Modeling Fault Reactivation and Induced Seismicity during Underground CO2 Injection

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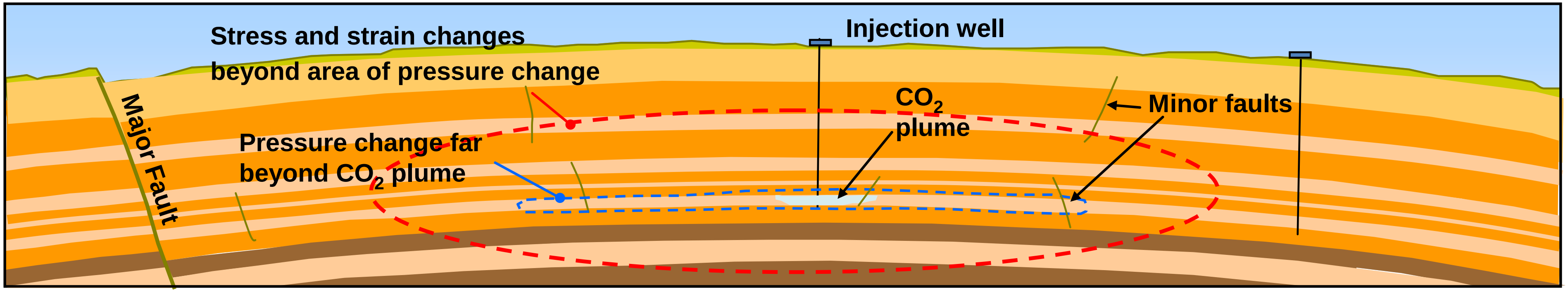


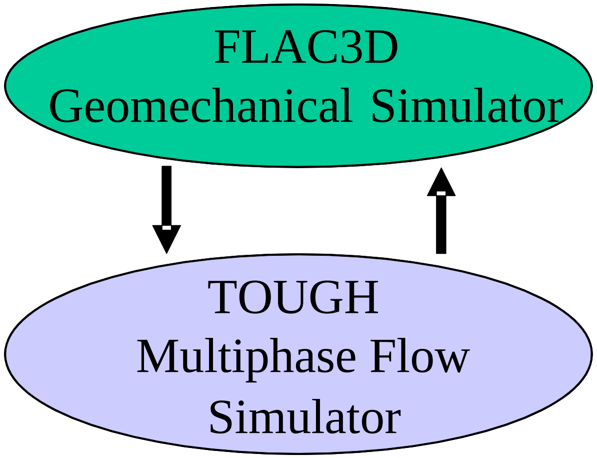
CO_2 storage in deep sedimentary formations

Outline of Presentation

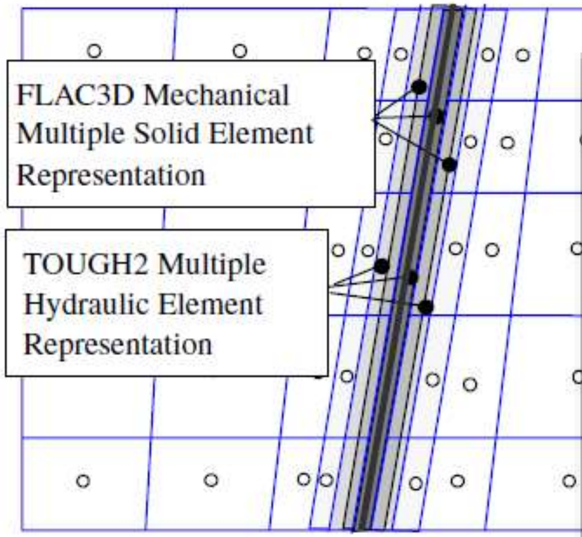
- Introduction
- Modeling approach
- CO_2 injection and fault activation
  - Potential magnitudes?
  - Potential leakage?
- Deep fracture/fault responses at In Salah
- Concluding remarks

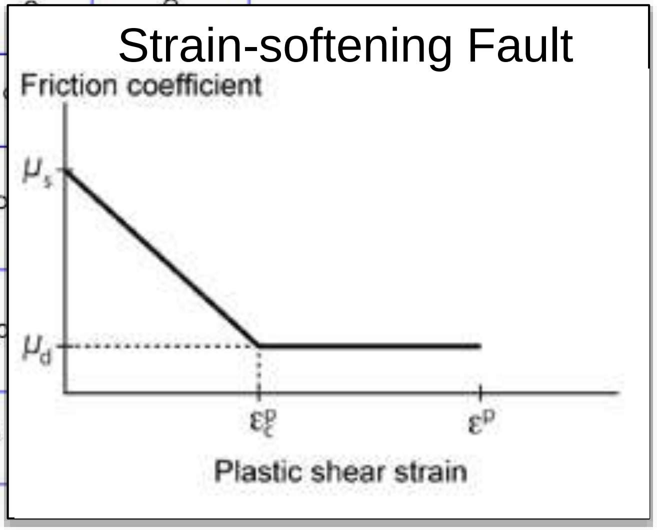
Modeling Fault Reactivation and Seismicity

TOUGH-FLAC Simulator

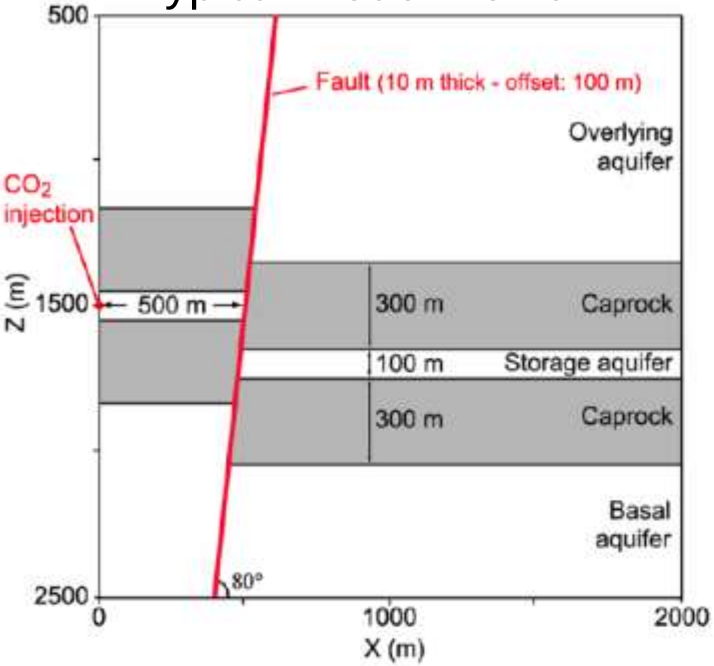


Typical Fault Discretization



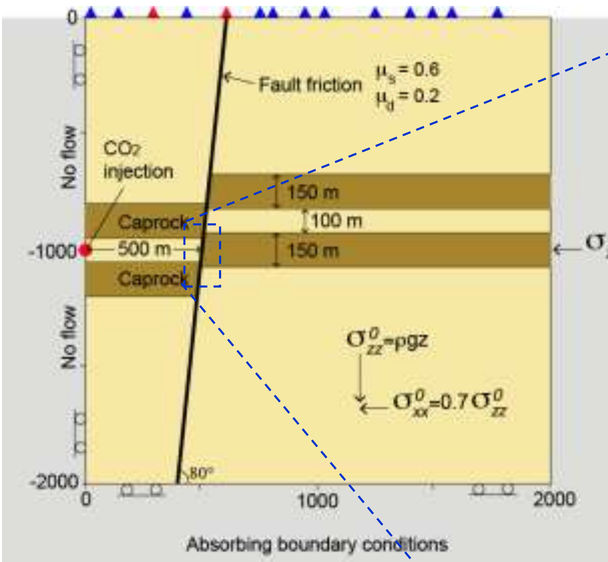


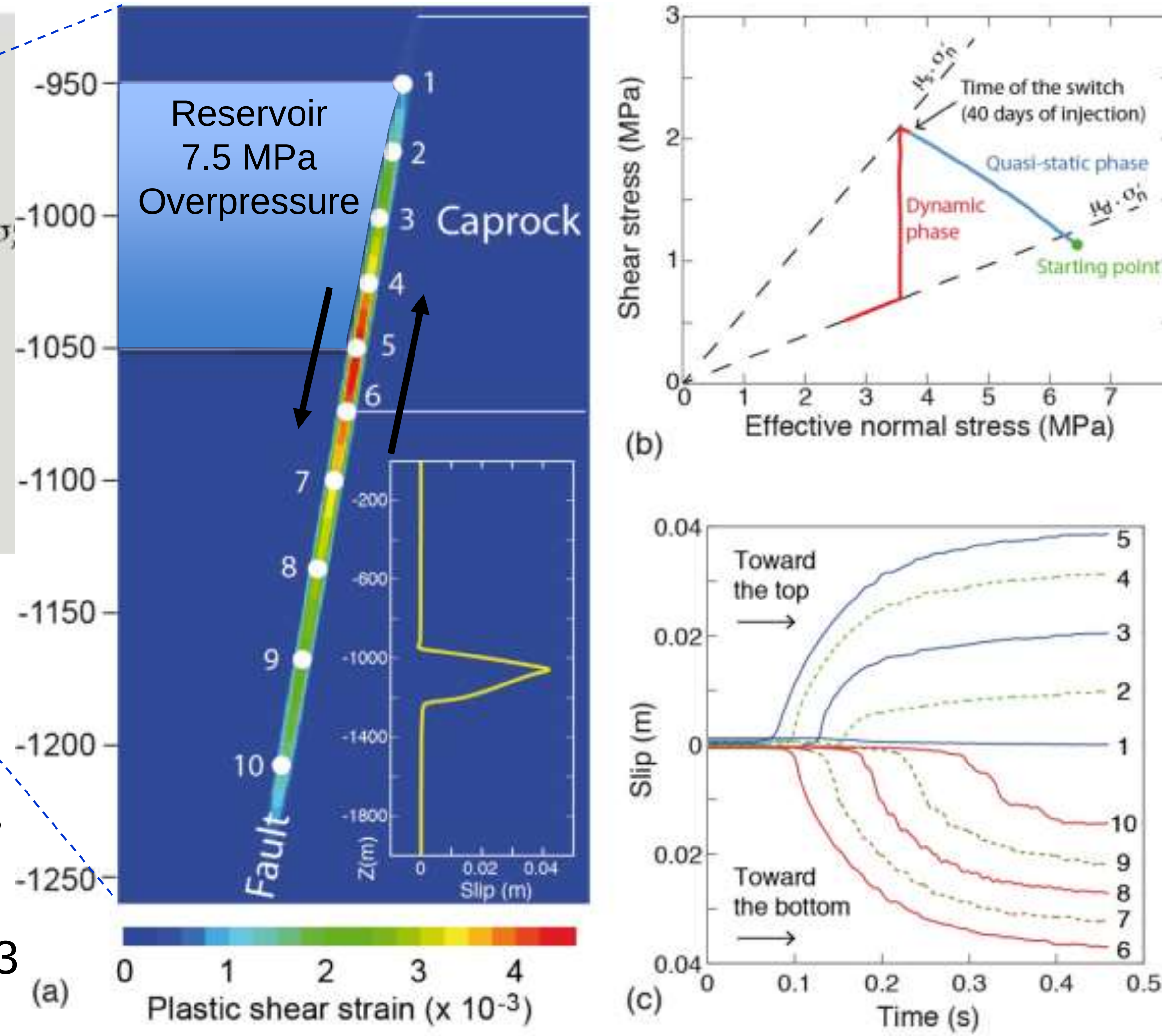
Typical Model Domain



- Anisotropic plasticity model allowing shear (Coulomb) failure along the fault plane
- Shear-induce fault permeability change
- Strain-softening plasticity to represent slip-weakening fault behavior (sudden slip)
- Seismic moment and moment magnitude calculated from Kanamori et al (e.g. $M_0 = \mu Ad$)

