Modeling Fault Reactivation, Induced Seismicity, and Leakage during Underground CO2 Injection

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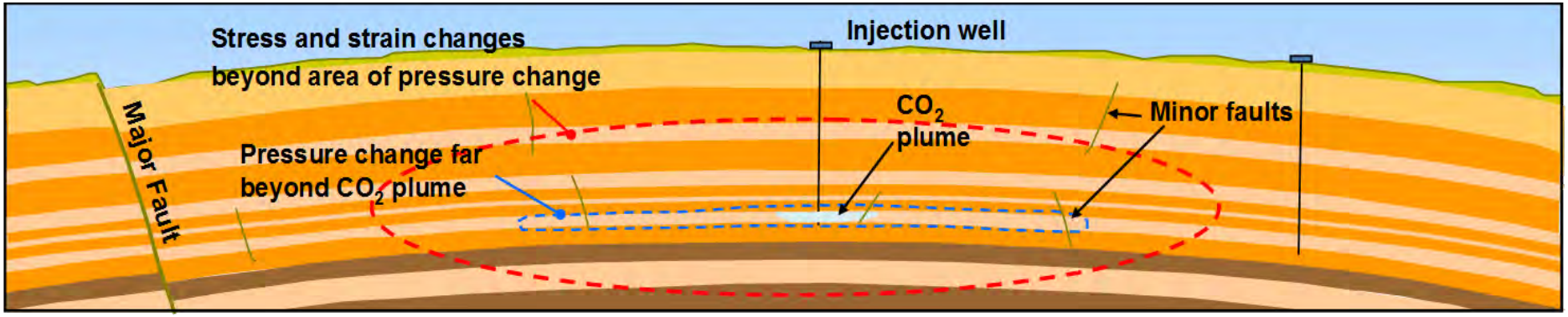
Berkeley, California

UK Carbon Capture and Storage Research Centre (UKCCSRC) specialist meeting , November 3, 2015

Geomechanics of CO_2 Storage in Deep Sedimentary Formations



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

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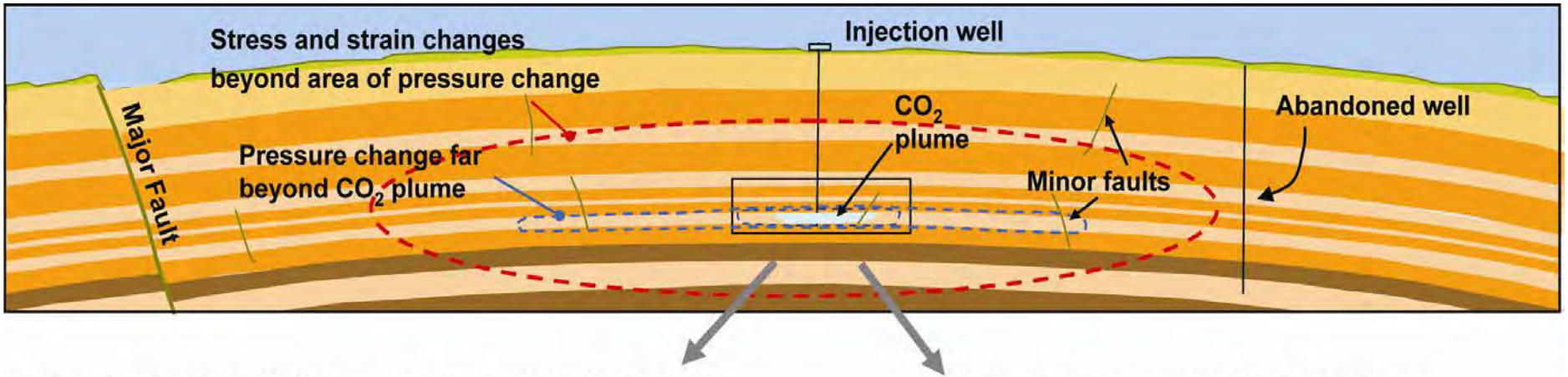
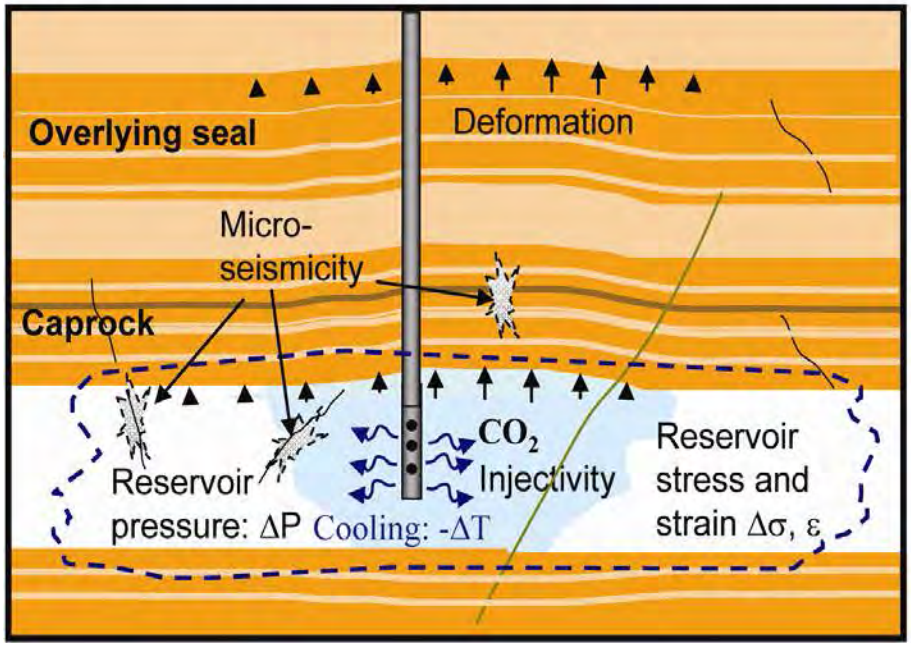


Injection-induced stress, strain and deformation



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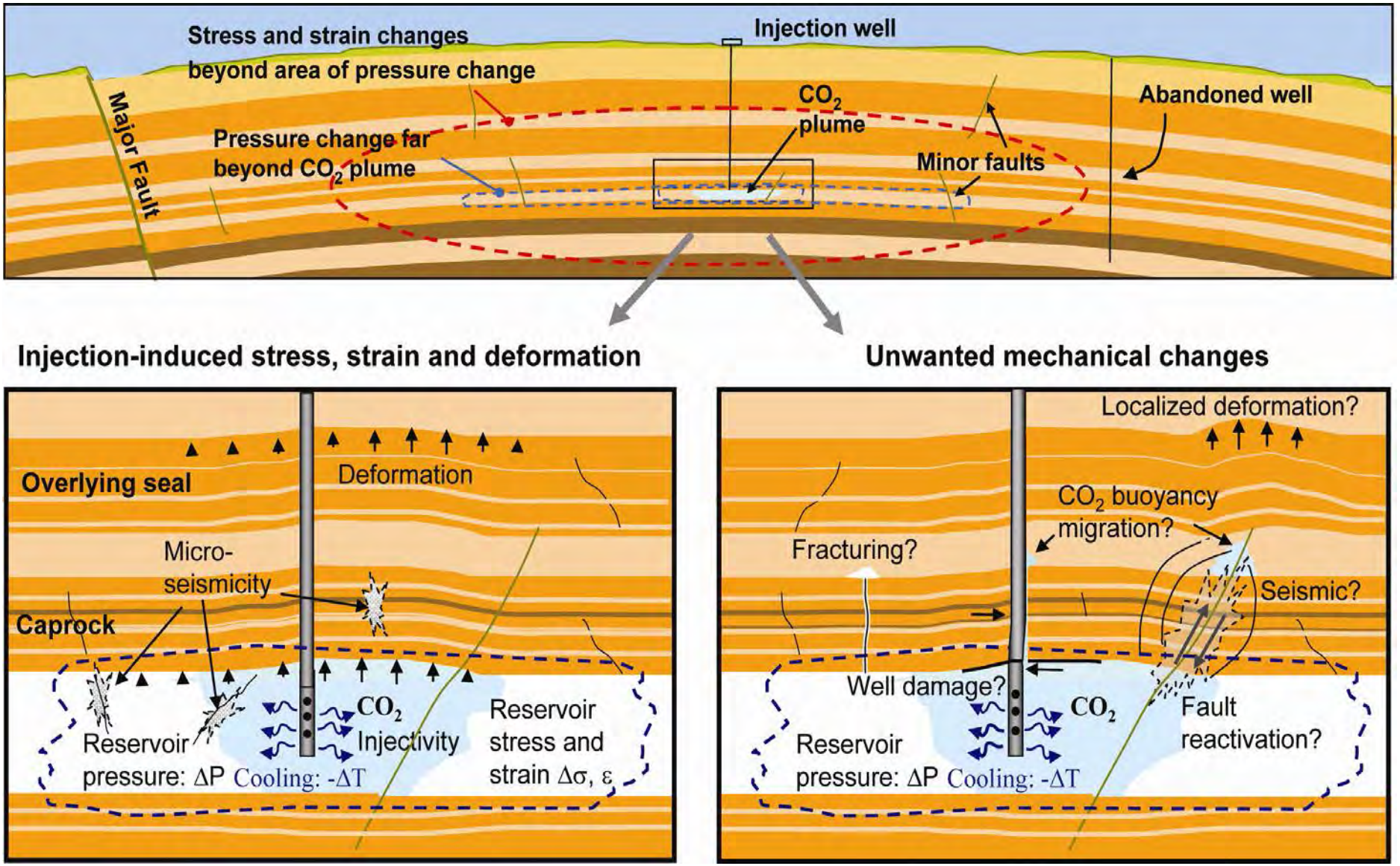

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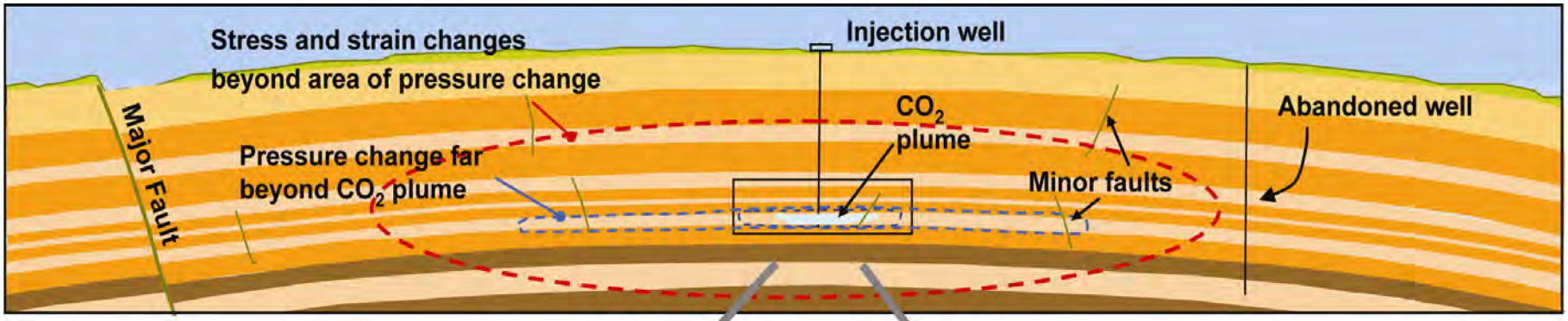
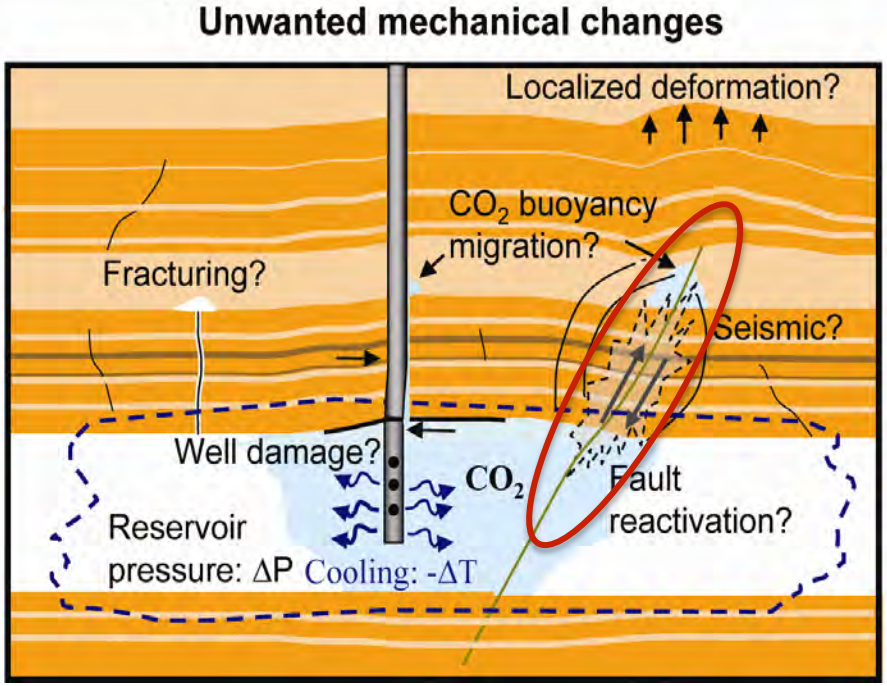
Potential Fault Reactivation and Notable Seismic Events



