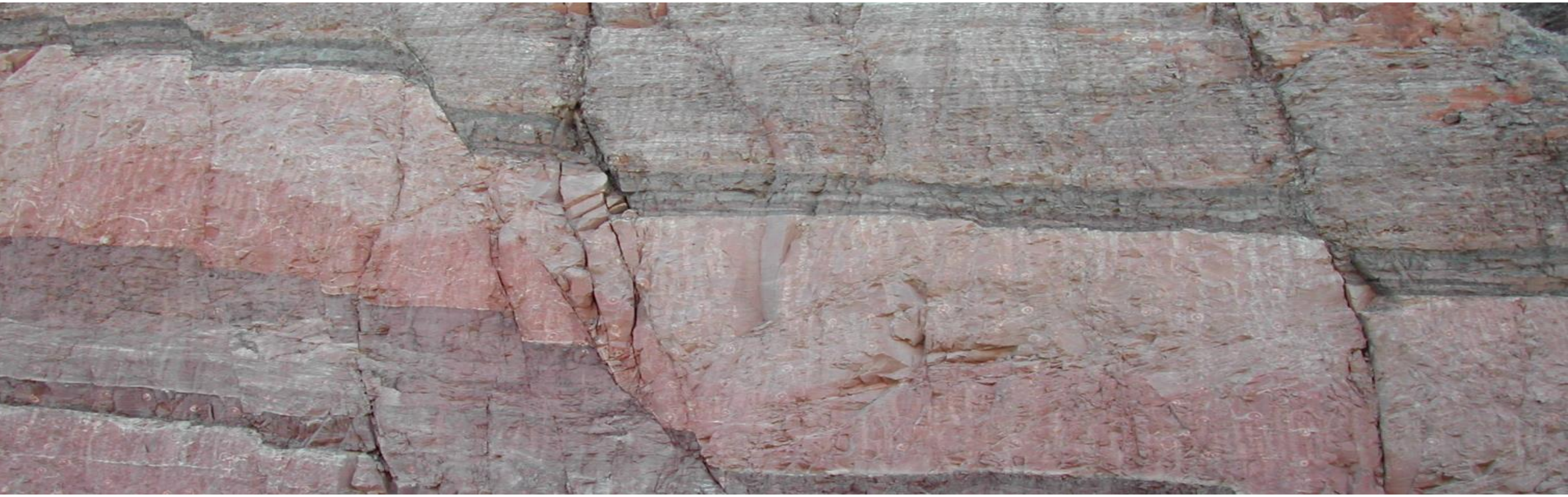
REVIEW ON CO_2 MIGRATION AND GEOLOGICAL FAULTS



Andy Nicol[1,2], Hannu Seebeck[1], Brad Field[1], David McNamara[1,5], Conrad Childs[3], James Craig[4], Alex Rolland[4]

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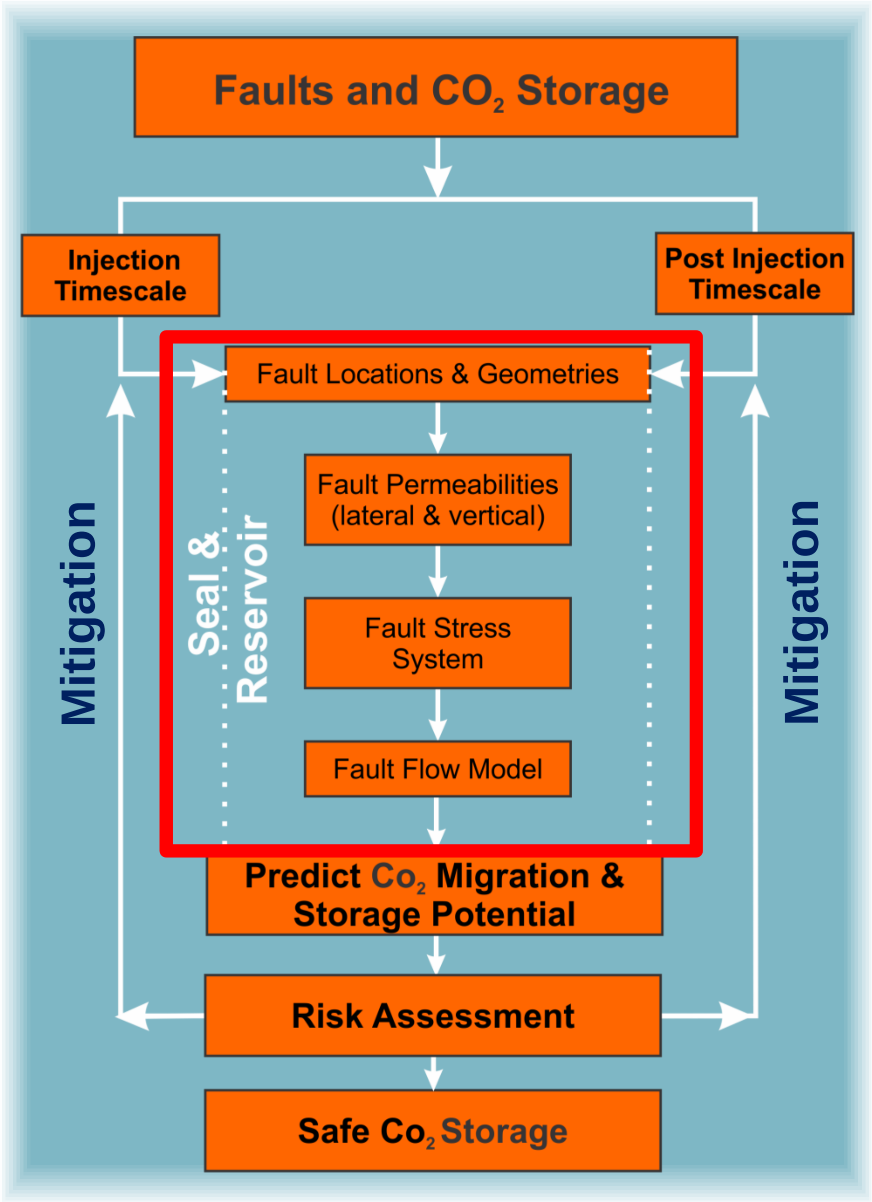
Faults as Pathways for CO2



- Fault zones are important to the secure, long term storage of CO_2
- They may provide leakage pathways out of target reservoirs.
- Fault characterization in targets, especially where faults extend into caprock and overlying formations, is vital as part of any risk assessment for CO_2 storage.

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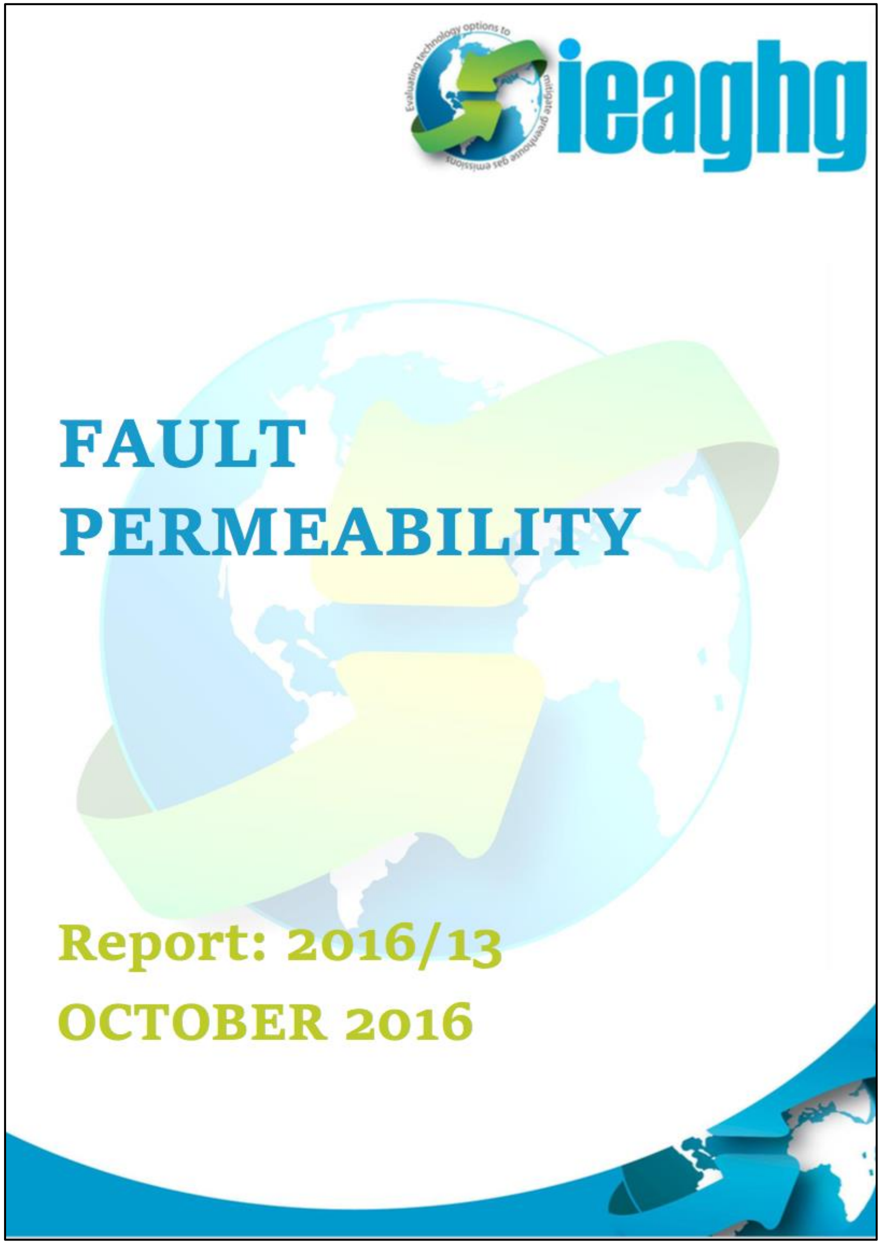
IEAGHG Report

Aim: Use publically available literature to examine when, where, and how faults may negatively or positively impact the storage and migration of injected CO_2.

