MODELING OF GEOMECHANICAL PROCESSES DURING INJECTION IN A MULTILAYERED RESERVOIR-CAPROCK SYSTEM AND IMPLICATIONS ON SITE CHARACTERIZATION

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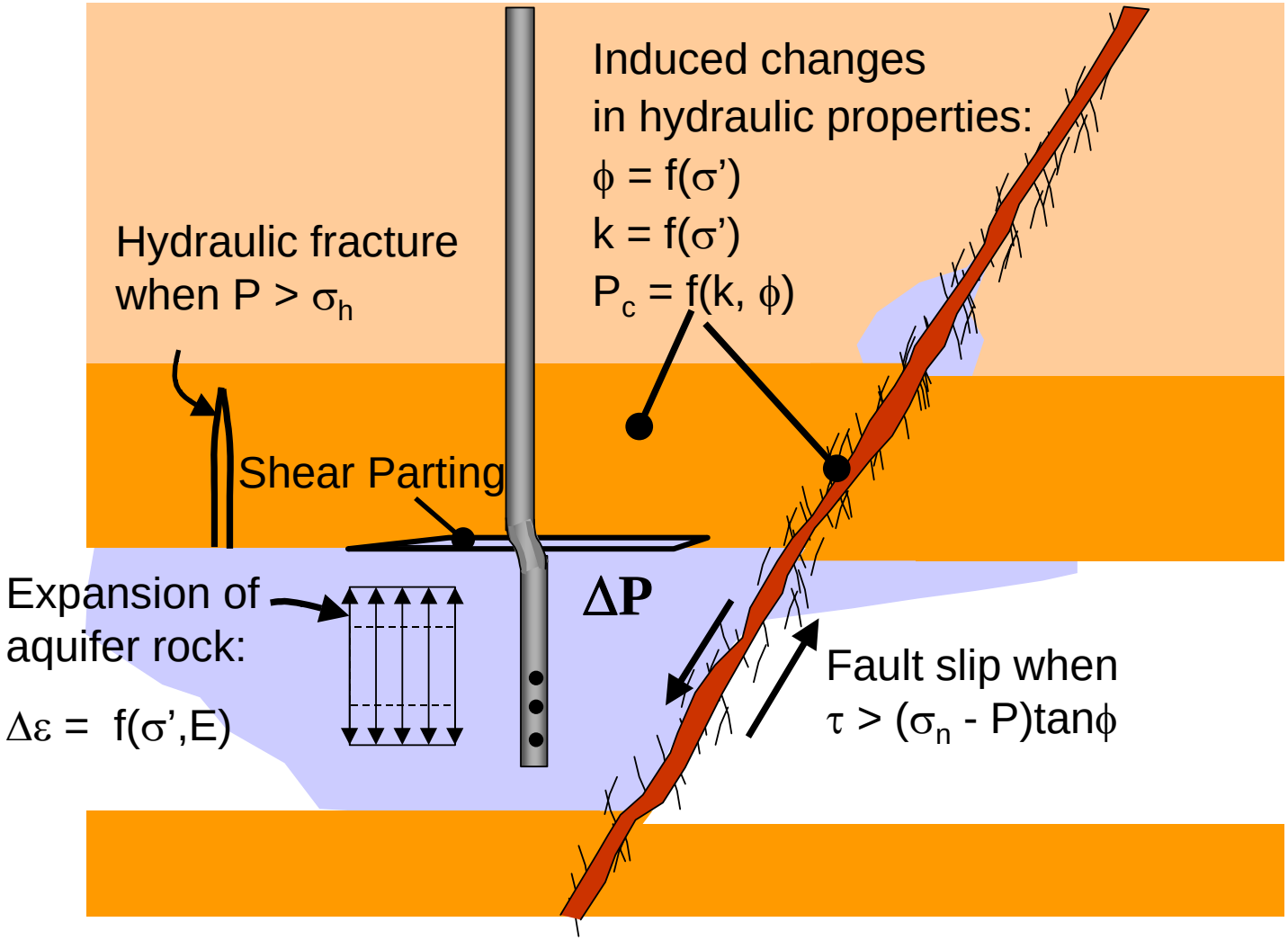
OUTLINE

- Introduction
- TOUGH-FLAC simulator for coupled reservoir-geomechanical analysis
- Modeling of injection into multilayered system (potential for fault slip)
- Modeling of fault-reactivation with shear-induced permeability changes (extent and magnitude of shear slip).
- Conclusions related to site characterization

INTRODUCTION

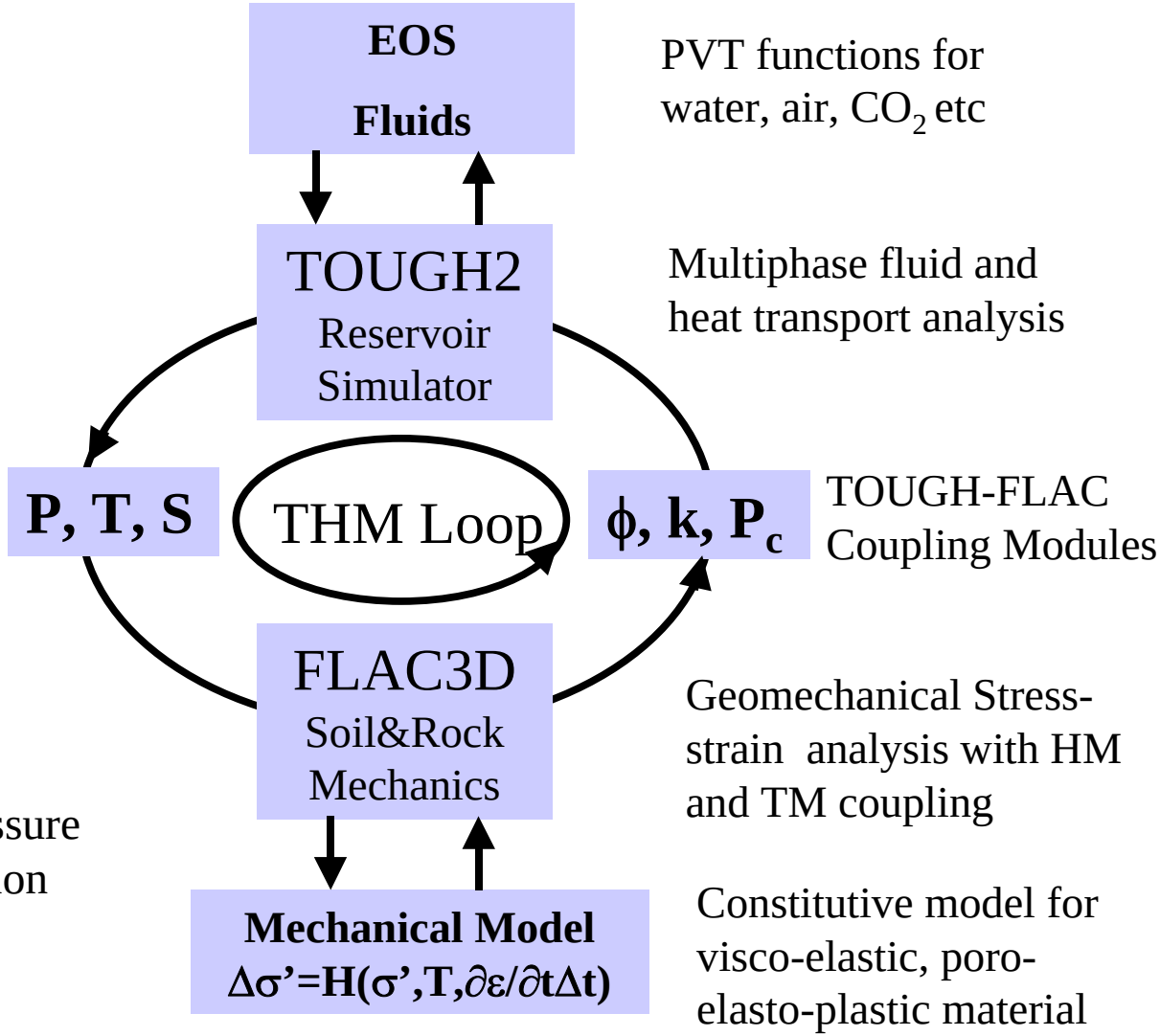
Geomechanical Processes in CO_2 storage



What is the maximum sustainable injection pressure?