- An important issue from safety, storage security, and public acceptance perspectives.
- Release of stored energy triggered by the injection.
- Not just limited to seismically active areas, but could also occur within the seismically quiet intraplate crust (Zoback and Gorelick., 2012).
- Undetected minor faults relevant



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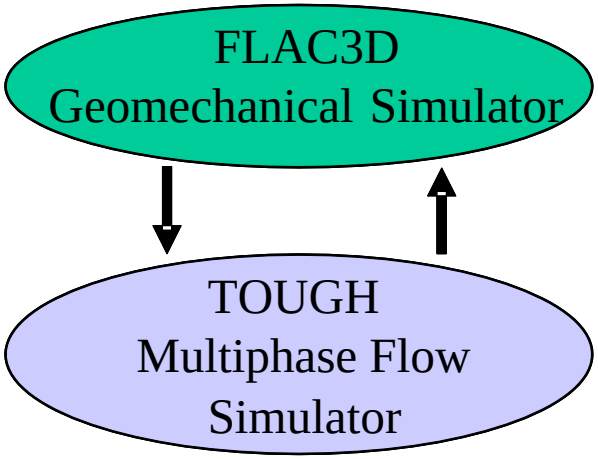
Outline of Presentation

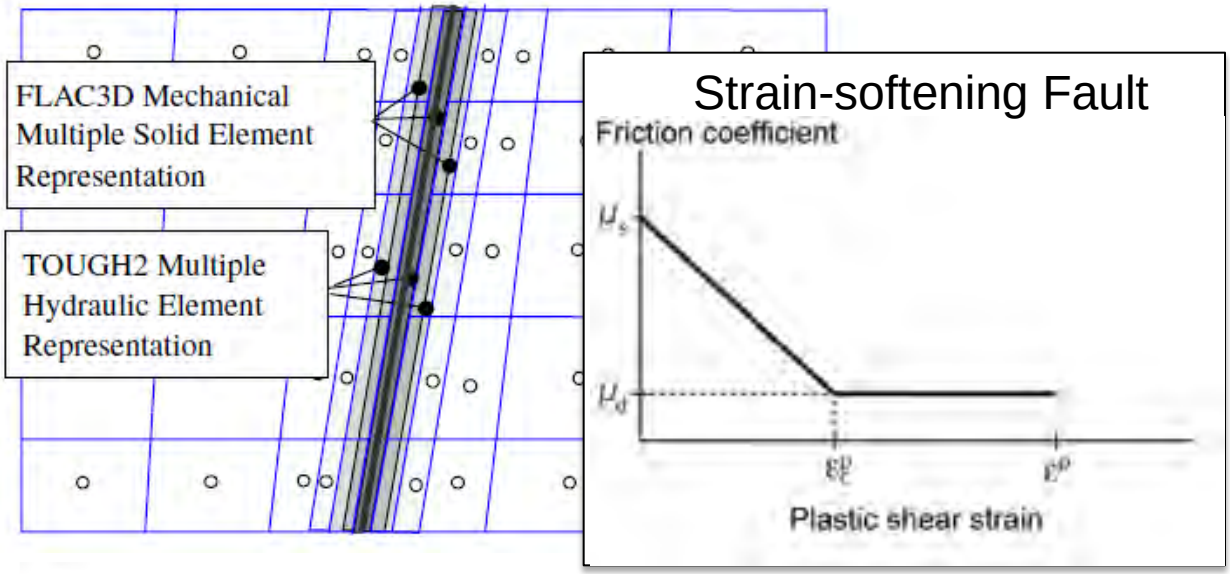
- Introduction
- Modeling approach
- CO2 injection and fault activation
  - Potential magnitudes?
  - Potential leakage?
- Deep fracture/fault responses at In Salah
- Concluding remarks

Modeling Fault Reactivation and Seismicity

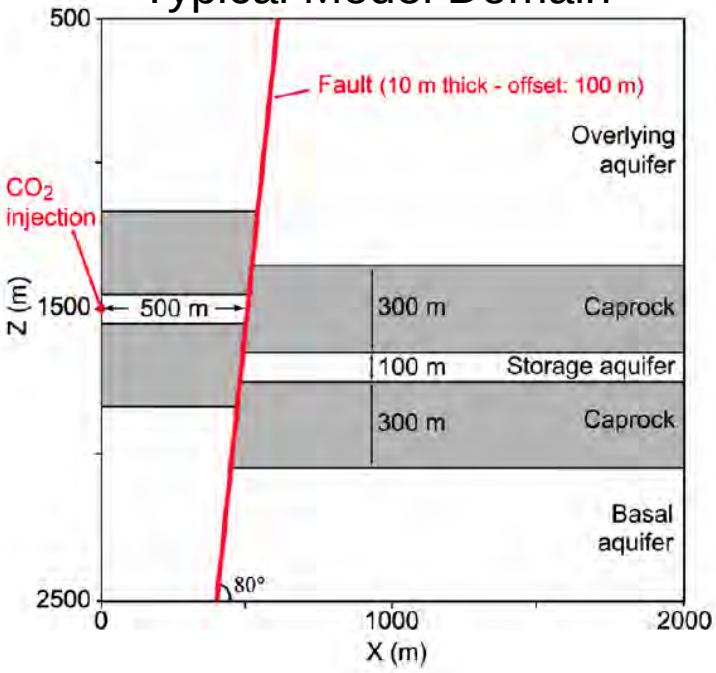
TOUGH-FLAC Simulator



Typical Fault Discretization

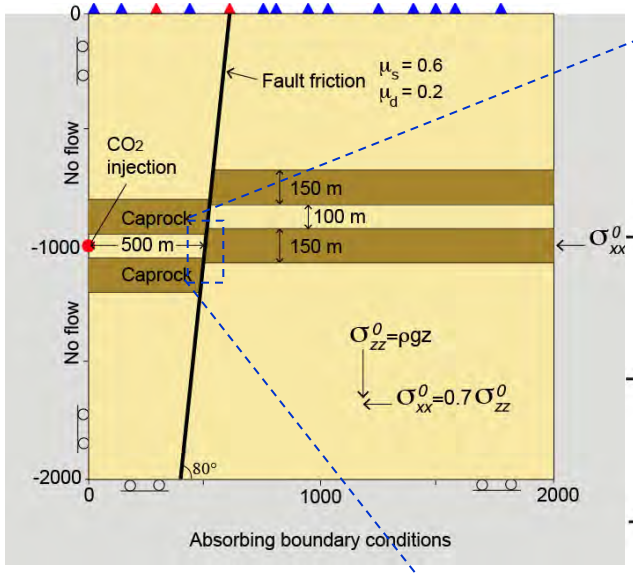


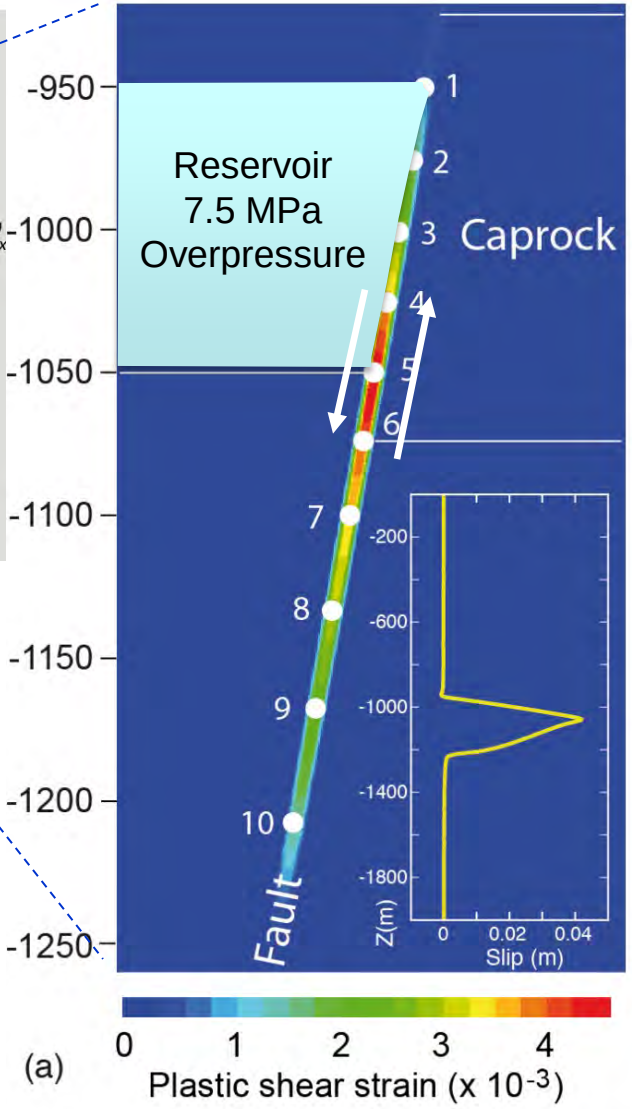
Typical Model Domain

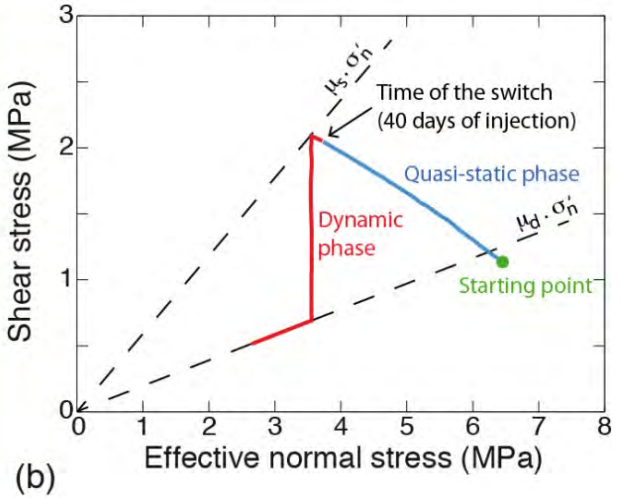


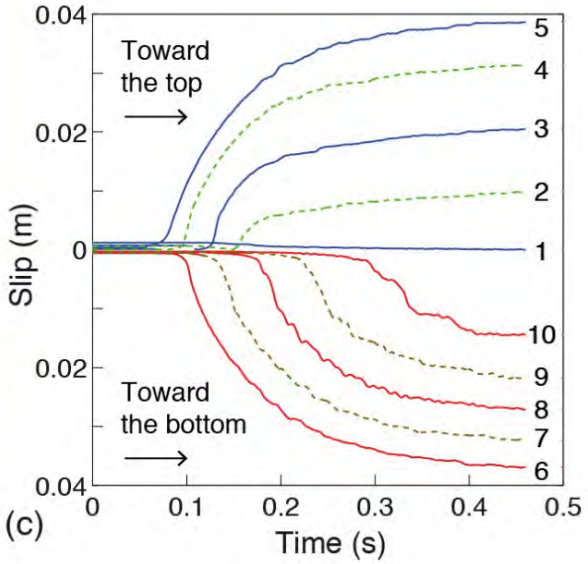
- Anisotropic plasticity model allowing shear (Coulomb) failure along the fault plane
- Shear-induce fault permeability change
- Strain-softening plasticity to represent slip-weakening fault behavior (sudden slip)
- Seismic moment and moment magnitude calculated from Kanamori et al (e.g. $M_0 = \mu Ad$)