IEAGHG, 2016. Fault permeability. Report 2016/13. October 2016.



ieaghg

FAULT PERMEABILITY

Report: 2016/13

OCTOBER 2016

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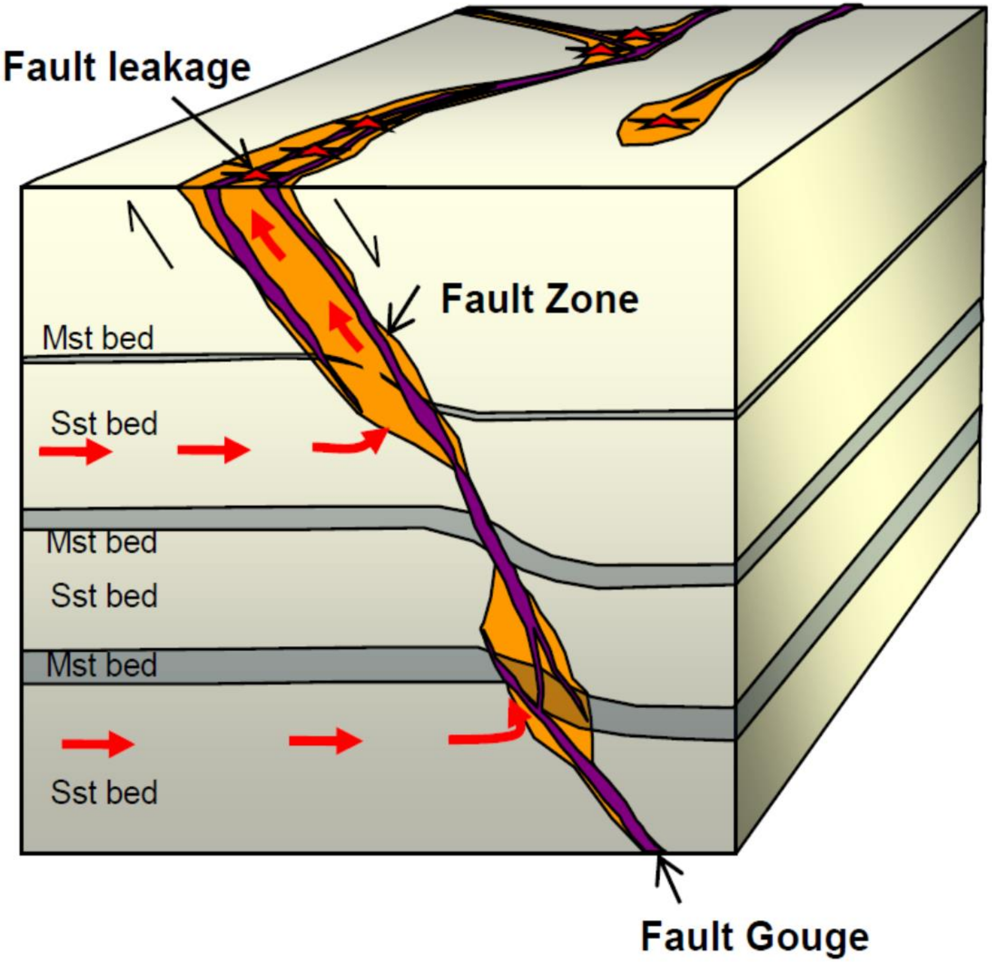
Role of Faults in a CO_2 Reservoir



- Faults act as seals and fluid migration routes in a reservoir.
- Fluid flow focused along faults at irregularities.
- Larger faults have higher flow rates.
- Predicting sites of fluid flow difficult with incomplete geomechanical and fault geometry data.

Role of Faults in a CO_2 Reservoir

Fault-zone permeability is controlled by many interdependent factors:

- Fault zone architecture (connectivity, aperture).
- Fault rock type
- The mechanical strength and permeability of the reservoir lithology
- Relationship between faults and the in-situ stress field.
- Pressure and gradients
- Fluid composition
- Extent of pre-existing mineralization

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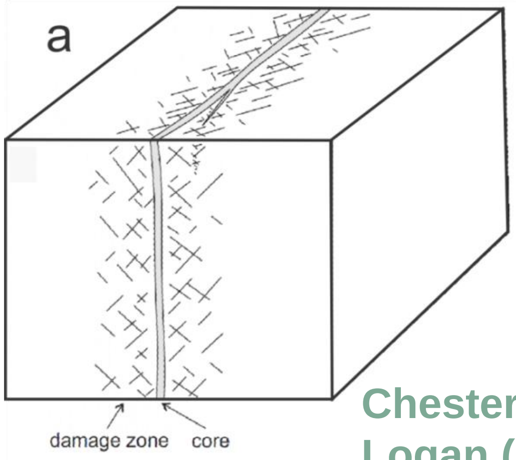
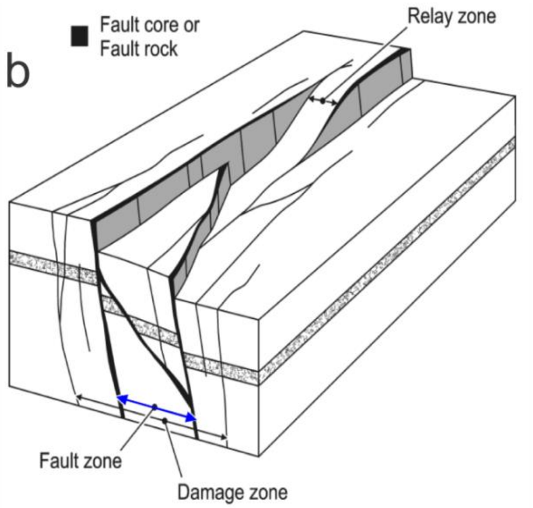
Fault Zone Architecture



Chester & Logan (1986)



Childs et al (2009)

- Fault zone structure is often complex.
- Rarely are they simple single planar features.
- Fault zone structure is dominated by lenses rather than planes.
- Faults are zones of deformed material not discrete surfaces.

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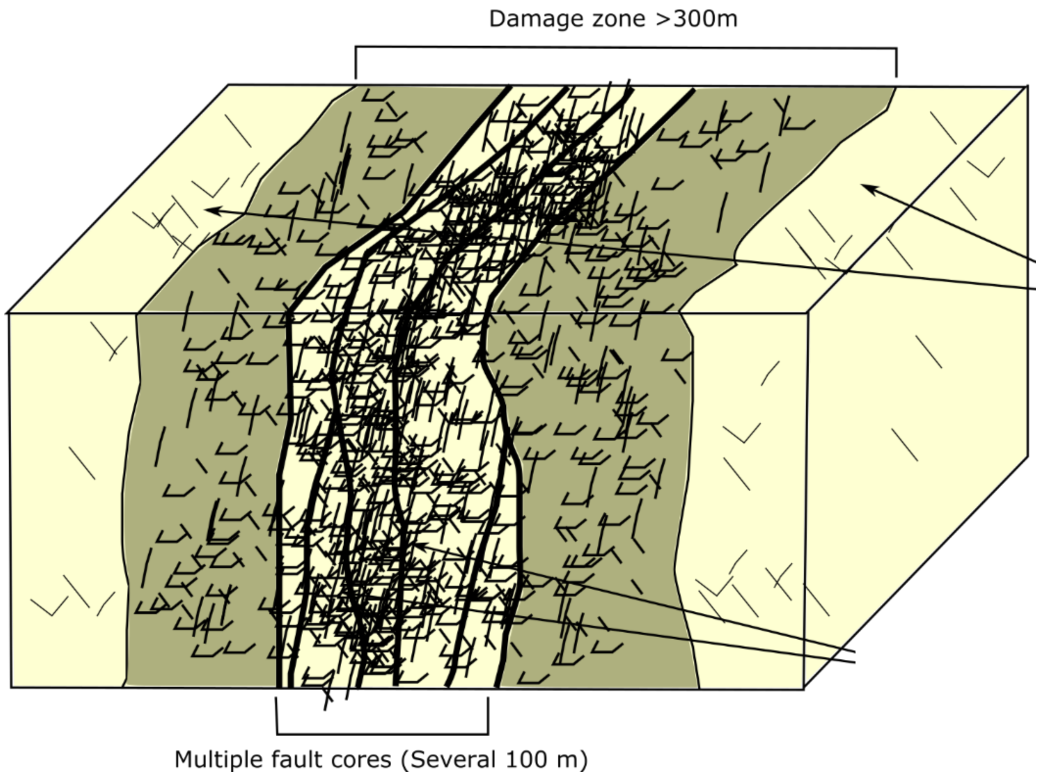
Fault Zone Architecture