Simulated CO2 Injection and Fault Activation

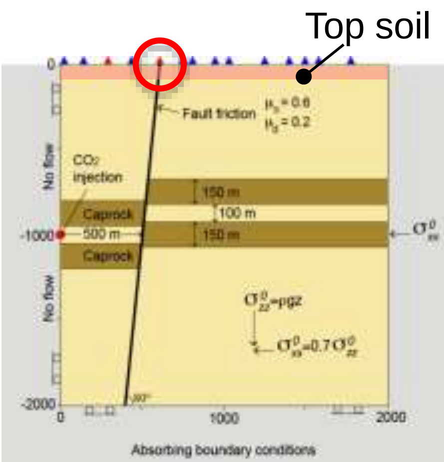


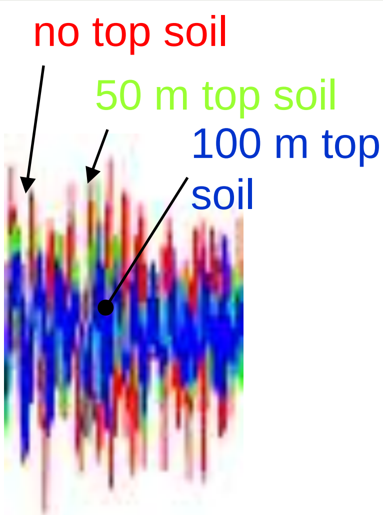


- Reactivation at about 10 MPa overpressure
- 4 cm fault slip over 0.4 seconds, peak slip 0.6 m/s
- 290 m fault rupture corresponding to M_w = 2.53

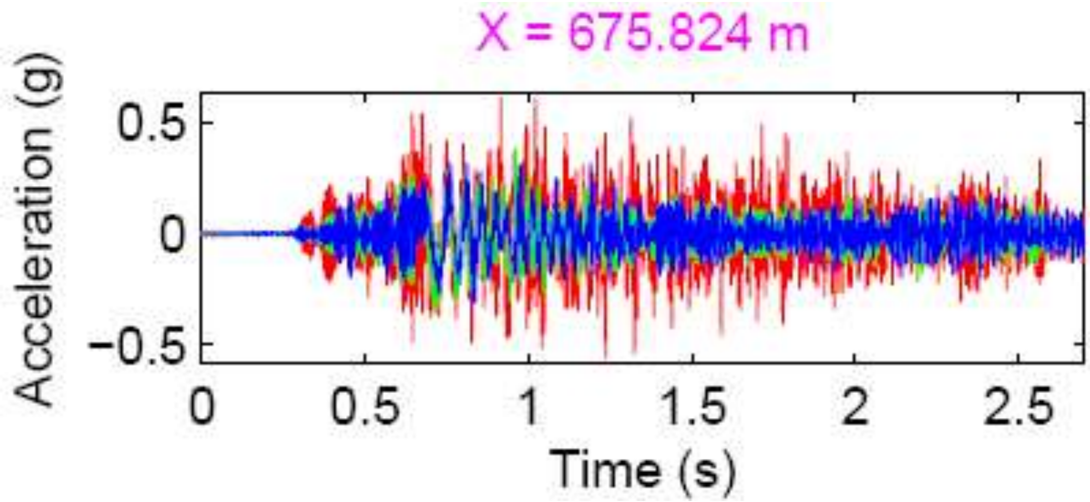
(Cappa and Rutqvist, GJI, 2012)

Ground Surface Motion at Top of the Fault

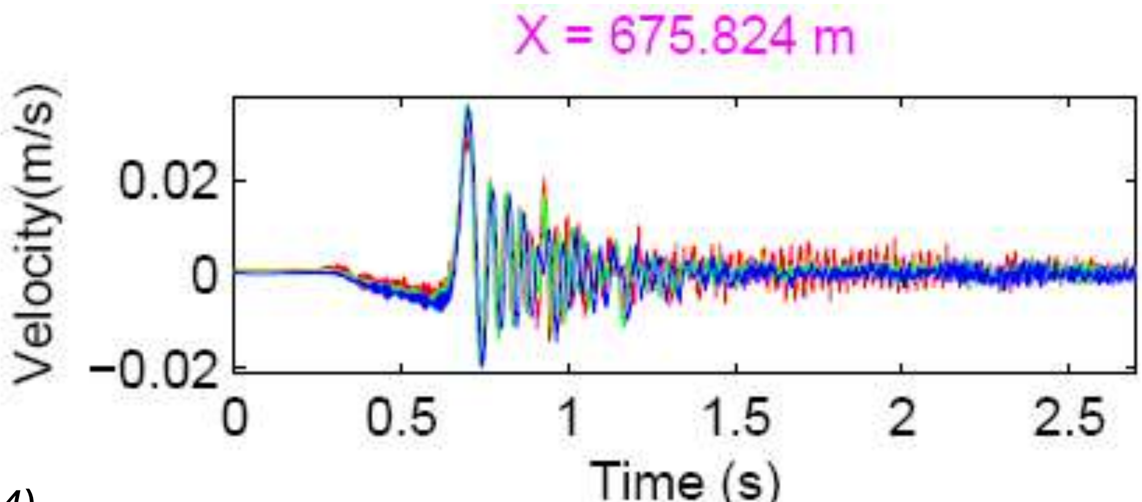




(*Rutqvist et al., IJGGC, 2014*)



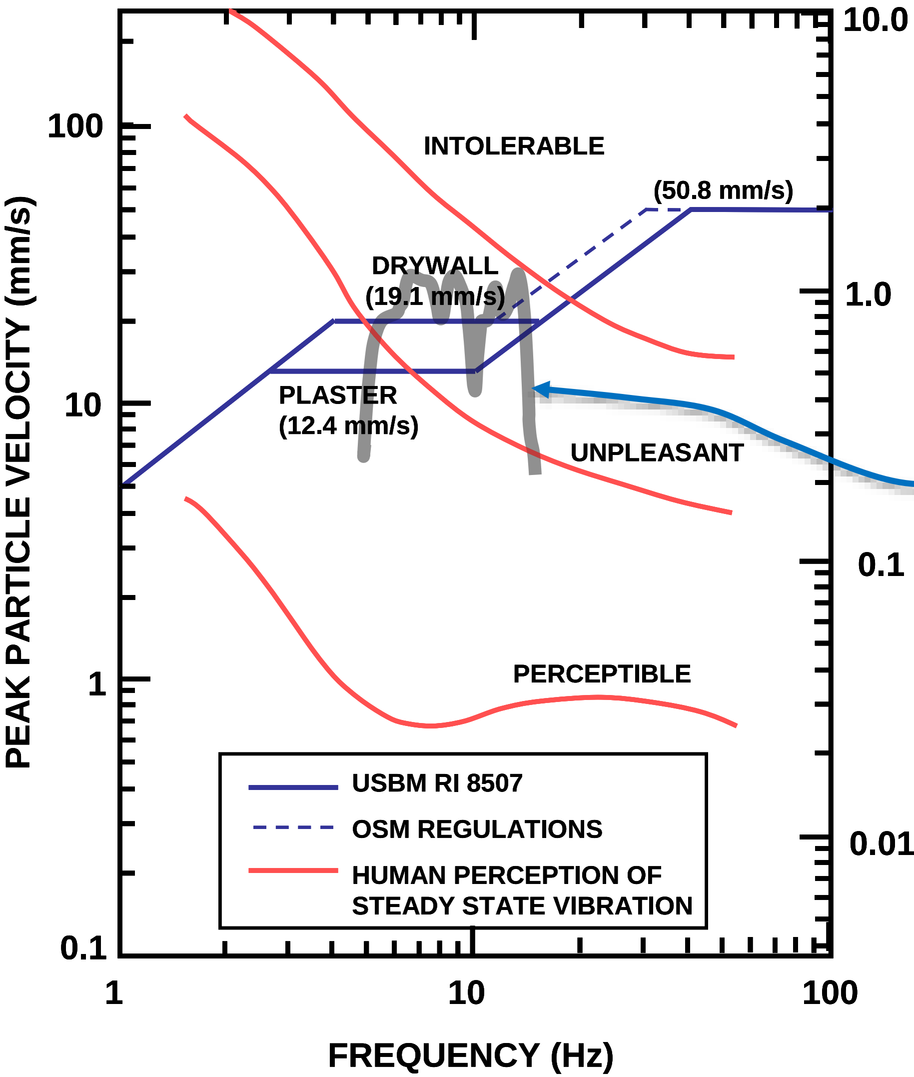
- PGA 0.6g at 30-40 Hz
- Damping of acceleration for thicker soil

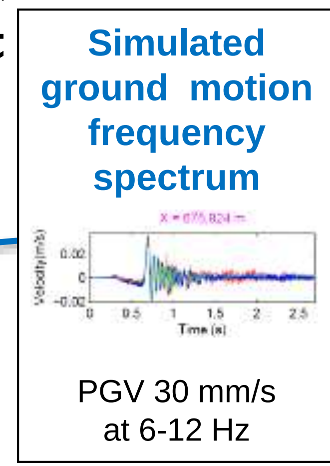


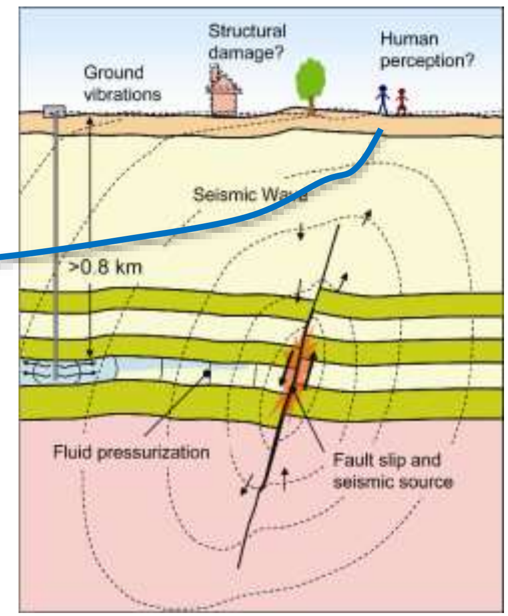
- PGV 30 mm/s at 6-12 Hz
- PGV for one jolt at a lower frequency

Building Damage and Human Perception

- USBM ground vibration criteria for building damage and human-perception limits for vibration