TOUGH-FLAC

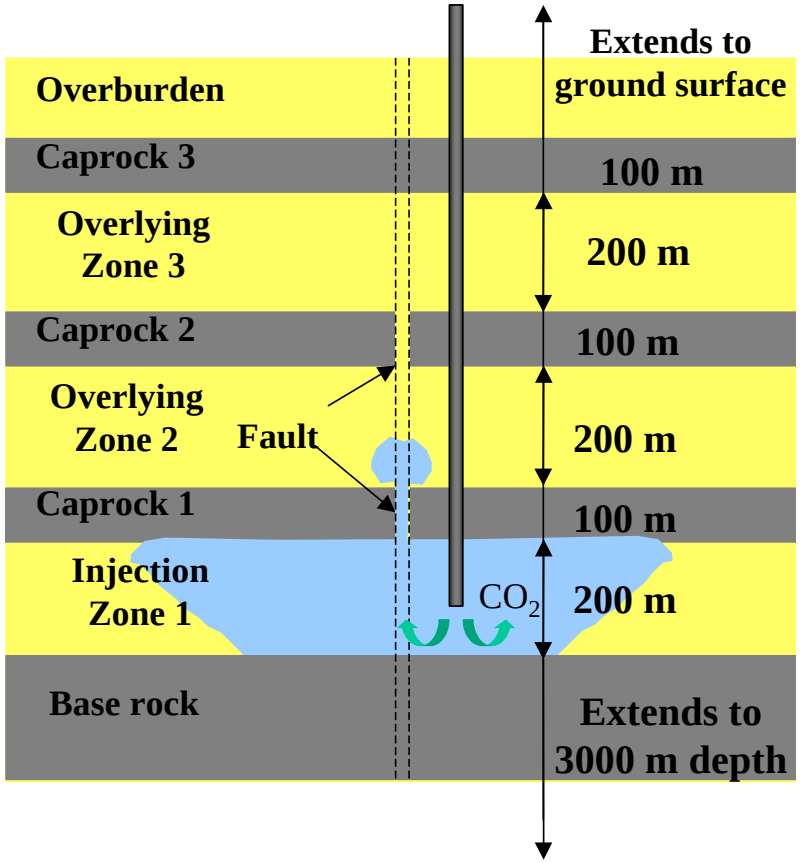
A numerical simulator for analysis of coupled multi-phase fluid flow, heat transport and mechanical deformations



P = Pressure
T = Temperature
S = Saturation
σ' = Stress
ϕ = Porosity
k = Permeability
P_c = Capillary pressure
H= Material function
ε = Strain
t = time

(Rutqvist *et al*, International Journal of Rock Mechanics, 2002)

MODELING OF INJECTION INTO A MULTILAYERED SYSTEM



- Inject CO_2 at a depth of 1600 m for 30 years representing a major CO_2 injection operation.
- Permeable faults (or discontinuous caprock) exists near the injection well, allowing upward CO_2 migration
- System is sealed from overburden by the uppermost Caprock 3.

Three different stress regimes:

1) Isotropic ($\sigma_h = \sigma_v$)

2) Compressional ($\sigma_h = 1.5\sigma_v$)

3) Extensional ($\sigma_h = 0.7\sigma_v$)

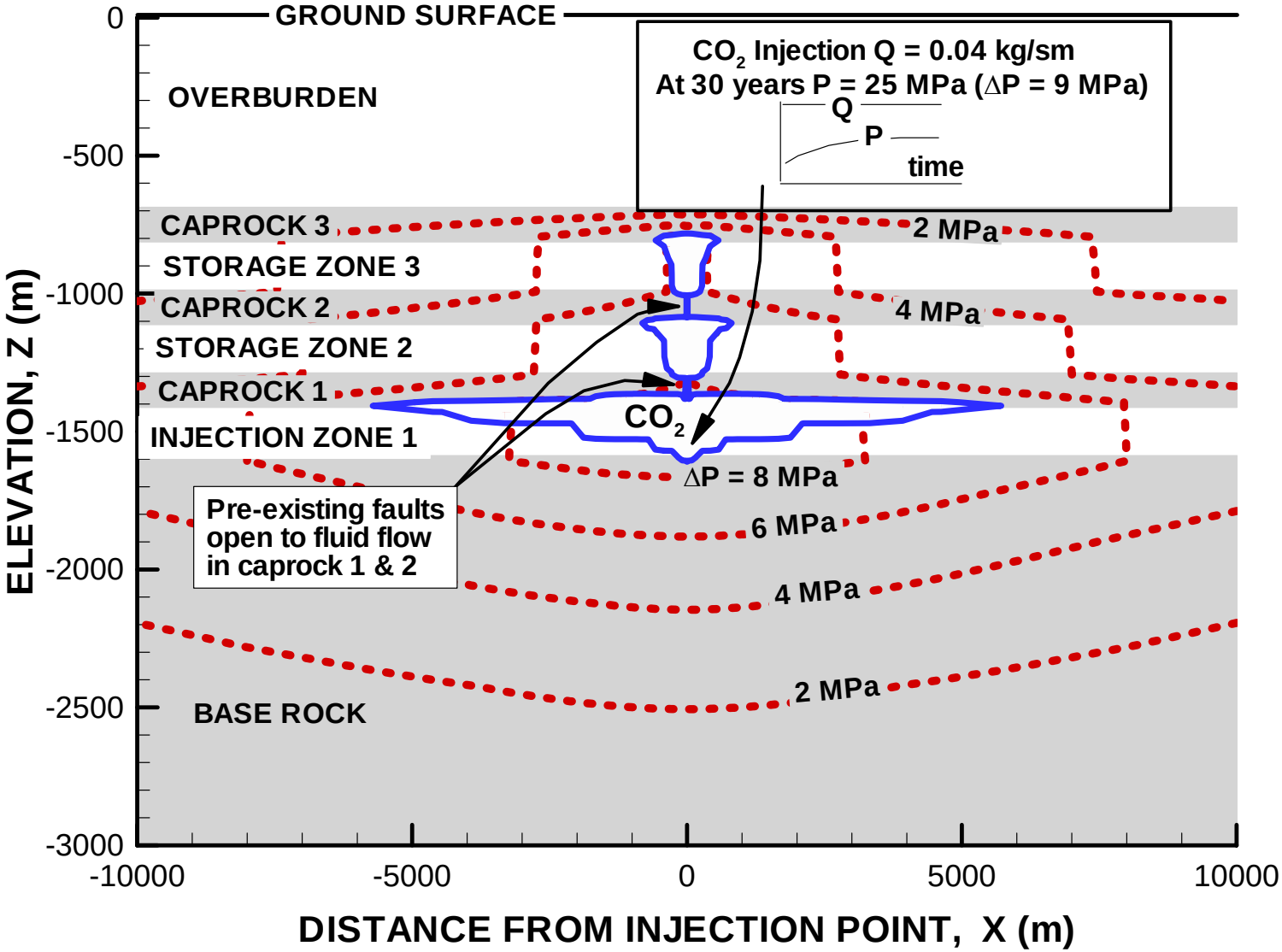
<u>Simulation Steps</u>

1) Calculate evolution of fluid pressure and the three-dimensional stress field.

2) Calculate the potential for shear slip and hydraulic fracturing by applying appropriate failure criteria.

CO_2 PLUME AND CHANGES IN FLUID PRESSURE

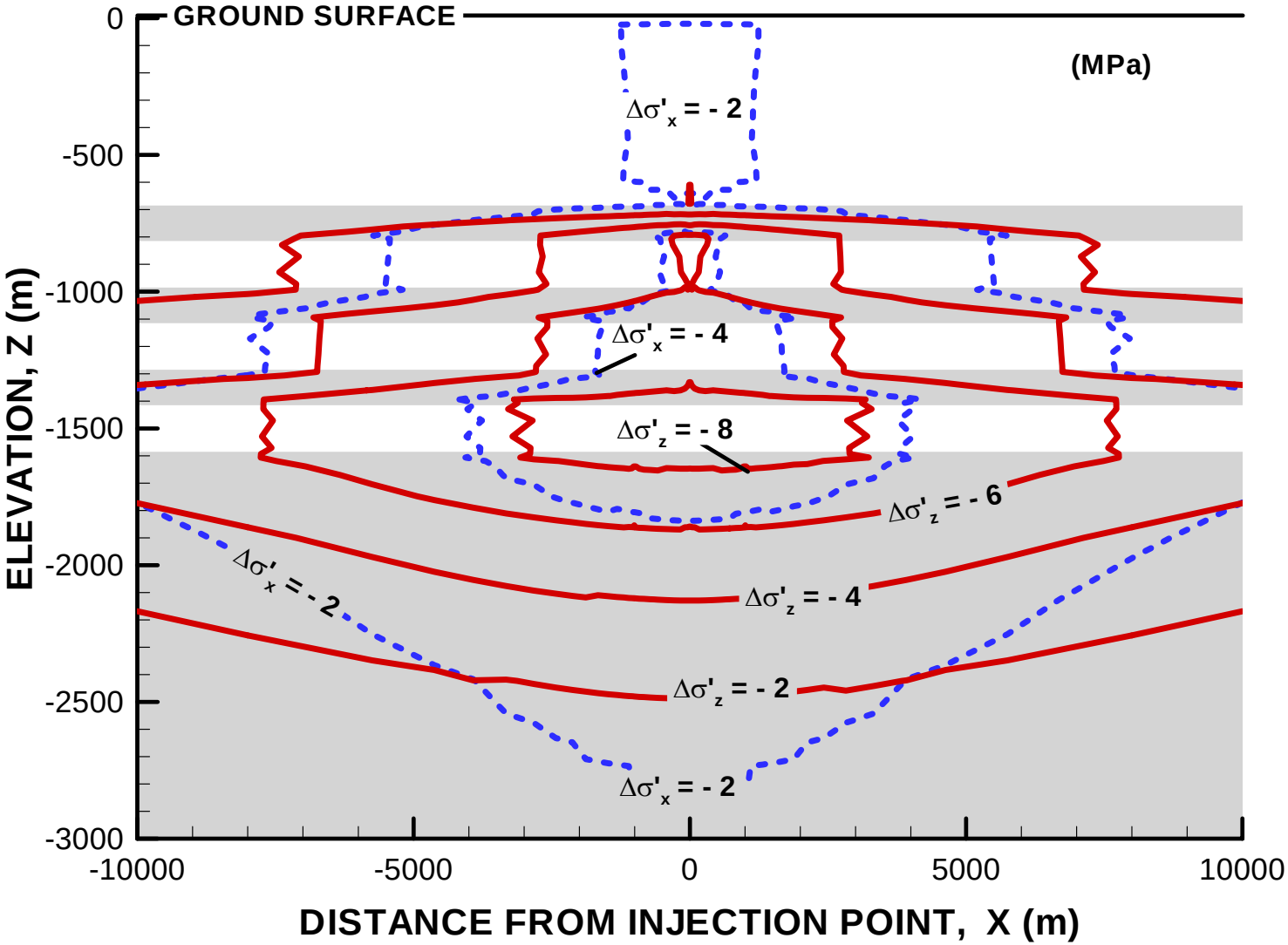
(At the end of the 30-year injection period)