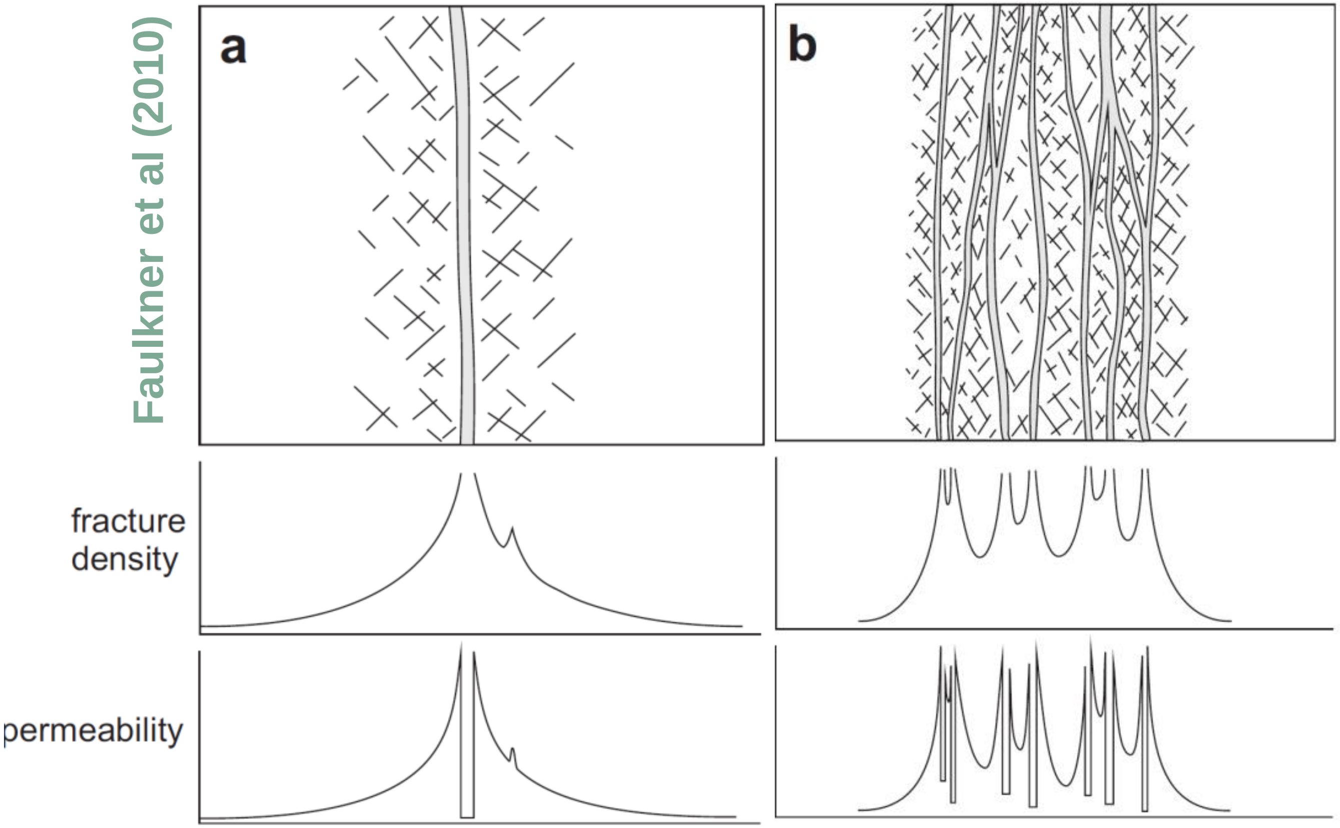


- Fault zones are 4-dimensional volumes of deformed rock with highly anisotropic and heterogeneous properties that evolve through time.

- Fault-zone complexity produces property variations along strike and down dip, which even over short distances (e.g. 4 m wide fault zone) can show at least three orders of magnitude permeability changes

Fault Rock Type & Permeability

Fault-zone complexities produce variations in structure and permeability along strike and down dip



Over relatively short distances faults zones can show at least three orders of magnitude variation in permeability.

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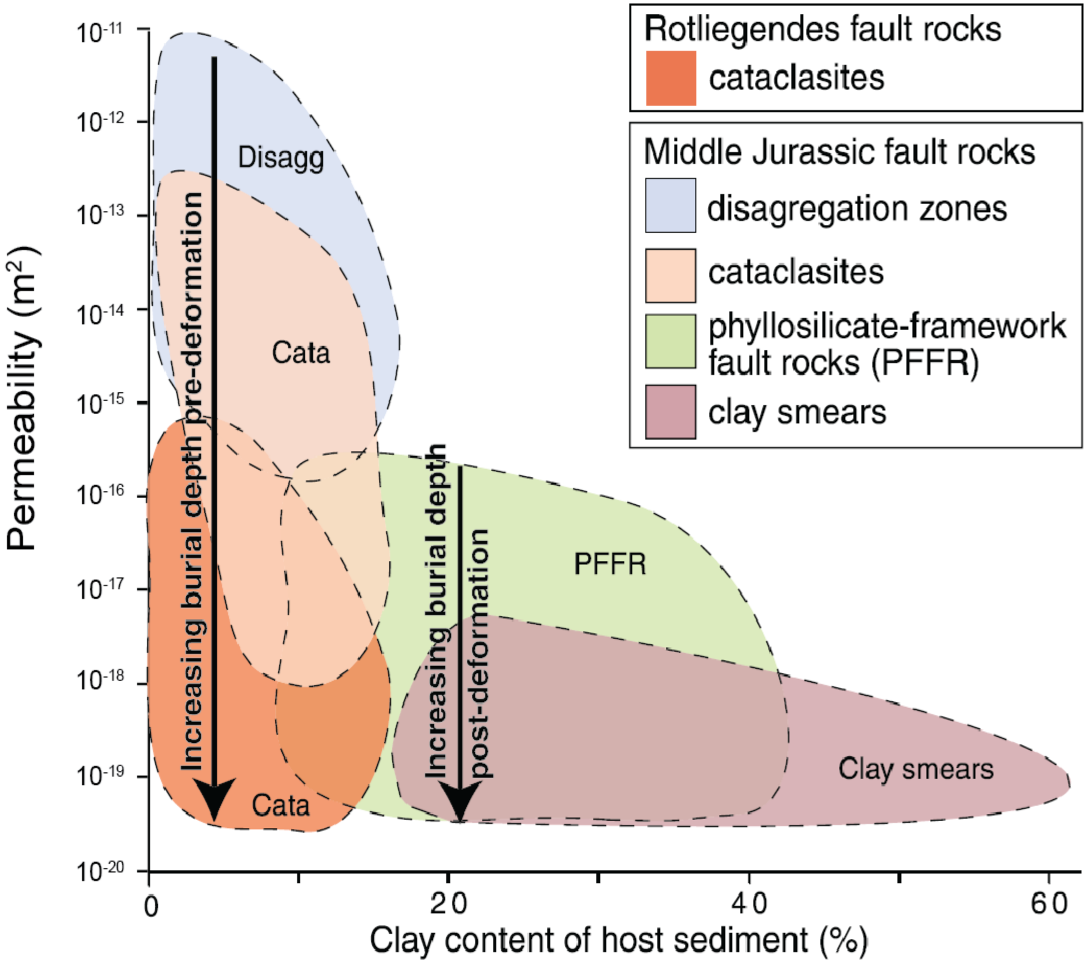
Fault Zone Permeability



Fisher and Knipe (2001)

- Fault core (rock) low permeability clay-rich rock.
- Fault damage zone can have elevated permeability.
- Fault zones impact on fluid flow dependent on many factors including, host rock type, stress conditions, fault zone architecture and depth of burial.
- Individual faults can enhance fault-parallel flow and retard fault-normal flow.

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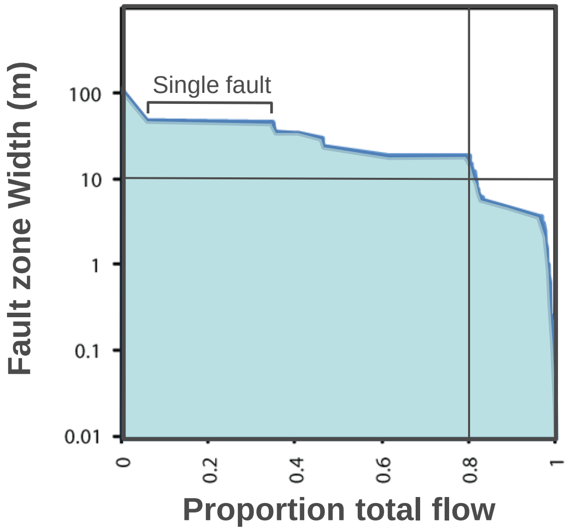
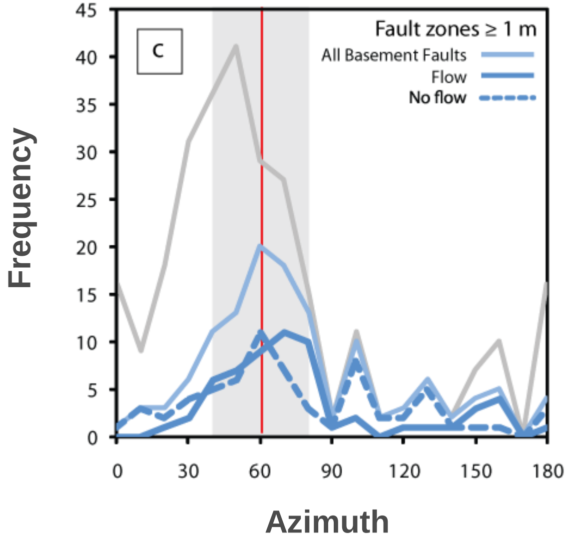
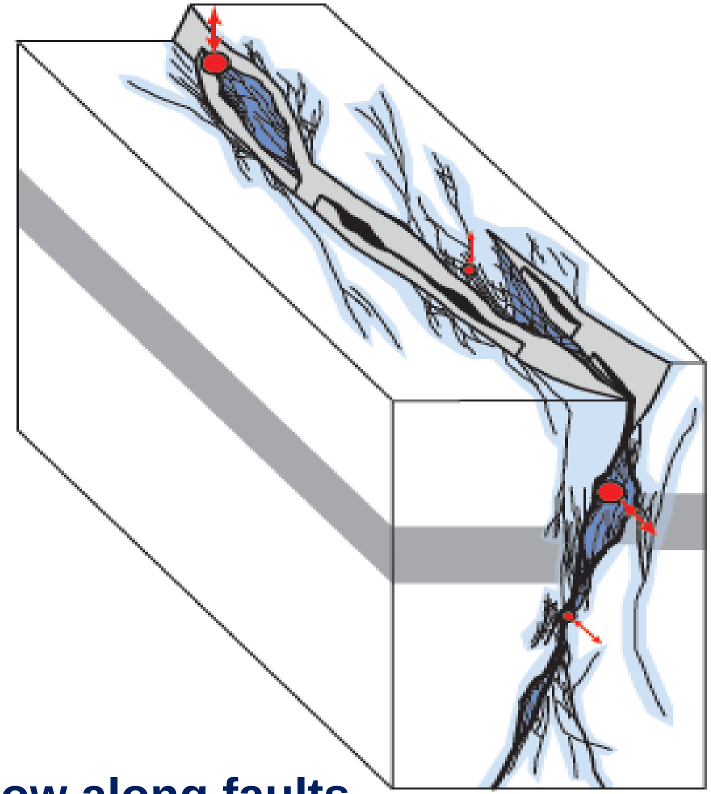
Fault Permeability – Empirical Data





Seebeck et al. (2014)



- ~90% water flow along faults.
- ~80% of flow from <3% of tunnel length (~37 km).
- ~50% of flow from 2 faults.
- Flow rates not strongly influenced by fault strike.
- Widest fault zones have highest flow rates.

