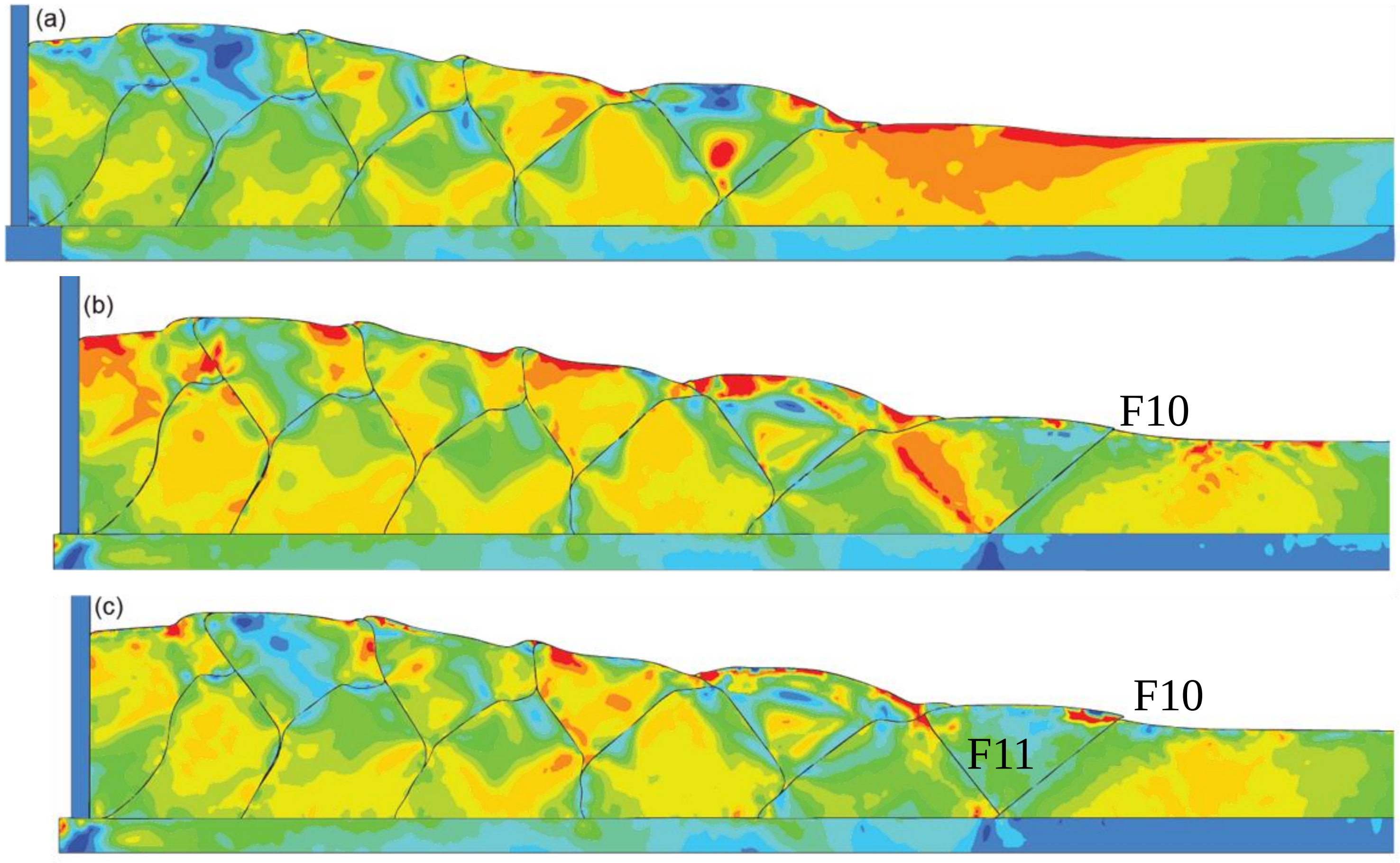
$$\mu_{sediments} = 0.44$$
$$\mu_{fault} = 0.25$$
$$\mu_{decollement} = 0.2$$

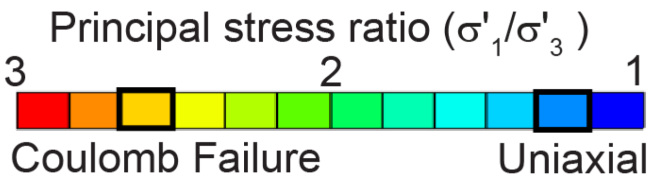




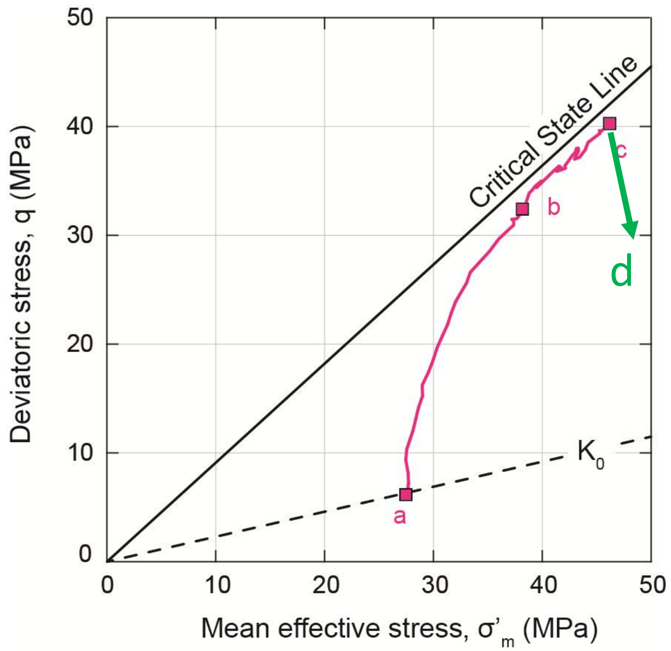
Doctoral research of Graciela Lopez-Campos