- Injection pressure 70% of lithostatic stress (about 1.5 times hydrostatic pressure)

INJECTION INDUCED CHANGES IN EFFECTIVE STRESSES

(At the end of the 30-year injection period)



Vertical stress: $\Delta\sigma'_v = \Delta\sigma_v - \Delta P$, $\Delta\sigma_v \approx 0$ (free vertical expansion)

Horizontal stress: $\Delta\sigma'_h = \Delta\sigma_h - \Delta P$, $\Delta\sigma_h \neq 0$ (restricted horizontal expansion)

EVALUATING THE POTENTIAL FOR SHEAR SLIP OR FRACTURING

Potential for Shear Slip

$$P_{sm} = P - P_{sc}$$

P_{sm} = Pressure margin for onset of shear slip

P = Fluid pressure

P_{sc} = Critical pressure for onset of shear slip

P_{sc} is estimated using a Coulomb failure criterion assuming cohesionless faults of any orientation may exist. The fault friction angle is set to 30° (friction coefficient μ=0.6)

Potential for Fracturing

$$P_{fm} = P - P_{fc}$$

P_{sm} = Pressure margin for onset of fracturing

P = Fluid pressure

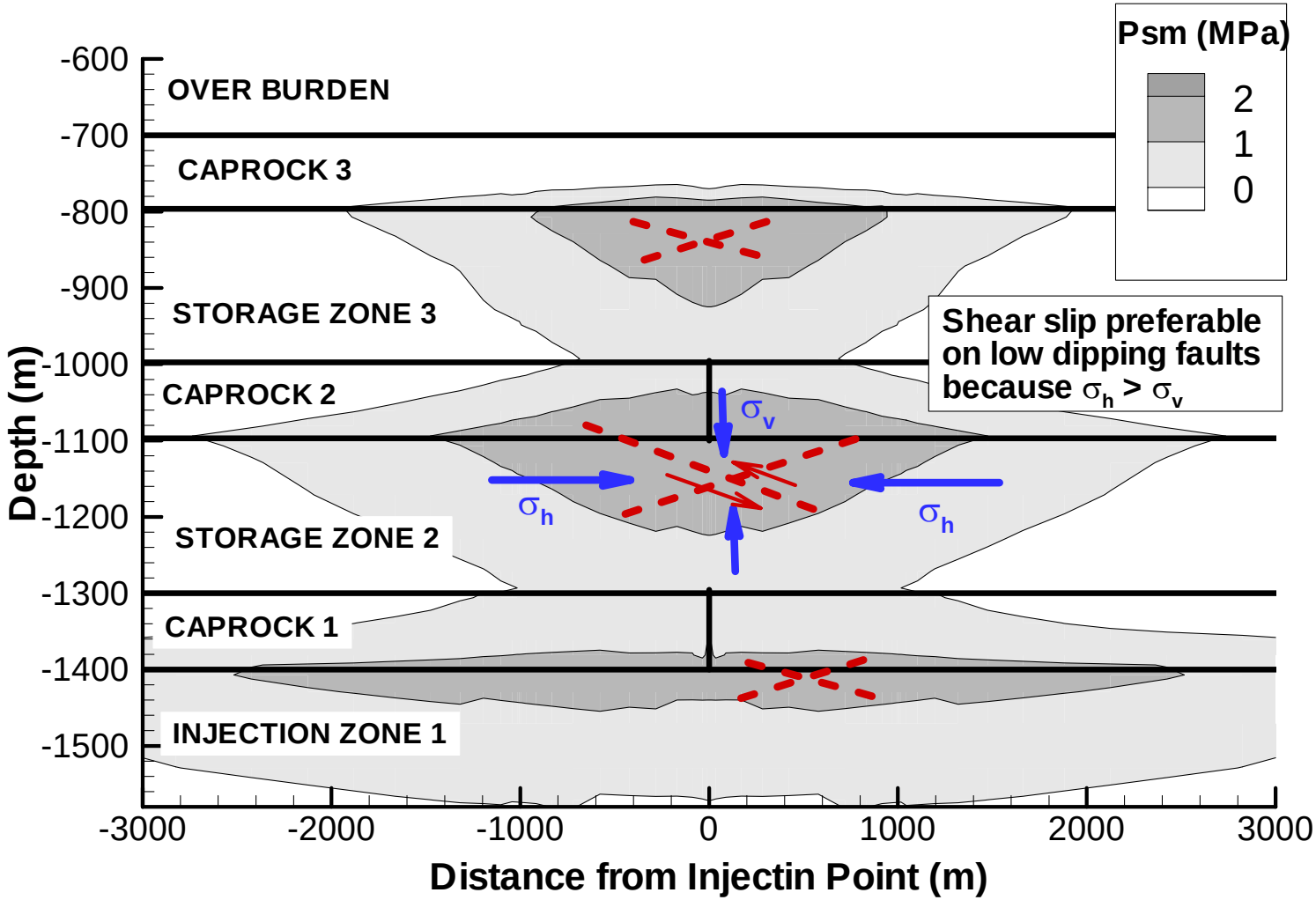
P_{fc} = Critical pressure for onset of fracturing

P_{fc} is estimated with the conservative assumption that a hydraulic fracture would develop as soon as P exceeds the minimum principal compressive stress

The pressure margin tells us how much further the fluid pressure can be increased before failure (shear slip or fracturing) is initiated.

POTENTIAL FOR SHEAR SLIP AND FRACTURING

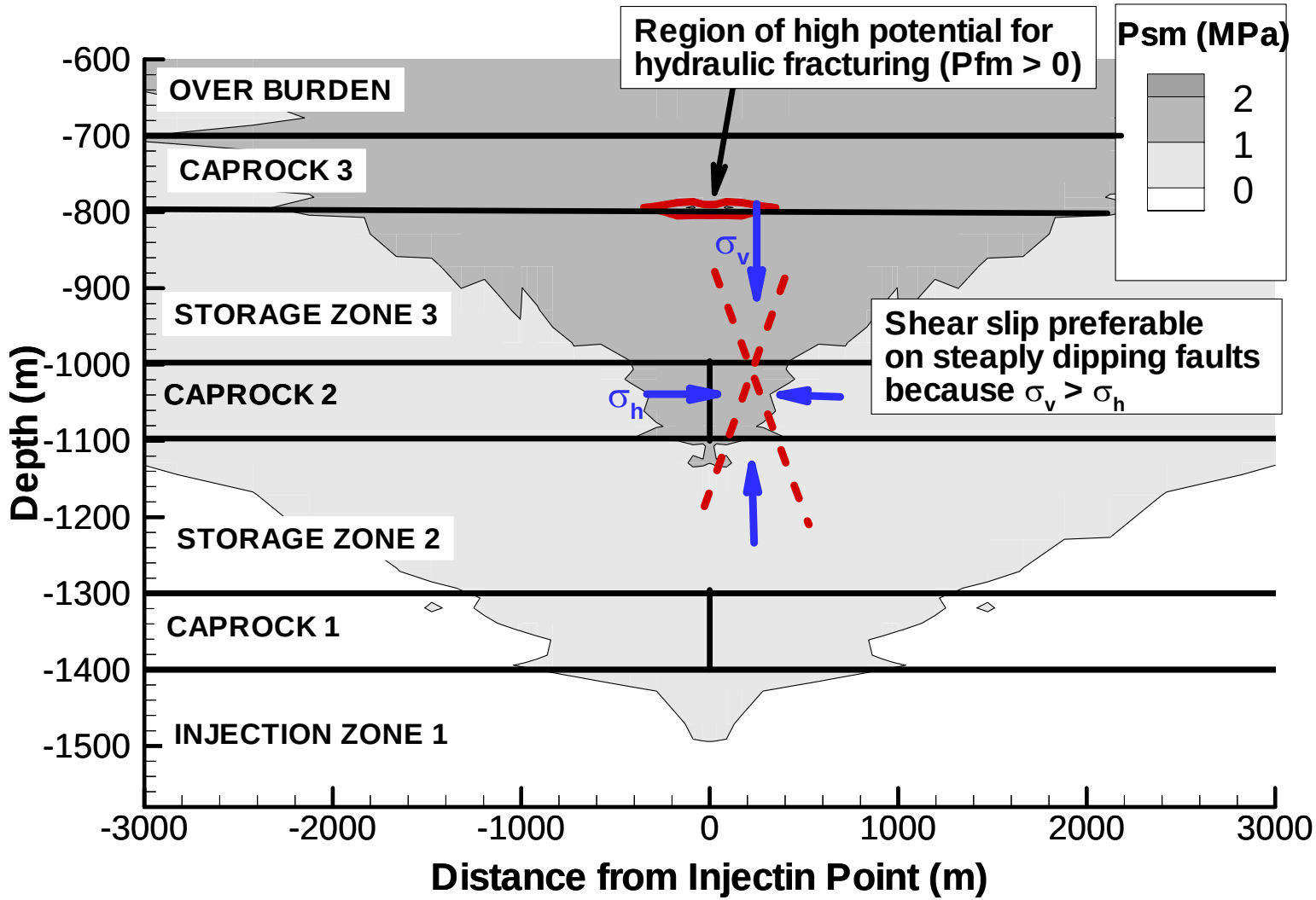
Compressional Stress Regime ($\sigma_h = 1.5\sigma_v$)



