Mechanisms of permeability and friction evolution in faults affecting reservoir-caprock systems :
Towards the development of an earthquake cycle ROM including fluid pressure

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Context: Induced seismicity risk is a concern for many CO_2 storage projects, as demonstrated by seismic activity observed at several recent CO_2 injection operations. The central objective of the NRAP Induced Seismicity Risk Task is to develop practical tools to support the assessment and management of induced seismicity risk at carbon storage operations. Under this task, LBNL researchers are developing new techniques to quickly link stress characteristics with estimates of caprock integrity, fault reactivation, and leakage to identify hazardous situations and address problematic seismicity should impactful situations arise. In phase II, LBNL reviewed the constitutive fault permeability transient evolution due slip and slip velocity, effective normal stress, given different rock brittleness, confining and deviatoric stresses and fault strength. In phase III, LBNL started developing a ROM that integrates the risk of fault leakage and induced seismicity, focusing on identification of potential leakage and seismically slipping zones of a reactive fault and how permeability decays after activation.

Key points about caprock fault from bibliography:

1 – Some caprocks are at the brittle-ductile transition at the CO2 storage depths
    Laboratory experiments show that a pore pressure increase can bring a fault from ductile to brittle state.
    A slow pore pressure increase can produce a more “tortuous” permeability increase (dilatant shear is spreading on more secondary fractures within the fault zone).
2 – The peak Coulomb strength must be exceeded for a fault permeability to increase.
    The plastic shear initiates and may eventually precede fault opening.
3 - A significant amount of slow dilatant slip/creep is preceding slip accelerations and seismicity.
    Seismicity is in general rare in clay-rich faults and mostly located outside the pressurized flow paths.
4 – Faults are thick zones - Inside the same fault zone, there is a competition between dilation and contraction during shear activation
    This is depending on the apparent ductility contrasts between fault materials (schematically, scaly clay = ductile and main fractures = brittle).
    A lot of dilation is occurring locally where fluid pressure is increasing in a fault zone. This favors large local permeability increase before a large-scale activation.

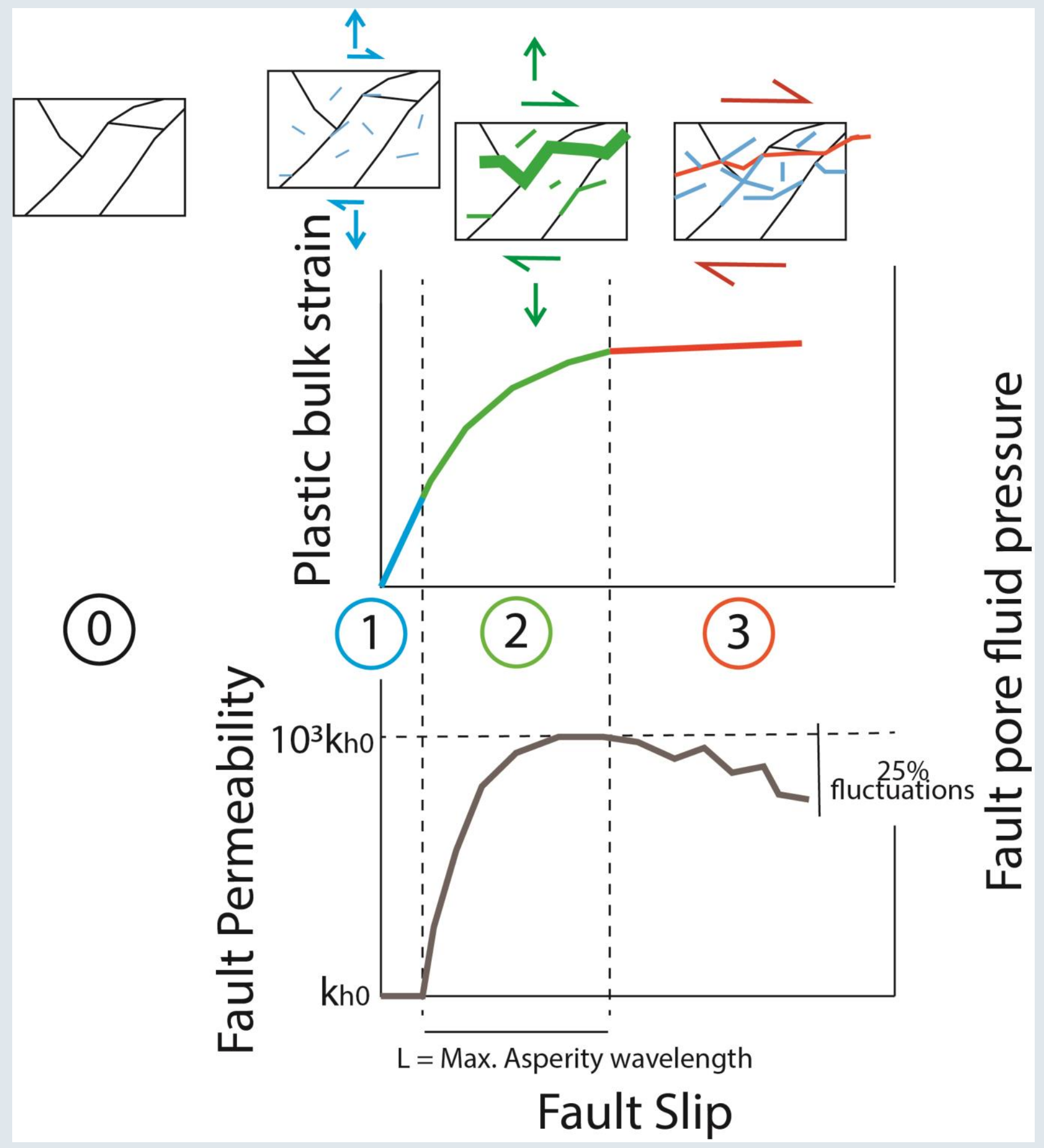
Conceptual Caprock potential permeability increase (deduced from bibliography):