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Fault Permeability – Predictive Models

Model Type	Techniques	Output
Shale Smear Algorithms (host rock lithologies and fault displacements)	Clay Smear Potential, Shale Smear Factor, Shale Gouge Ratio	Across-fault transmissibility for fluid flow model (e.g., Eclipse)
Fault Geomechanics (stresses and fault geometries)	Slip Tendency, Fault Stability, Dilation Tendency	Along-fault permeability in fluid-flow models
Geomechanical fluid-flow simulator (rock and fluid properties, stresses and fault geometries)	Fault permeability in dynamic fluid flow reservoir models (e.g. Tough, Tough-flac).	

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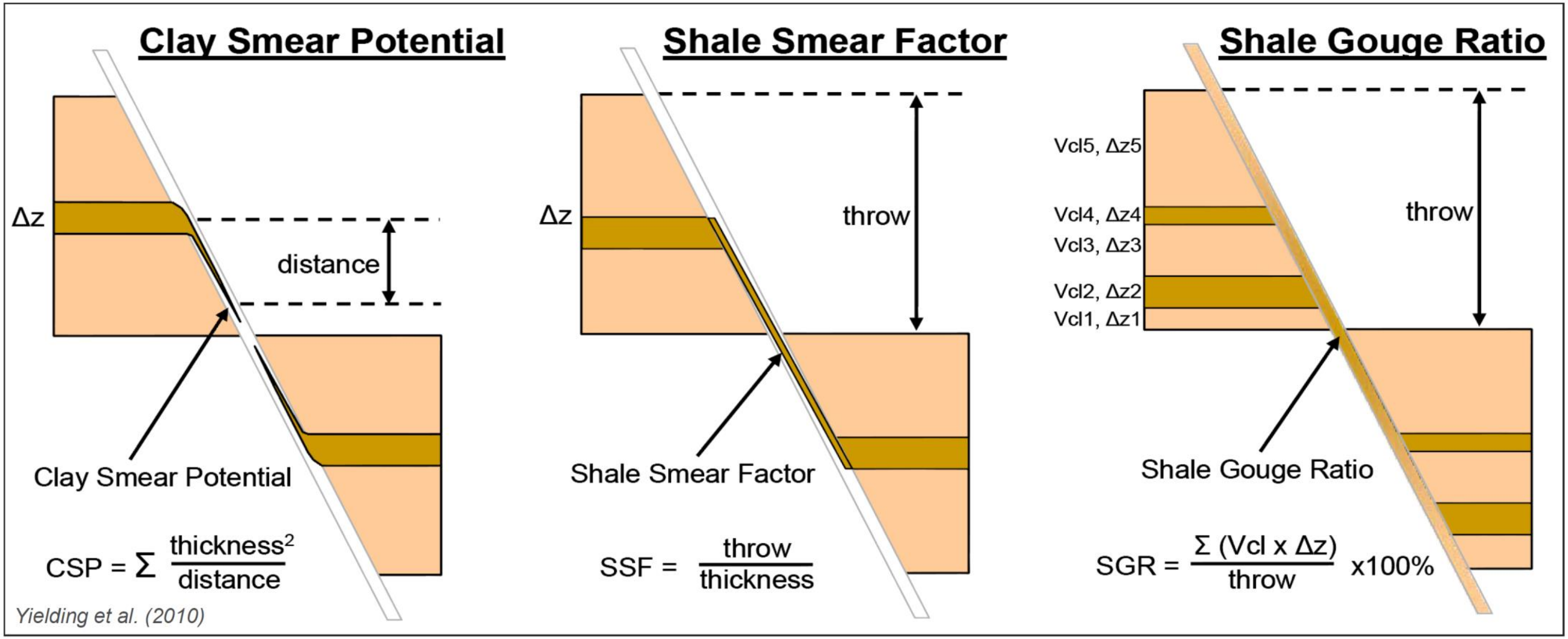
Fault Normal Permeability



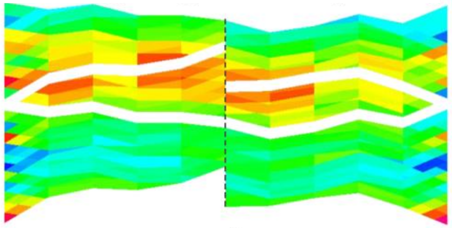
$$CSP = \Sigma \frac{\text{thickness}^2}{\text{distance}}$$

$$SSF = \frac{\text{throw}}{\text{thickness}}$$

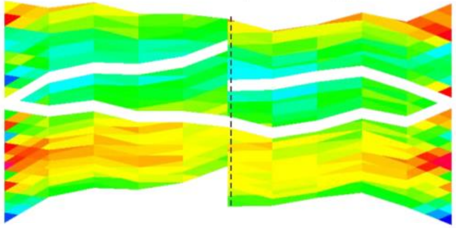
$$SGR = \frac{\Sigma\,(Vcl \times \Delta z)}{\text{throw}} \times 100\%$$

Yielding et al. (2010)

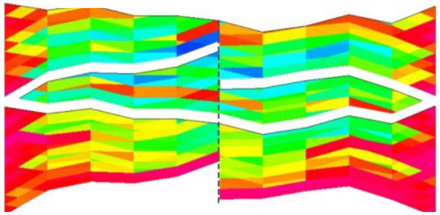
Shale Smear Algorithms and Fluid Flow



Shale Gouge Ratio



Permeability (*Kf*)



Transmissibility multiplier

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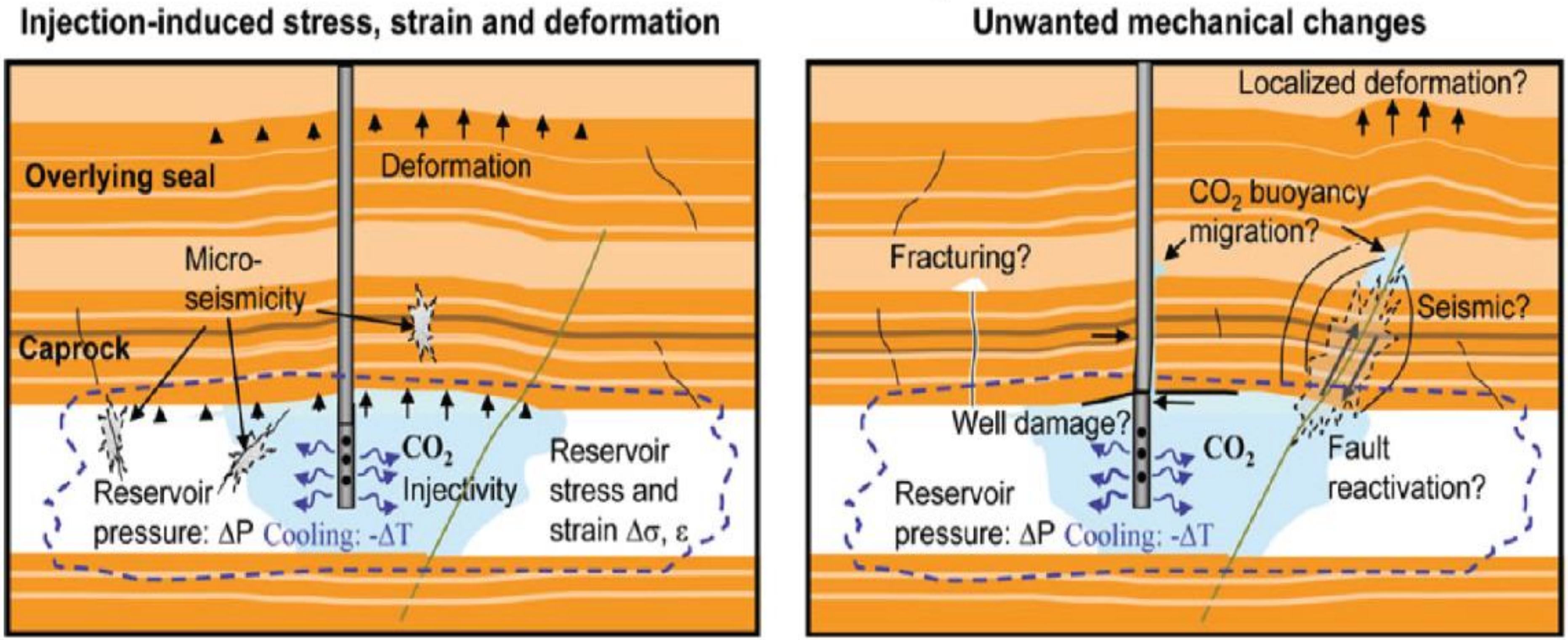
CO_2 Reservoir Scale Geomechanical Models