Fault slip is most likely in subhorizontal faults at the interface between the permeable formation layers and an overlying caprock.

POTENTIAL FOR SHEAR SLIP AND FRACTURING

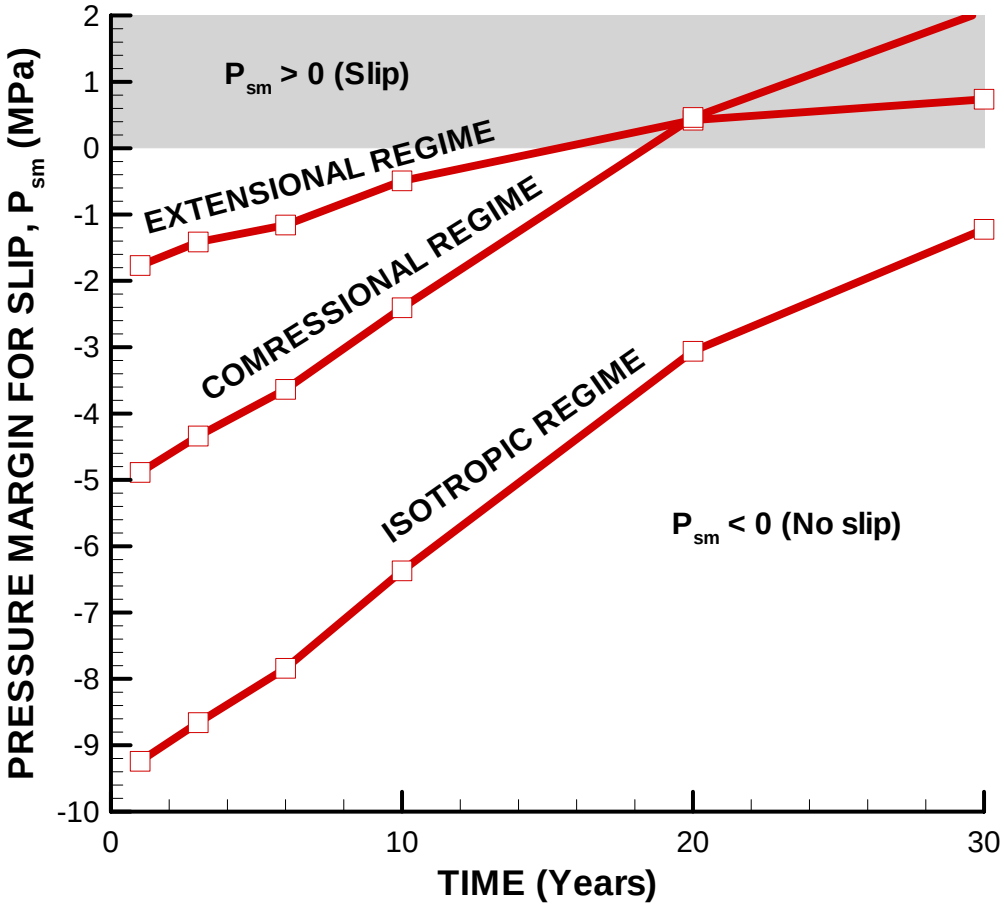
Extensional Stress Regime ($\sigma_h = 0.7\sigma_v$)



Fault slip is most likely in subvertical faults in the upper parts and in the overburden rock above the zone of increased fluid pressure.

EVOLUTION OF PRESSURE MARGIN FOR SHEAR-SLIP

(at the uppermost caprock)

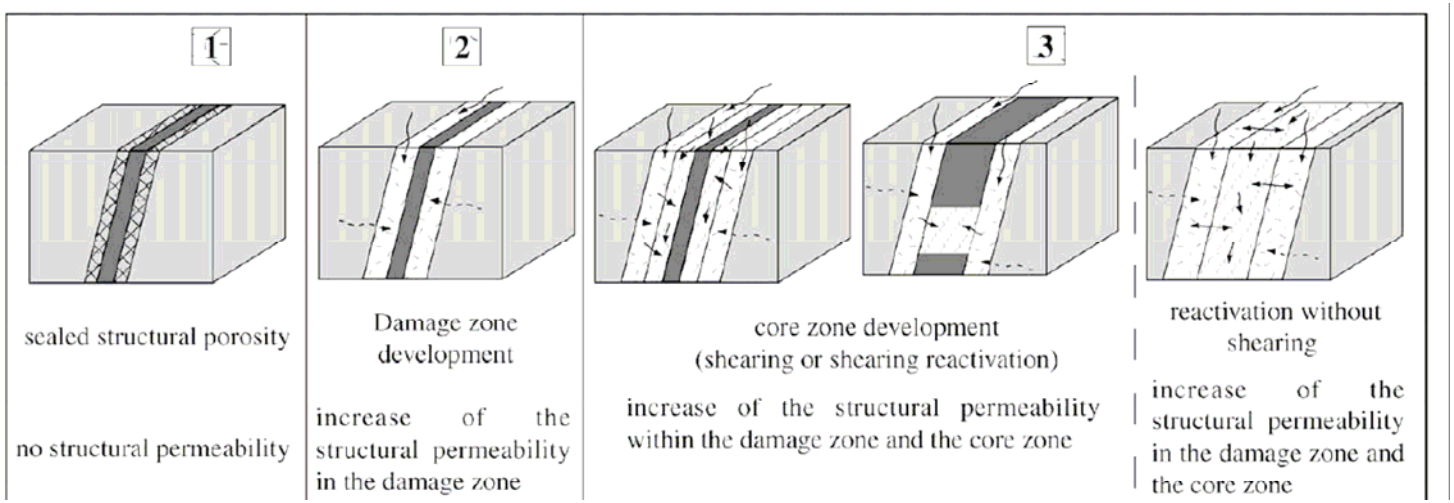


- Onset of shear-slip could occur after about 15 to 20 years for extensional or compressional regimes.
- Shear-slip not likely for the isotropic regime.

$\Rightarrow$ in situ stress important to characterize

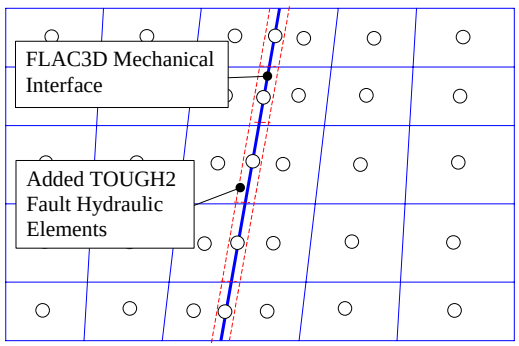
MODELING OF HYDROMECHANICAL FAULT REACTIVATION WITH SHEAR-INDUCED PERMEABILITY CHANGE

How to model coupled hydromechanical behavior of a fault/fault zone?