Simulated CO2 Injection and Fault Activation





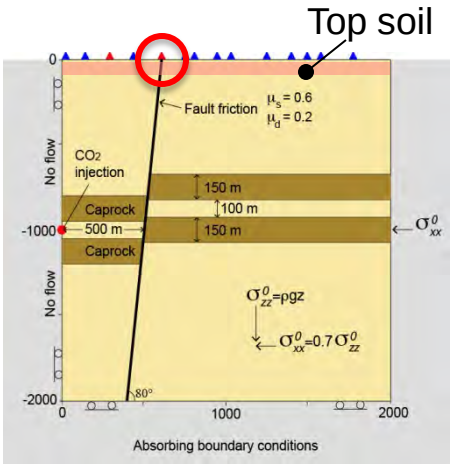


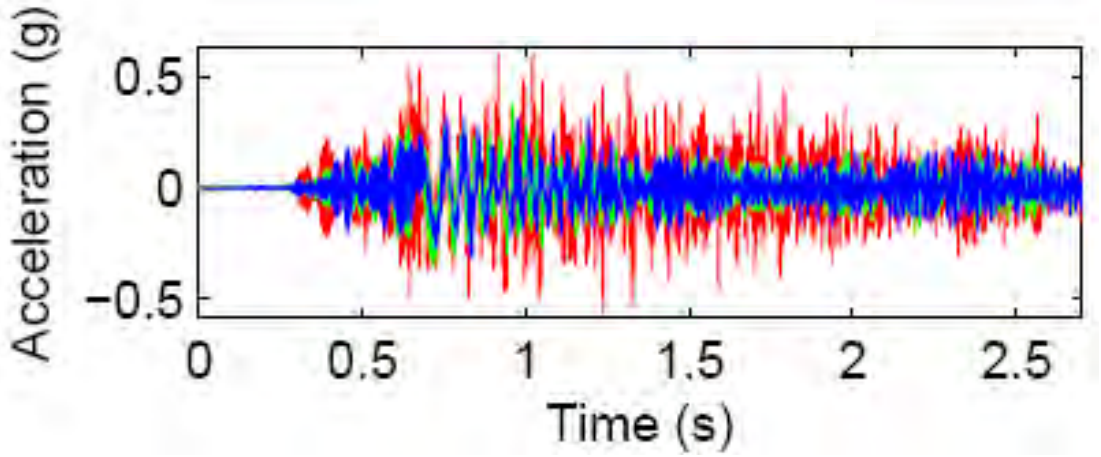


- Reactivation at about 7.5 MPa overpressure
- 4 cm fault slip over 0.4 seconds, peak slip 0.6 m/s
- 290 m fault rupture corresponding to $M_w = 2.53$

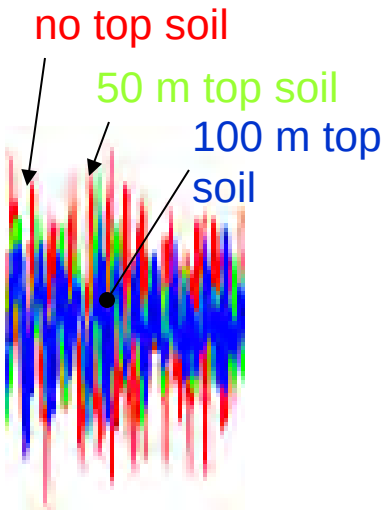
(Cappa and Rutqvist, GJI, 2012)

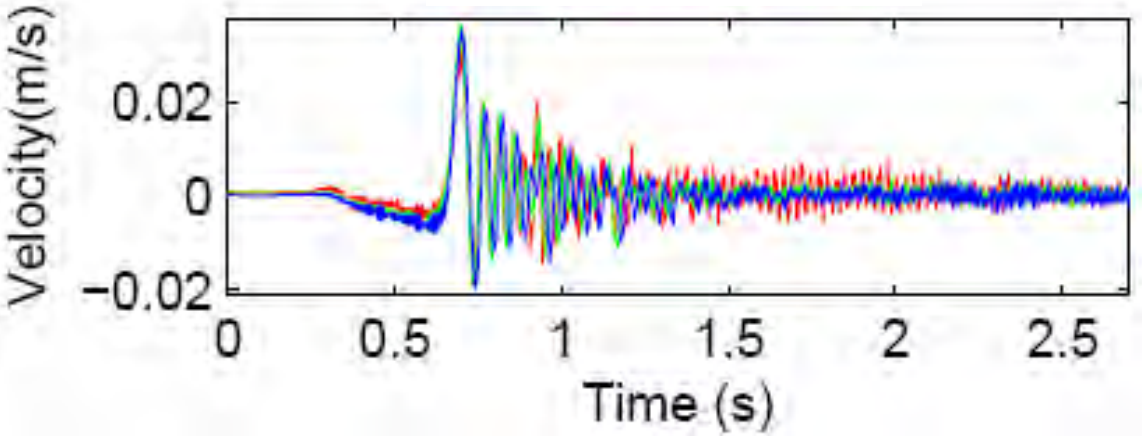
Ground Surface Motion at Top of the Fault





- PGA 0.6g at 30-40 Hz
- High frequency acceleration damped for soil



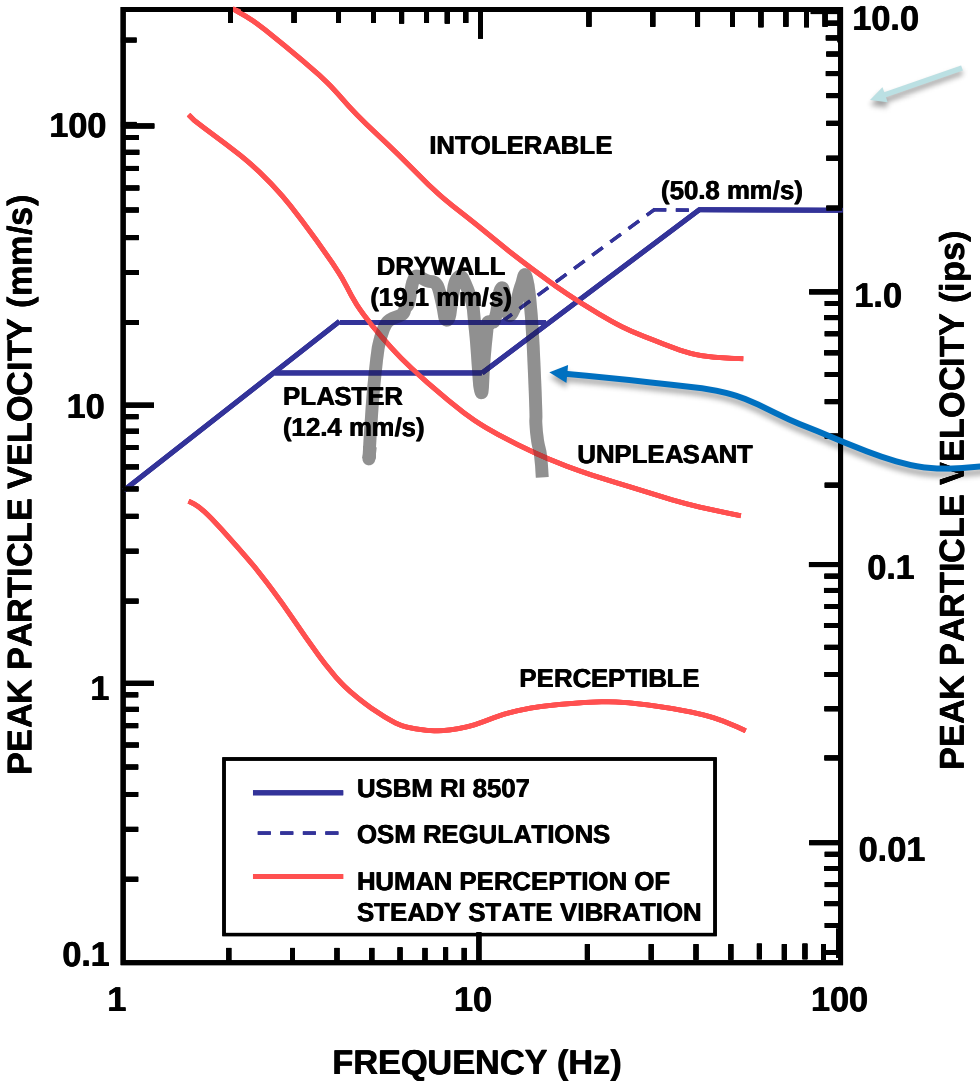


- PGV 30 mm/s at 6-12 Hz
- PGV for one jolt at a lower frequency

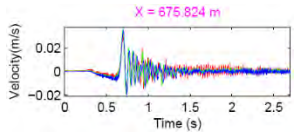
(*Rutqvist et al., IJGGC, 2014)*

Building Damage and Human Perception

US Bureau of Mines (USBM) ground vibration criteria for building damage and human-perception limits for vibration



Simulated ground motion frequency spectrum



PGV 30 mm/s
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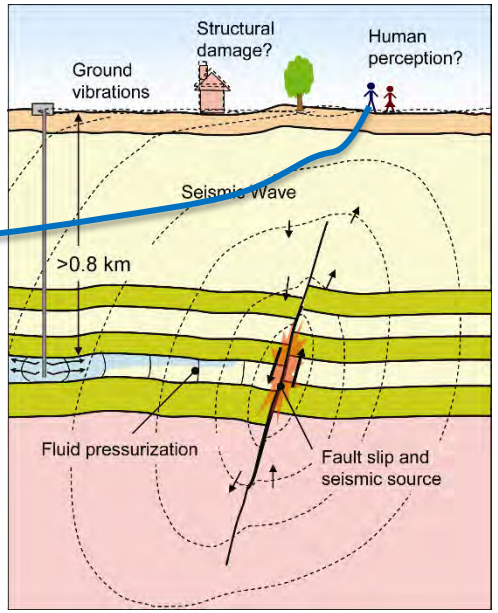
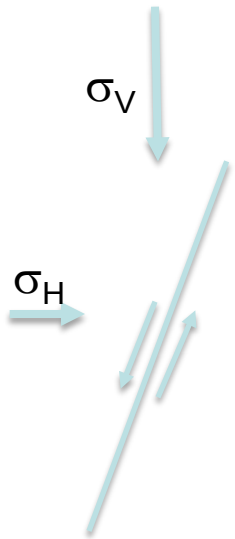