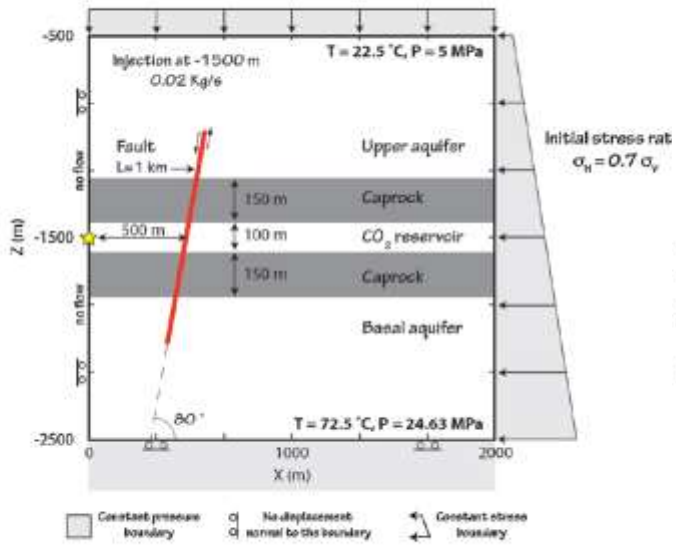


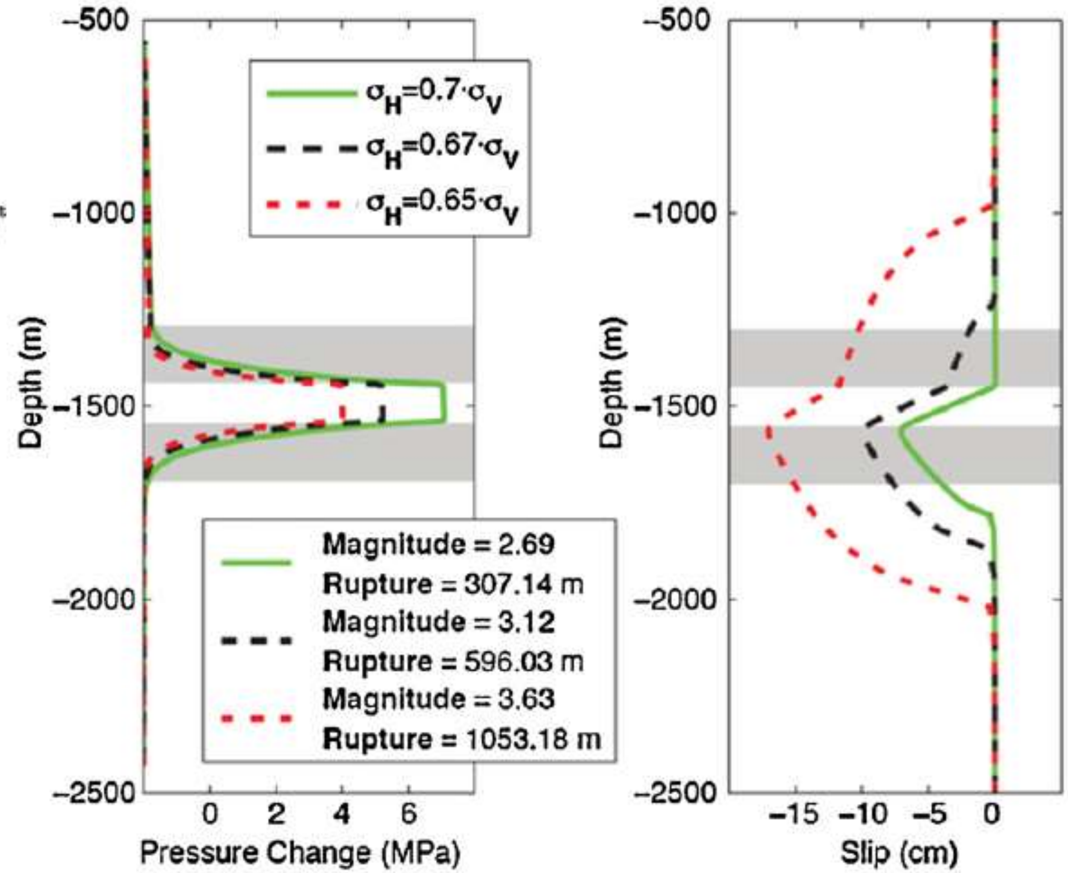
- In this example vibrations could cause cosmetic building damage and clearly felt by humans

Rutqvist et al 2014 (Int. J Greenhouse Gas Control)

Reactivation of a Minor Fault

Small initial shear offset (i.e. <10 m) and 1 km long: undetected?

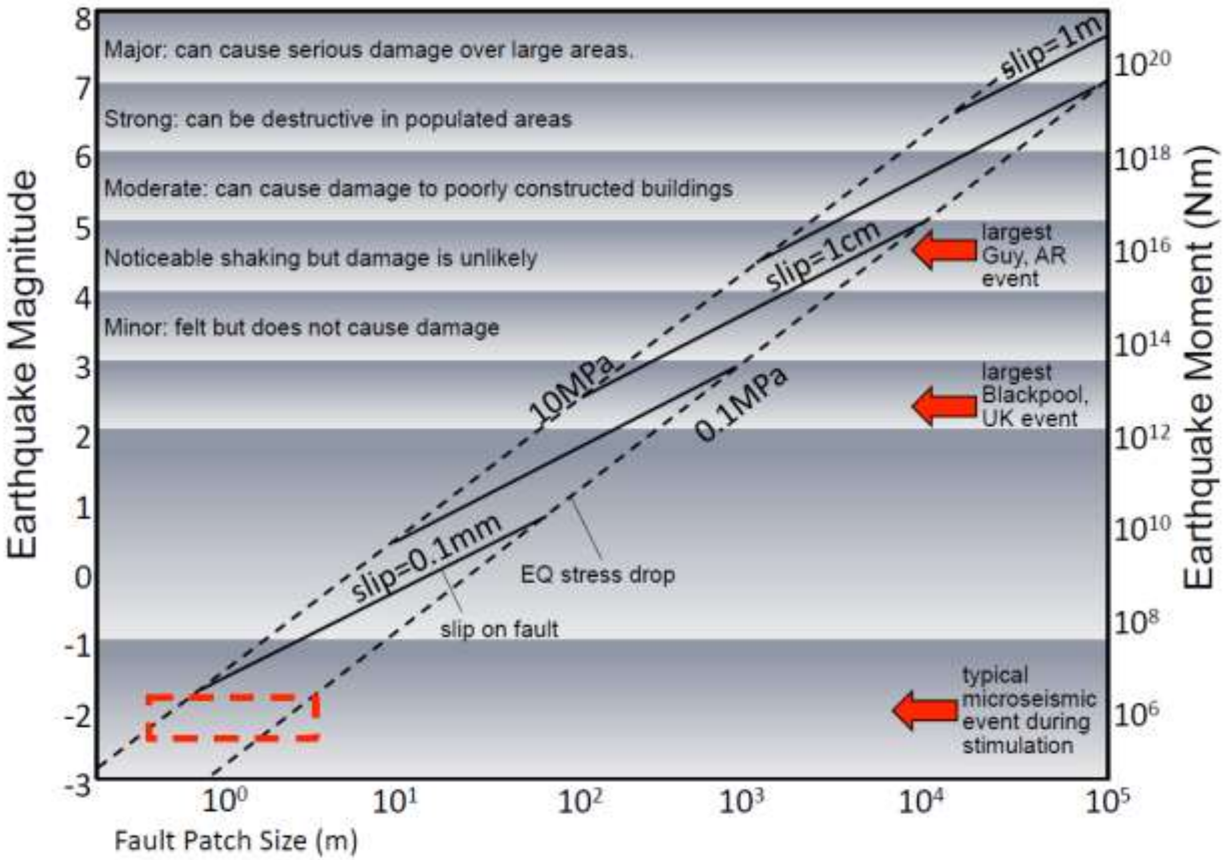




When the horizontal-to-vertical stress ratio was reduced to as low as 0.65, the shear strength drops during reactivation to a value below the prevailing shear stress and the fault could thereby rupture in a self-propagating manner (Mazzoldi et al., IJGGC 2012).

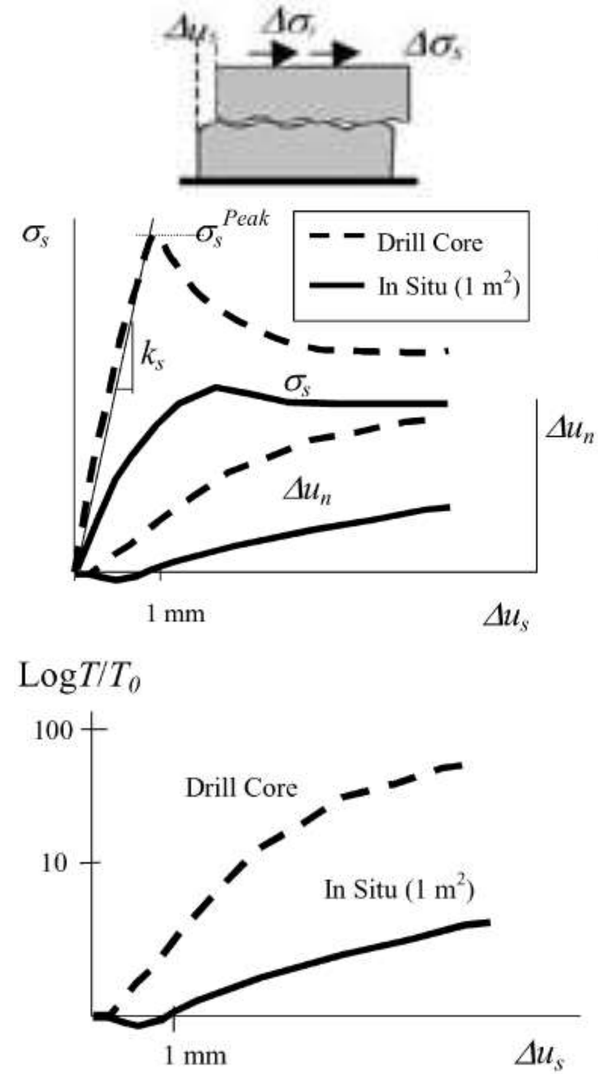
Potential Shear-Induced Permeability and Leakage

Shear slip and stress drop associated with a seismic event:



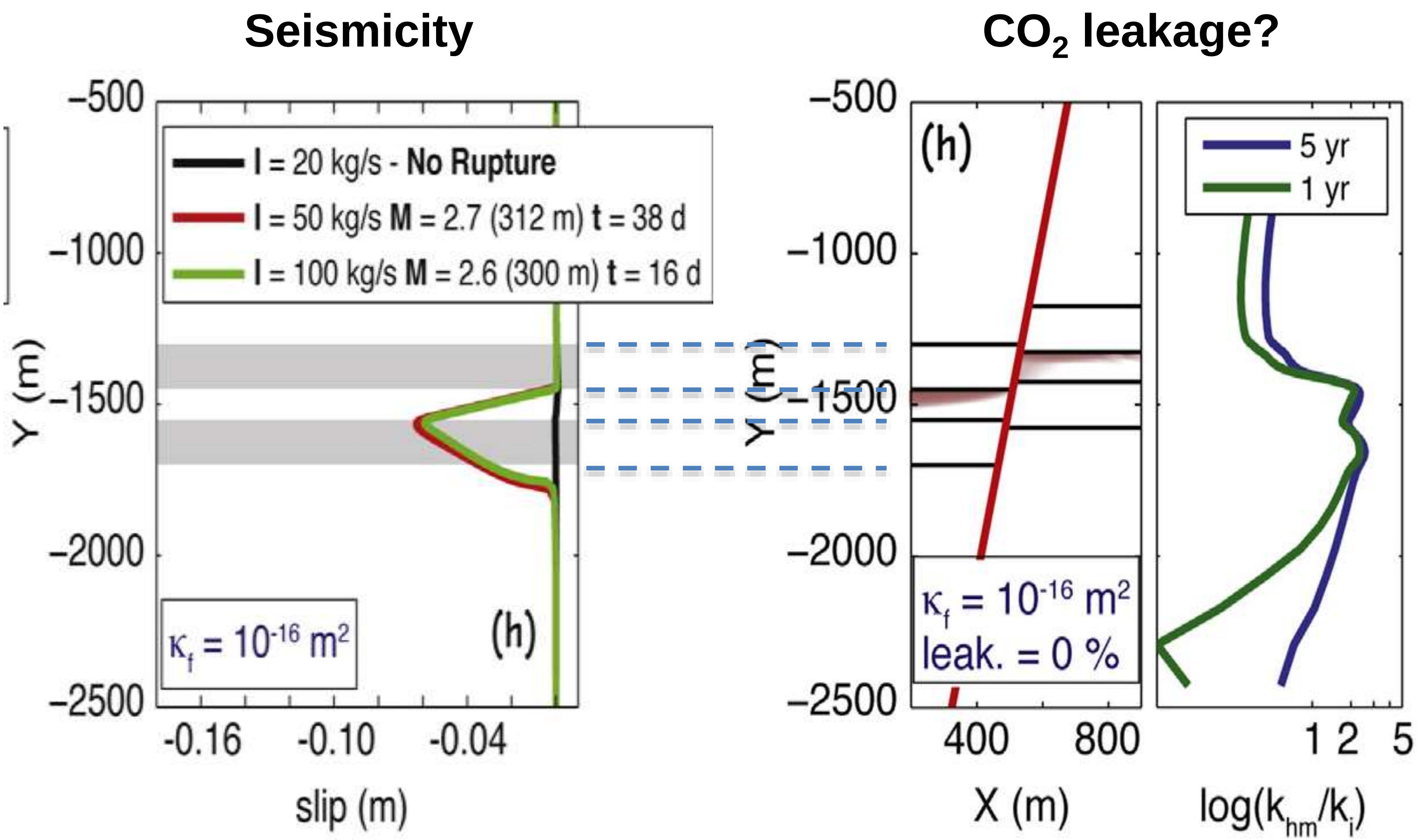
Zoback and Gorelick (2012)

Shear-induced permeability



Rutqvist and Stephansson (2003)

Seismicity and Leakage

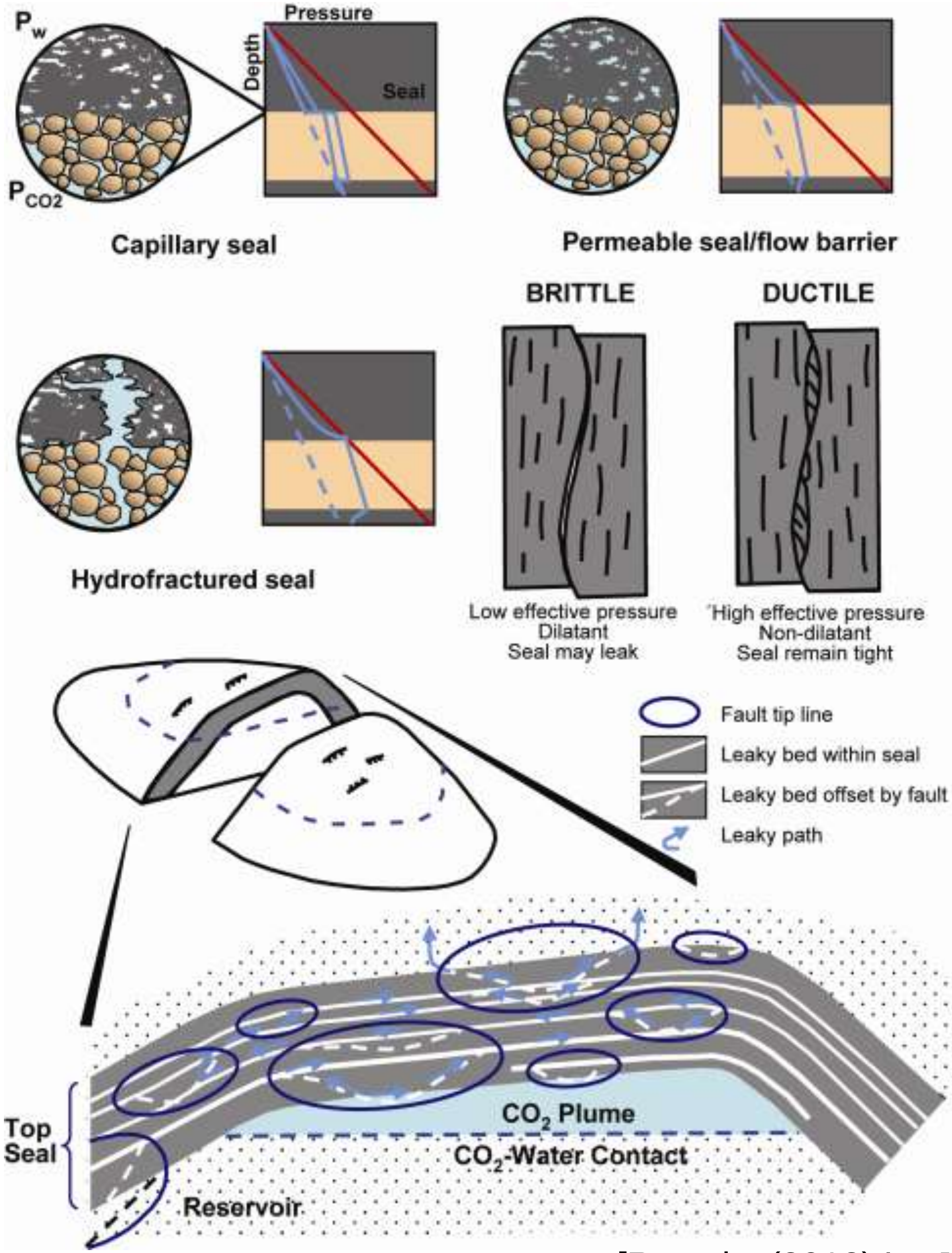


In this simulation example we simulated a seismic event that might be felt but with no upward CO_2 leakage

Rinaldi et al 2014 (nt. J Greenhouse Gas Control)

Caprock Sealing Performance: Ductile vs Brittle Properties

Top seal integrity for hydrocarbon (Ingram et al. 1997) applied to CO2 storage.



Ideally, the caprock should be plastic (ductile), in a self-sealing mechanical state, having a high capillary entry pressure and low permeability.

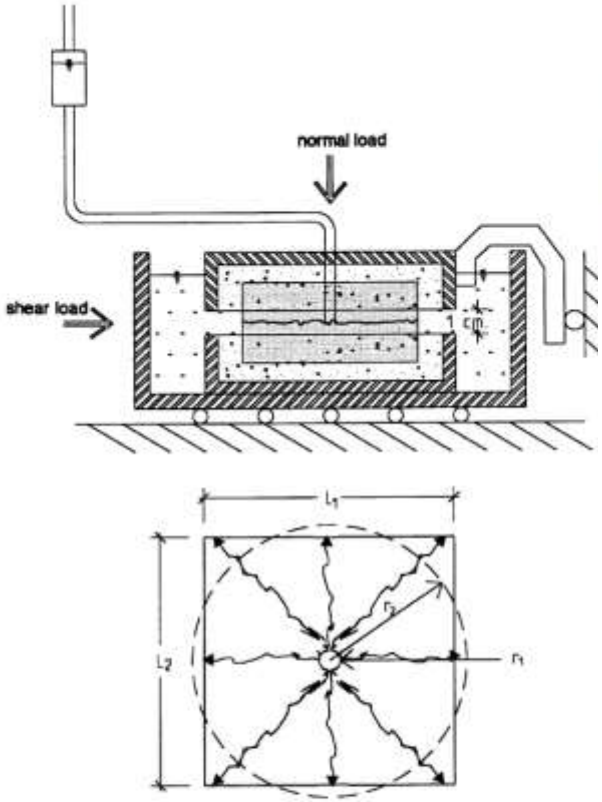
Laboratory data indicates capillary entry pressure for CO_2/brine ranging from less than 0.1 MPa up to 10 MPa $\Rightarrow$ permeability flow barrier rather than capillary seal?

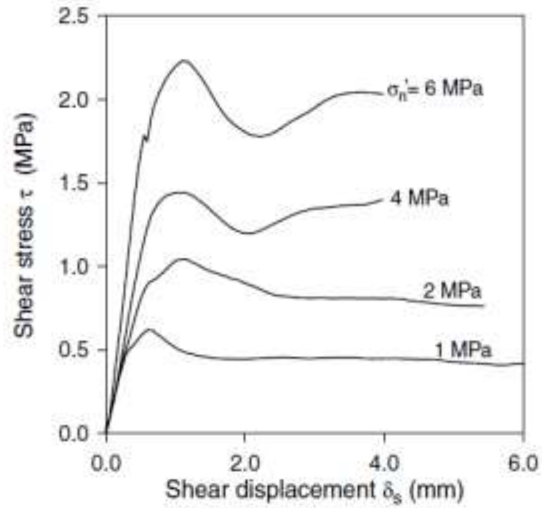
Fractures and faults important (observed from natural analogues)l

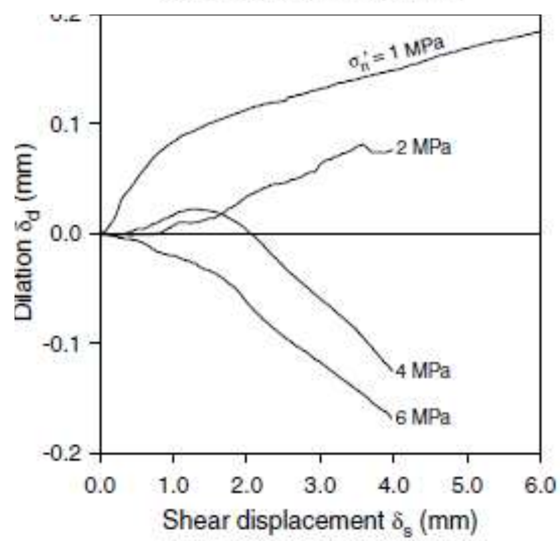
[Rutqvist (2012) Int J Geotechnical and Geological Engineering]