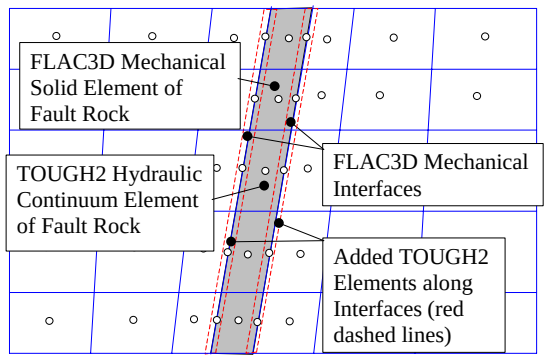


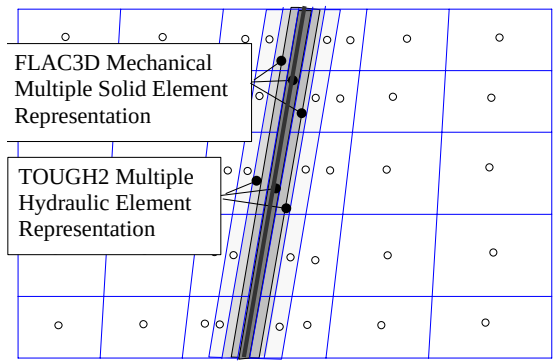
Conceptual model of fault zone (Constantin et al., 2004)

Single Fault Plane



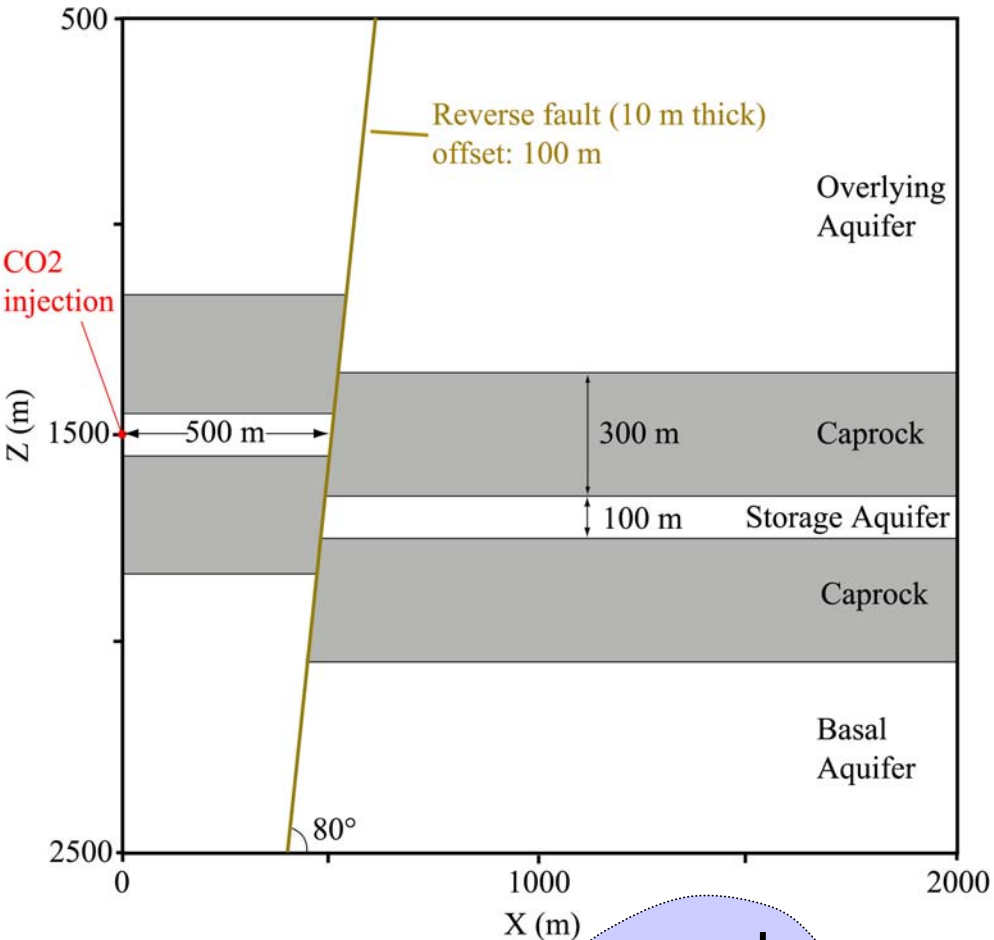
Fault Core + Damaged Zone

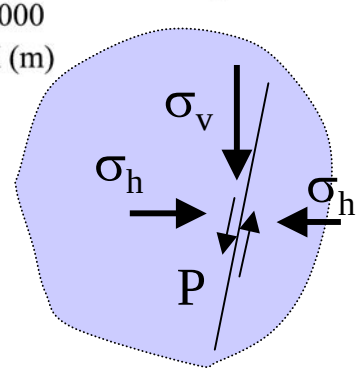




Current Approach: Interface element or solid element with anisotropy of mechanical (elasto-plastic) and hydrologic properties

MODELING OF HYDROMECHANICAL FAULT REACTIVATION WITH SHEAR-INDUCED PERMEABILITY CHANGE





- Bounded injection zone, extensional stress regime ($\sigma_h = 0.7\sigma_v$)
- A cohensionless fault with fault friction angle 25°
- Fully reactivated fault (maximum shear strain) $\Rightarrow$ permeability increase by two-orders of magnitude

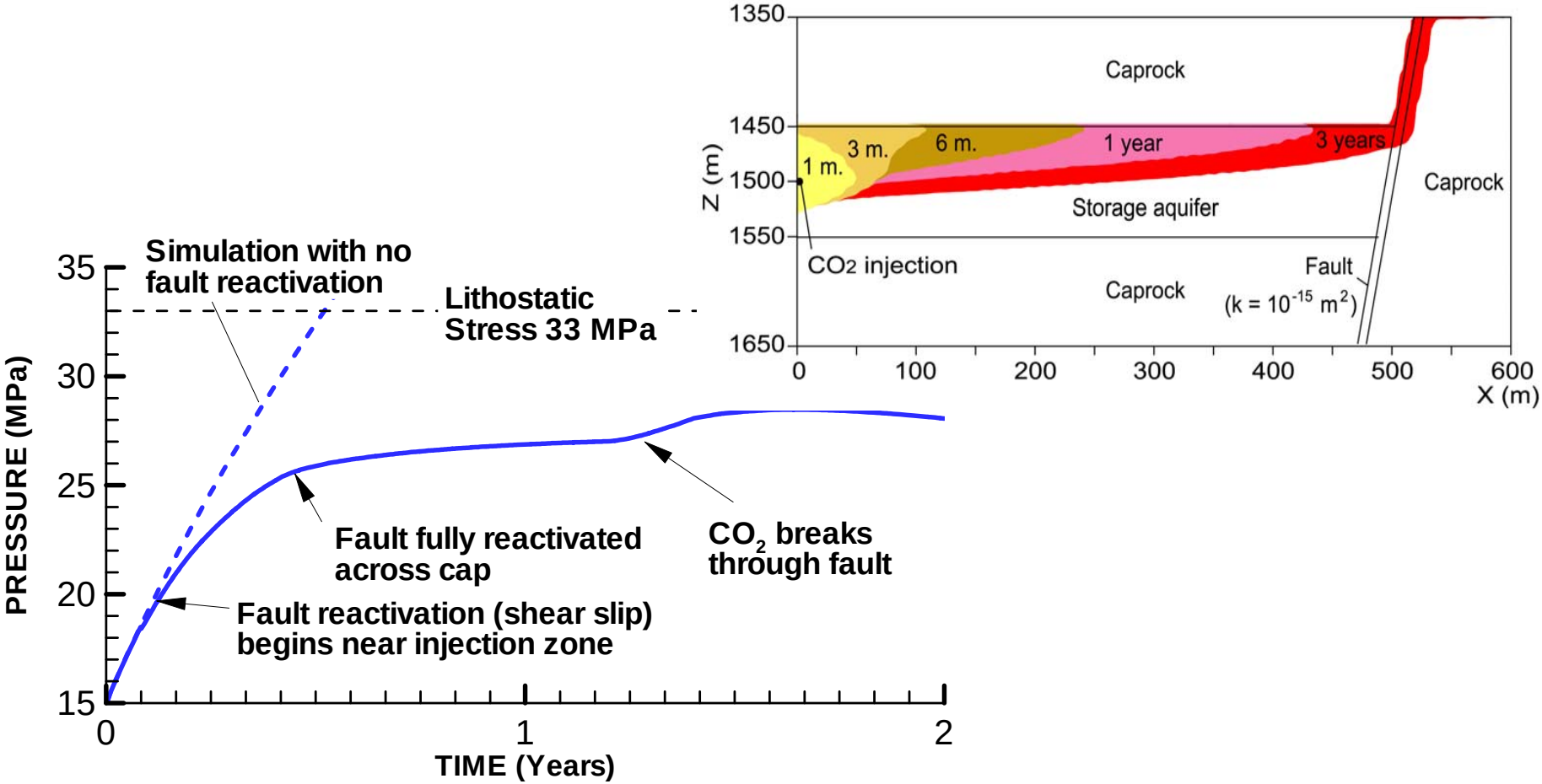
Analytic estimate of sustainable fluid pressure:

σ_v = 33 MPa (Lithostatic stress)