Differential stress in faulted upper plate





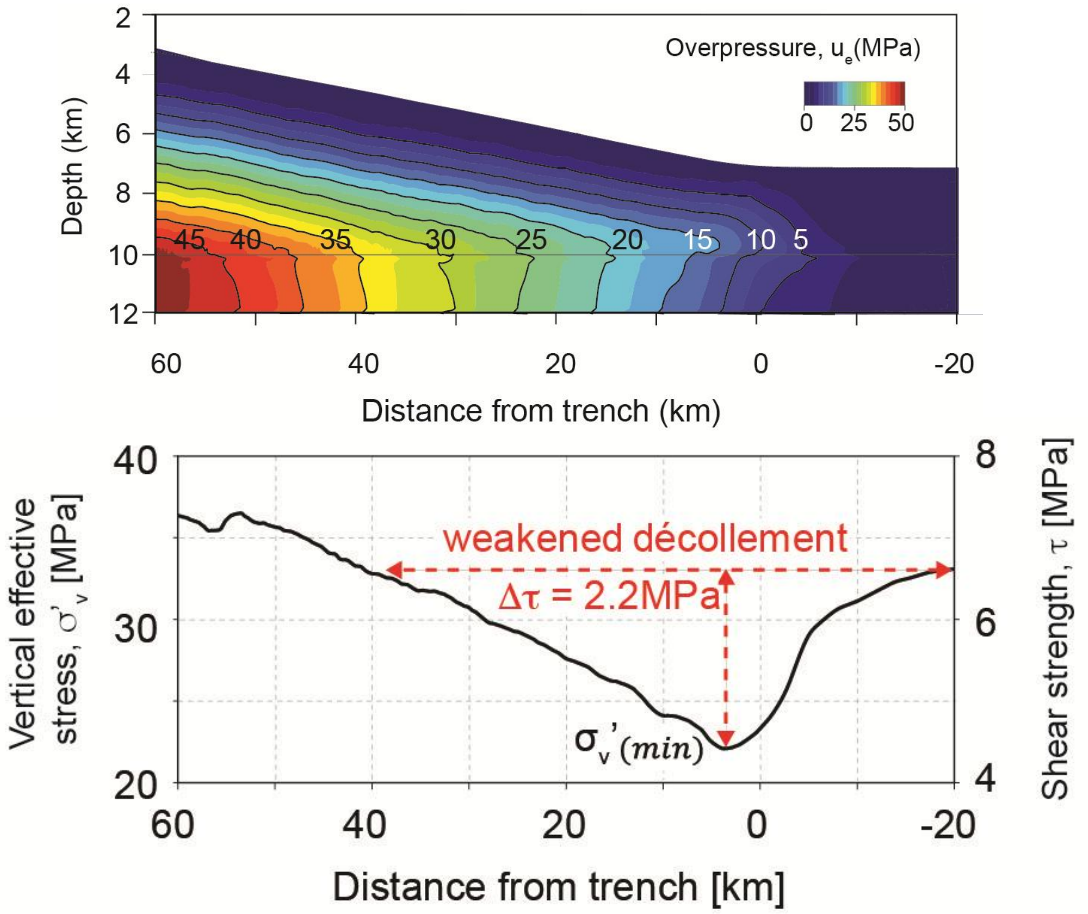
Time 6.96 Ma



- Fault generation decreases the differential stress of the intact sediment
- Stress heterogeneity in the upper plate
- Persistent presence of high differential stresses near the toe → potentially higher overpressures at the leading edge of the wedge

Key points

- Both mean and shear stress contribute to pressure generation; shear-induced overpressures are significant at and outboard of the trench
- Overpressure increases faster than overburden at the trench area
- High overpressures result in a weakened décollement that onsets ahead of the trench and persists tens of km into the subduction zone
- Fluid expulsion is highest at the trench