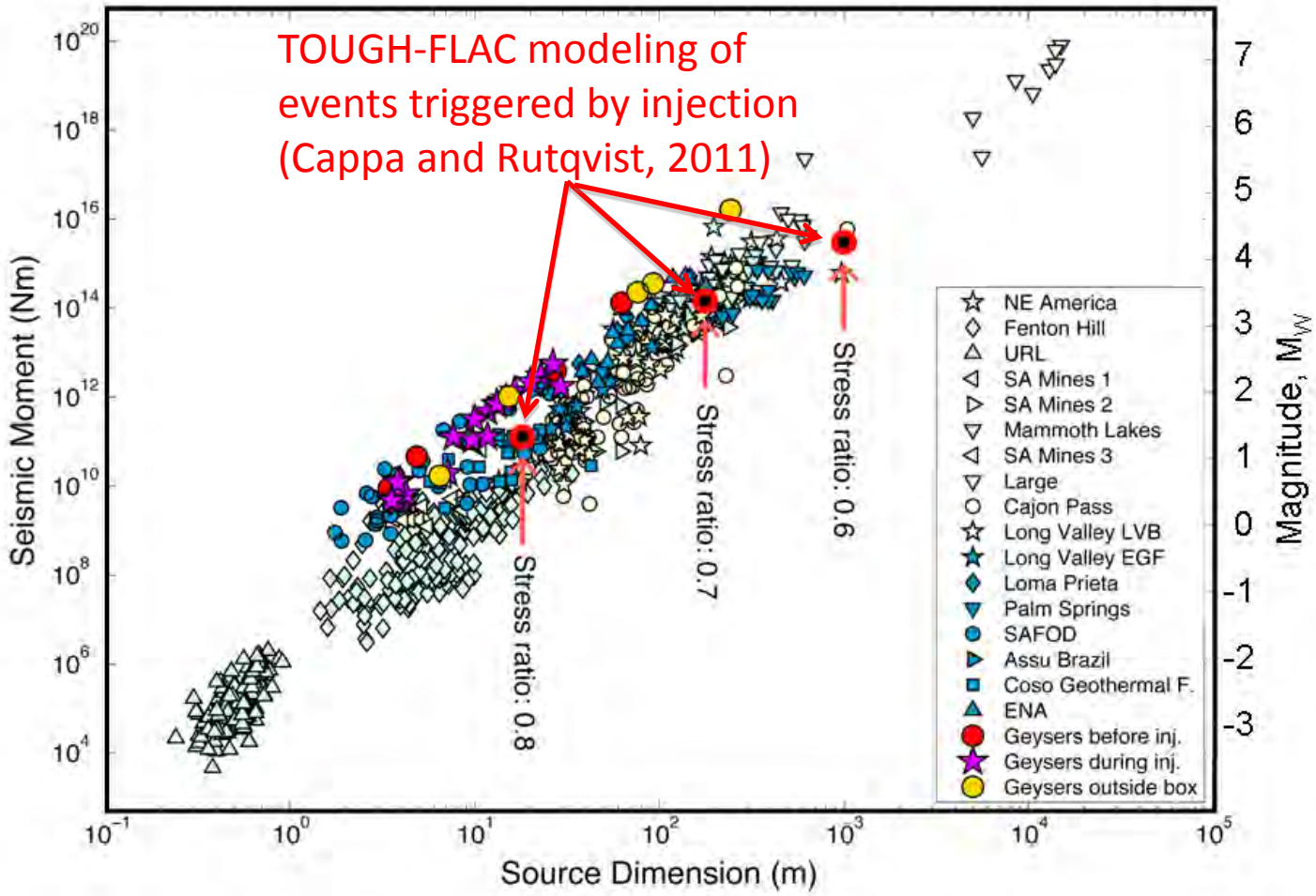
- In this example vibrations could cause cosmetic building damage and clearly felt by humans

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

Rupture Size of a Notable (Felt) Seismic

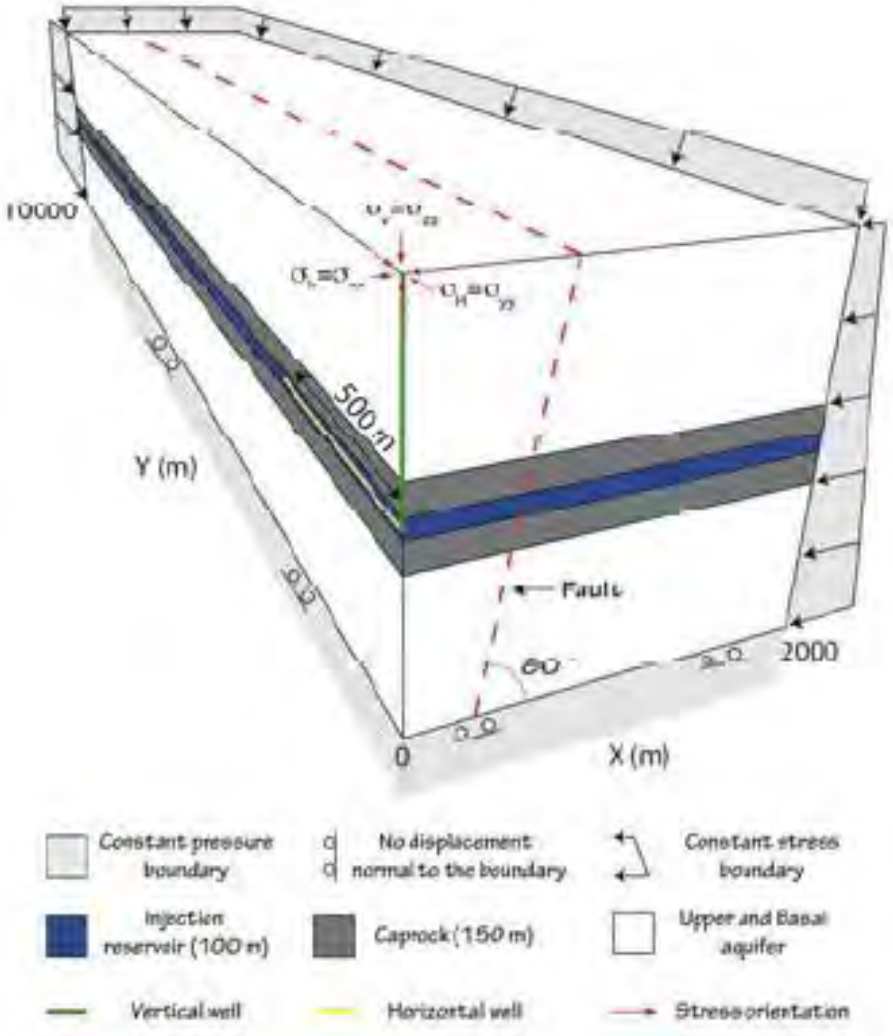


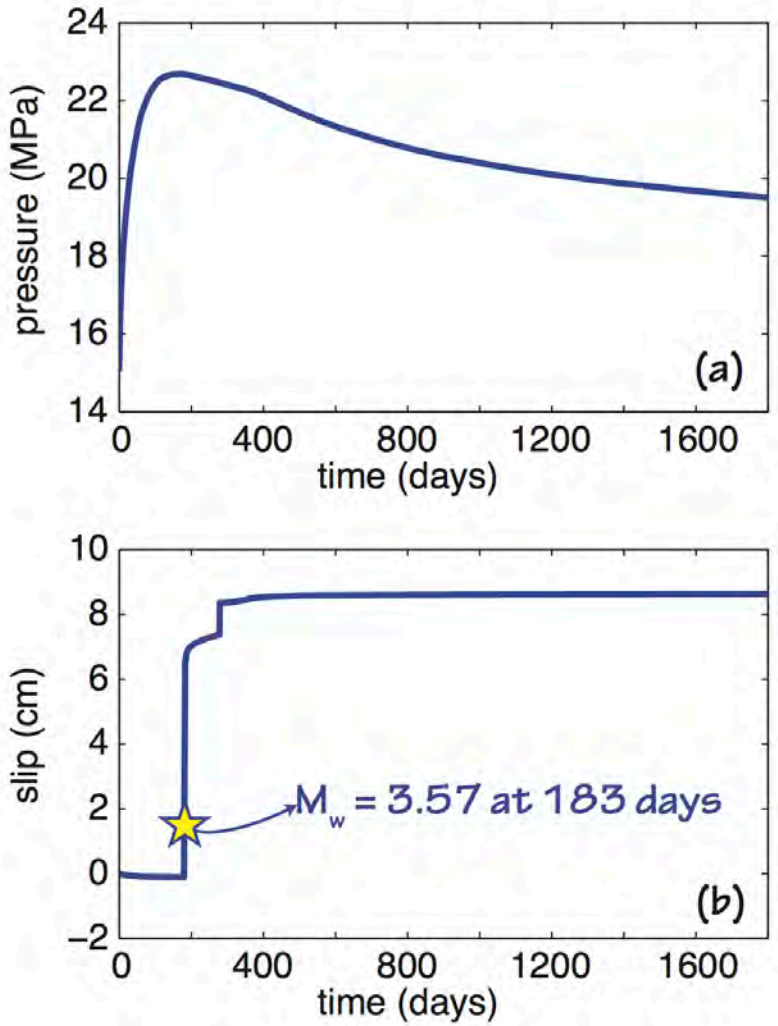
Stress ratio = σ_H / σ_V = 0.6, 0.7 or 0.8



- Largest magnitude when fault exposed to the highest shear stress (horizontal/vertical stress ratio = 0.6)
- A notable (felt) event, e.g. magnitude 4, requires a km-sized fault rupture
- What about 2D model simplification?

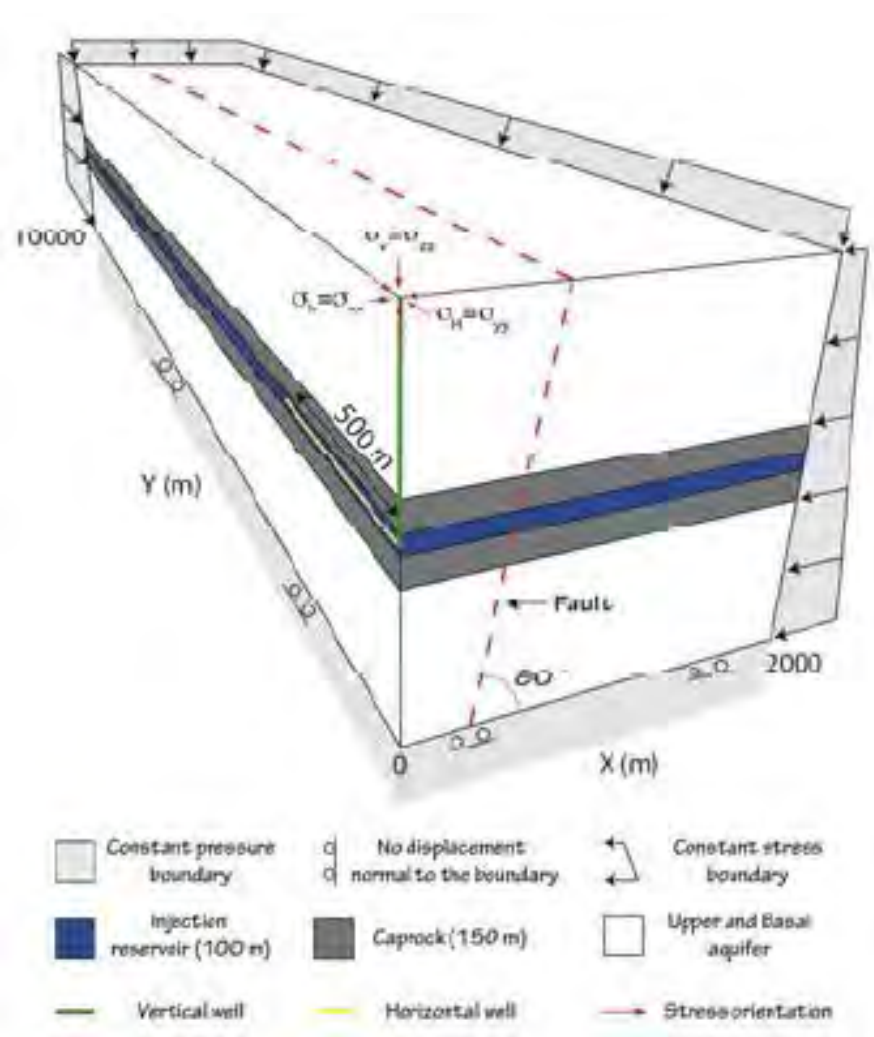
3D Modeling of Fault Reactivation and Seismicity