Schematic model CO_2 storage project

Rutqvist 2012



- ❖ **Geomechanical models can be matched with reservoir performance.**
- ❖ **Flow simulation modelling suggests that low-permeability fault rock may compartmentalise reservoirs giving rise to increased pressures and promoting upward flow of CO_2.**

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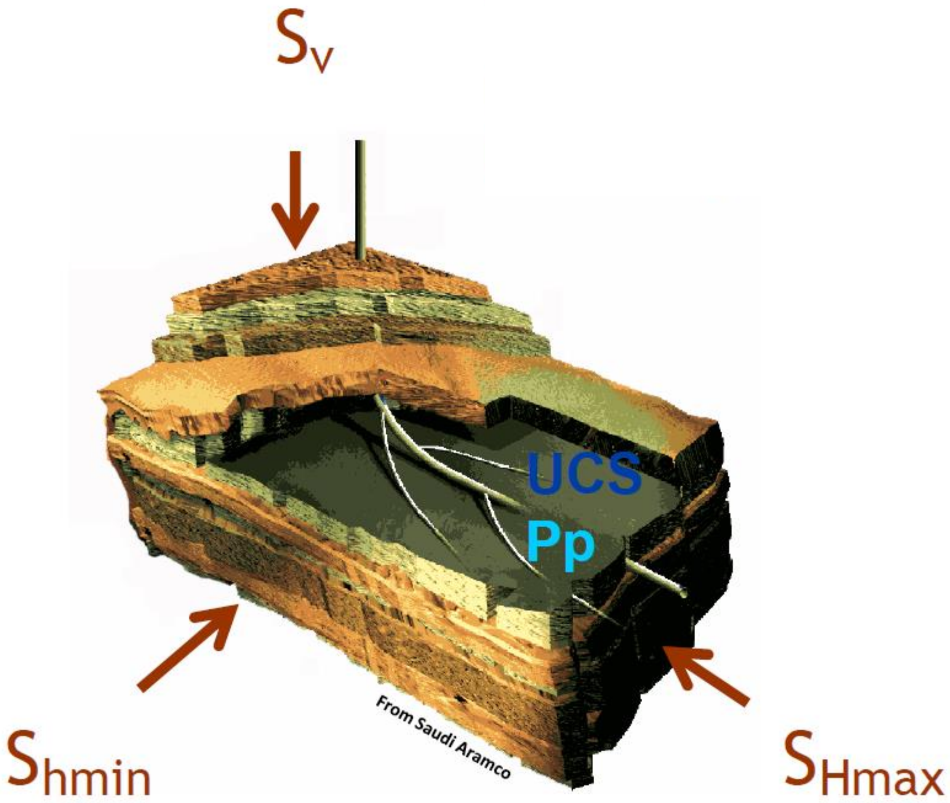
Predicting Fault Migration Pathways



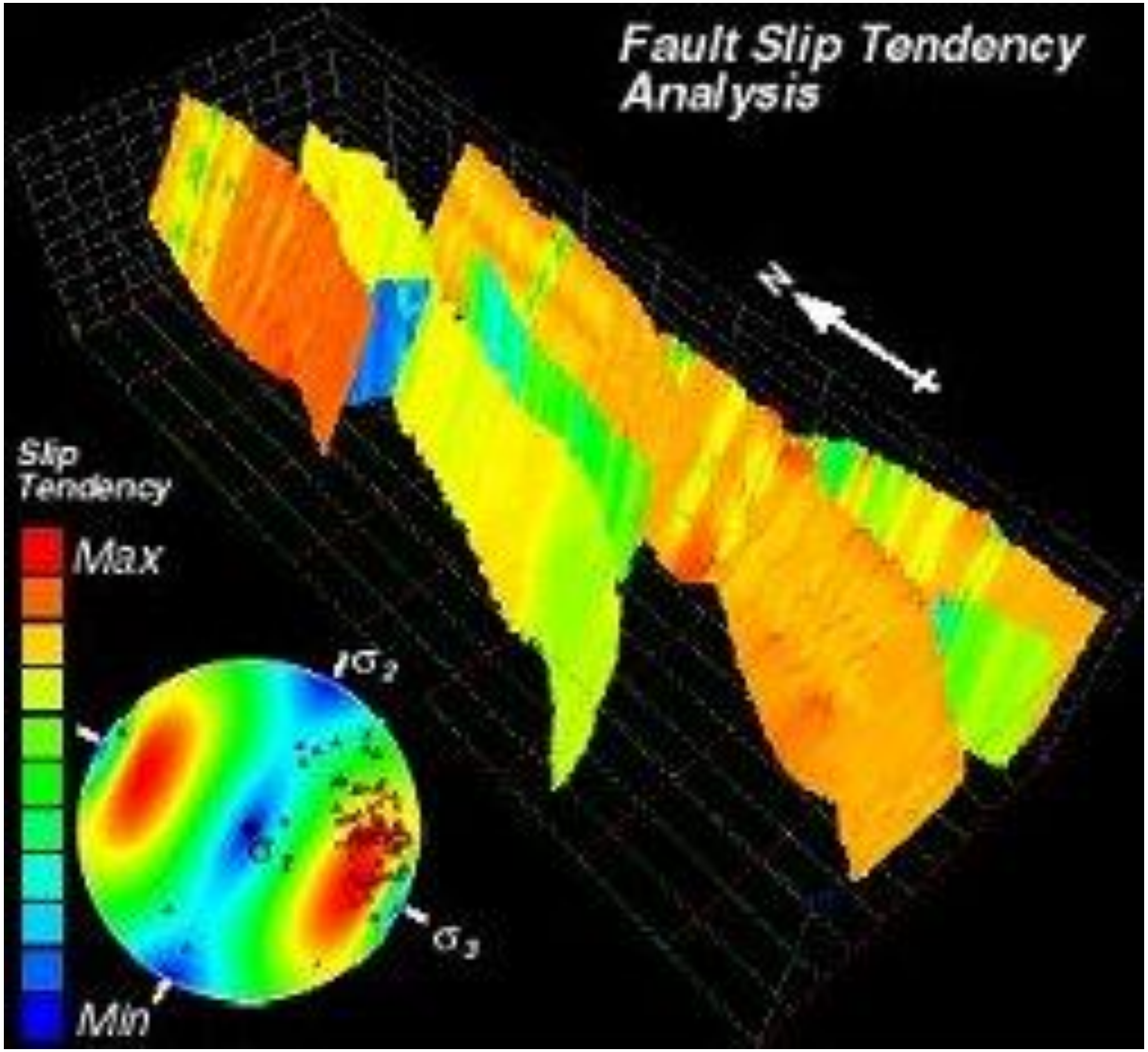
From Saudi Aramco

Geomechanical models of faults allow identification of their likelihood to slip and dilate allowing fluid escape.

Requires knowledge of:

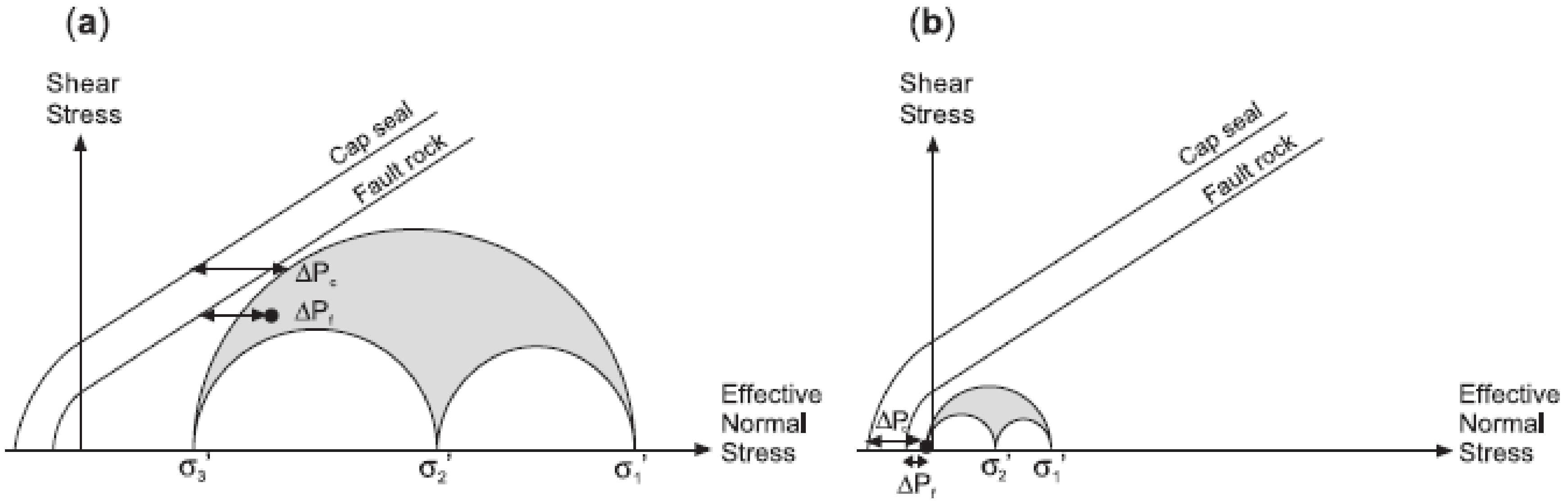
- **Structural architecture of subsurface**
- **In-situ stress orientations**
- **In-situ stress magnitudes**
- **Pore pressure monitoring data (both pre, during, and post activity)**
- **Rock strength properties (UCS, tensile strength).**

Predicting Fault Migration Pathways



Combining data on the stress field and 3D fault orientation you can use geomechanics to determine which faults in a reservoir are likely to slip and possible rupture your seal rock.