0 – Initial inactive caprock fault
- While inactive, the initial permeability of caprock faults may be as low as the intact caprock permeability

① – Slow pore pressure and background strain rate increase in the caprock activate fault creep
- Initially low consolidated fault materials under ductile conditions switch from compaction to dilation.
- A minimum pore pressure (FPmin) threshold must be reached to initiate such dilation and creep.
- Dilatant creep initiates through diffuse shear activation of the fault zone fractures.
- At this phase, there is no significant increase in fault permeability.

② – Local high permeable flow paths create along a reduced number of highly dilatant secondary faults (for example, 3 fractures were identified as flow channels in the 6 m thick MtTerri shale fault)
- It seems that flow paths preferentially create on fractures bounding the initially ductile fault materials.
- A second pore pressure threshold (FOP), higher than FPmin, must be reached for significant permeability increase.
- Field scale experiments show that FOP corresponds to an about 80% decrease in the fault mean normal stress.
- During this period, local three-orders of magnitude fault permeability increases are possible

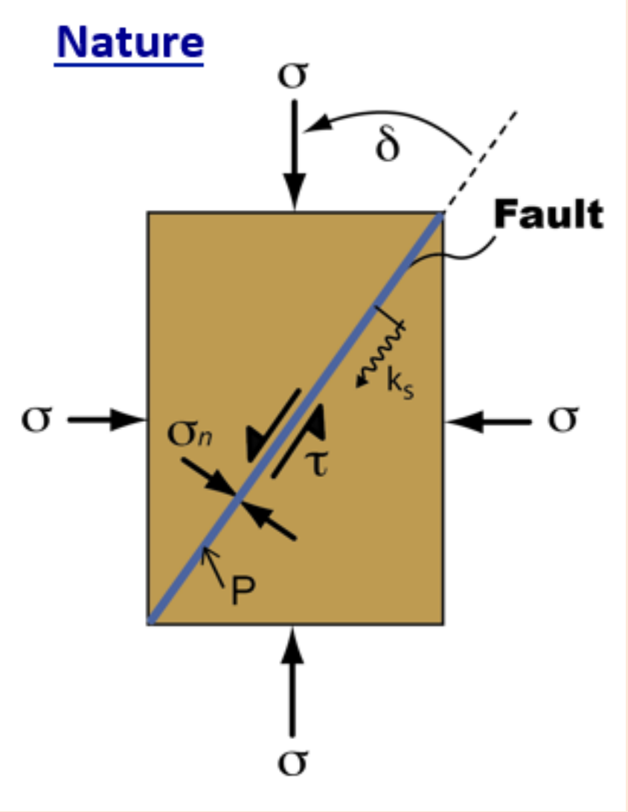
③ – Flow paths may create and destroy as a function of the amount of shear and shear velocity
- About 25% permeability fluctuations are observed in active faults
- Permeability fluctuations may depend on fault asperity scale
- Asperities play two roles: complex bulk hydromechanical response and heterogeneous stress-strength related to asperity geometry
- Rare long term permeability measurements show a very slow and incomplete sealing of faults