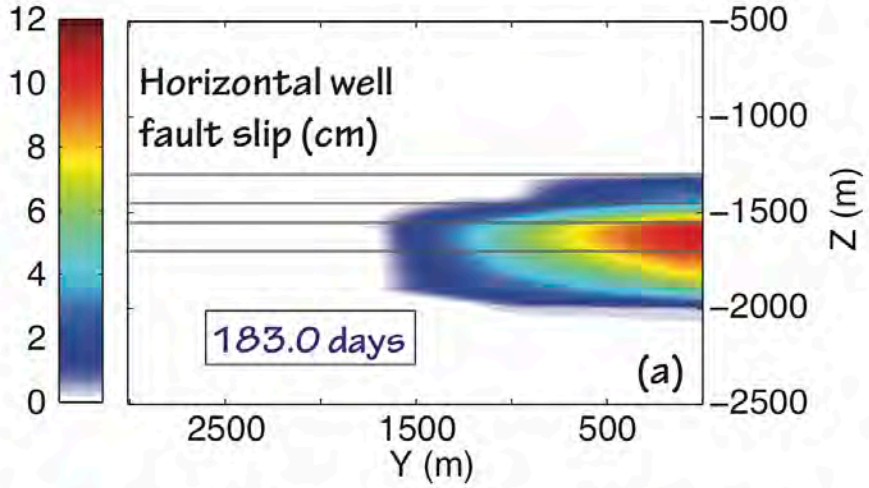


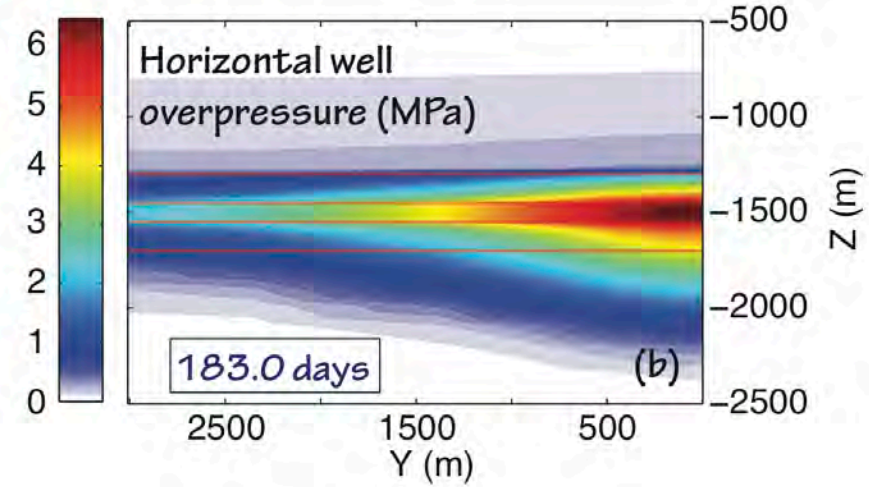
- Flow in the third dimension (not confined within 2D plane strain model)
- Longer time for pressure buildup before reactivation ⇒ slightly larger magnitude

3D Modeling of Fault Reactivation and Seismicity



Contours on Fault Plane

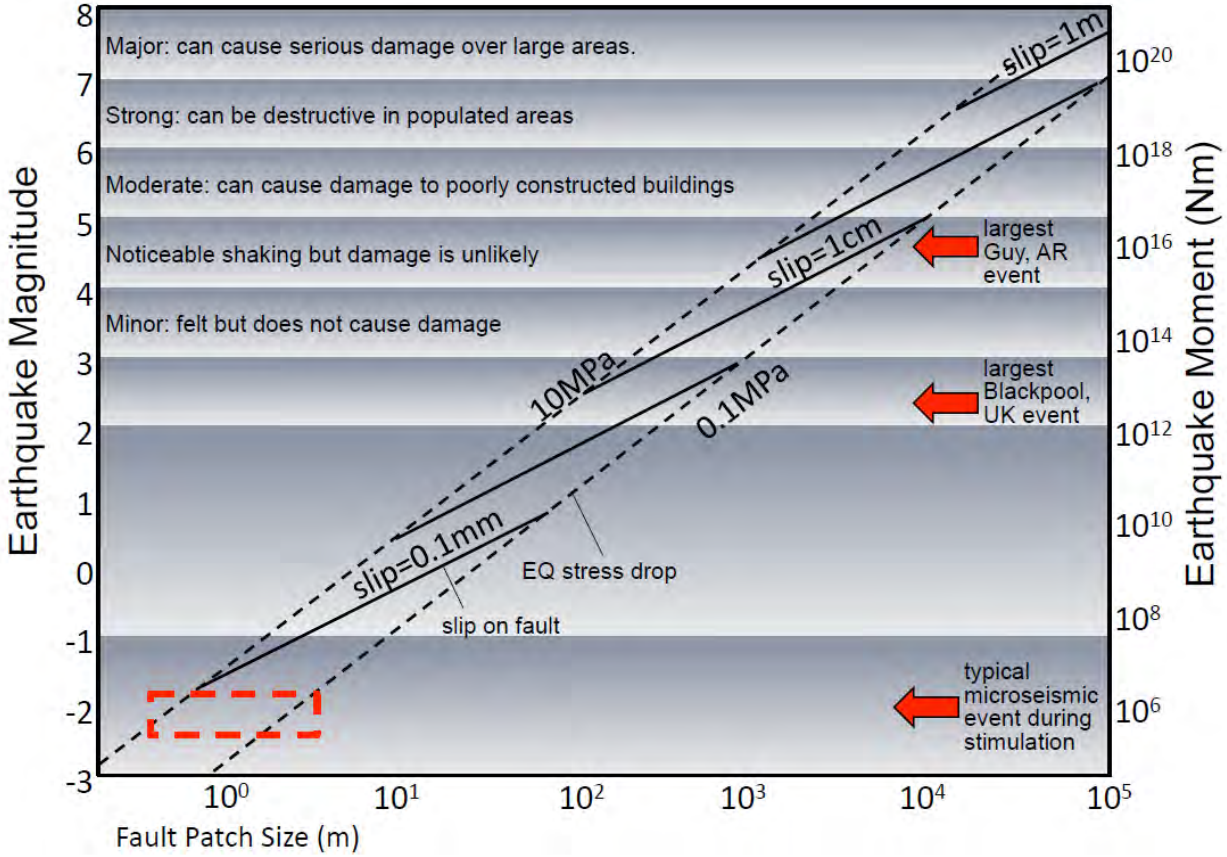




- Rupture area elongated along strike of fault
- Large fault area pressurized at rupture $\Rightarrow$ felt events, e.g. M = 3 - 4

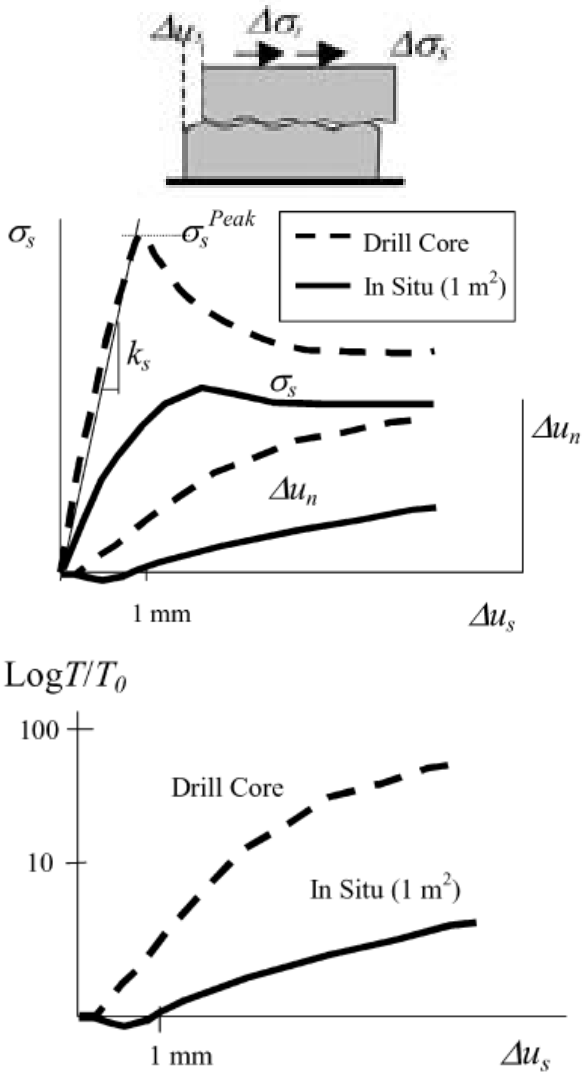
Potential Shear-Induced Permeability and Leakage

Shear slip and stress drop associated with a seismic event:



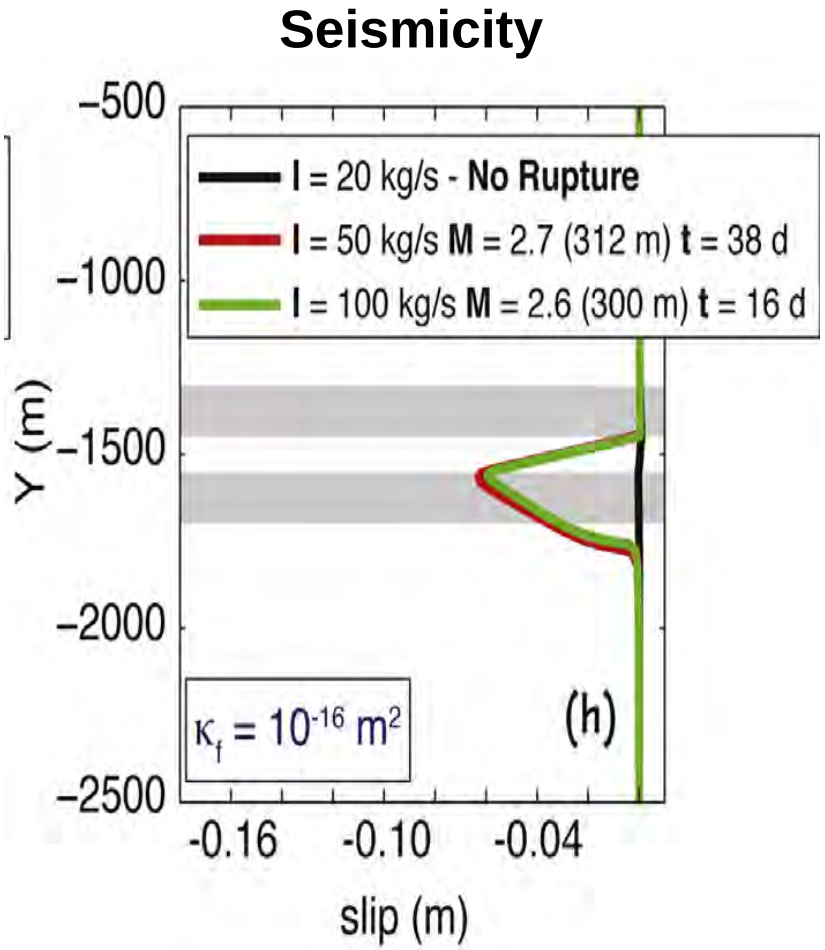
Zoback and Gorelick (2012)

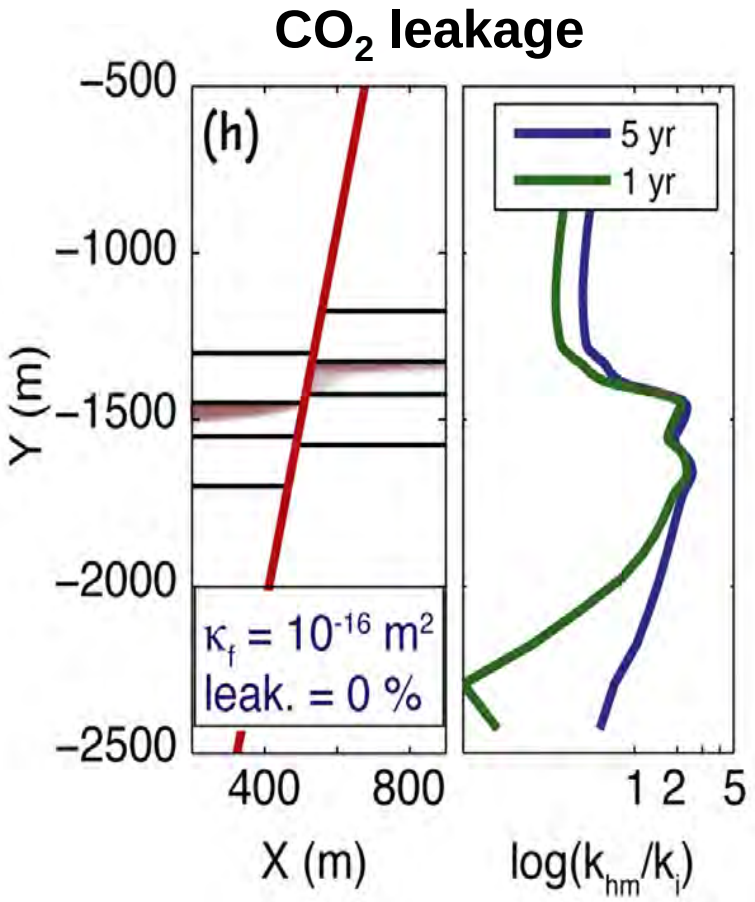
Shear-induced permeability



Rutqvist and Stephansson (2003)