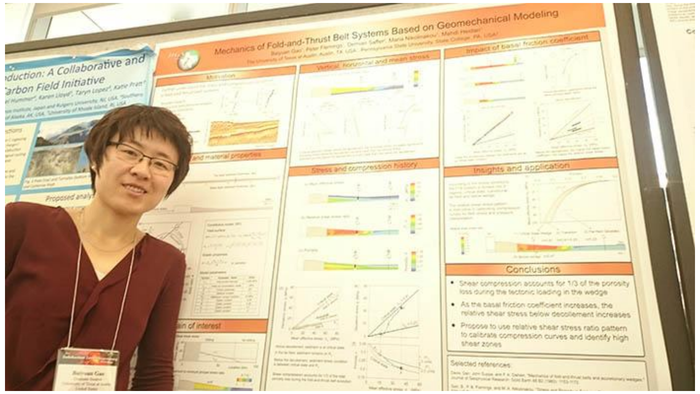


Acknowledgements

Peter Flemings

Demian Saffer

Baiyuan Gao



UTIG

INSTITUTE FOR GEOPHYSICS

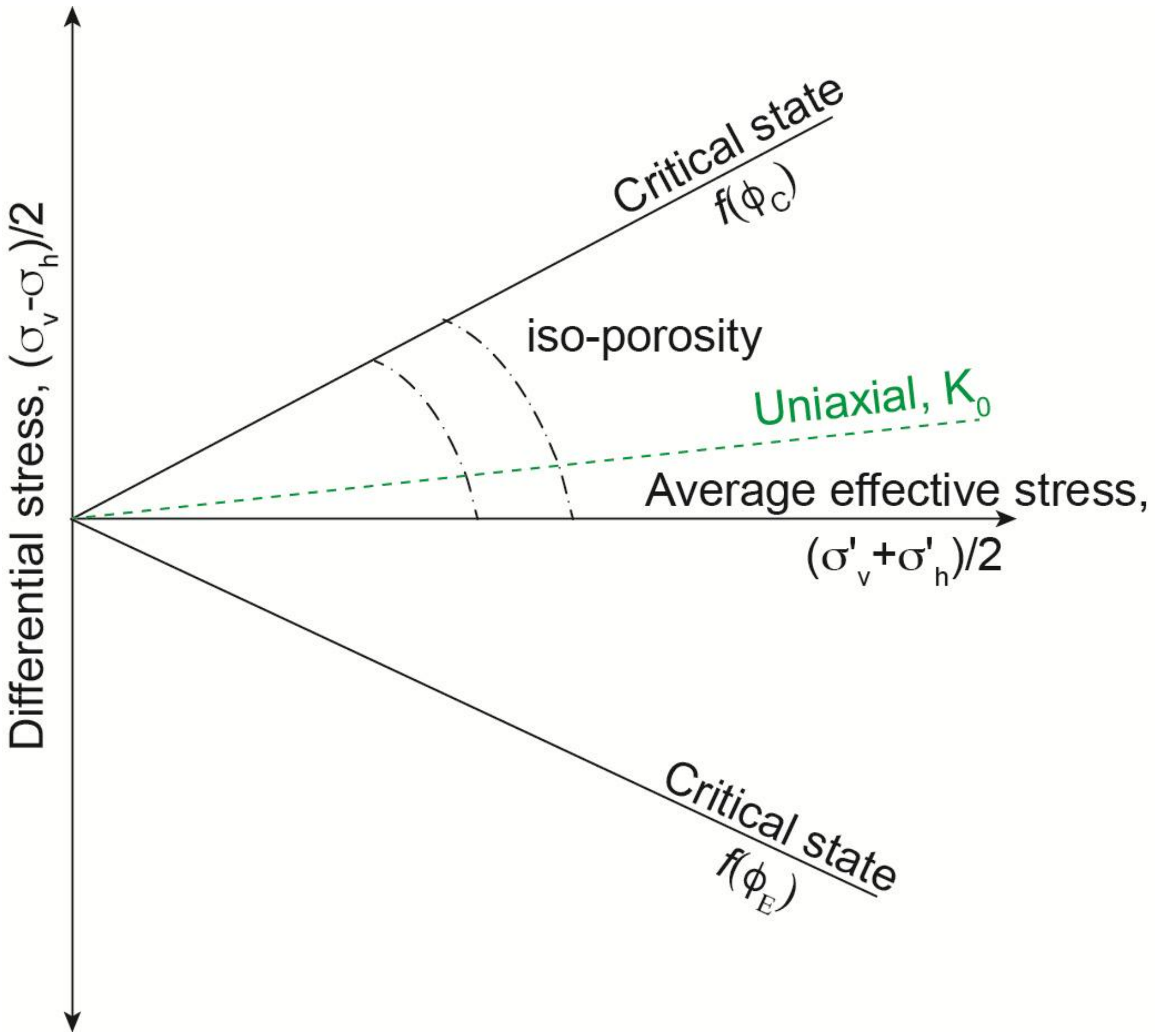
GeoFluids

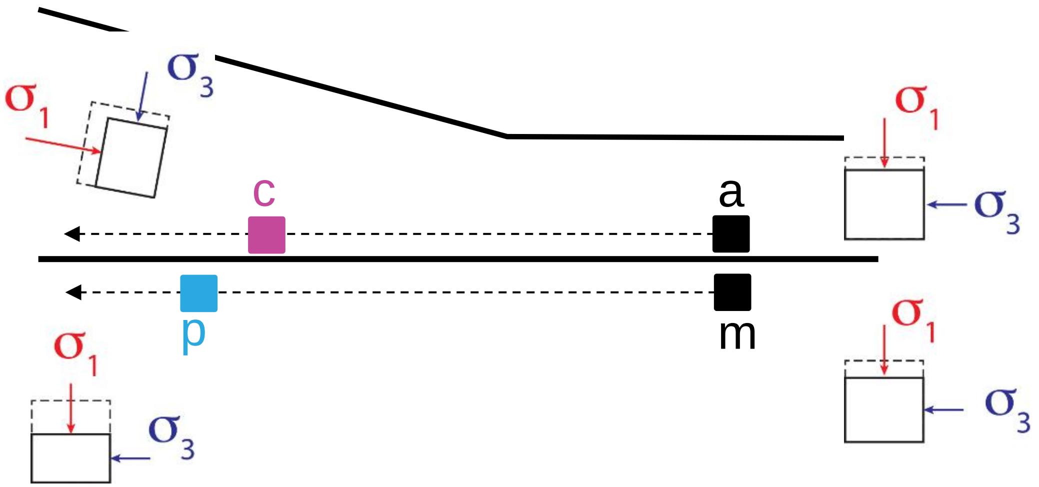
TEXAS Geosciences

The University of Texas at Austin

Jackson School of Geosciences

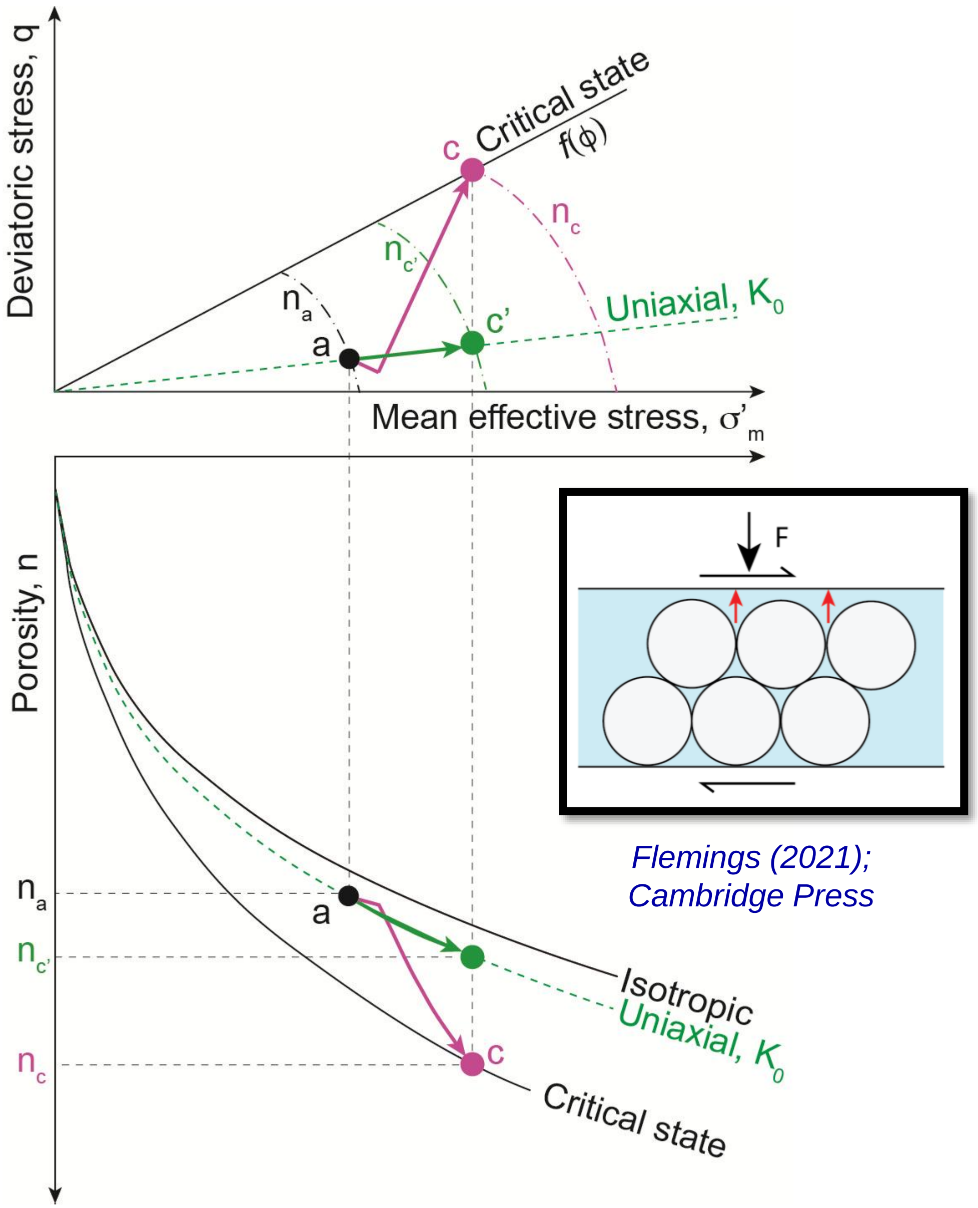
Incorporation of critical state soil mechanics



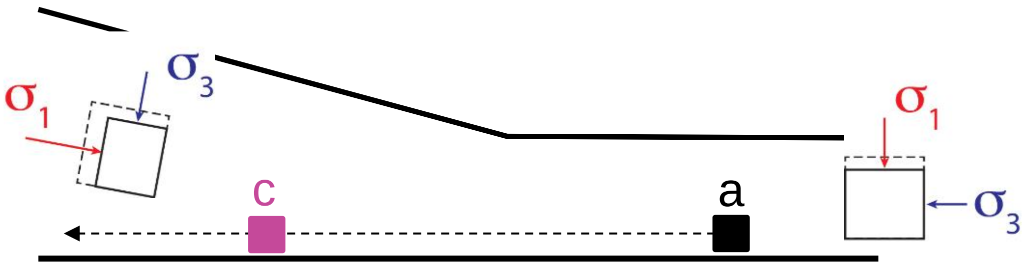


- Framework interrelates mean (average) stress, differential stress, and porosity
- All three evolve as sediment enters the wedge
- Stress state in footwall remains ~ uniaxial