σ_h = 23 MPa

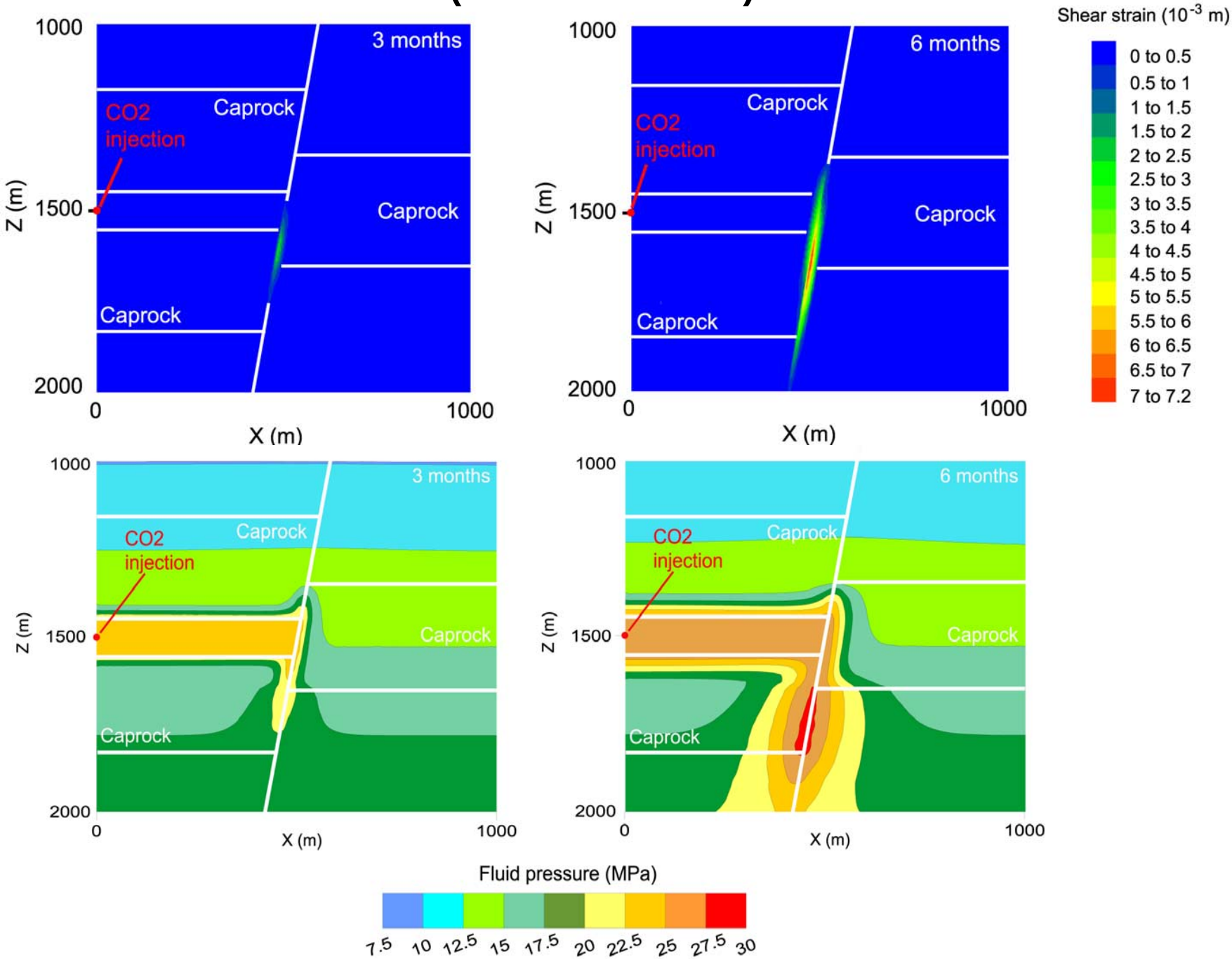
$$P_{crit} = \sigma_n - \frac{\tau}{\mu} = 17.4\ \mathbf{MPa}$$

EVOLUTION OF CO2 PHASE AND INJECTION PRESSURE



- Limited shear slip begins at an injection pressure of about 19 MPa, but shear slip does not propagate across cap until an injection pressure of about 25 MPa
- Analytic estimate of maximum sustainable pressure (17.4 MPa) is conservative

EVOLUTION OF SHEAR SLIP (SHEAR STRAIN) AND FLUID PRESSURE

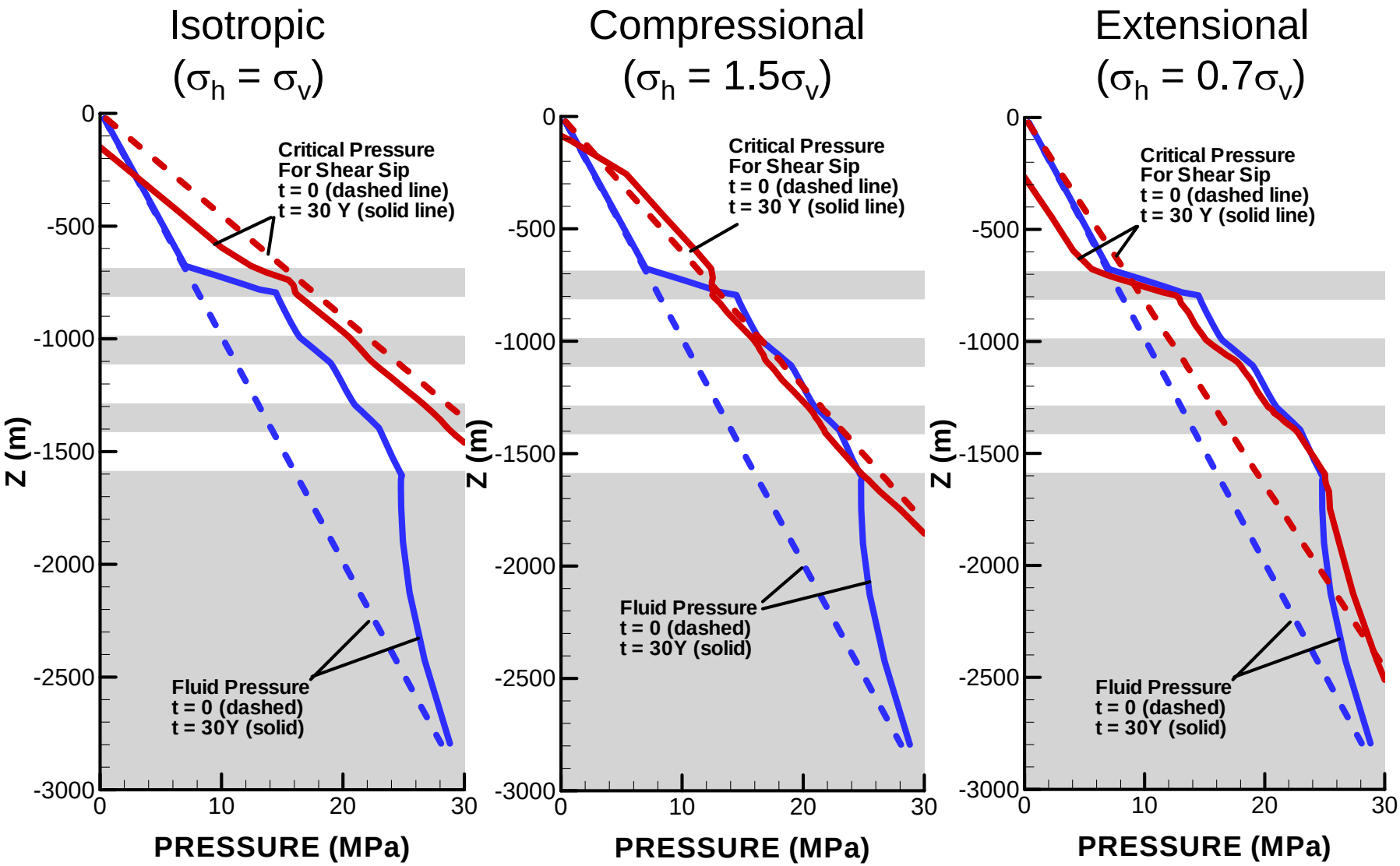


CONCLUSIONS RELATED TO SITE CHARACTERIZATION OF INDUSTRIAL CO_2 INJECTION SITES

- The three-dimensional in situ stress field should be carefully characterized and monitored (if possible).
- Potential for fault reactivation and fracturing should be analyzed for the entire region affected by mechanical stress changes, which is generally more extensive than the region affected by fluid pressure (e.g in the overburden).
- The maximum sustainable injection pressure should be estimated using a site-specific coupled reservoir-geomechanical modeling that correctly accounts for local evolutions of fluid pressure and the three-dimensional stress field.
- The mechanical and coupled hydrological-mechanical properties of various formations, including permeable formations and caprocks should be characterized.