Seismicity and Leakage



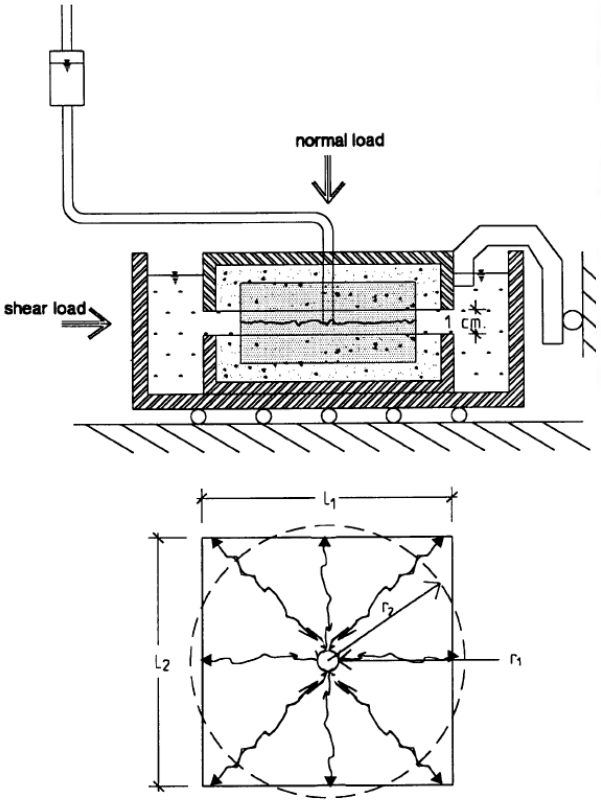


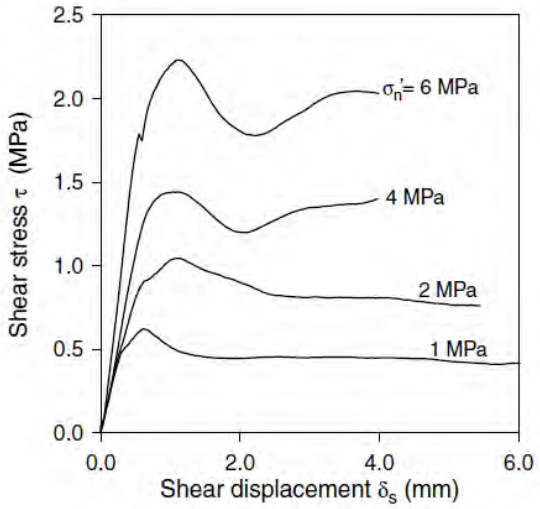
In this simulation example we simulated a seismic event that might be felt but with no upward CO_2 leakage

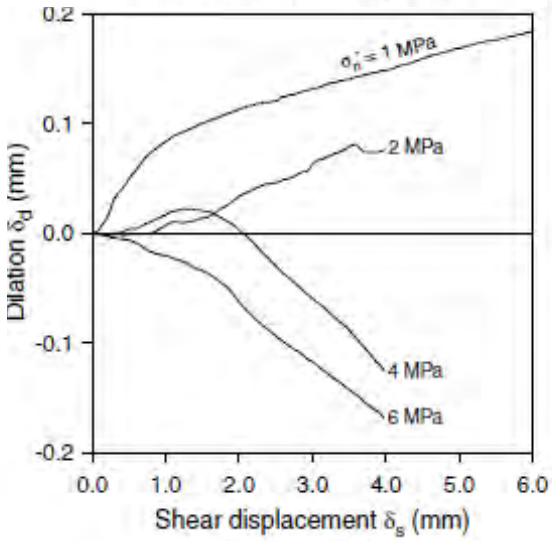
Rinaldi et al 2014 (nt. J Greenhouse Gas Control)

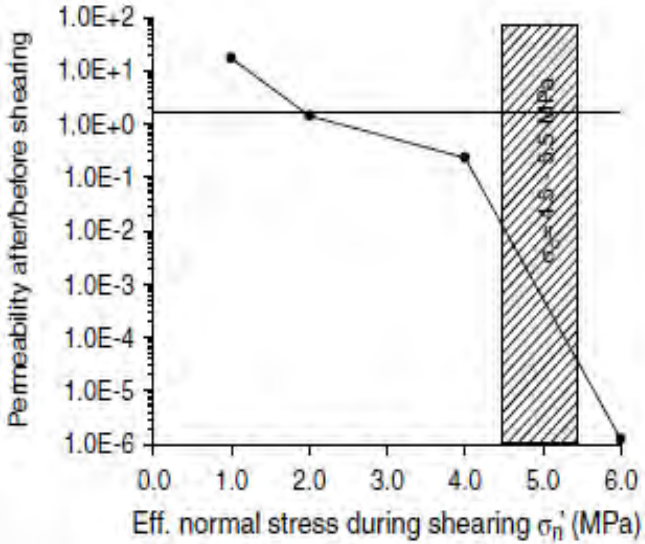
Example of Shear-Permeability Tests on Shale Fractures

Gutierrez et al. (2000)





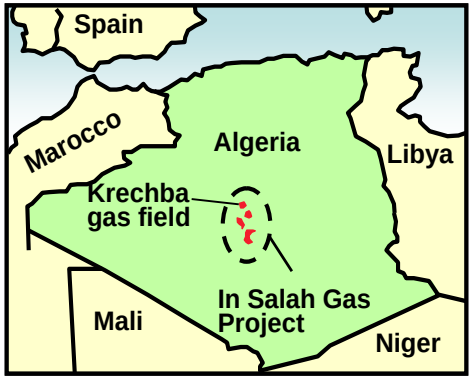


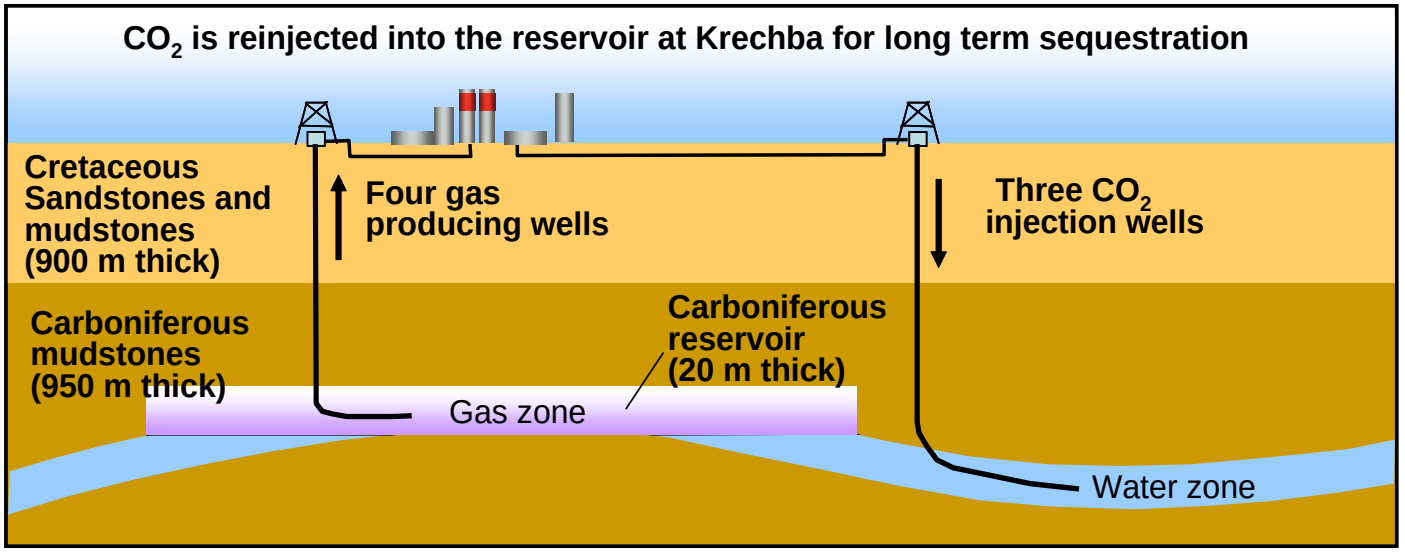


Under higher stress normal to fracture the permeability decreases with shear (at stress level higher than the uniaxial compressive rock-strength)

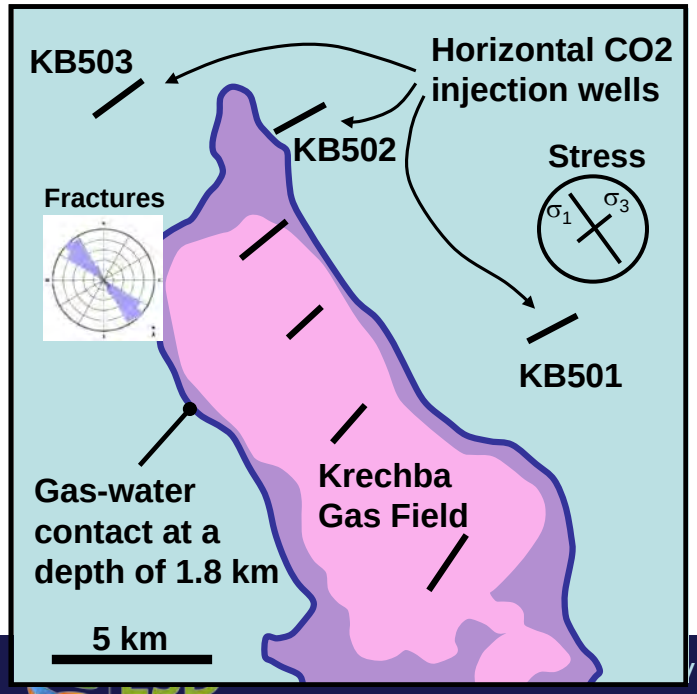
The In Salah CO_2 Storage Project, Algeria

In Salah Gas JV
(BP, Staoil, Sonatrach)