Incorporation of critical state soil mechanics

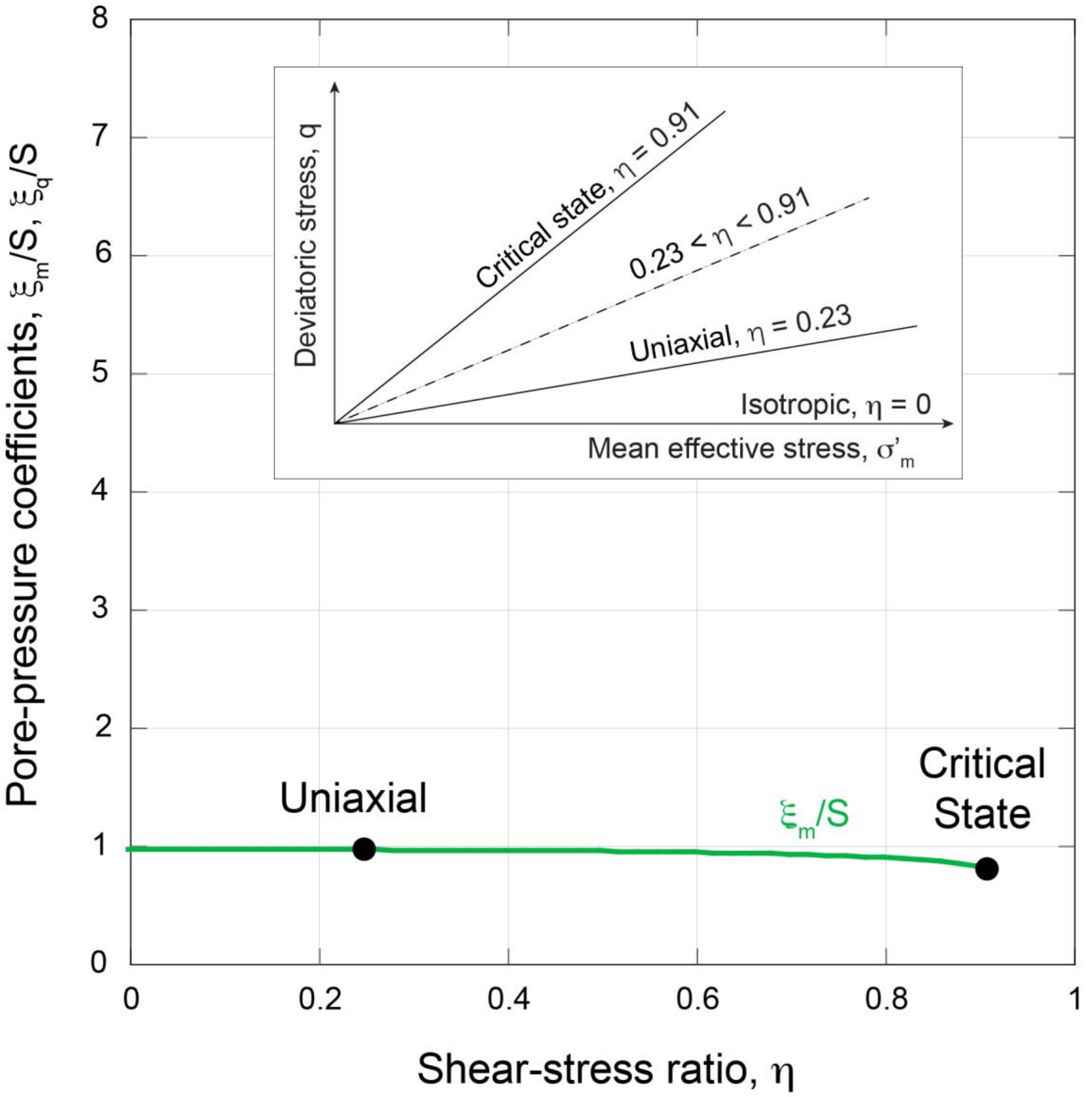


Flemings (2021); Cambridge Press



- Mean stress, differential stress, and porosity are interrelated
- Changes in both mean and differential stress can cause compaction, or, in the case of limited drainage, excess pore pressure (overpressure)

Importance of pre-loading stress state for pressure generation



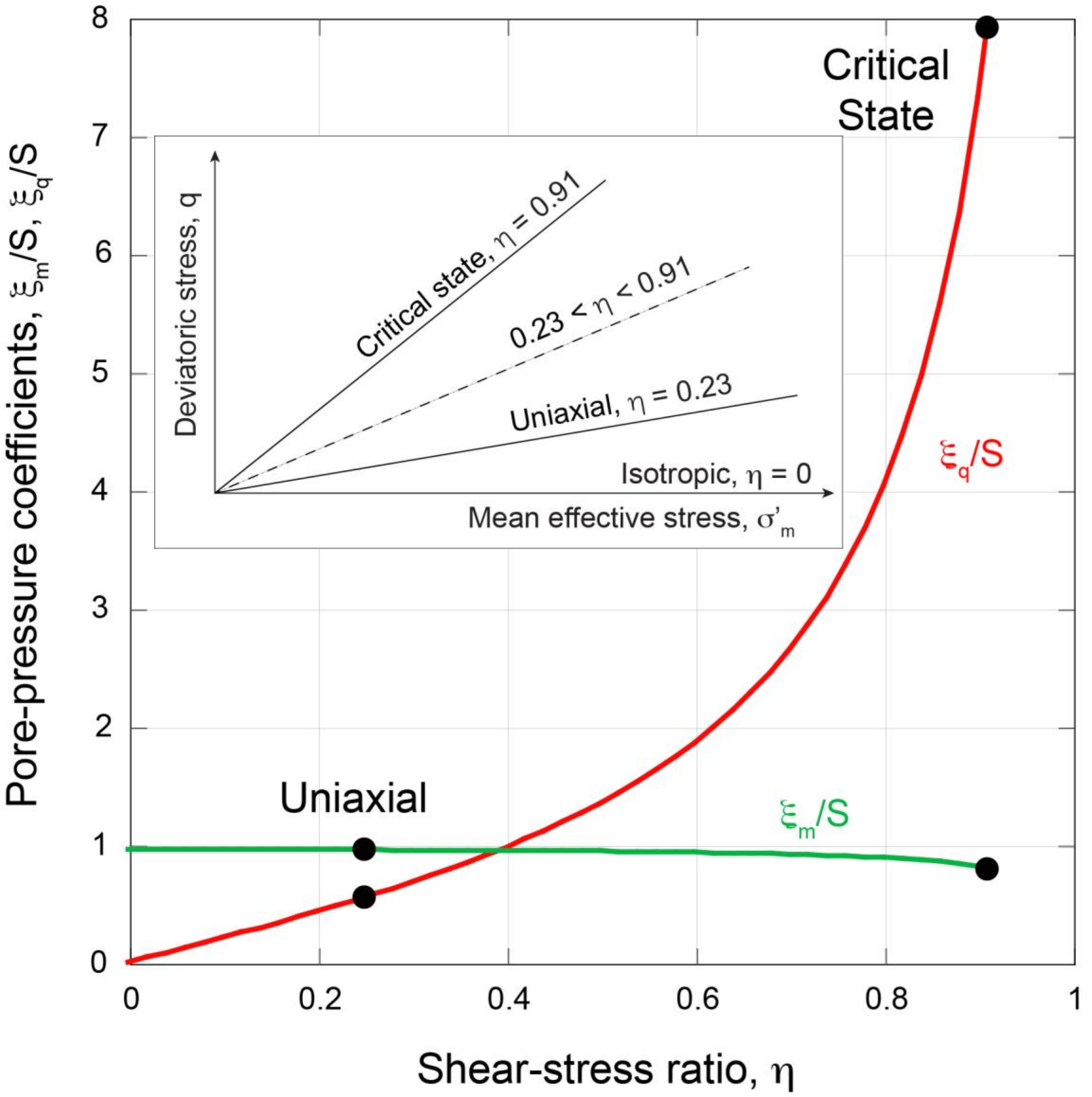
Pressure | Mean-induced | Shear-induced | Pressure dissipation

$$\frac{Du}{Dt} = \frac{\xi_m}{S}\frac{D\sigma_m}{Dt} + \frac{\xi_q}{S}\frac{Dq}{Dt} + \frac{1}{S\rho_f}\nabla\cdot\left(\frac{\rho_f k}{\mu}\nabla\cdot u_e\right)$$

- The mean-stress pressure coefficient is relatively insensitive to the initial, pre-loading stress state
- Mean-induced pressures are ~ equal to change in mean stress:

$$Du_e^m \approx D\sigma_m$$

Importance of pre-loading stress state for pressure generation



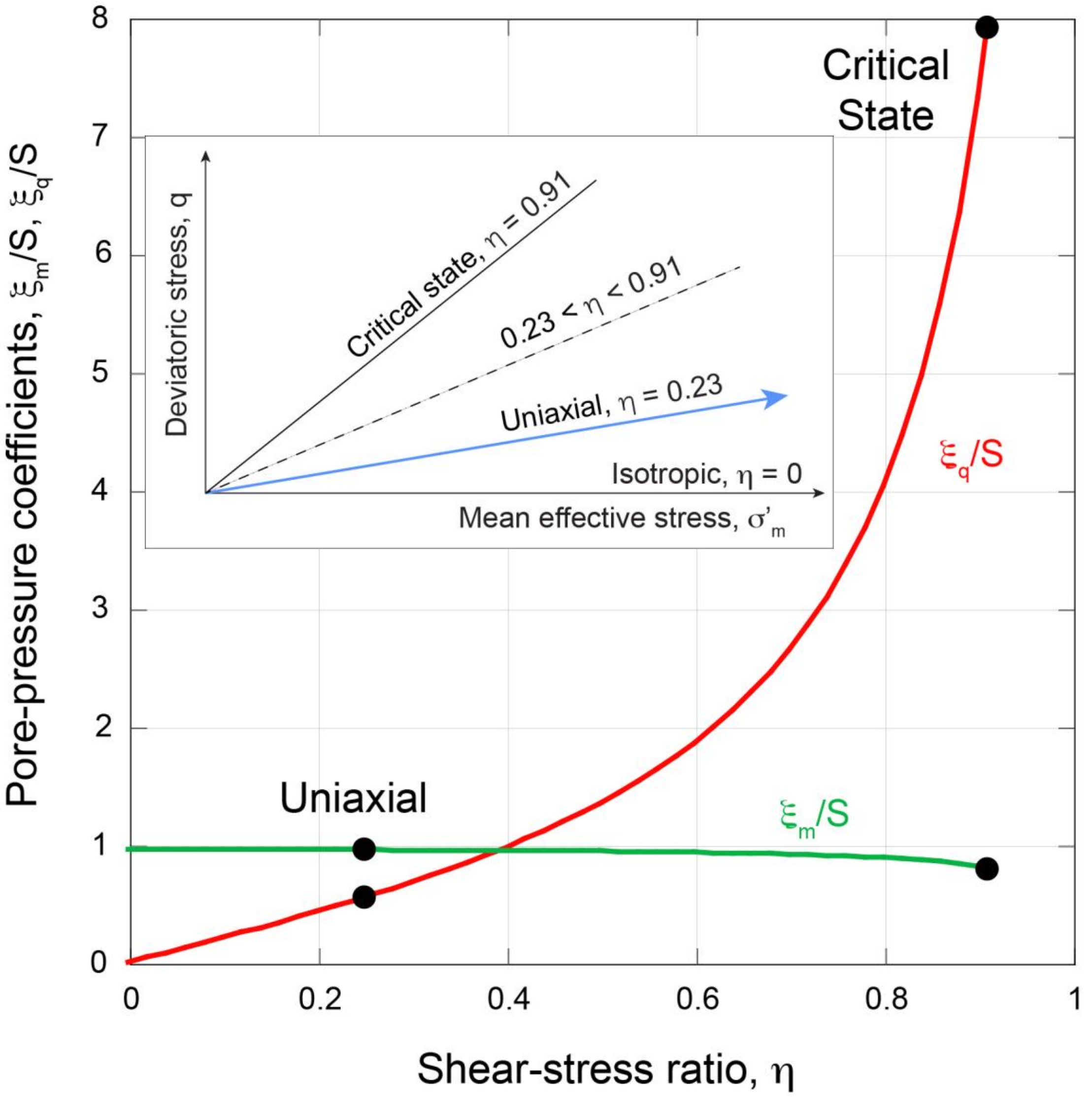
Pressure | Mean-induced | Shear-induced | Pressure dissipation

$$\frac{Du}{Dt} = \frac{\xi_m}{S}\frac{D\sigma_m}{Dt} + \frac{\xi_q}{S}\frac{Dq}{Dt} + \frac{1}{S\rho_f}\nabla\cdot\left(\frac{\rho_f k}{\mu}\nabla\cdot u_e\right)$$

- Shear-stress pressure coefficient is very sensitive to the amount of shear in the initial stress state
- Can increase by a factor of 20 between uniaxial and critical initial states