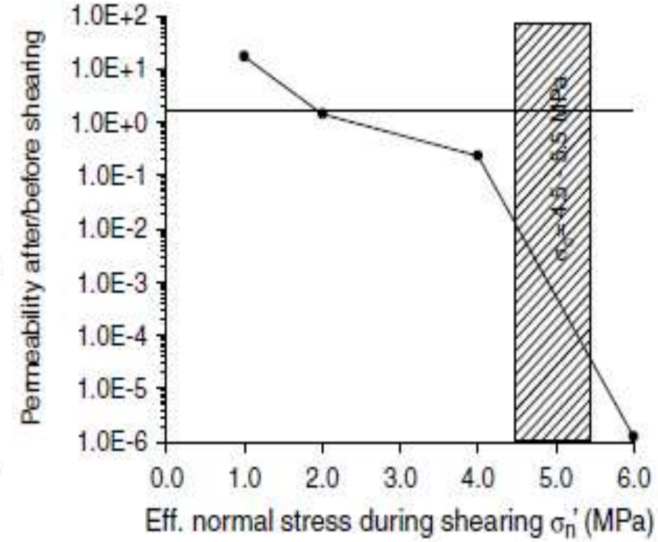
Example of Shear-Permeability Tests on Shale Fractures

Gutierrez et al. (2000)





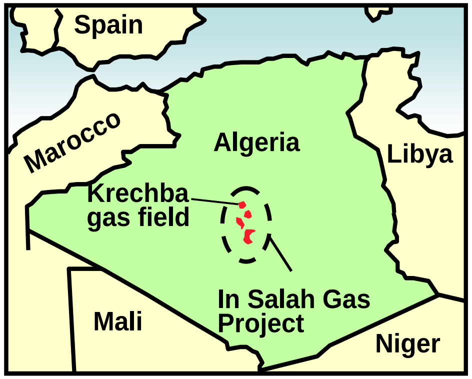


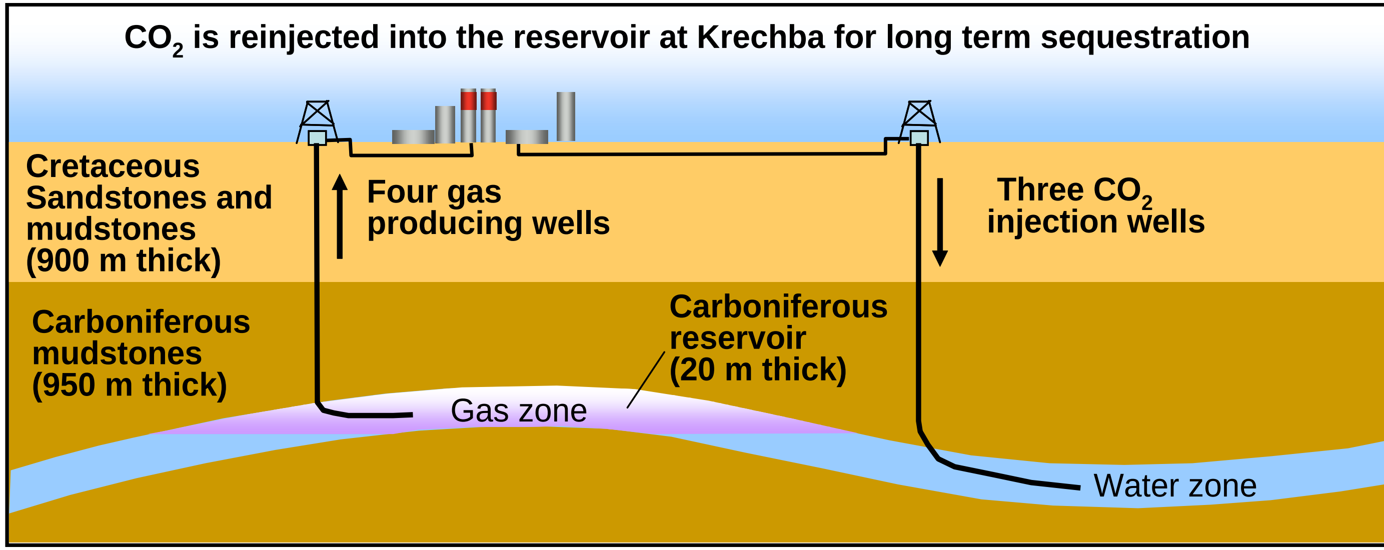


Under higher stress normal to fracture the permeability decreases with shear (at stress level higher than the uniaxial compressive rock-strength)

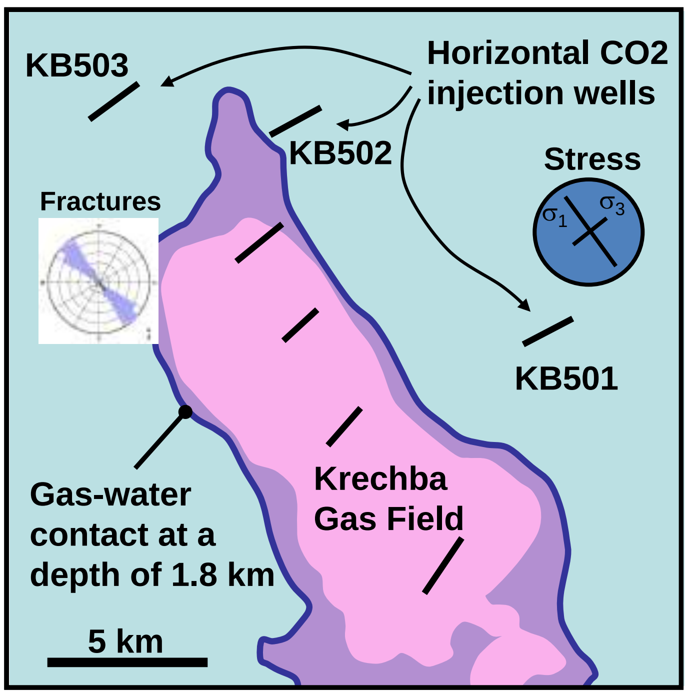
The In Salah CO_2 Storage Project, Algeria

In Salah Gas JV
(BP, Staoil, Sonatrach)



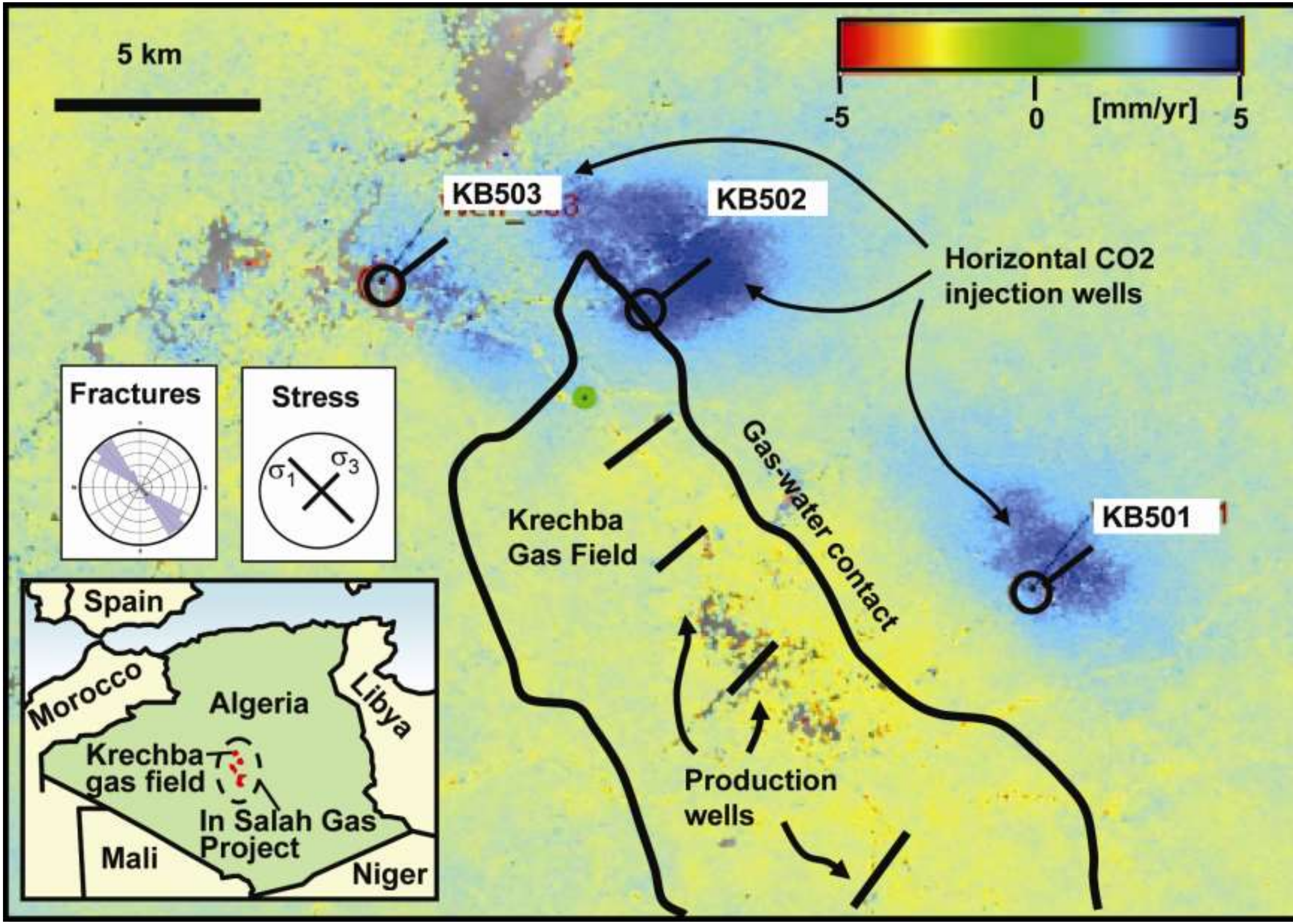


Plane view of Krechba Gas Field



- The CO_2 injected at a depth of about 1,8 to 1,9 km into a 20 m thick formation of relatively low permeability.
- Nearly one million tonnes CO_2 per year injected from 2004 to 2011 at 3 horizontal injection wells
- Bottom hole pressure limited to below the fracturing gradient $\Rightarrow$ maximum pressure increase of about 100 bar (160% of hydrostatic)
- 900 m thick caprock with multiple low permeability formations

In Salah Ground Surface uplift 2004-2007 from Satellite (InSAR)



Rutqvist et al (2010)