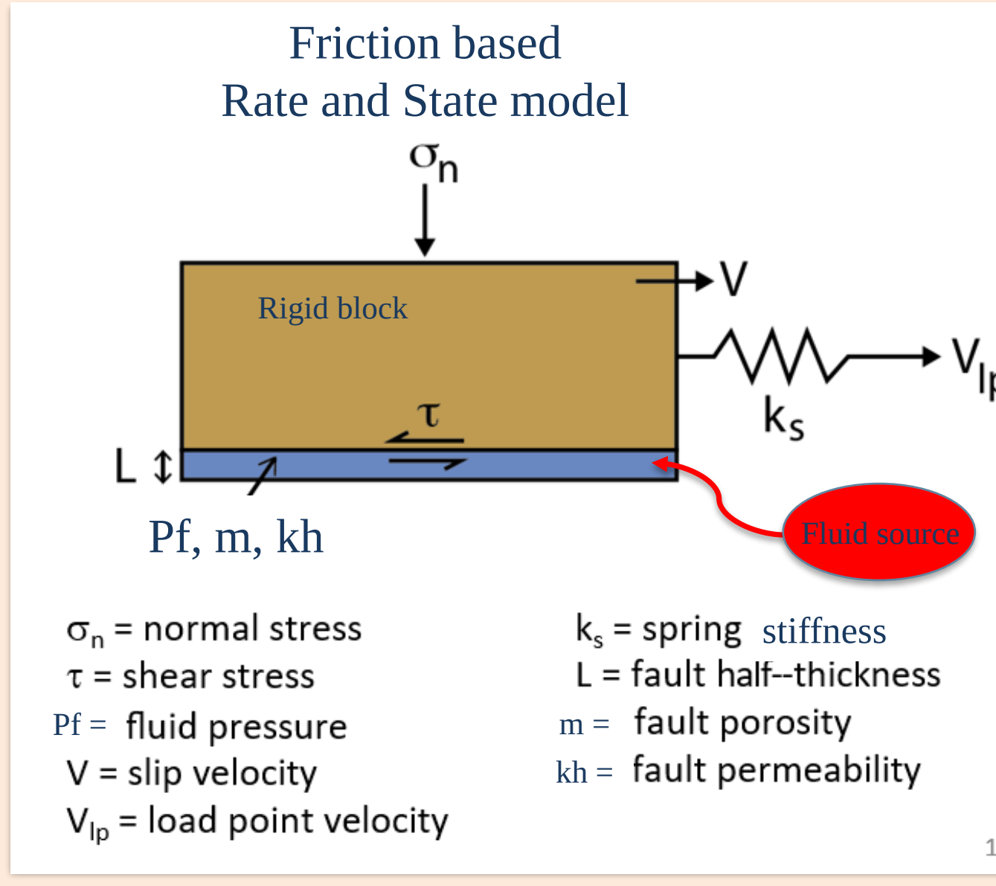


Towards a ROM to help better assess caprock fault leakage

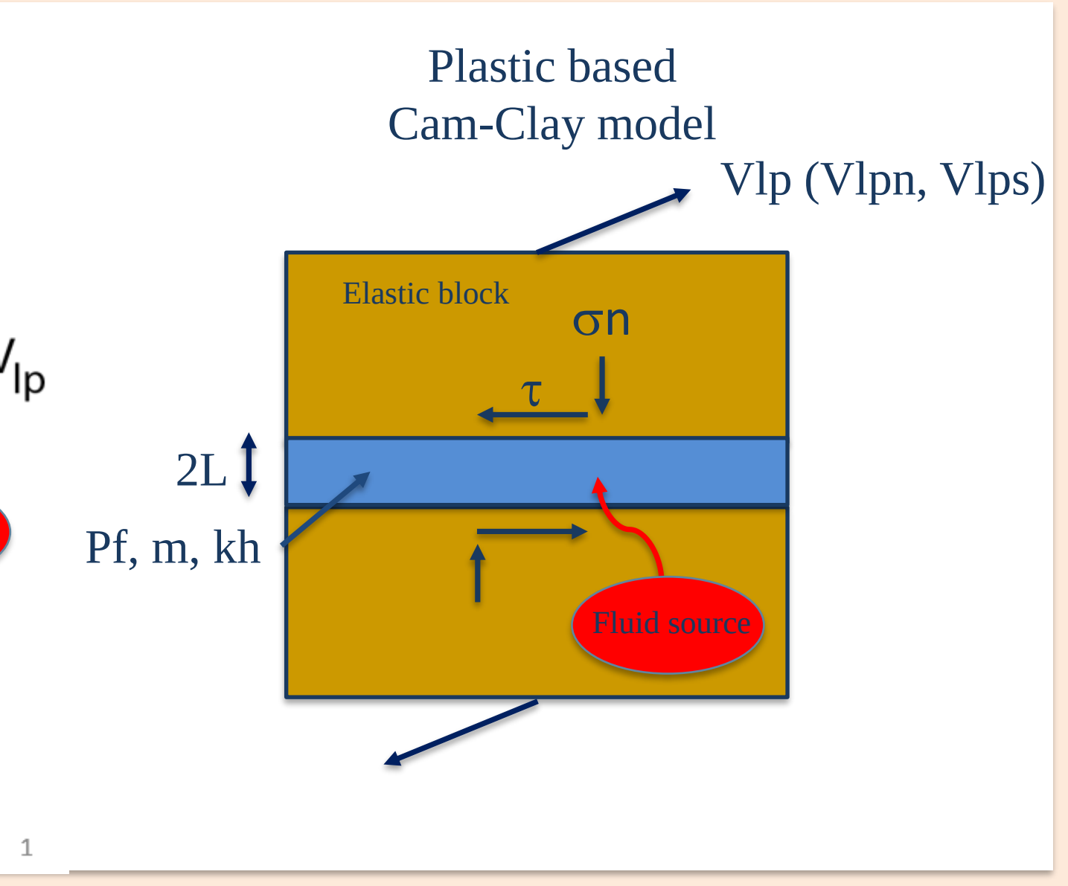
- Provide an analytical model in which the fault zone is schematized as a hydromechanical interface surrounded by elastic rock
- Implement different types of permeability laws in the model
- Provide insights on the conditions that can lead to fault slow slip versus seismic slip, and associated fault permeability changes