Geomechanics and Critical Risk



a) Critical Risk – Fault Reactivation in Shear

A fault suitably oriented for shear reactivation in the reservoir is a higher risk to the resource than cap rock failure.

b) Critical Risk – Fault Reactivation in Tension

A fault suitably oriented for tensile reactivation in the reservoir is a higher risk to the resource than cap rock failure.

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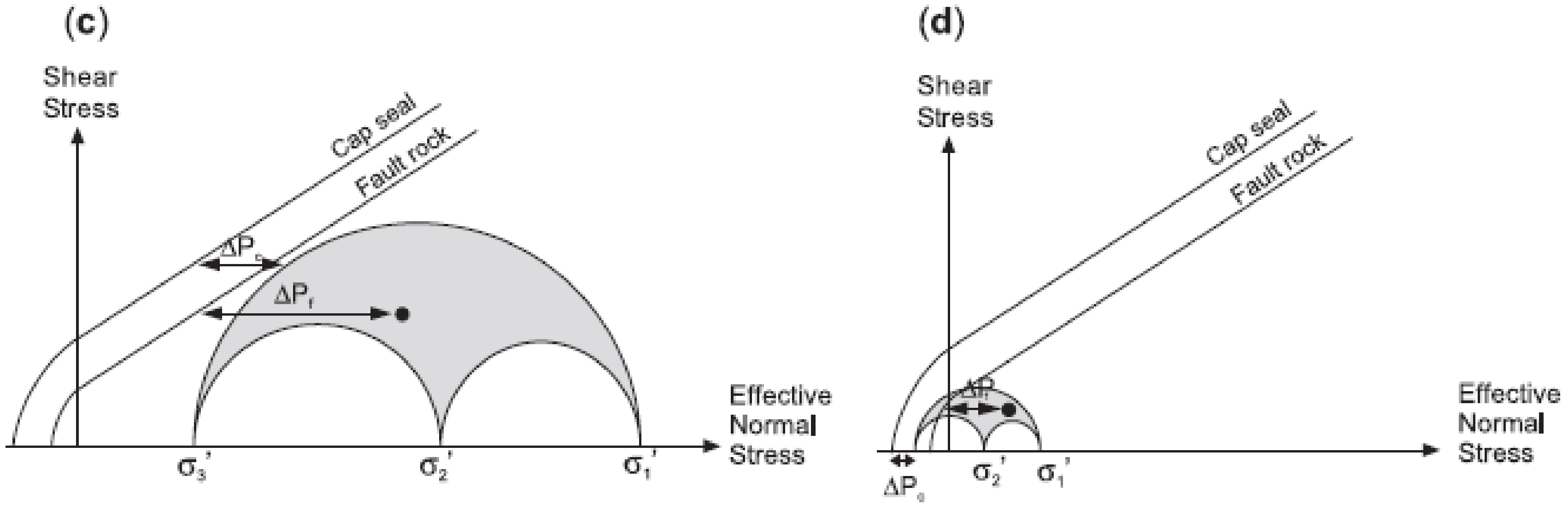
Geomechanics and Critical Risk



c) Critical Risk – Shear Failure in the Cap rock

Fault not suitably oriented for reactivation in the reservoir and so shear failure of the cap rock is a higher risk to the resource.

d) Critical Risk – Tensile Failure in the Cap rock

Fault not suitably oriented for reactivation in the reservoir and so tensile failure of the cap rock is a higher risk to the resource.

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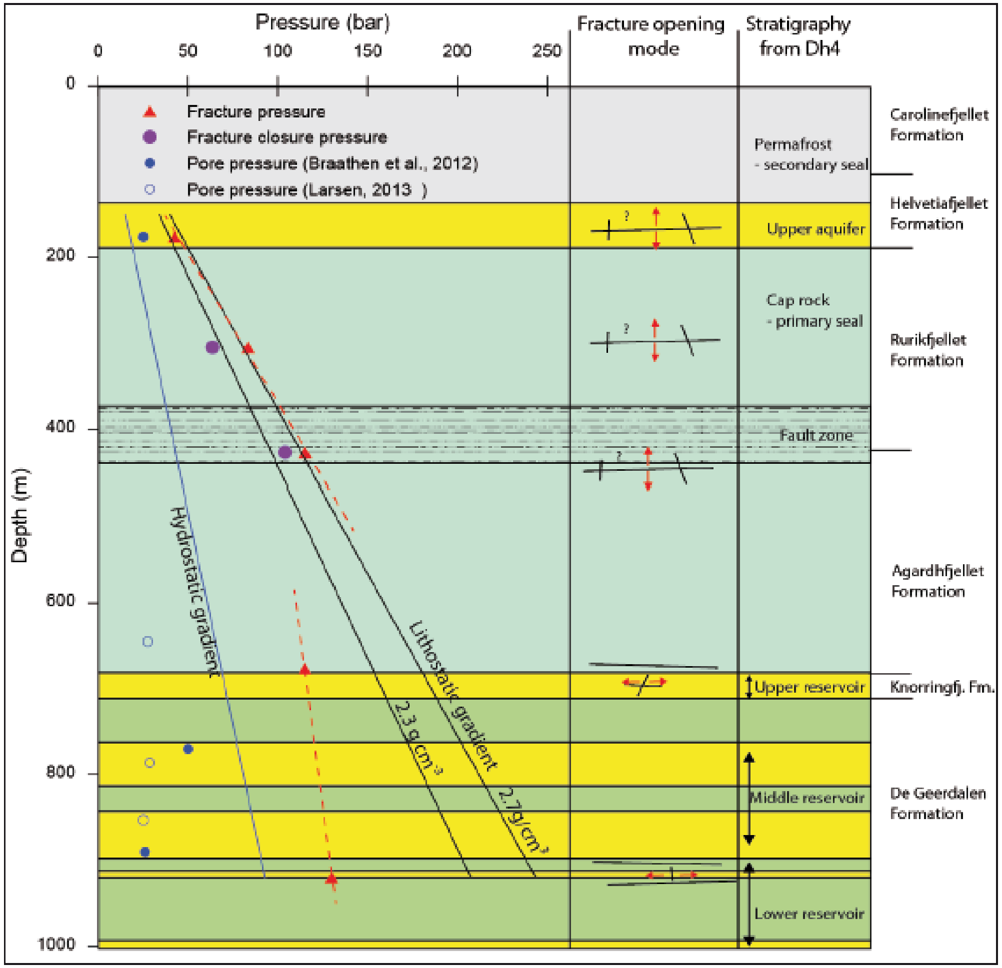
Stress and CO_2 Storage - Longyearbyen

- Lithologies have pre-existing fractures and high tensile strengths an so are unlikely to fail by new structures, but may fail along existing ones.
- σ_3 in the reservoir overburden is low and close to S_v in areas.
- Thus the opening of vertical fractures ($P_p > \sigma_3$) and horizontal fractures ($P_p > S_v$) are equally possible.
- Vertical migration of injected CO_2 depends on if reservoir pressure > σ_3 or S_v and how connected the existing fracture network is.



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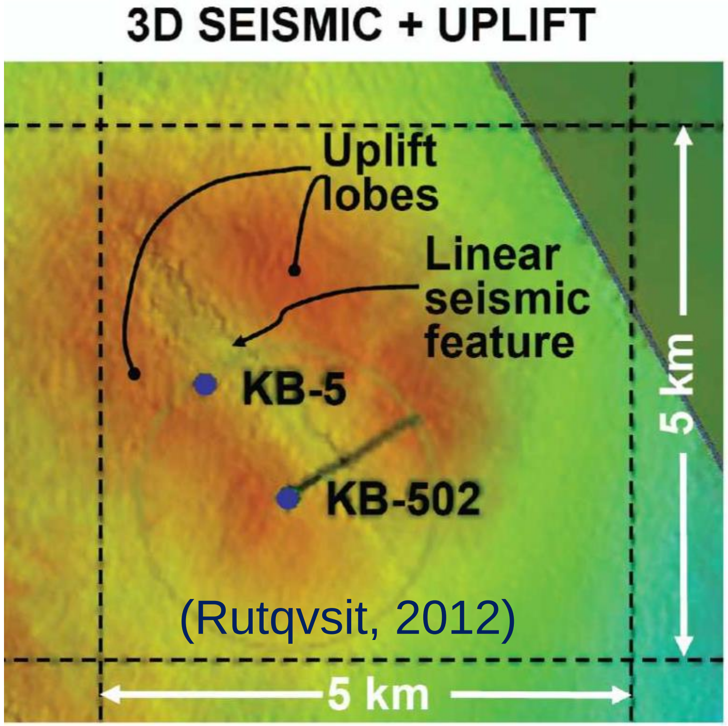
CO_2 Reservoir Scale Geomechanical Models

Rutqvist et al., 2016 – Lessons from recent modelling

Heterogeneous fault properties, commonly encountered in faults intersecting multilayered shale/sandstone sequences, effectively impede upward CO_2 leakage.