$$Du_e^q >> Dq$$

Importance of stress path for pressure generation

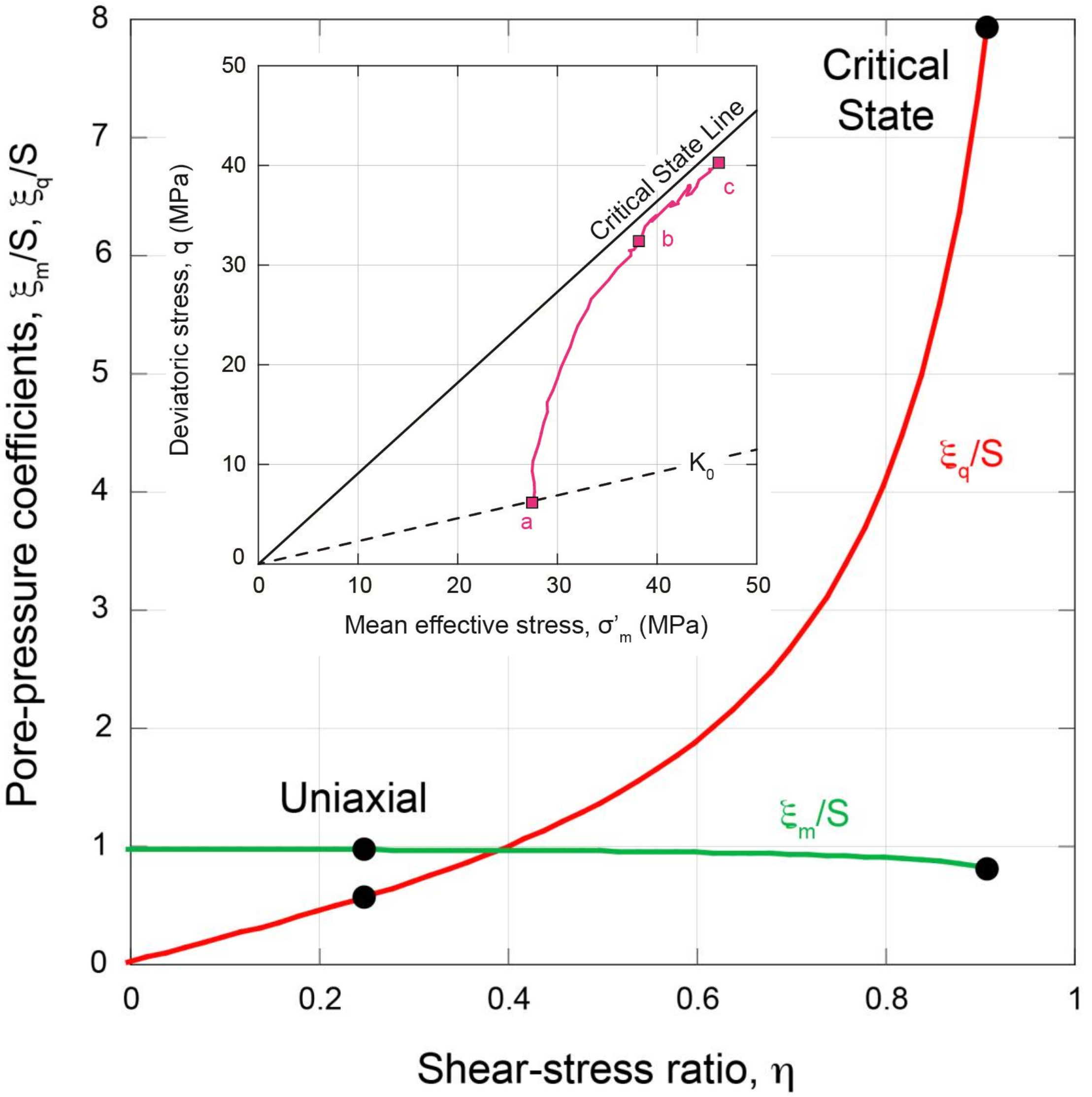


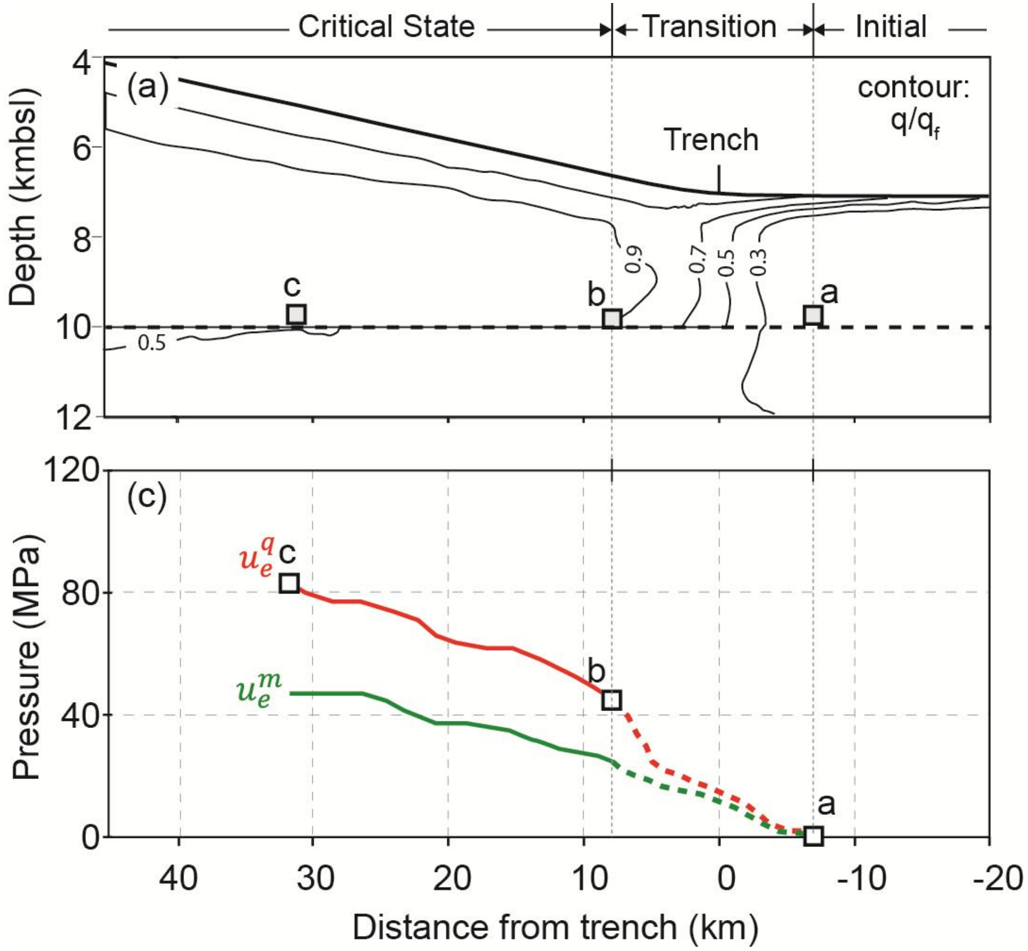
Pressure | Mean-induced | Shear-induced | Pressure dissipation

$$\frac{Du}{Dt} = \frac{\xi_m}{S}\frac{D\sigma_m}{Dt} + \frac{\xi_q}{S}\frac{Dq}{Dt} + \frac{1}{S\rho_f}\nabla\cdot\left(\frac{\rho_f k}{\mu}\nabla\cdot u_e\right)$$

- The shear-stress pressure coefficient increases after each loading increment
- Importance of shear-induced pressures in tectonic environments undergoing change in stress state (thrust belts, salt)
- Poro-elastic approach cannot capture these pressures

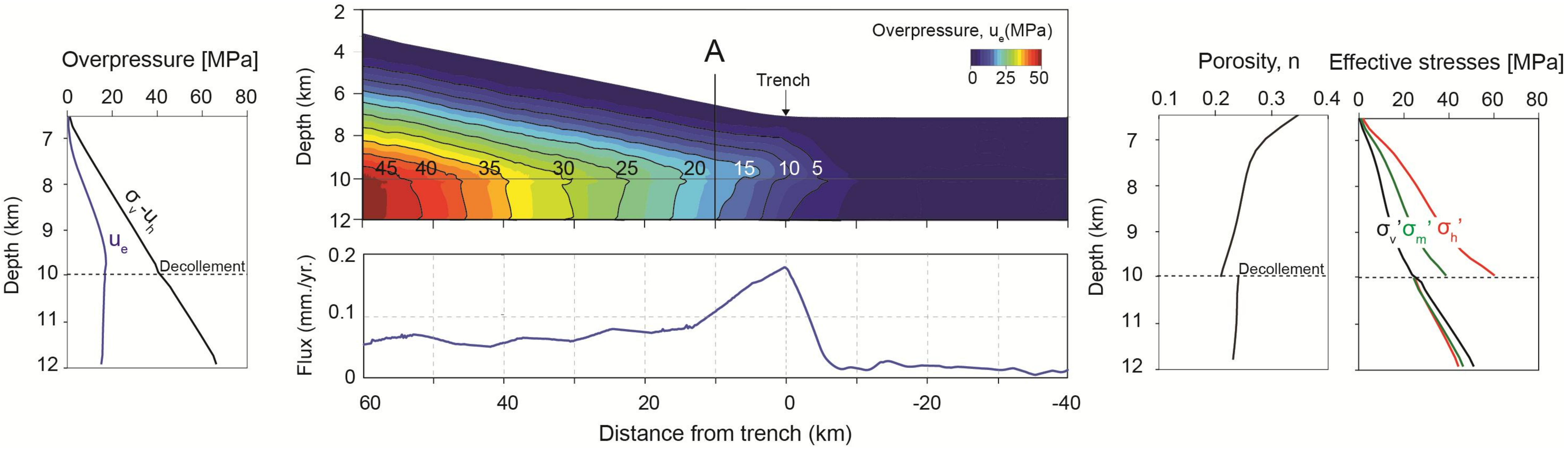
Importance of pre-loading stress state for pressure generation





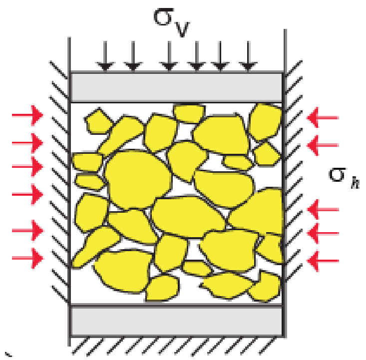
- Shear-induced pressures are significant at the trench where the stress state evolves.

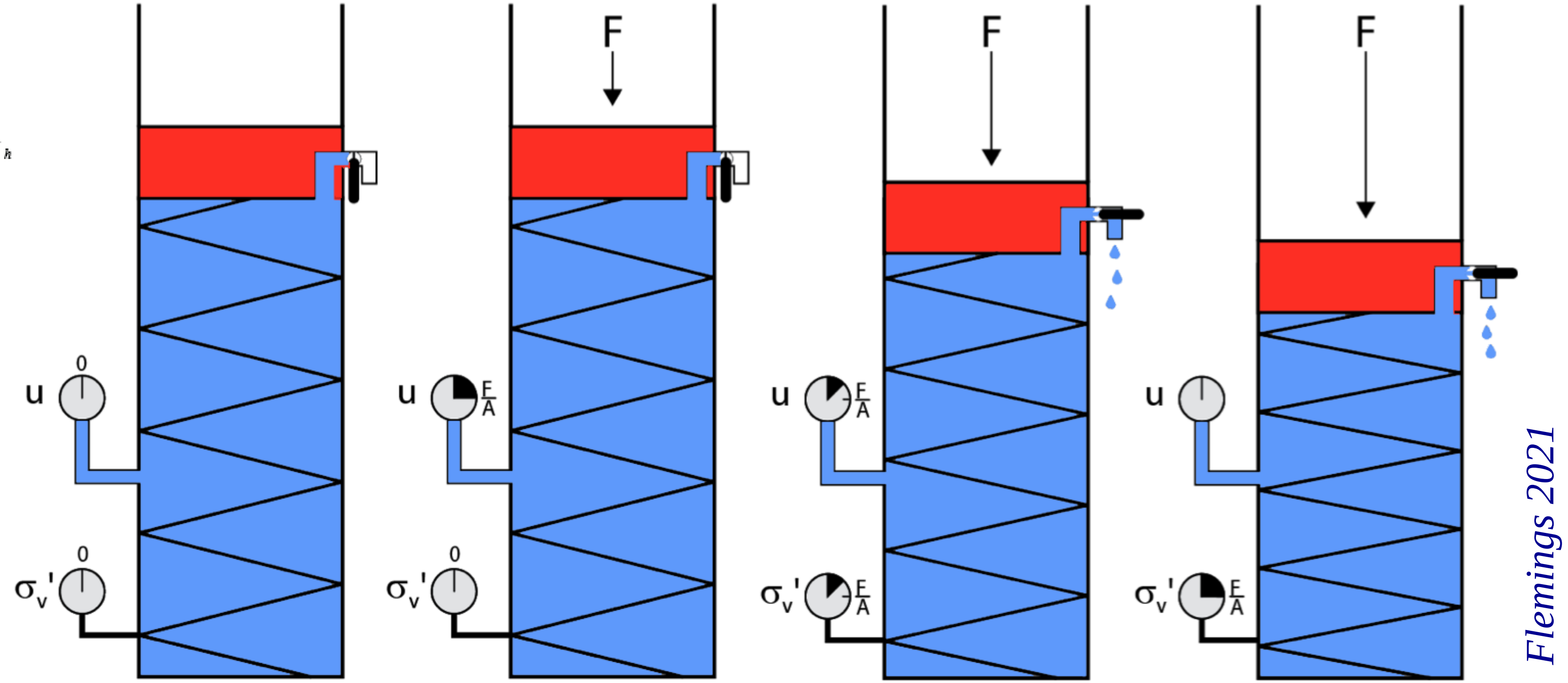
Overpressure and stress profiles at trench