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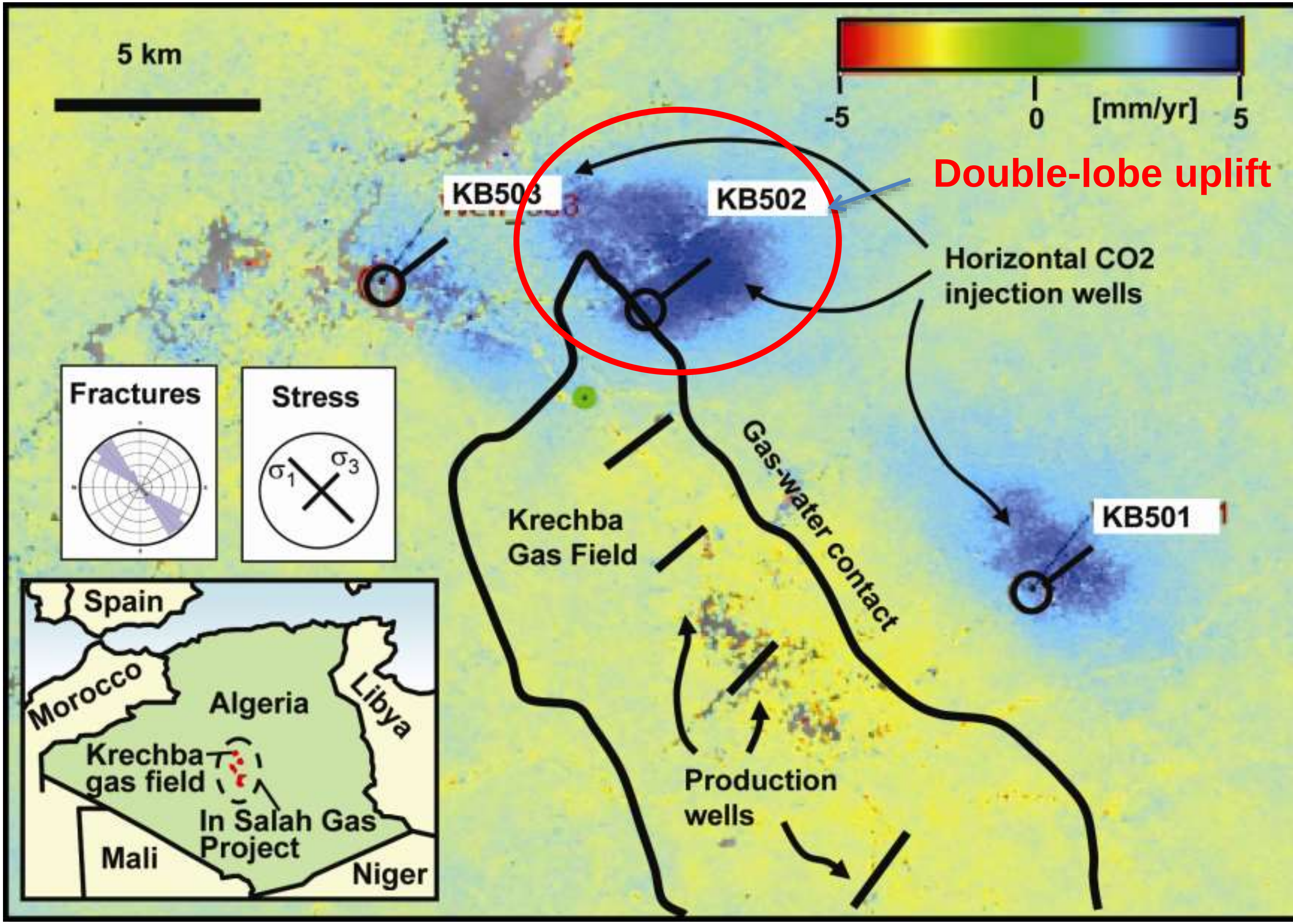
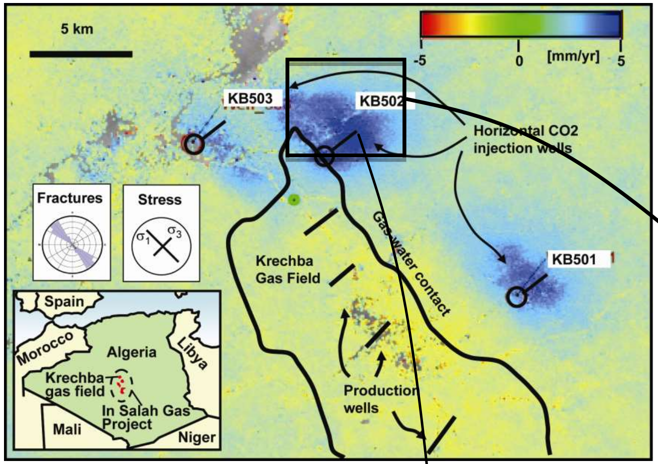
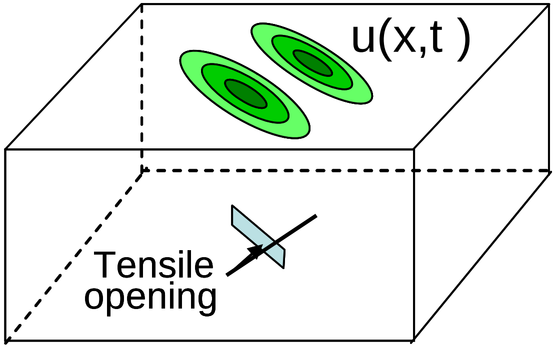


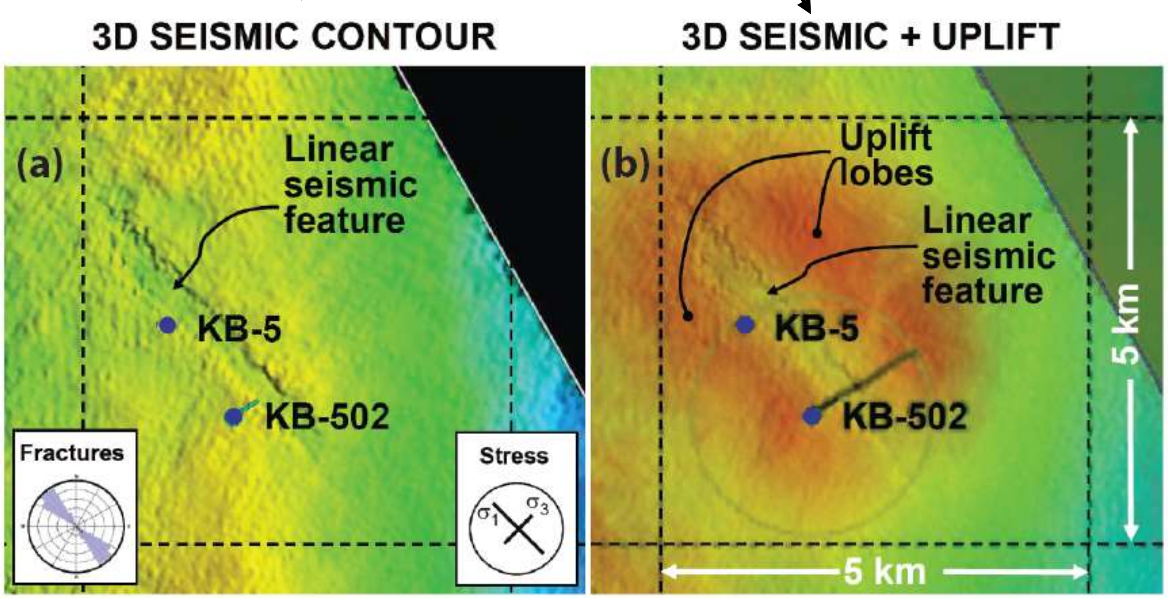
Rutqvist et al (2010)

In Salah Deep Fault or Fracture Zone Responses



- Vasco et al. (GRL, 2010) interpreted observed double-lobe (uplift) response to be caused by a tensile opening feature at the injection zone.



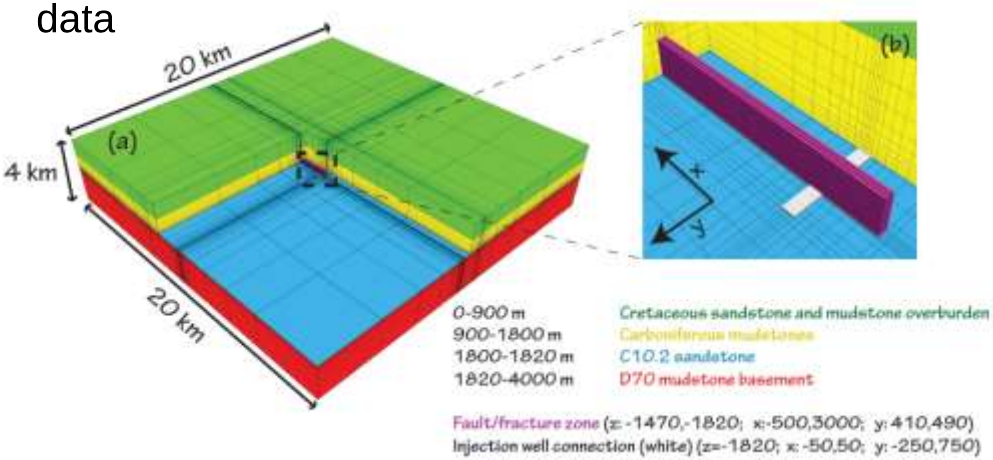


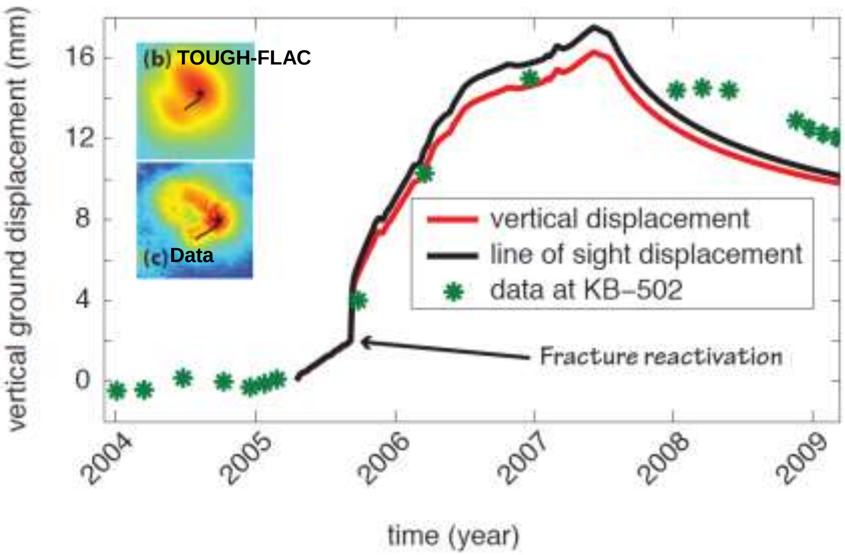
(Rutqvist, 2012)

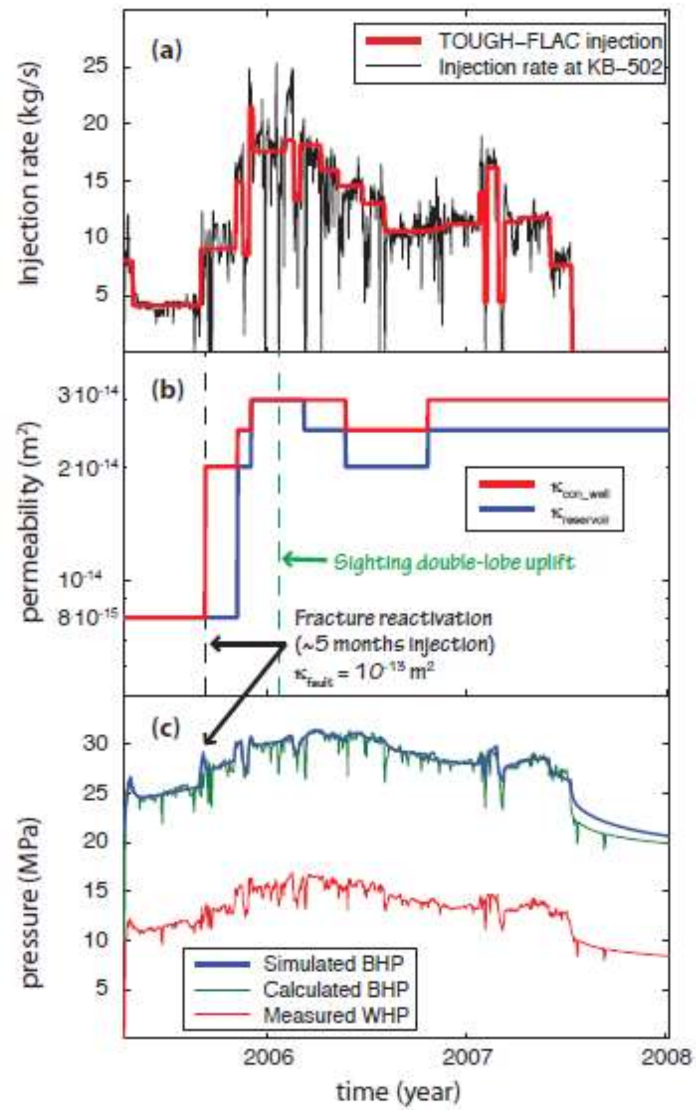
Seismic contour in caprock 150 m above injection zone and surface uplift after 3 years