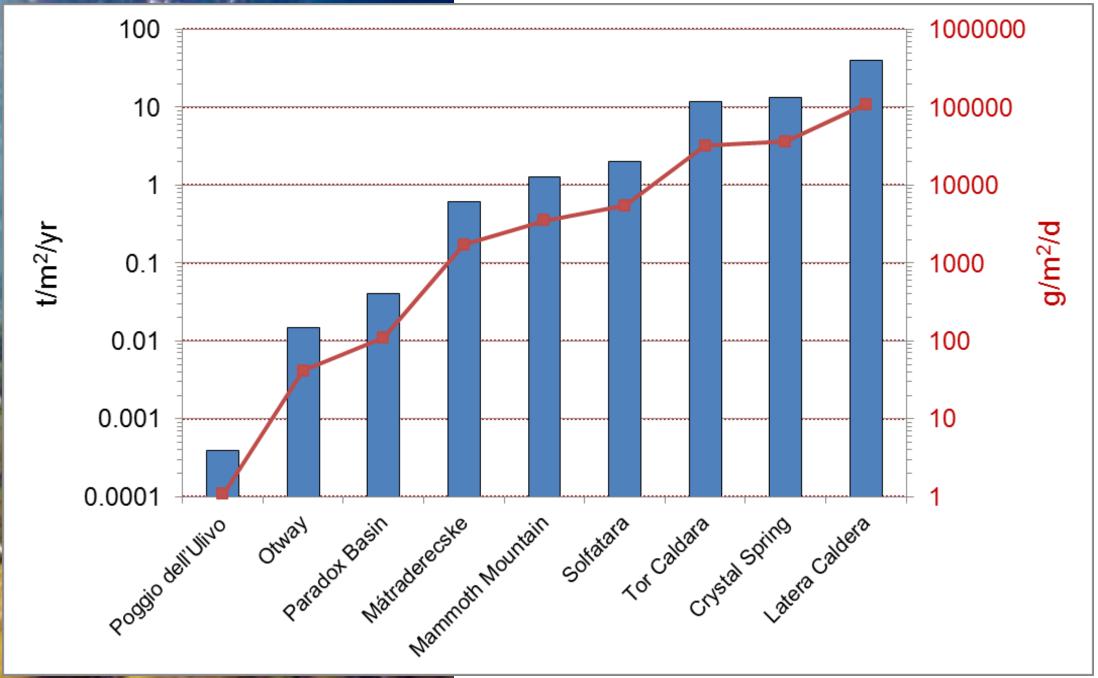
(Rutqvsit, 2012)

Simulations show that a sizable seismic event may not open a new flow path across the entire thickness of an overlying caprock and is unlikely to cross multiple overlying caprocks.

Site specific model simulations of In Salah CO2 storage site show deep fractured zone responses and microseismicity occur in the brittle fractured sandstone reservoir, but require reservoir overpressure close to the magnitude of the least principal stress.

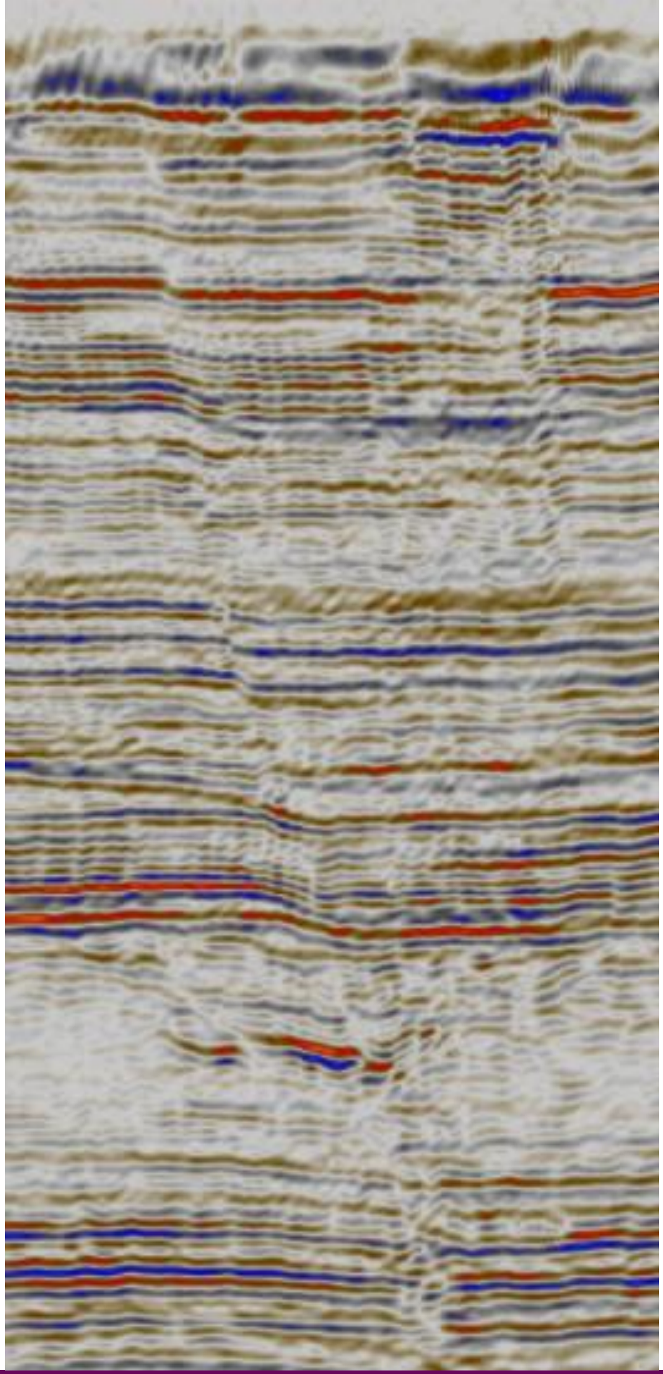
Natural CO2 Fault Seeps

Panarea Island, Greece (Canamarra et al., 2011).



- Sample biased towards high values and not inferred to be representative of CO_2 storage sites.
- Natural seeps show that faults can promote the upward flow of CO_2.
- Migration and leakage rates along faults of up to 1000 m/yr and 15000 t/yr, respectively, possible.
- These rates are site specific.

Recommendations for Future Research



- ❖ Improved definition and quantification of fault hydraulic properties (reservoir and caprock),
- ❖ Continued development and sensitivity testing of fault seal and geomechanically-derived permeability predictions,
- ❖ Validation of flow models using empirical fluid flow data from fault zones,
- ❖ Incorporation into risk assessment.

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Risk Assessment Guidelines

- Faults represent risk of migration of injected CO_2
- No specific guidelines for how faults should be treated in a risk assessment framework.

Guidelines development could address key questions including:

i) Under what geological and stress conditions are faults likely to constitute a leakage risk and warrant further investigation or avoidance?
ii) What monitoring of faults is necessary/useful to record along-fault migration?
iii) What constitutes acceptable levels of migration from the geological container and how do we record these migration rates?
iv) What course of action should be taken if migration exceeds pre-defined limits?

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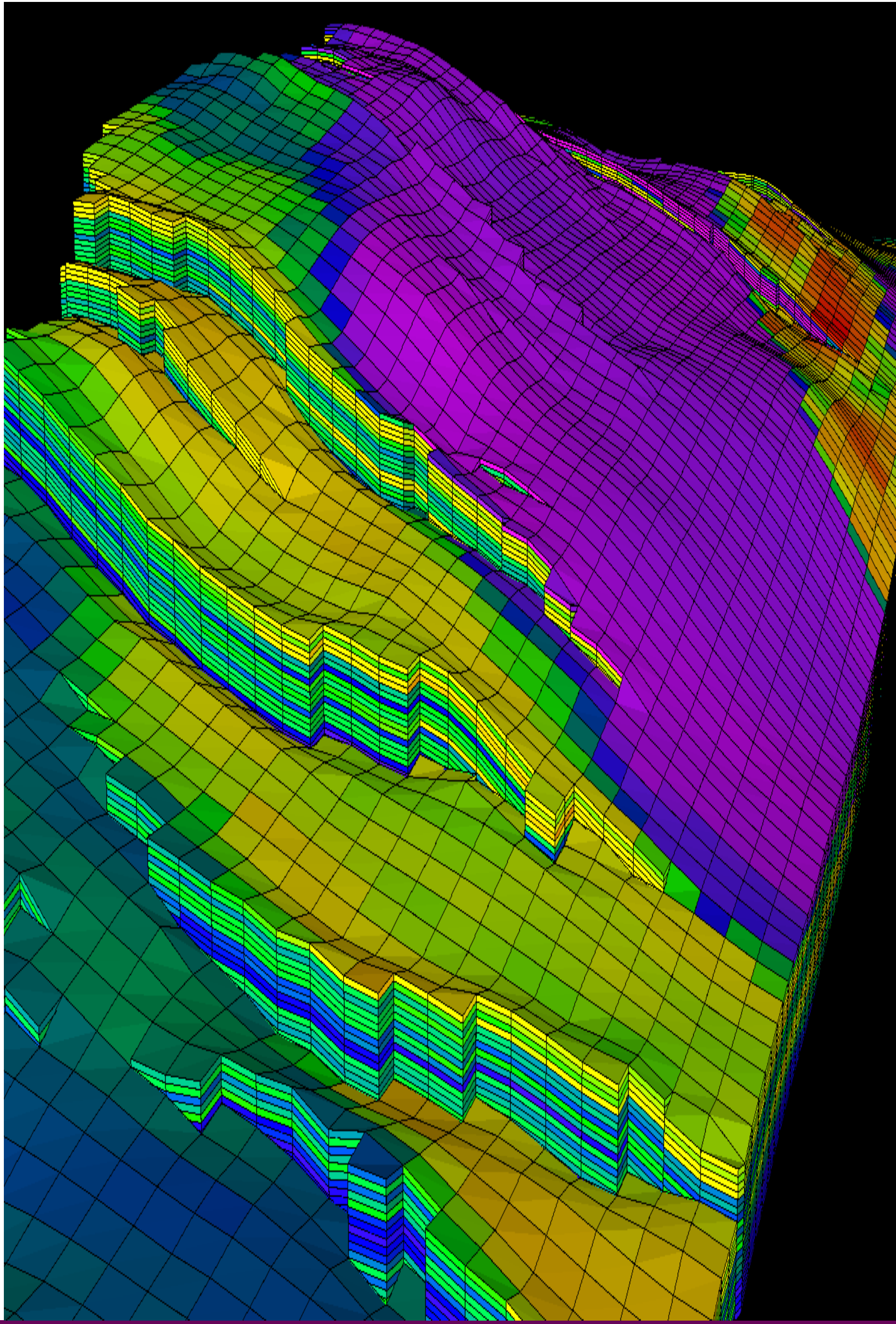
Conclusions

- Faults are complex. They can compartmentalise reservoirs and promote migration of CO_2.
- Fault permeability is stress, rock type, and fault geometry dependent.
- Along-fault flow can be highly heterogeneous and difficult to predict.
- Leakage along faults at natural seeps can be up to 15000 t/yr.
- In situ flow data are essential for testing permeability predictions and fluid flow models.