- Focused dewatering at trench
- Increase in horizontal effective stress and differential stress
- Porosity loss

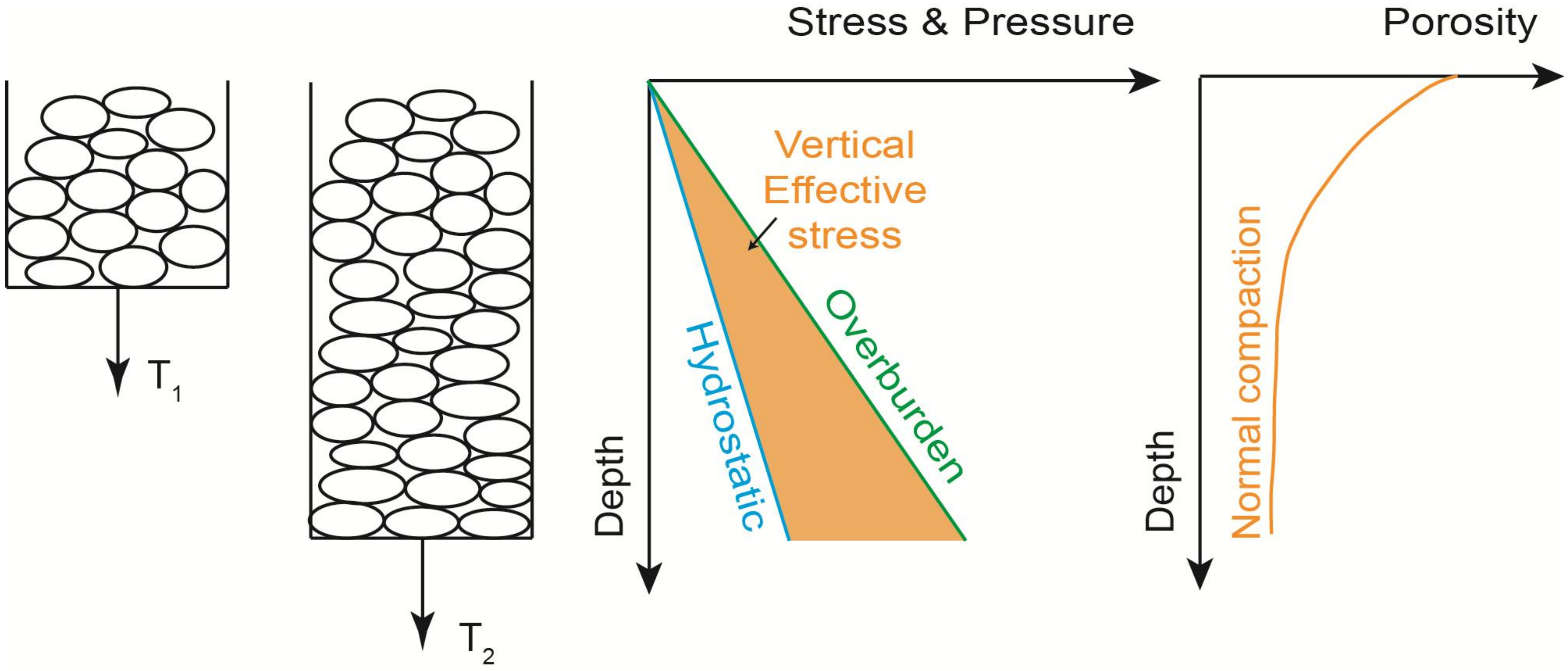
Porous fluids and overpressure





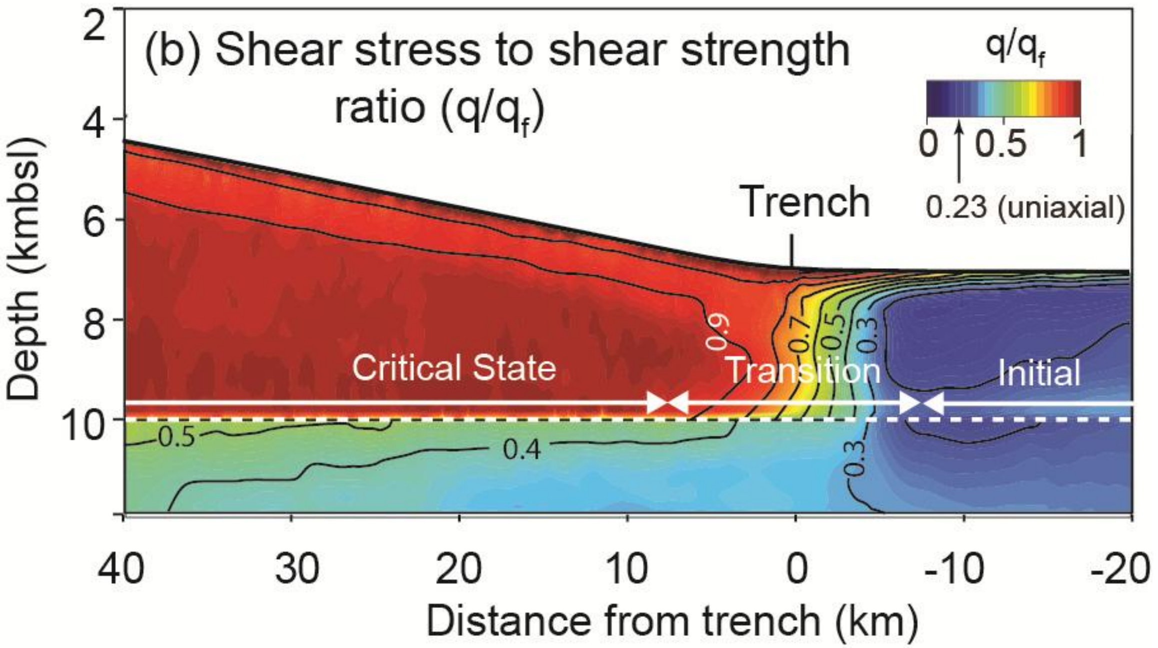
- External compression load tends to decrease volume
- Overpressures develop if pore fluid cannot flow out of compressed volume
- Overpressure dissipation depends on permeability and compressibility of mud rocks

Overpressure and compaction



- Total stress = effective stress + pore pressure
- Overpressure decreases the effective stress and inhibits compaction
- Sources of overpressure: rapid deposition, tectonic or geologic loading