Implementations of permeability law(s) in both Rate and State and in modified Cam-Clay constitutive models (using MATLAB software)



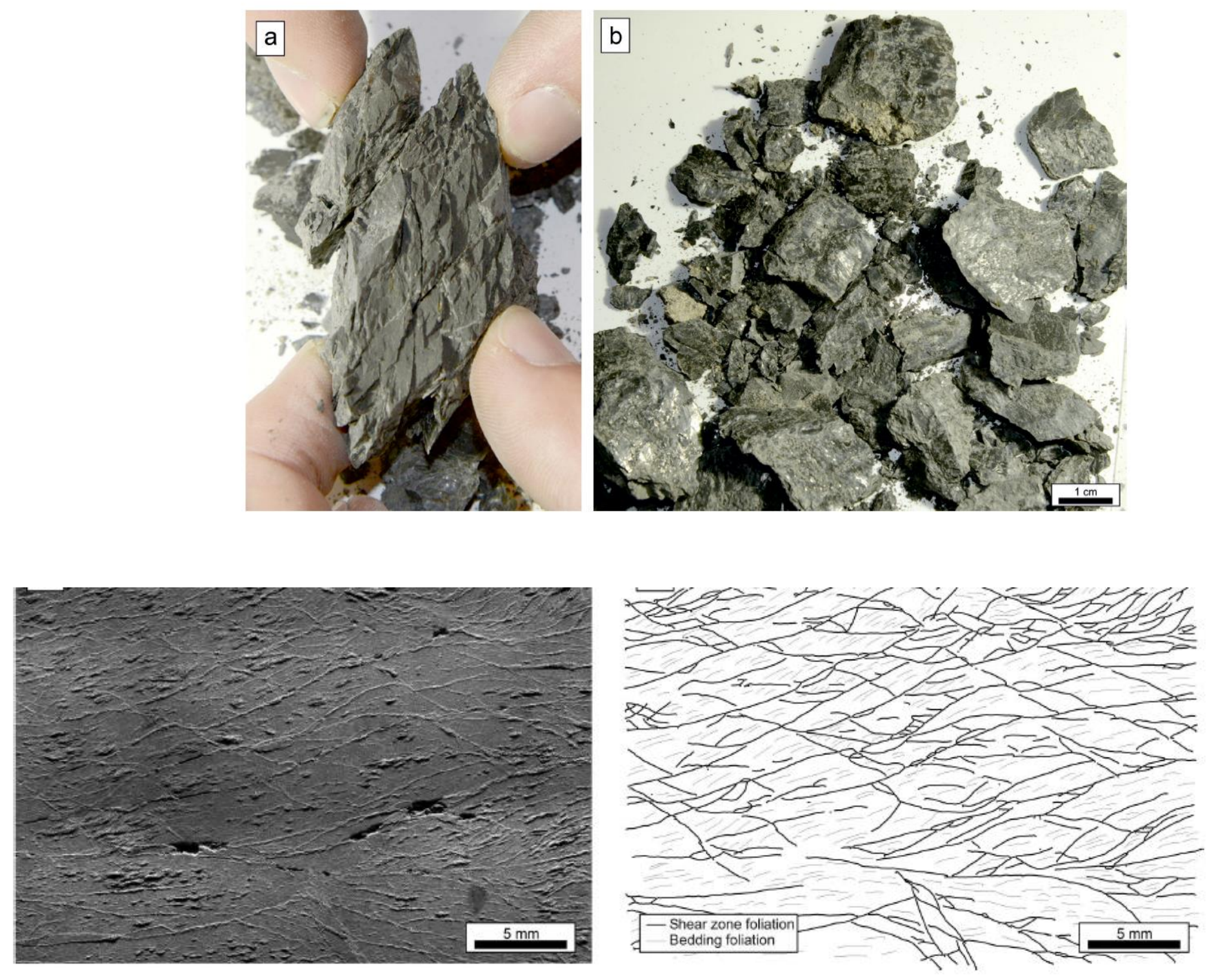

Friction based
Rate and State model

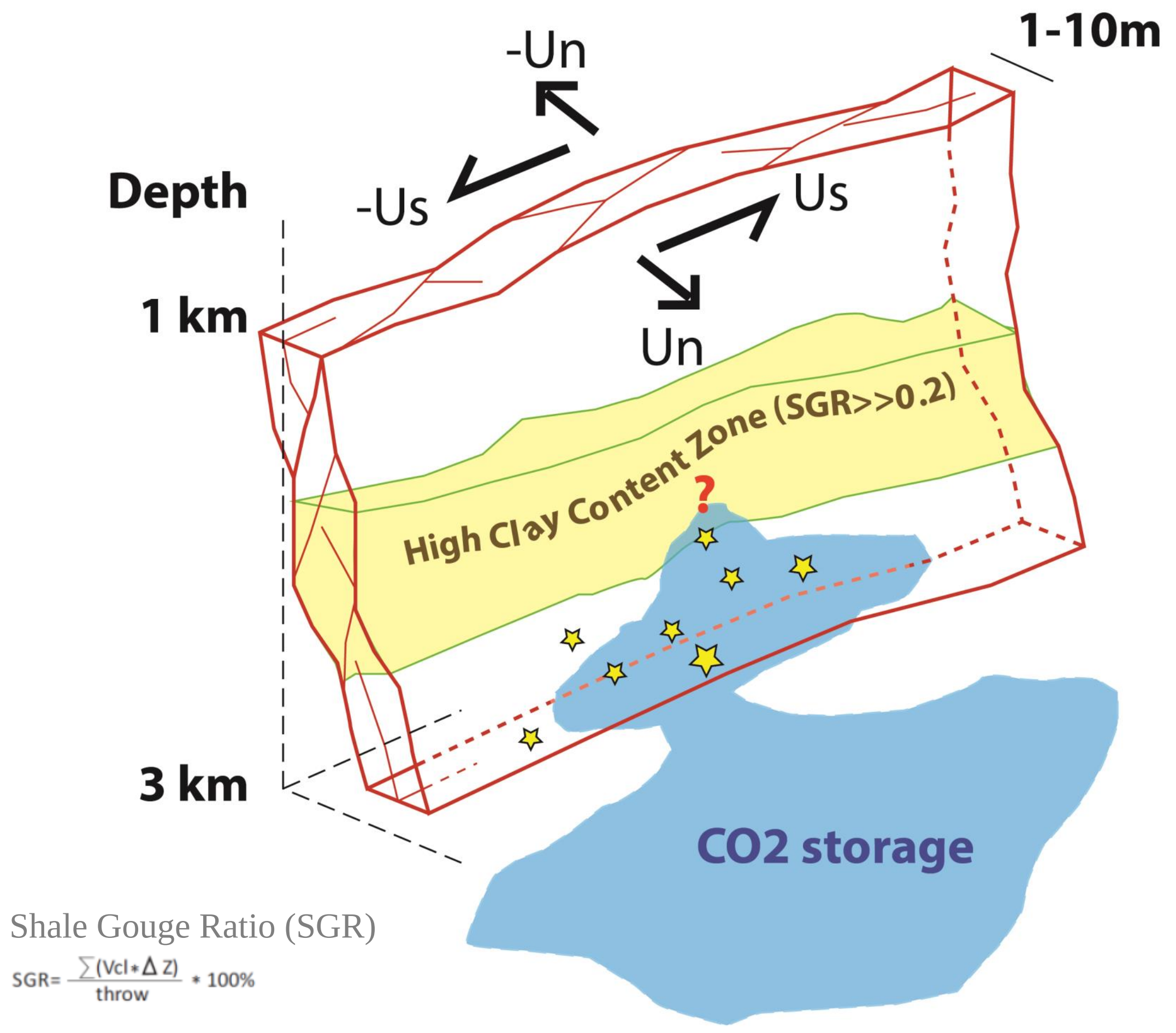
σ_n = normal stress
τ = shear stress
Pf = fluid pressure
V = slip velocity
V_{lp} = load point velocity
k_s = spring stiffness
L = fault half--thickness
m = fault porosity
kh = fault permeability


Plastic based
Cam-Clay model

Cam-Clay model	Rate and State model
Block (CC model) Thickness (m) : 5000 m Density (kg/m³) : 2260 Young Modulus (MPa) : 10000 Poisson ratio : 0.25 Far field velocity (m/yr): (Vlps,Vlpn)=(0.007,-0.002)	Block (RST model) Shear Modulus (MPa) : 4000 Poisson ratio : 0.25 Far field velocity (m/yr): (Vlp)=(0.007)
Fault (CC model) Half Thickness (m) : 5 m Porosity: 0.1 Criterion coefficient (M): 1.2 Pre-consolidation stress (MPa): σ'_{m0} = 60 Yield law coefficient: 25	Fault (RST model) Half Thickness (m) : 5 m Porosity: 0.1 Steady state friction : 0.6 Rate and state constants: a = 0.0012 b = 0.0018 Critical slip distance (m): 0.001 Dilatancy coefficient 10^{-4}
Fault fluid (CC and RST models) Compressibility (MPa-1) : 0.008 Initial fault pressure (MPa): 14.7 Initial permeability (m2): 10-16 External pressure (MPa): 20	
Initial effective stress Shear stress (MPa): 6 Effective Normal stress (MPa): 9	

Example of shale fault ductile material
(“scaly clay”) (courtesy of C.Nussbaum)