In Salah Deep Fault or Fracture Zone Responses

Rinaldi, Rutqvist (2013) TOUGH-FLAC modeling with simultaneous matching of transient uplift and injection data







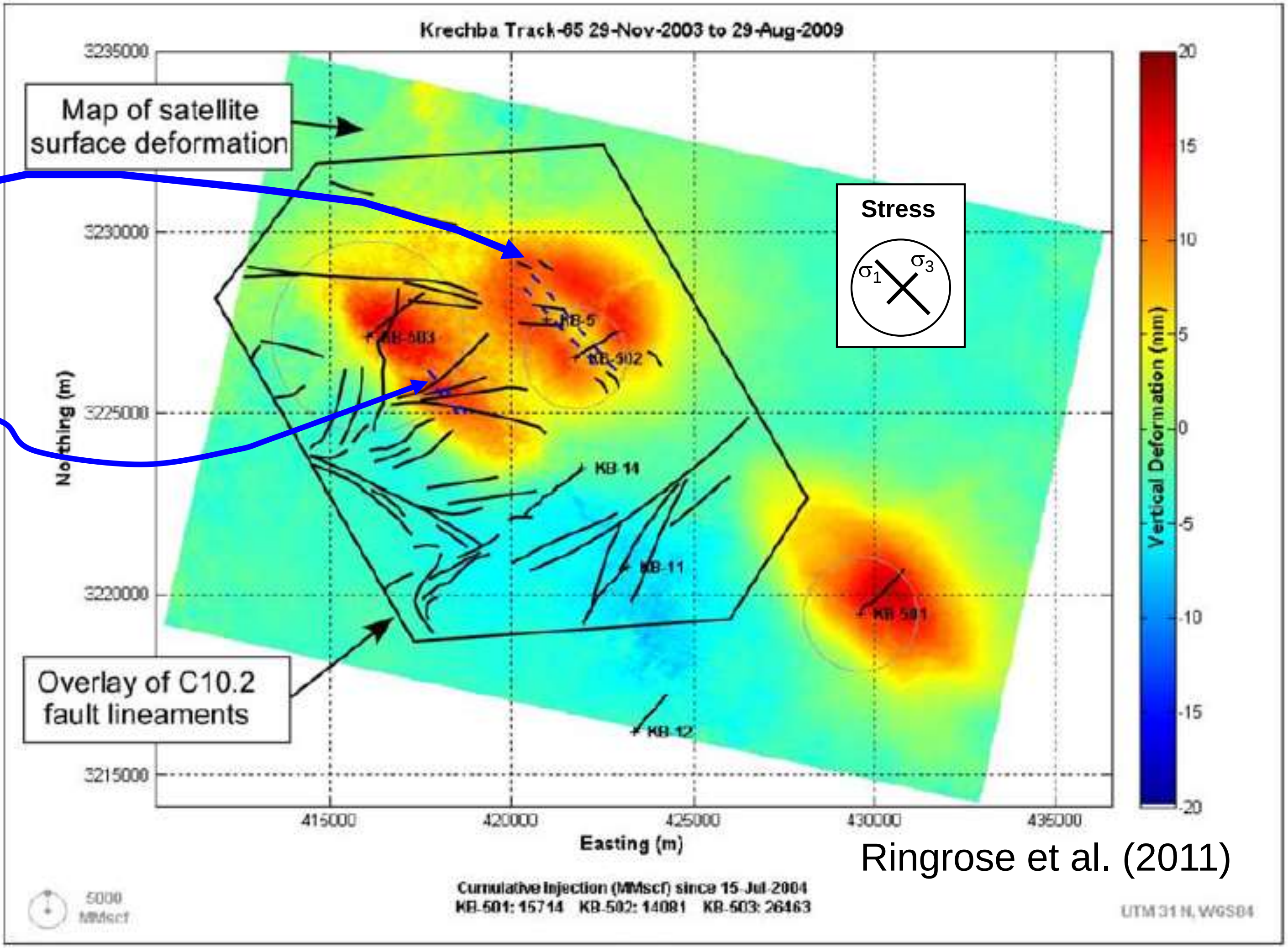
Modeling indicates that the fracture zone extends a few hundred meters up from the reservoir (contained within the 900 m thick caprock)

In Salah Deep Fault or Fracture Zone Responses

Injection pressure sufficiently high to induce deep fracture zone opening

Minor faults indicated from 3D seismic (Ringrose et al., 2011)

Theoretically close to critically stressed for shear reactivation (Morris et al., 2011)



Ringrose et al. (2011)

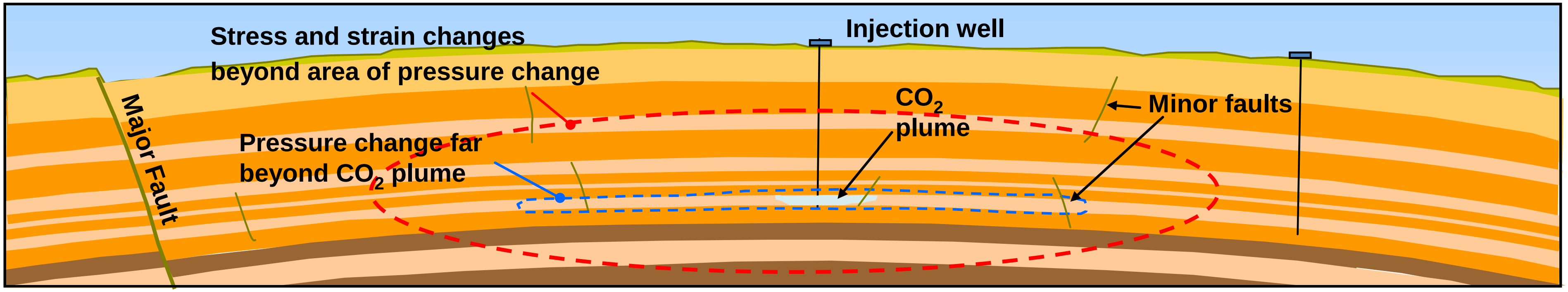
However, CO_2 injection at In Salah has not resulted in any felt seismic events or substantial strike-slip shear movements (Max magnitude 1.7, (Stork et al. 2014))

Concluding Remarks

- We used numerical modelling to induce reactivation of steeply dipping faults at a high injection pressure in an unfavourable stress regime.

- We simulated events of magnitudes < 4 that would not result in any structural damage, but could likely be felt and cause concern in the local community.

- At In Salah, injection pressure was relatively high indicating minor faults being critically stressed for reactivation, but no felt seismic event has been reported.



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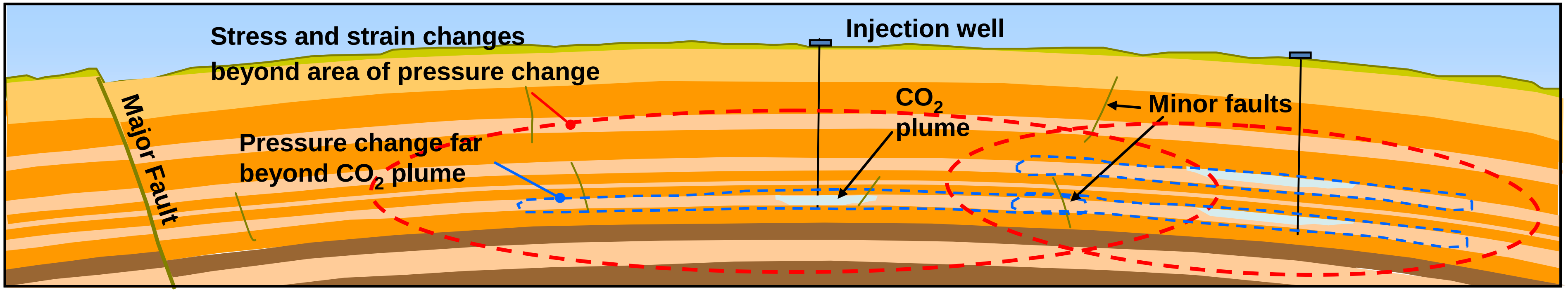
- At In Salah, injection pressure was relatively high indicating minor faults being critically stressed for reactivation, but no felt seismic event has been reported.

- At future large-scale CO2 operations (much larger than In Salah), it is the large-scale and long-term pressure buildup, associated crustal straining, and potential undetected (minor) faults that might be of greatest concern.



Thank you!

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Rutqvist J. The geomechanics of CO2 storage in deep sedimentary formations. International Journal of Geotechnical and Geological Engineering, 30, 525–551 (2012).

Rutqvist J., Cappa F., Rinaldi A.P., and Godano M. Modeling of induced seismicity and ground vibrations associated with geologic CO2 storage, and assessing their effects on surface structures and human perception. *International Journal of Greenhouse Gas Control* 24, 64–77 (2014).