Critical wedge



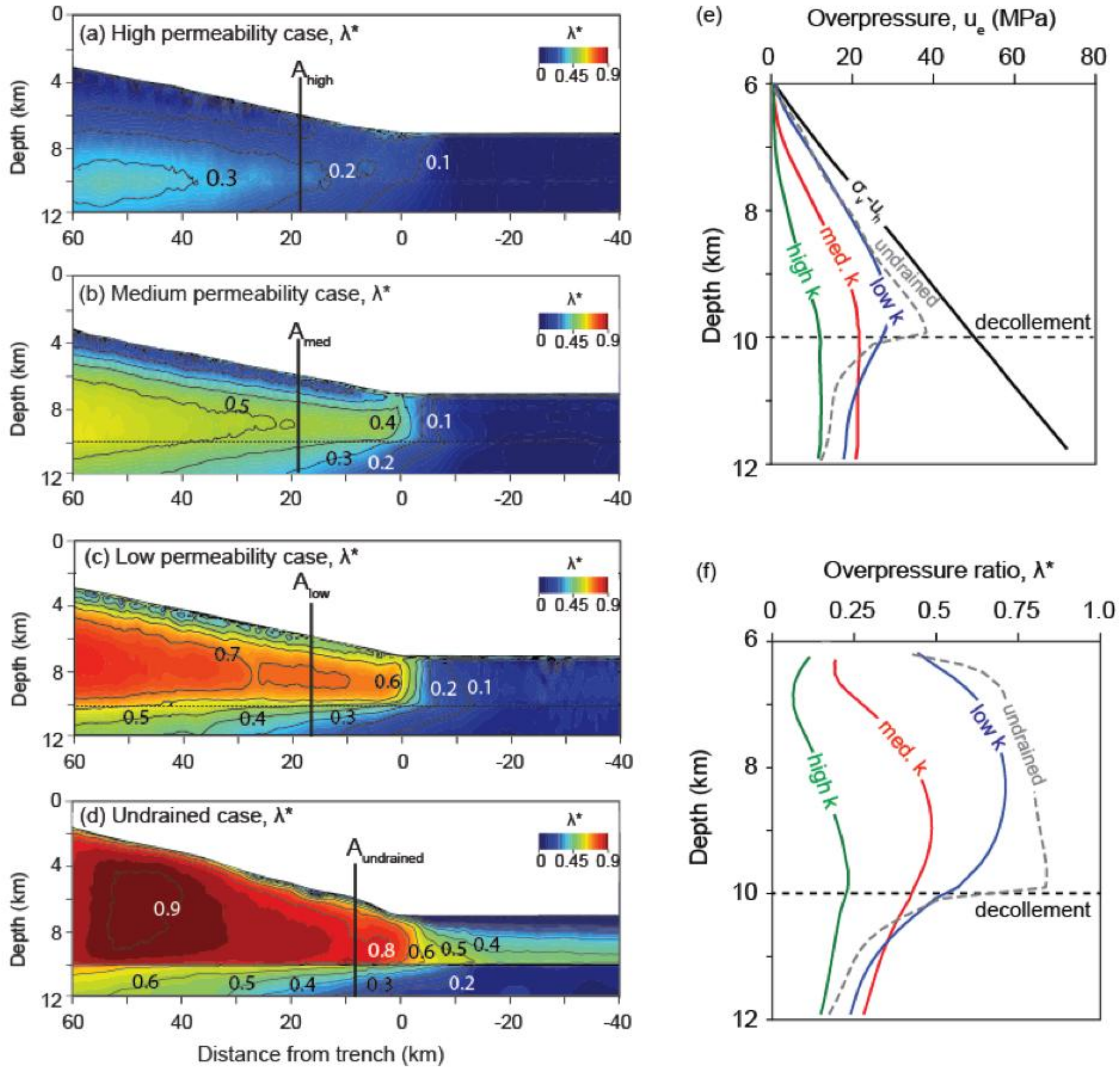
Inside the wedge the stress state is at passive (Coulomb) failure:

$$\eta_\tau = \frac{q}{\sigma'_m} = \frac{3(1 - K_\tau)}{(1 + 2K_\tau)}$$

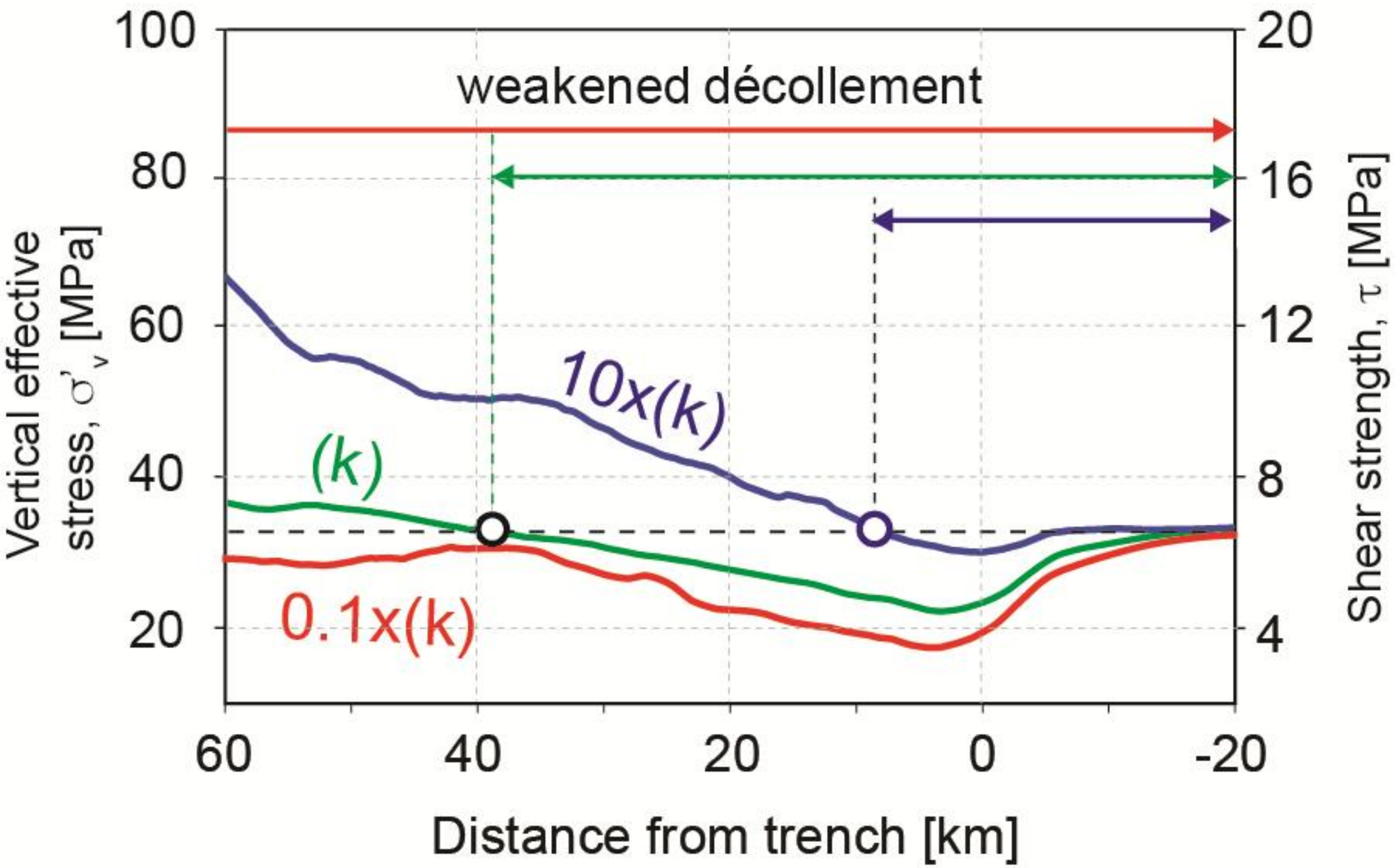
$$K_\tau = \frac{\sigma'_{3,\tau}}{\sigma'_{1,\tau}} = \frac{1 - sin\phi'}{1 + sin\phi'}$$

Differential stress is a function of mean effective stress

Impact of sediment permeability to overpressure generation



Impact of permeability on décollement strength



Decreasing mudrock permeability amplifies and expands the weakened décollement region