The End

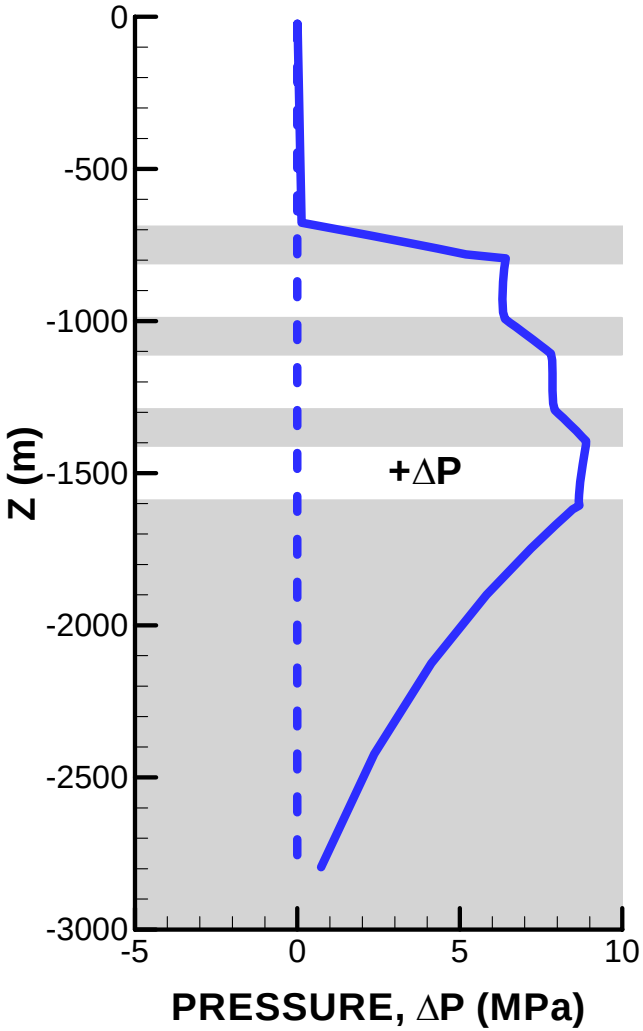
FLUID PRESSURE AND CRITICAL FAULT-SLIP PRESSURE

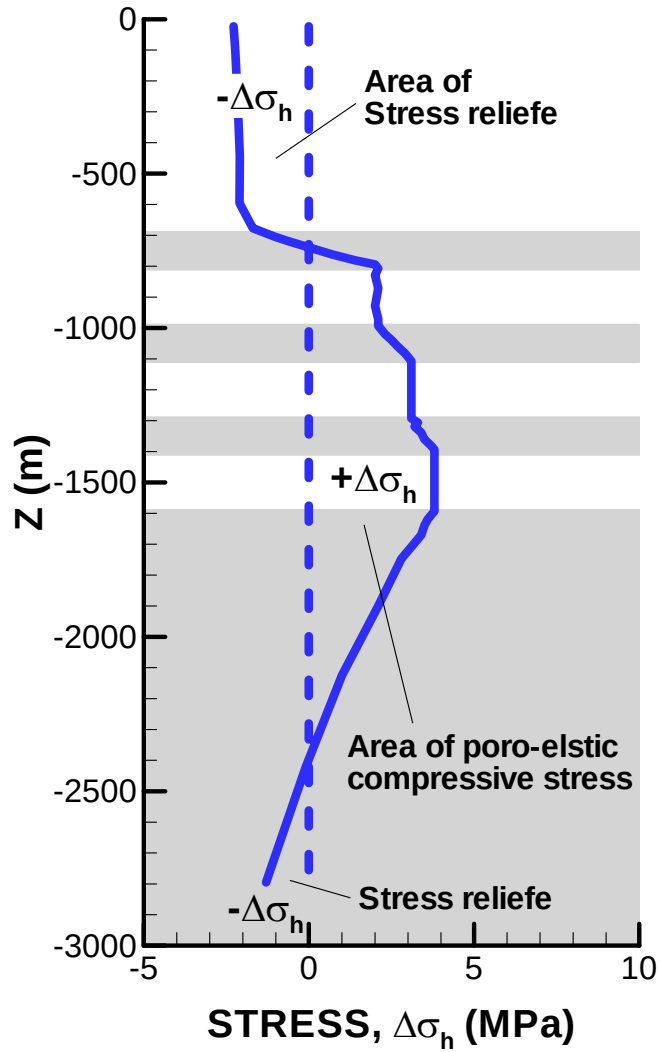


- Highest potential for shear-slip occurs in the upper parts of the pressurized CO2 zone, near interface with the uppermost caprock.

INJECTION INDUCED CHANGES IN TOTAL HORIZONTAL STRESS

(Poro-elastic stressing at 30 years)





- Important to consider poro-elastic stress

Potential for Fault Slip (Coulomb Slip Criterion)

Critical Shear Stress

$$\tau_{cr} = C + (\sigma_n - P)\tan\phi$$

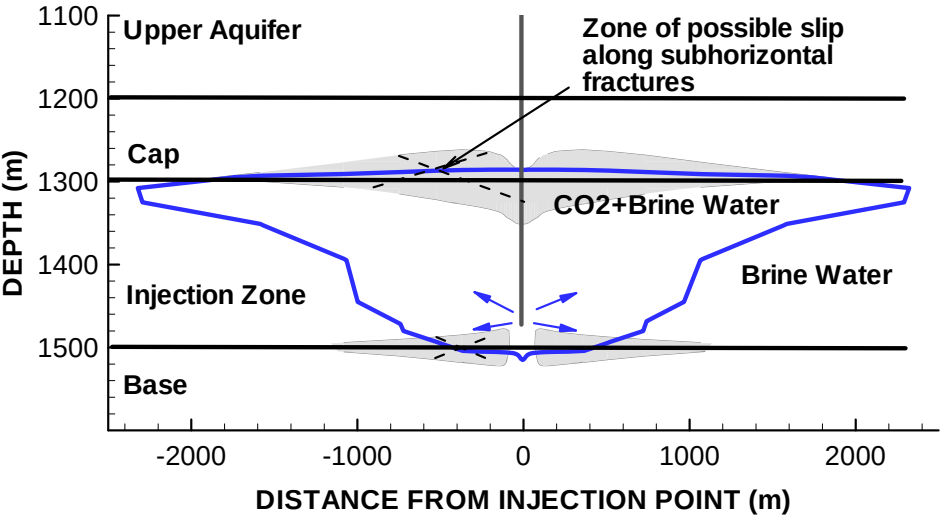
Cohesion = 0

Stress normal to fault

Fluid pressure

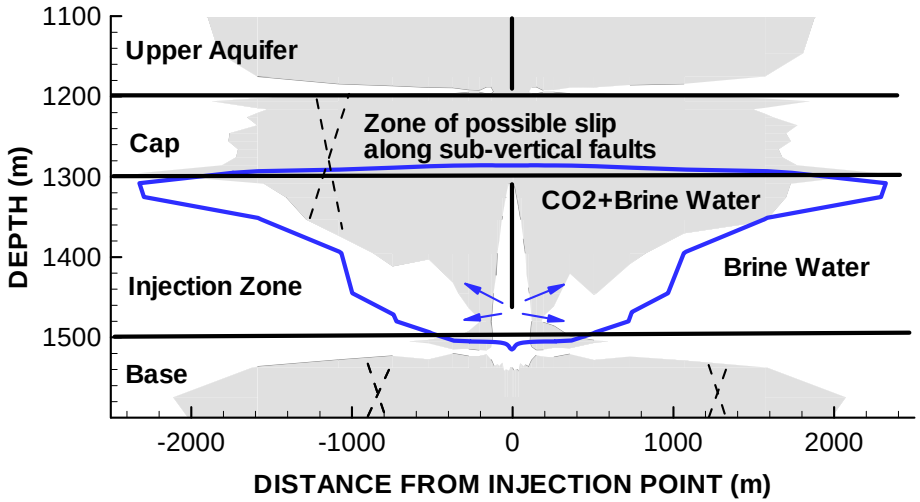
Friction angle = 25°

Compressional Regime ($\sigma_h = 1.5\sigma_v$)



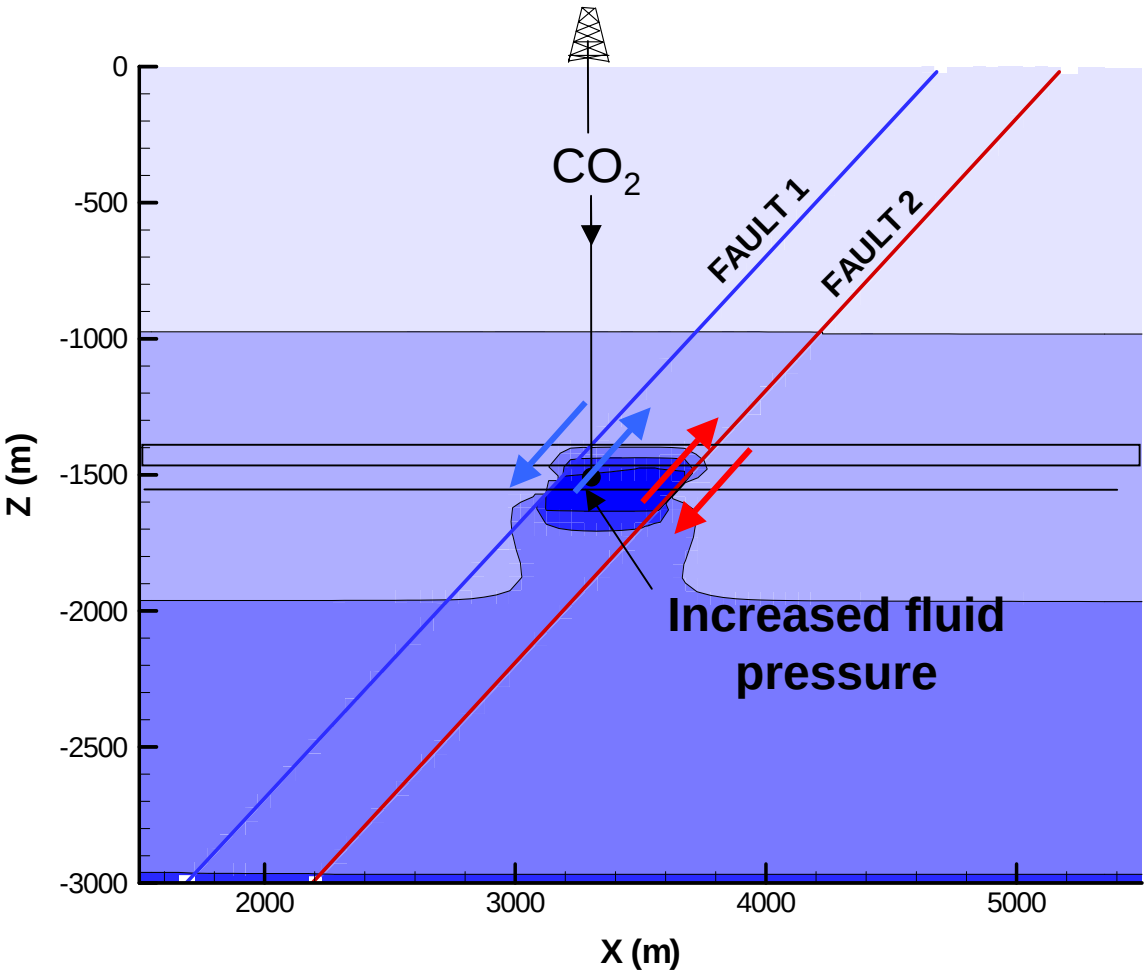
- Shear slip could occur at the lower part of the caprock along existing subhorizontal fractures
- Shear slip not likely to propagate through the upper part to the cap