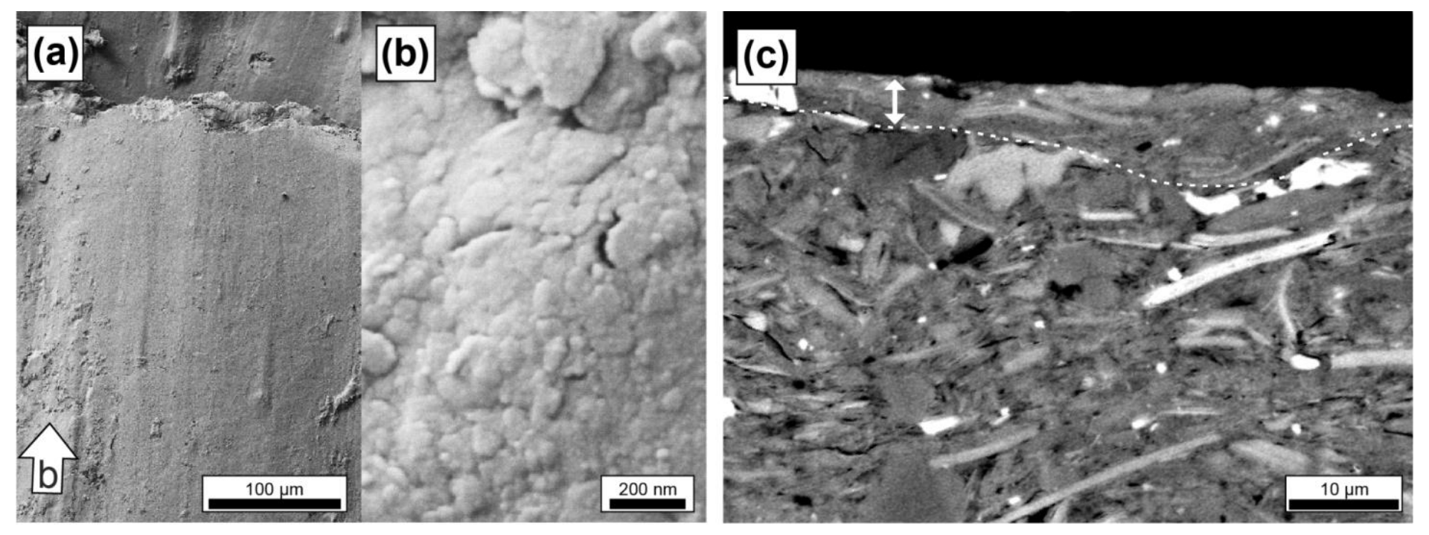




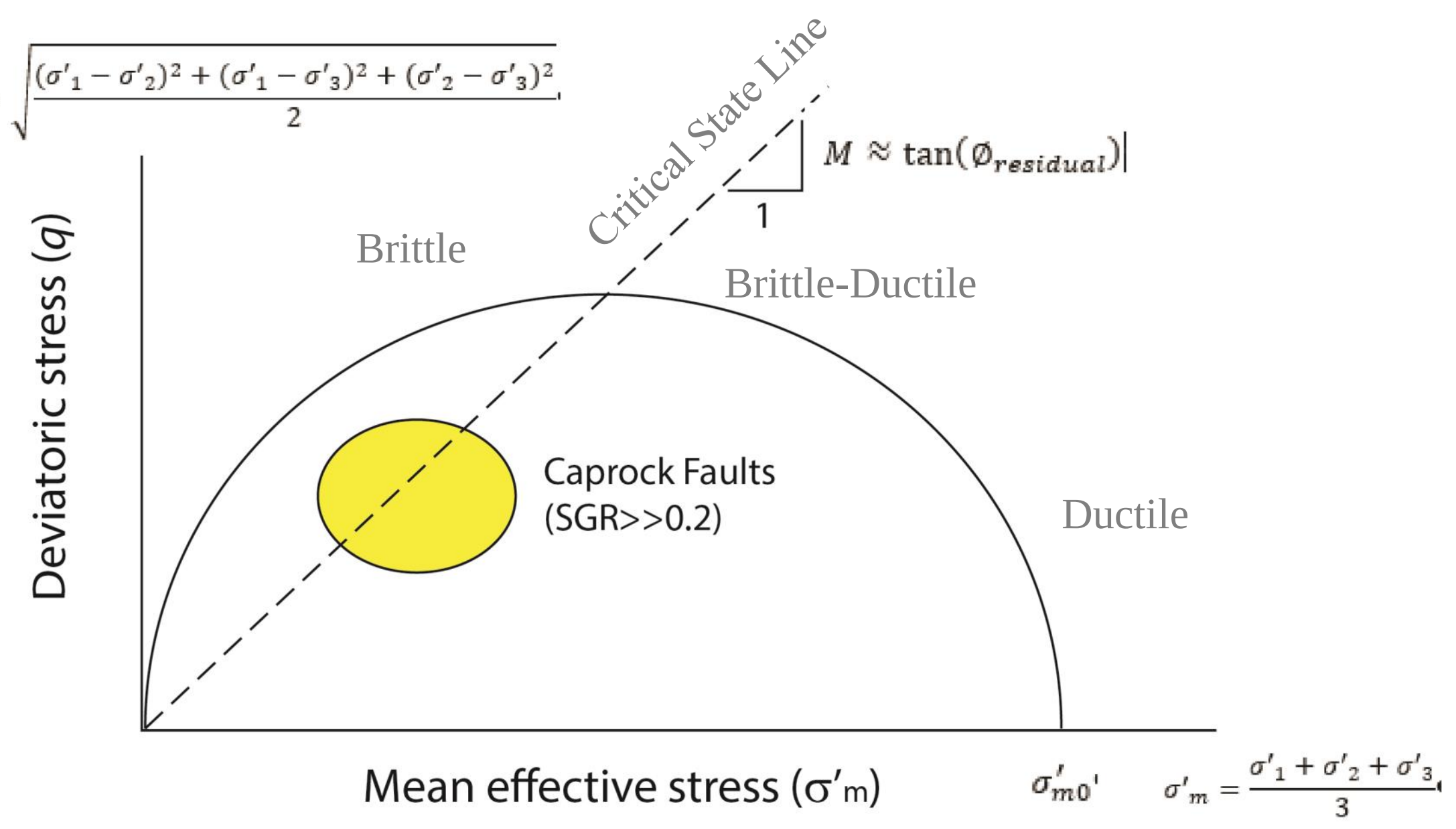
Shale Gouge Ratio (SGR)