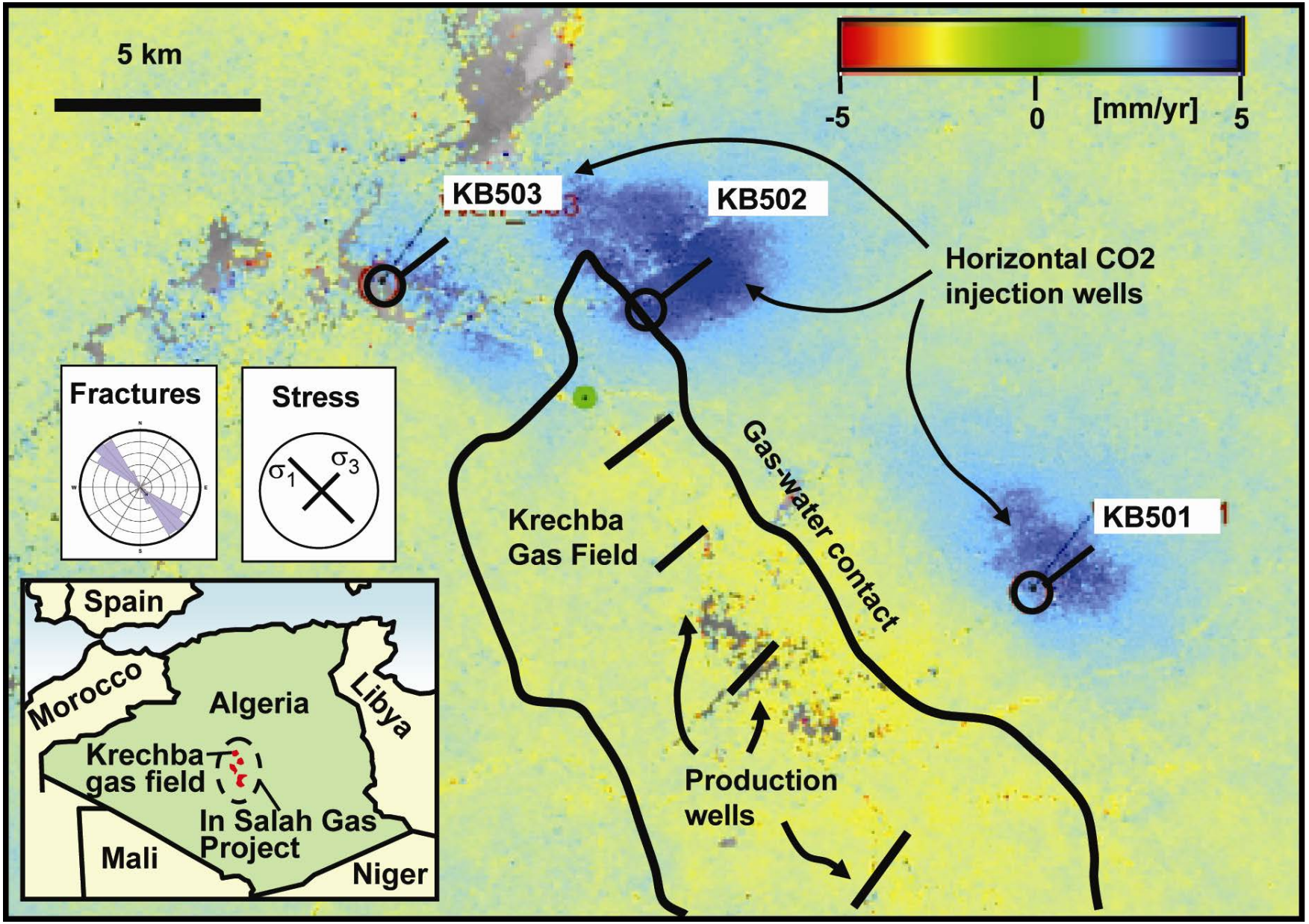


Plane view of Krechba Gas Field



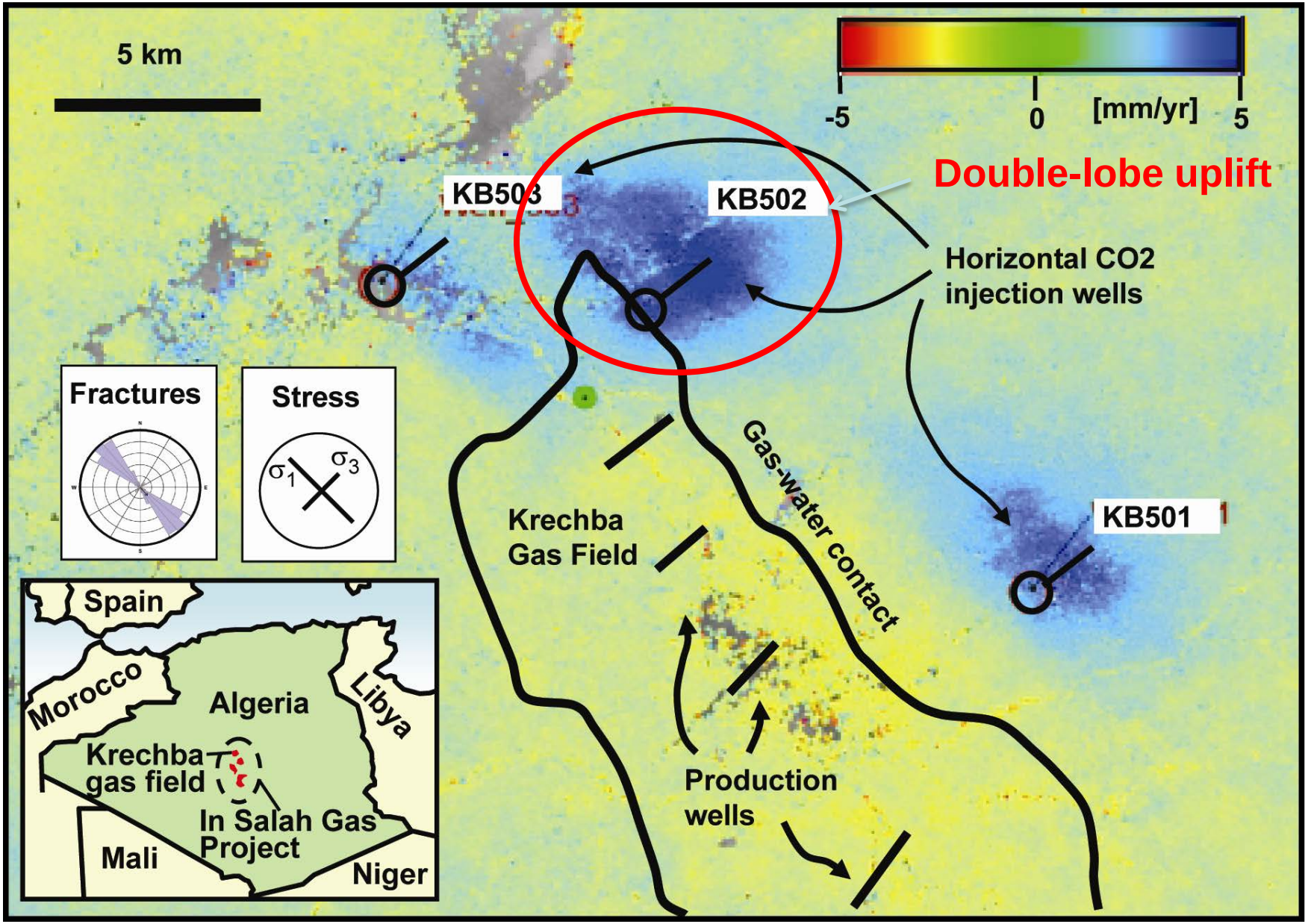
- The CO_2 injected at a depth of about 1,8 to 1,9 km into a 20 m thick formation of relatively low permeability.
- Nearly one million tonnes CO_2 per year injected from 2004 to 2011 at 3 horizontal injection wells
- Bottom hole pressure limited to below the fracturing gradient ⇒ maximum pressure increase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

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



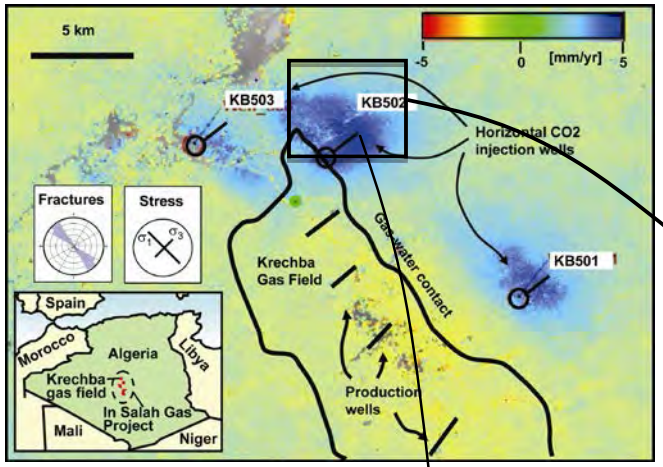
Rutqvist et al (2010)

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

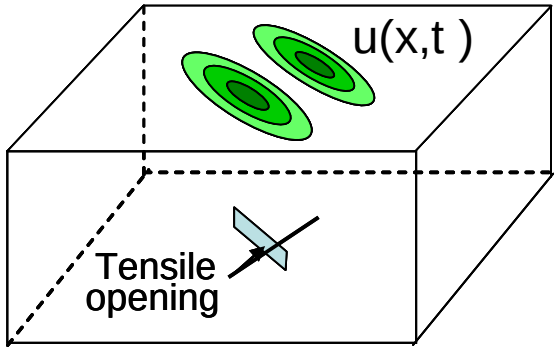


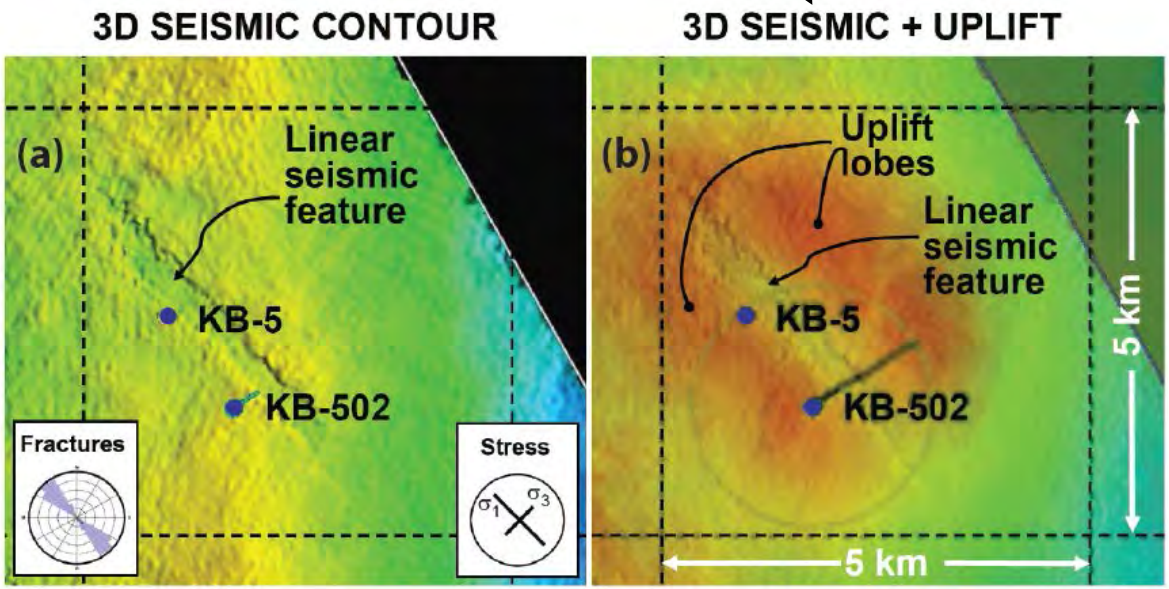
Rutqvist et al (2010)

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.



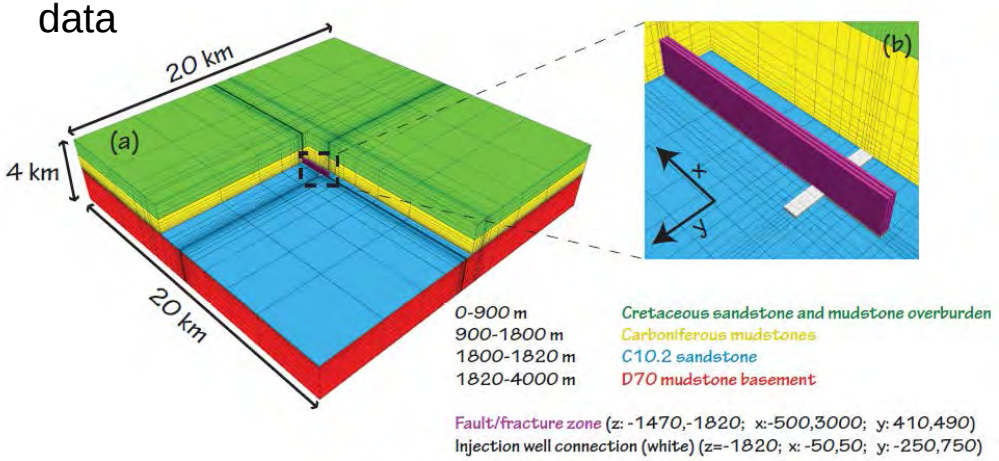


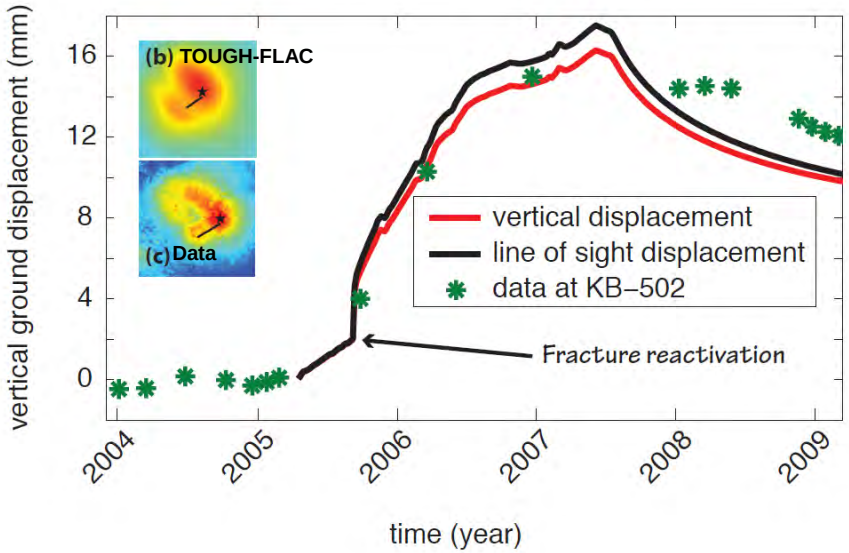
(Rutqvist, 2012)