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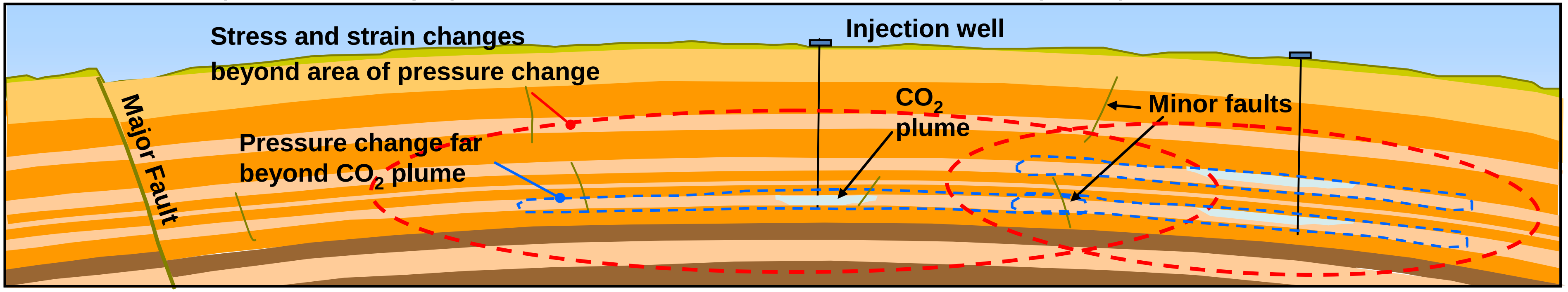
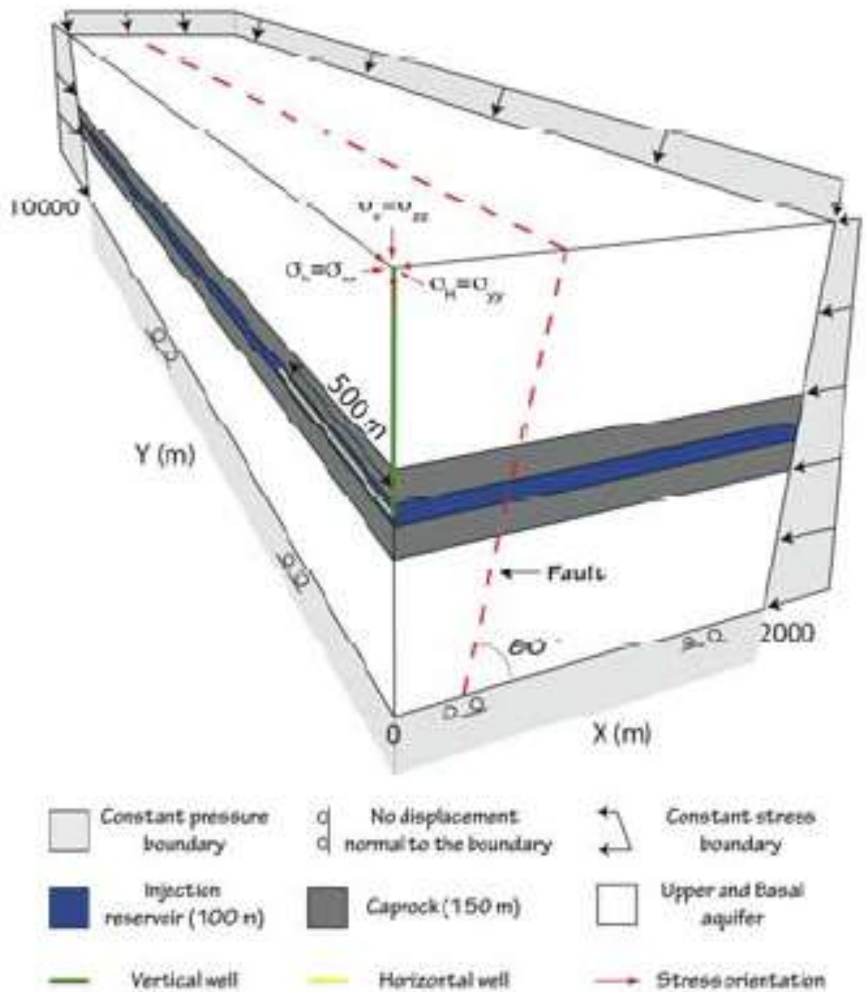
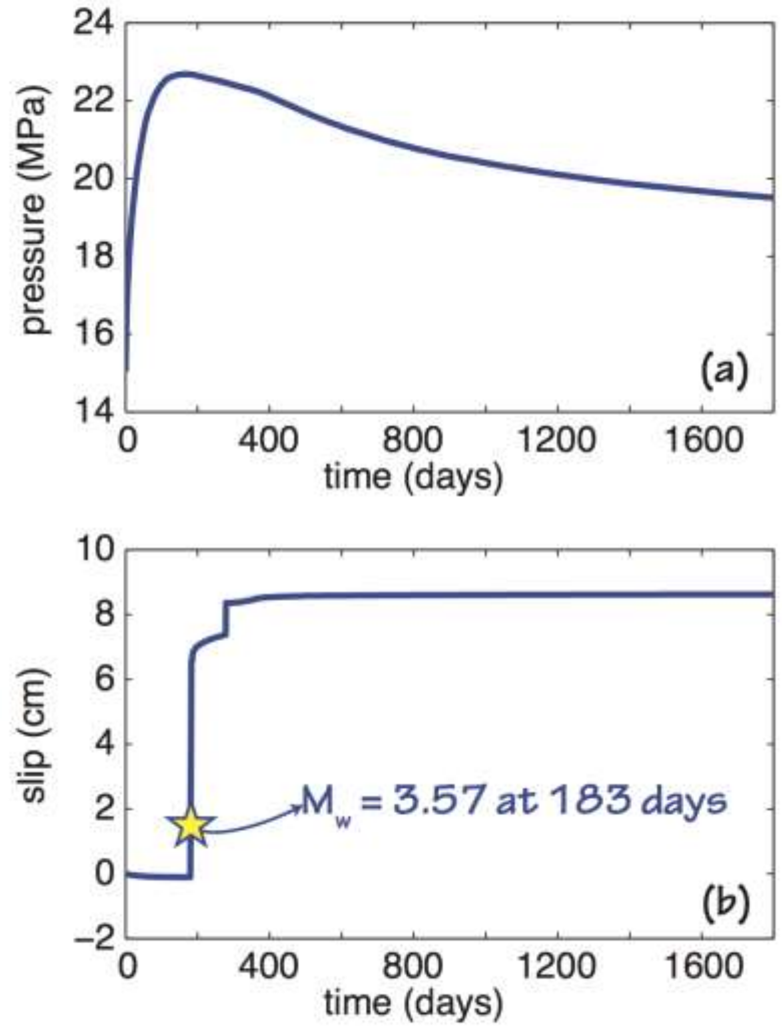


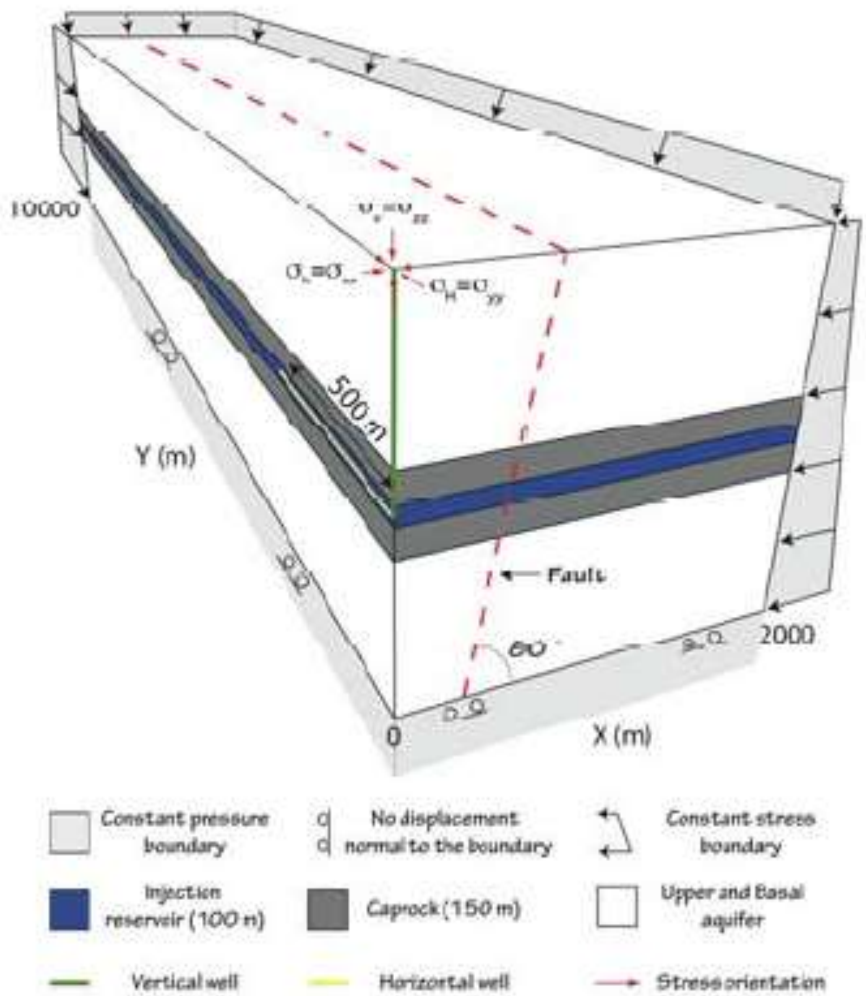
3D Modeling of Fault Reactivation and Seismicity

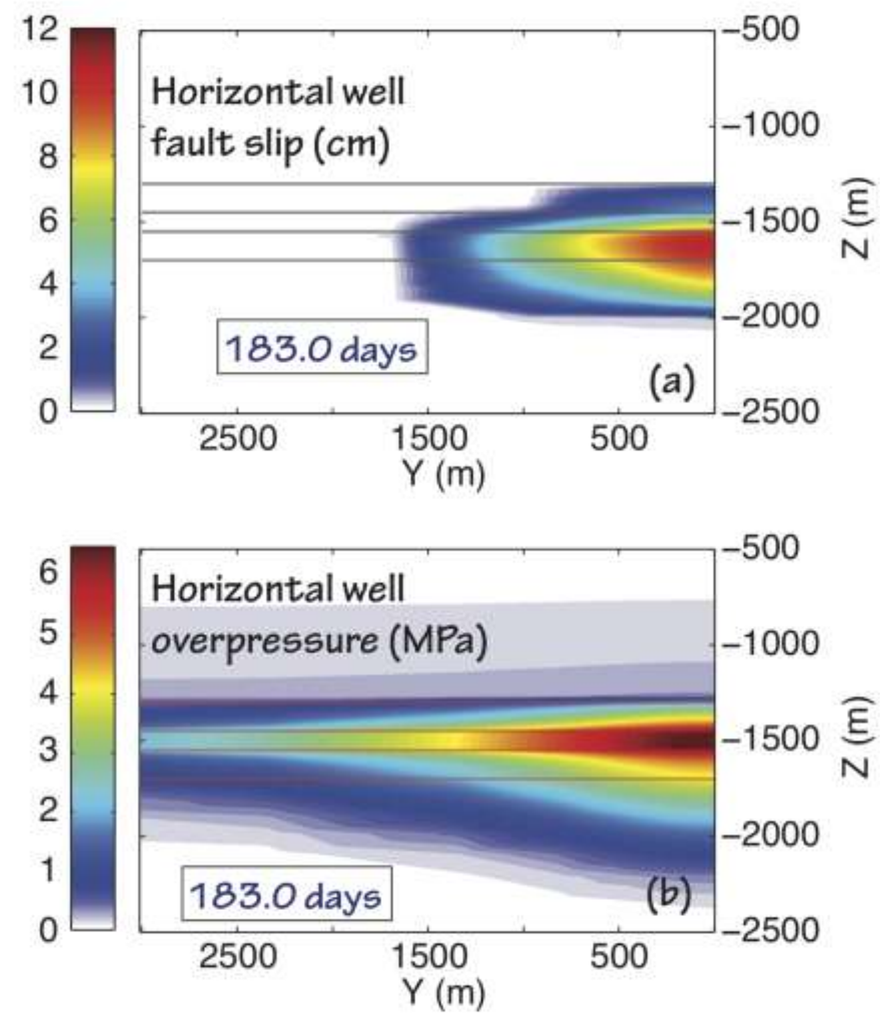




A bit longer before reactivation ⇒ slightly larger magnitude

3D Modeling of Fault Reactivation and Seismicity





Rupture area elongated along strike of fault