$$SGR = \frac{\sum(Vcl * \Delta Z)}{throw} * 100\%$$

Brittle secondary fault in shale (courtesy of C.Nussbaum)

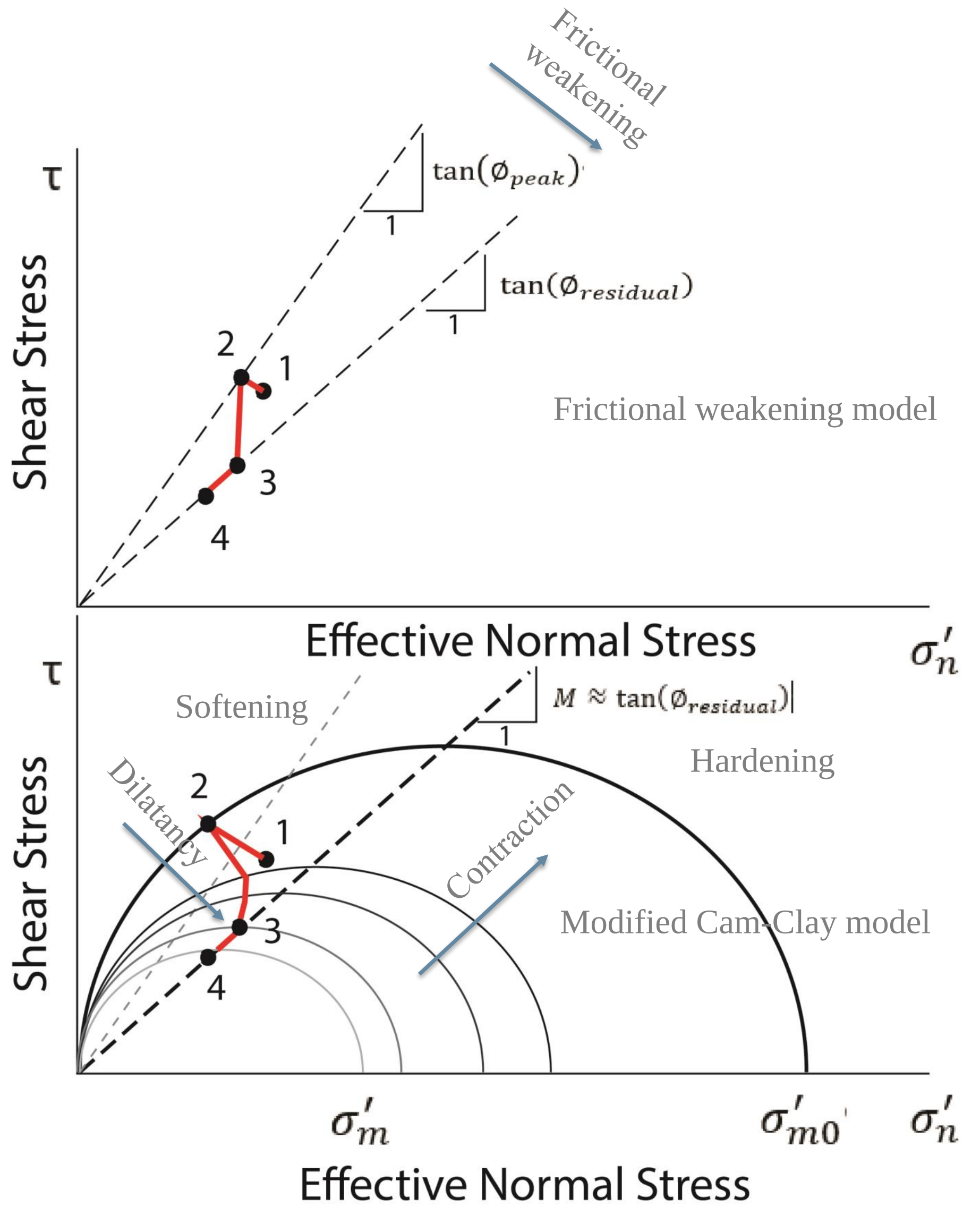


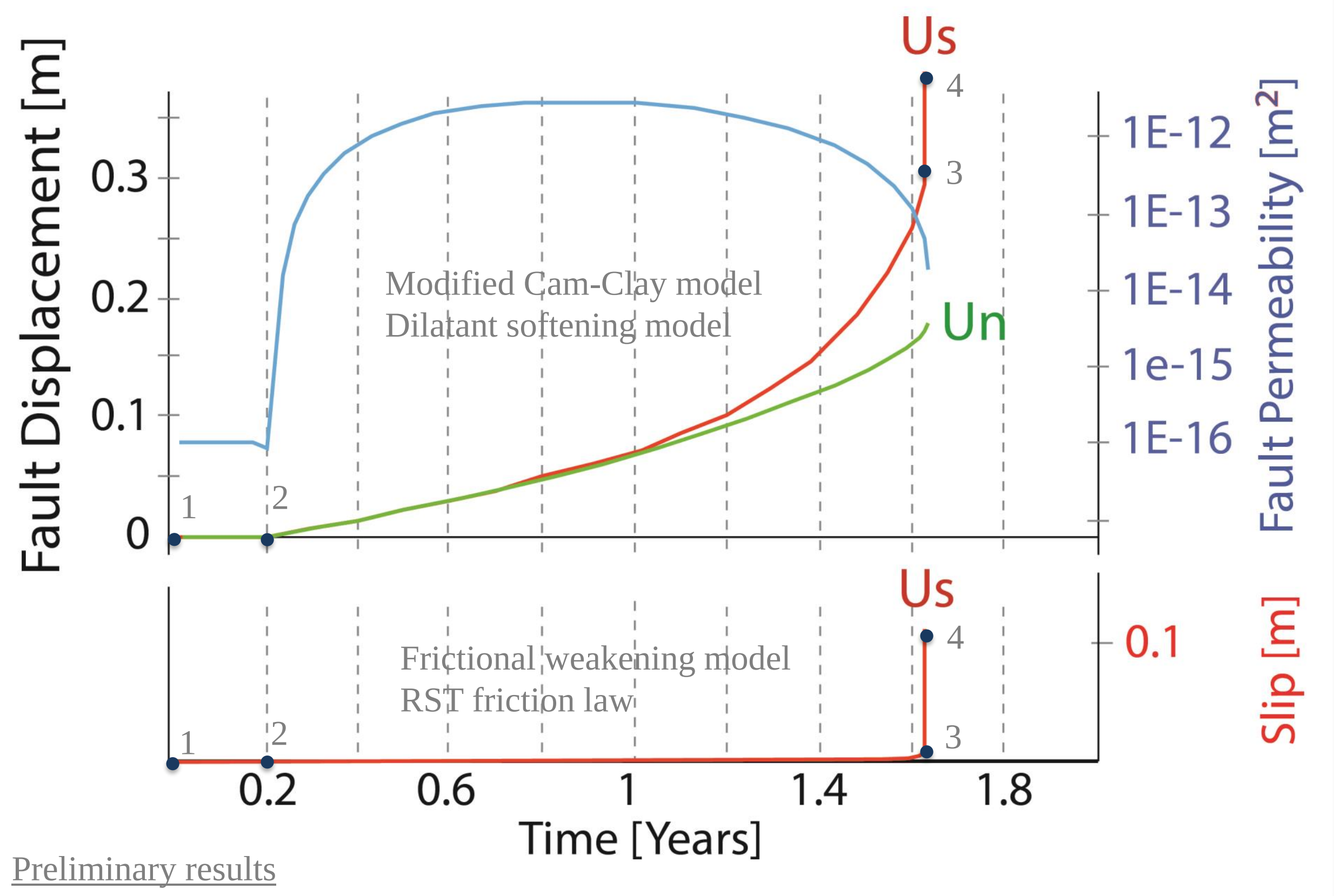
$$q = \sqrt{\frac{(\sigma'_1-\sigma'_2)^2+(\sigma'_1-\sigma'_3)^2+(\sigma'_2-\sigma'_3)^2}{2}}$$



$$\sigma'_m = \frac{\sigma'_1+\sigma'_2+\sigma'_3}{3}$$

Preliminary results: Estimation of a caprock fault activation and leakage potential at 1.5km depth





Preliminary results
- RST frictional and CC models allow estimating a consistent fault slip acceleration date and amplitude (period 3-4 of plastic instability, 15cm slip, 30-40cm/s)
- RST underestimates the preceding slow slip period and the associated fault permeability increase (period 2-3 of plastic stability, 30cm slip with CC and 8mm slip with RST)
- CC is better considering the effects of fault bulk plastic deformation on slip and leakage

Next steps:
- Develop a 3D fault leakage model
- Develop an interface to help end-users define model input parameters from a bibliographic catalogue
- Compare ROM with advanced fully coupled HM models 3DEC and TOUGH-FLAC3D

Some Bibliographic references used to make this work…

Segall and Rice (1995), Samuelson et al. (2011); Maury et al. (2020); Piau et al. (2020); Noel et al. (2021); Eyre et al. (2019); Ingram and Urai (1999); Donze et al. (2020); Cappa et al. (2022); Jeanne et al. (2018), Henry et al. (2019); Brantut et al. (2008); Gutierrez et al. (2000);…