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Thank You

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Fault Activation

- A fault represents a plane of weakness in a rock.

- As stresses build up on faults they eventually overcome the strength of the fault rock and reactivate.

- Requires less energy than creating a new fracture, which is why existing faults continue to grow over time.

- The strength/friction that resists fault reactivation slip on that fracture is the **Coefficient of Sliding Friction (μ_f)**.

- This is the shear stress required to reactivate slip on the fracture divided by the normal stress acting against slip.

$$\mu_f = \frac{\sigma_s}{\sigma_n}$$

Fault Activation

- **If the fracture has a cohesive strength (C_f) then the equation becomes:**

$$\mu_f = \frac{\sigma_s - C_f}{\sigma_n}$$

- **The C_f is usually small.**

- **After numerous experiments a rock physics researcher called J.D. Byerlee found the critical shear stresses for rock at low and high confining pressures – Byerlee's Law.**

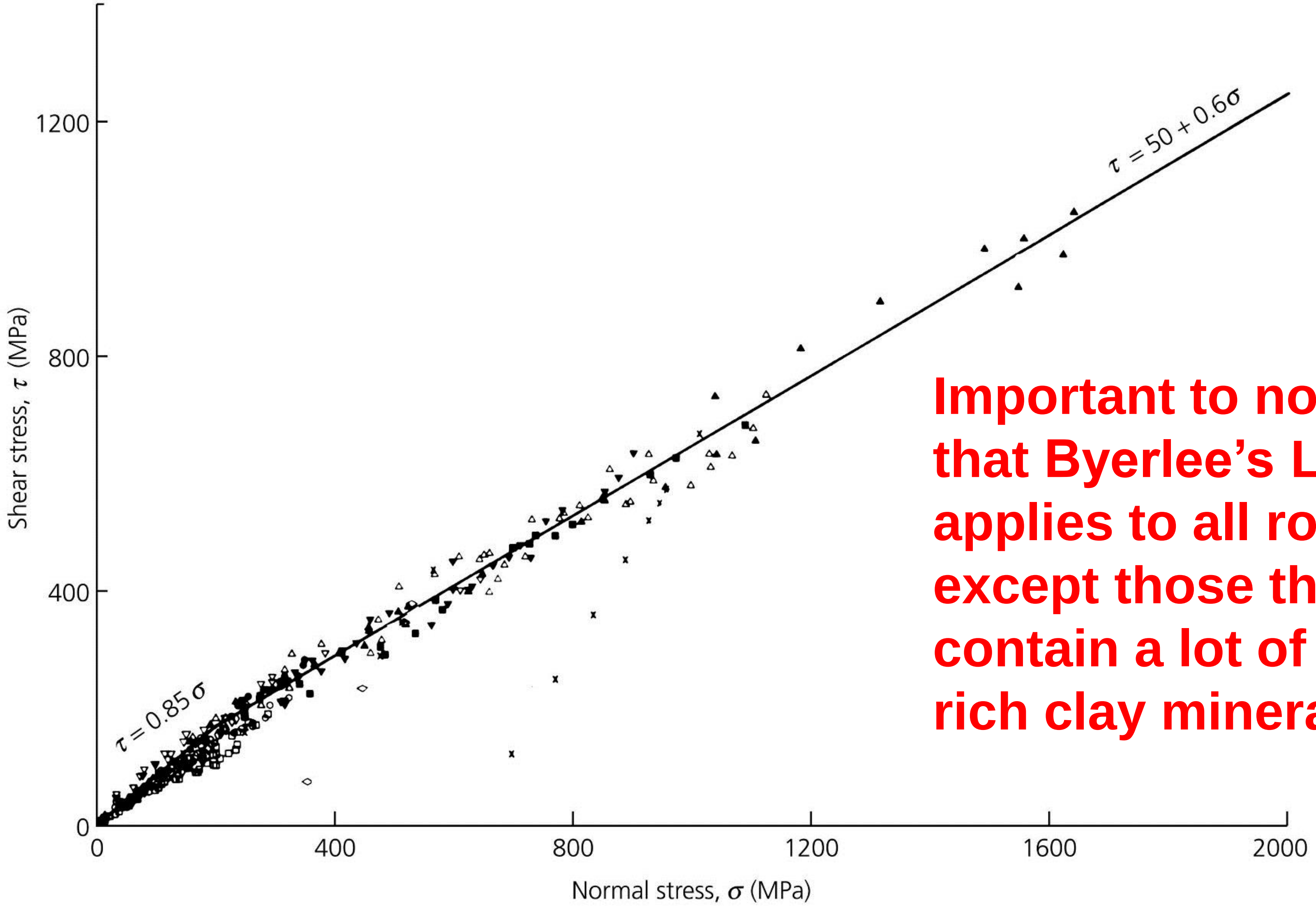
$$\sigma_s = 0.85\sigma_n$$

For σ_s <200 MPa

$$\sigma_s = 0.5 + 0.6\sigma_n$$

For σ_s >200 MPa

Fault Activation



Important to note that Byerlee's Law applies to all rocks except those that contain a lot of H_2O rich clay minerals.

Fault Activation

The Effect of Pore Pressure

- **Pore pressure (P_p) has a weakening effect on rock strength.**

- **Introducing pore pressure means rock strength is now governed by Effective Stress ($\bar{\sigma}$):**

$$\bar{\sigma} = \sigma - P_p$$

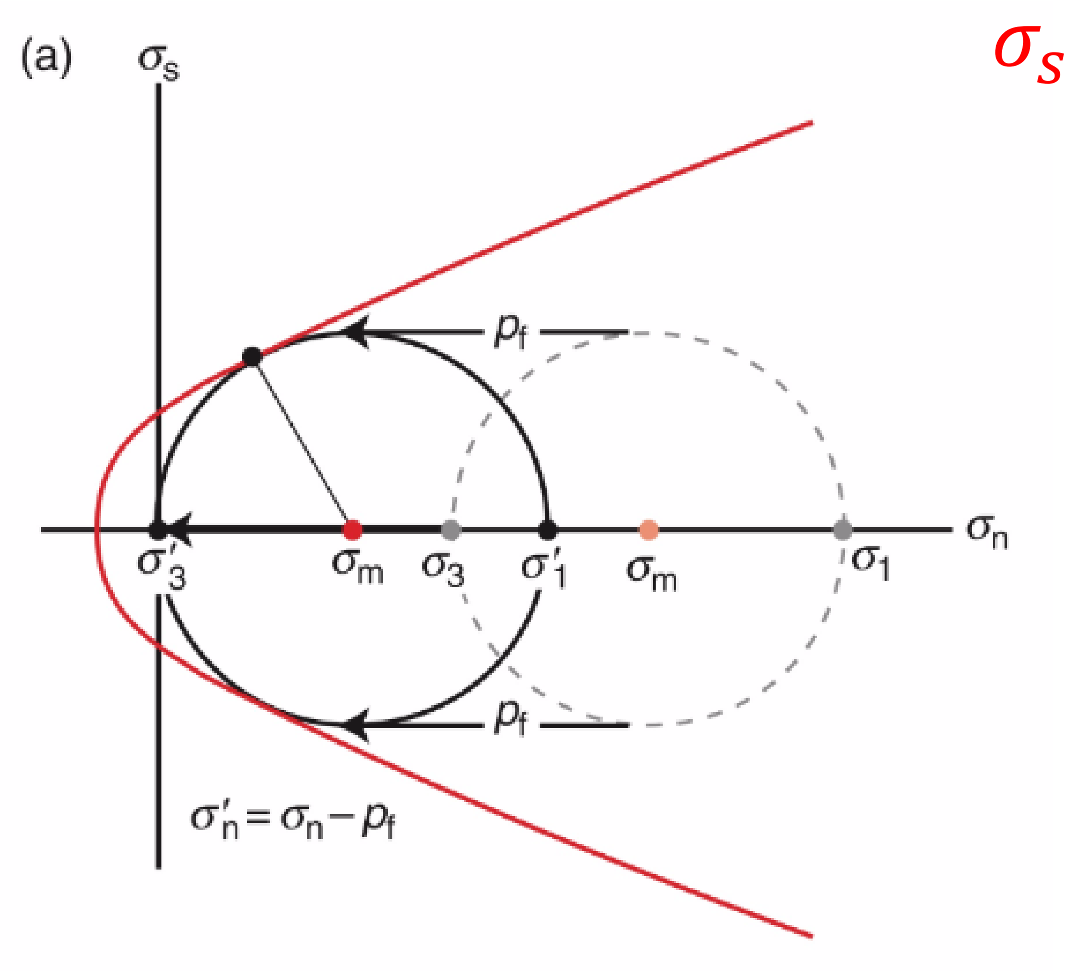
- **Fracture formation will be able to occur at lower differential stresses by increasing the pore pressure.**

$$\sigma_s = \mathrm{C} + \mu(\sigma_n - P_p)$$

Fault Activation

The Effect of Pore Pressure

$$\sigma_s = \mathrm{C} + \mu(\sigma_n - P_p)$$



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