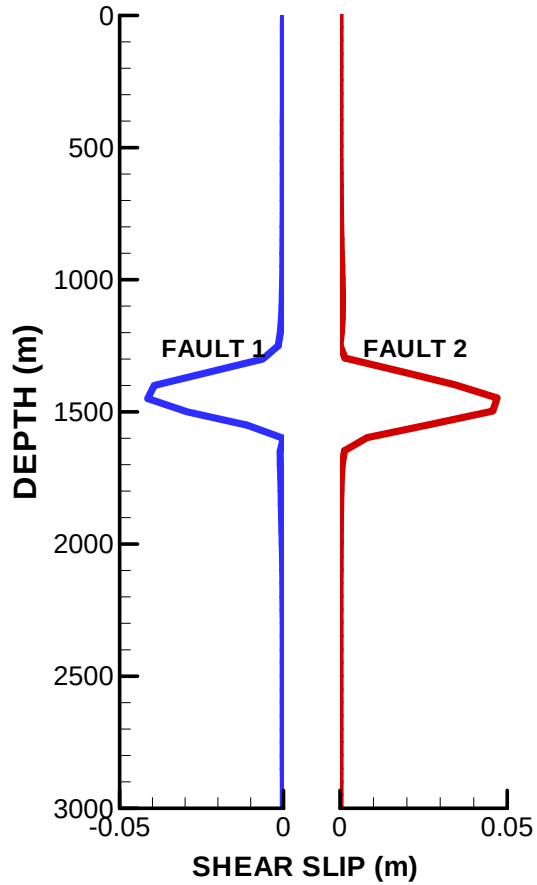
Extensional Regime ($\sigma_h = 0.7\sigma_v$)



- Shear slip could occur within and about the injection zone along existing subvertical fractures
- Shear slip could propagate through cap

Discrete Fault Reactivation Analysis with TOUGH-FLAC





- Maximum fault slip about 5 cm
- Fault reactivation limited to 100 meters above and below pressurized zone

Table 1. Rock properties

Property	**Inject. Zone**	**Caps**	**Fault**
Young's modulus, E (GPa)	5	5	2.5
Poisson's ratio, ν (-)	0.25	0.25	0.25
Saturated density, ρ_s (kg/m^3)	2260	2260	2260
Flow porosity, ϕ (-)	0.1	0.01	0.1
Permeability, k, (m^2)	1×10^{-13}	1×10^{-19}	1×10^{-14}
Residual CO_2 saturation (-)	0.05	0.05	0.05
Residual liquid saturation (-)	0.3	0.3	0.3
van Genuchten, P_0 (kPa)	19.9	621	0.9
van Genuchten, m (-)	0.457	0.457	0.457

GEOMECHANICAL FAULT-SLIP ANALYSIS

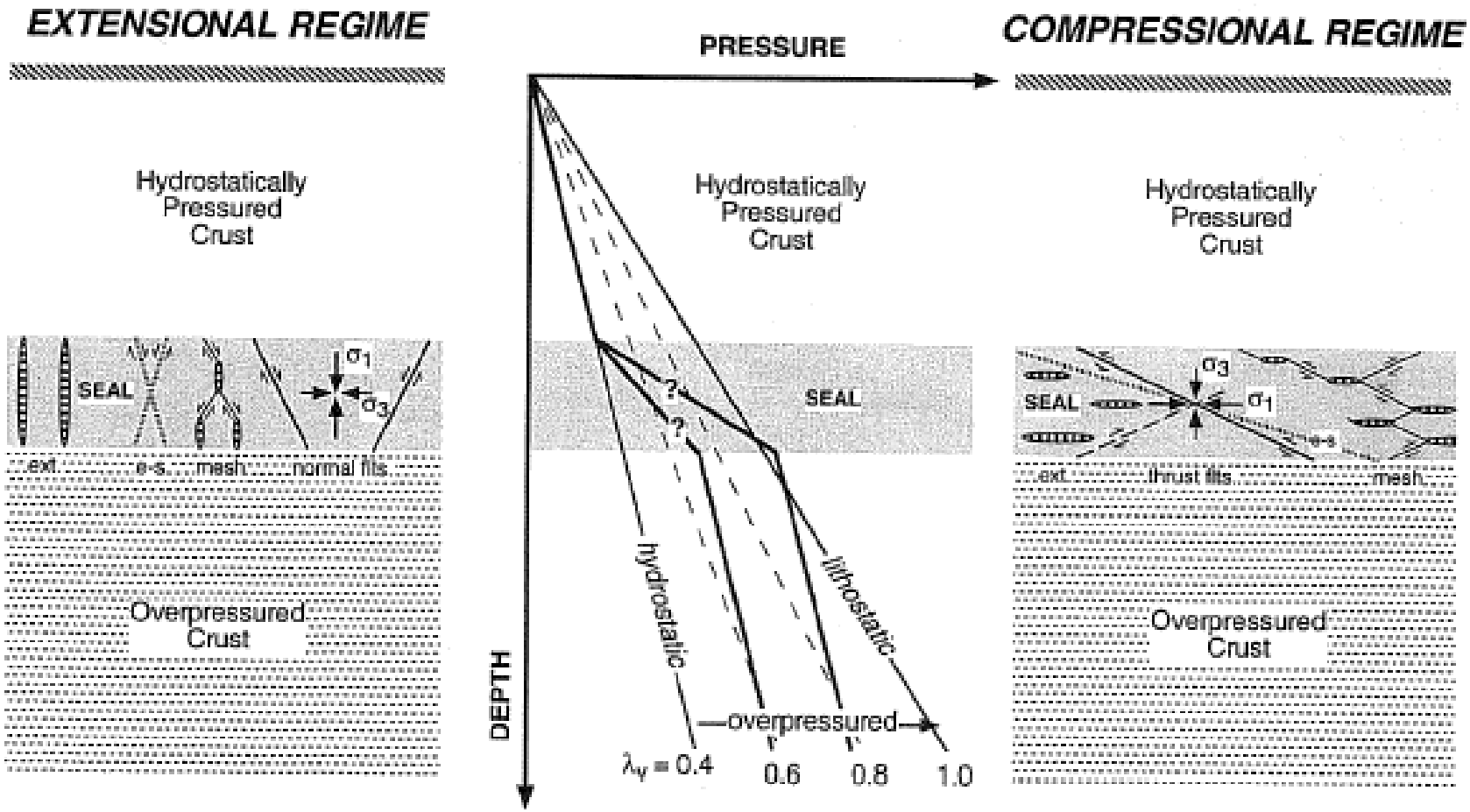
Three Approaches:

1) Analytical analysis of potential for fault slip (slip tendency): Estimate maximum sustainable pressure from current (undisturbed) regional stress field at the depth of injection (e.g. Barton et al., *Geology*, 1995; Streit and Hillis *Energy*, 2004).

2) Coupled hydromechanical numerical analysis of potential for fault slip: Based on calculated distribution and injection induced evolution of local three-dimensional stress field and fluid pressure (e.g. Rutqvist and Tsang, *Environmental Geology,* 2002).

3) Fully coupled hydromechanical analysis of fault slip and shear induced permeability changes: Calculate extent and magnitude of fault slip and permeability changes along discrete fault planes, and its impact on CO_2 migration.

NATURALLY OVERPRESSURED SEDIMENTS AND GAS RESERVOIRS



- Reshear of cohesionless faults favorably oriented for frictional reactivation provides the lower limiting bound to overpressures (Sibson, AAPG, 2003).

  ⇒ Geomechanical analysis of fault slip (not just fracturing) is essential for estimating maximum sustainable pressure at a CO_2 injection site.