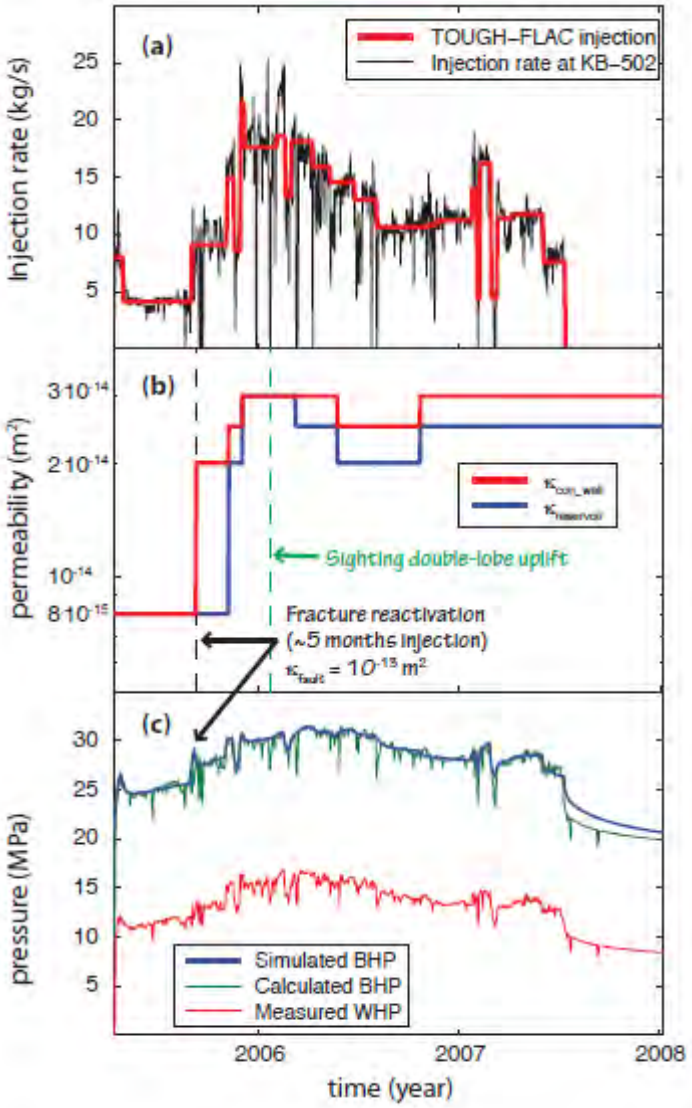
Seismic contour in caprock 150 m above injection zone and surface uplift after 3 years

In Salah Deep Fault or Fracture Zone Responses

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







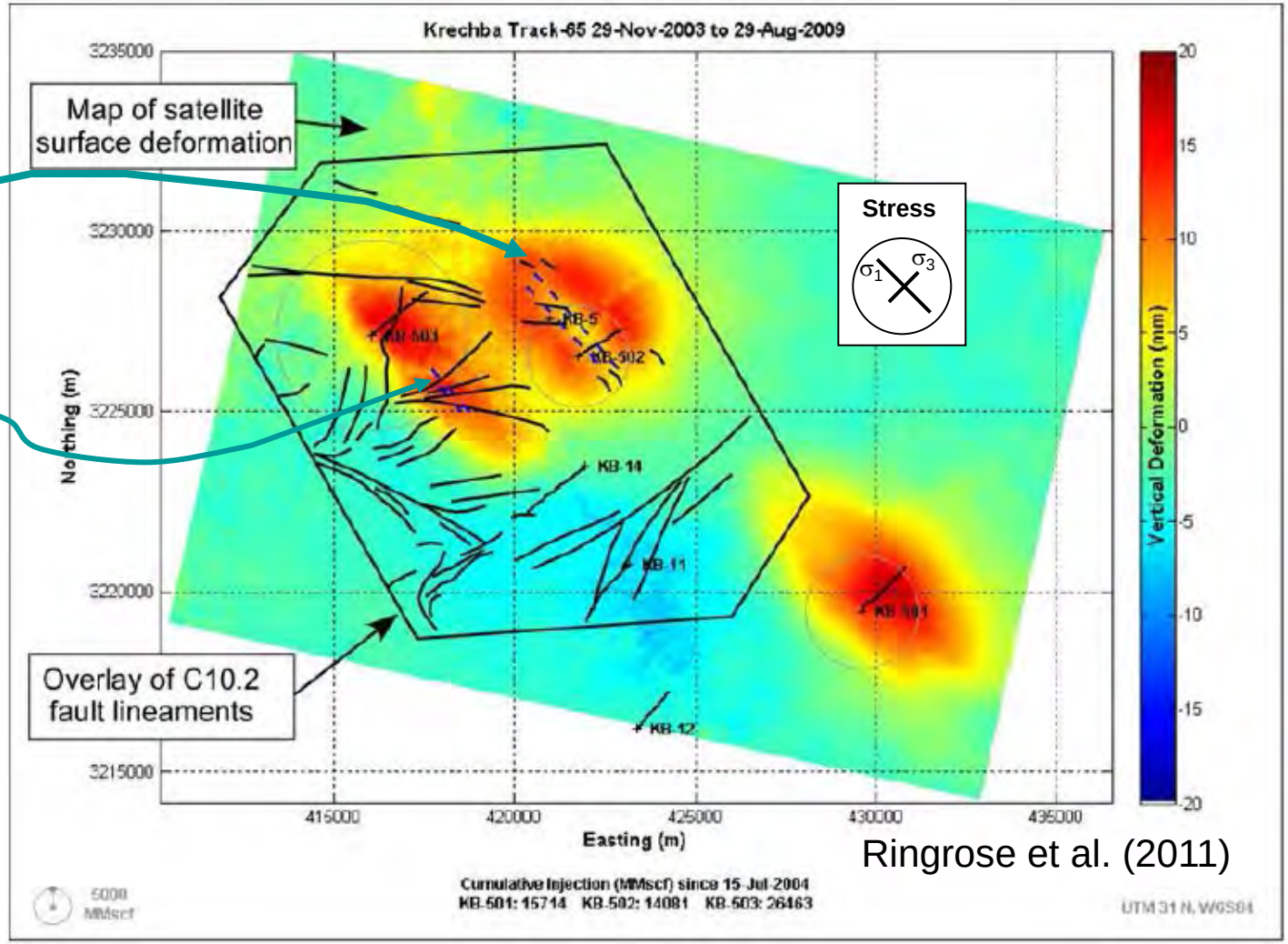
Modeling indicates that the fracture zone extends a few hundred meters up from the reservoir (contained within the 900 m thick caprock)

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)

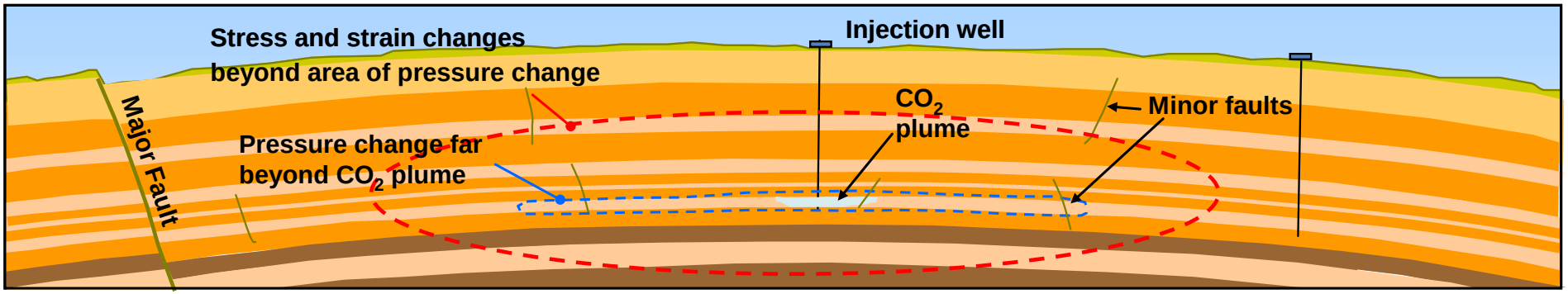
However, CO2 injection at In Salah has not resulted in any felt seismic events or substantial strike-slip shear movements (Max magnitude 1.7, (Stork et al. 2014))

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.



Concluding Remarks

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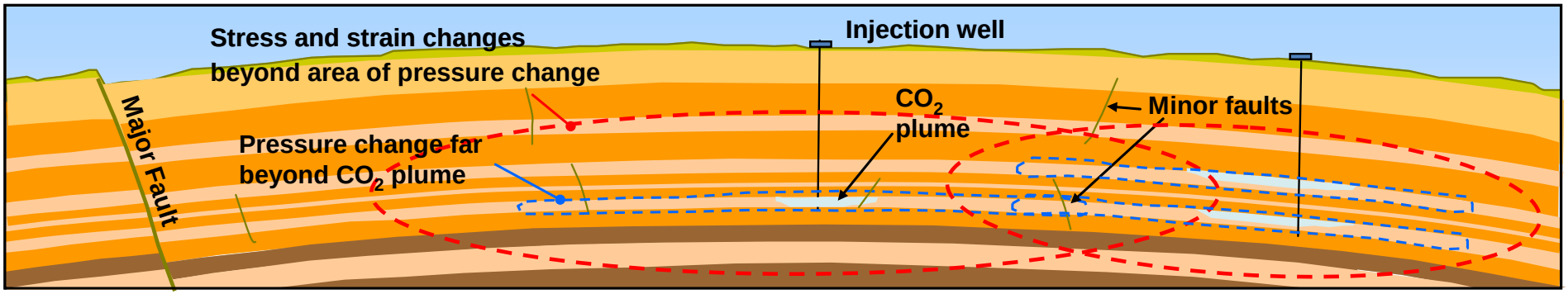
- At In Salah, injection pressure was relatively high indicating minor faults being critically stressed for reactivation, but no felt seismic event has been reported.

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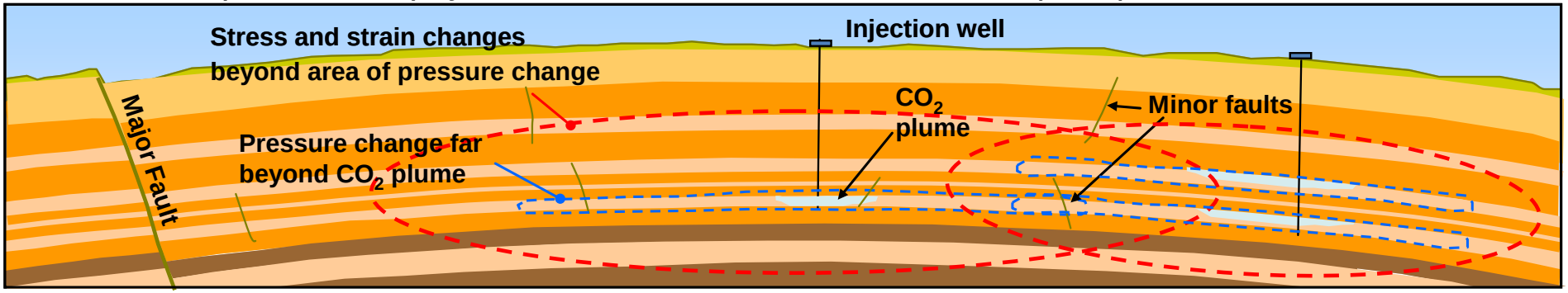
Rutqvist J. The geomechanics of CO2 storage in deep sedimentary formations. International Journal of Geotechnical and Geological Engineering, 30, 525–551 (2012).

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).

Rinaldi A.P. and Rutqvist J. Modeling of deep fracture zone opening and transient ground surface uplift at KB-502 CO2 injection well, In Salah, Algeria. International Journal of Greenhouse Gas Control 12, 155–167 (2013).

Cappa F. and Rutqvist J. Seismic rupture and ground accelerations induced by CO2 injection in the shallow crust. Geophysical Journal International, 190, 1784–1789 (2012).

Cappa F. and Rutqvist J. Impact of CO2 geological sequestration on the nucleation of earthquakes. Geophysical Research Letters, 38, L17313, (2011).