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Impact of fault rock properties on CO2 storage in sandstone reservoirs

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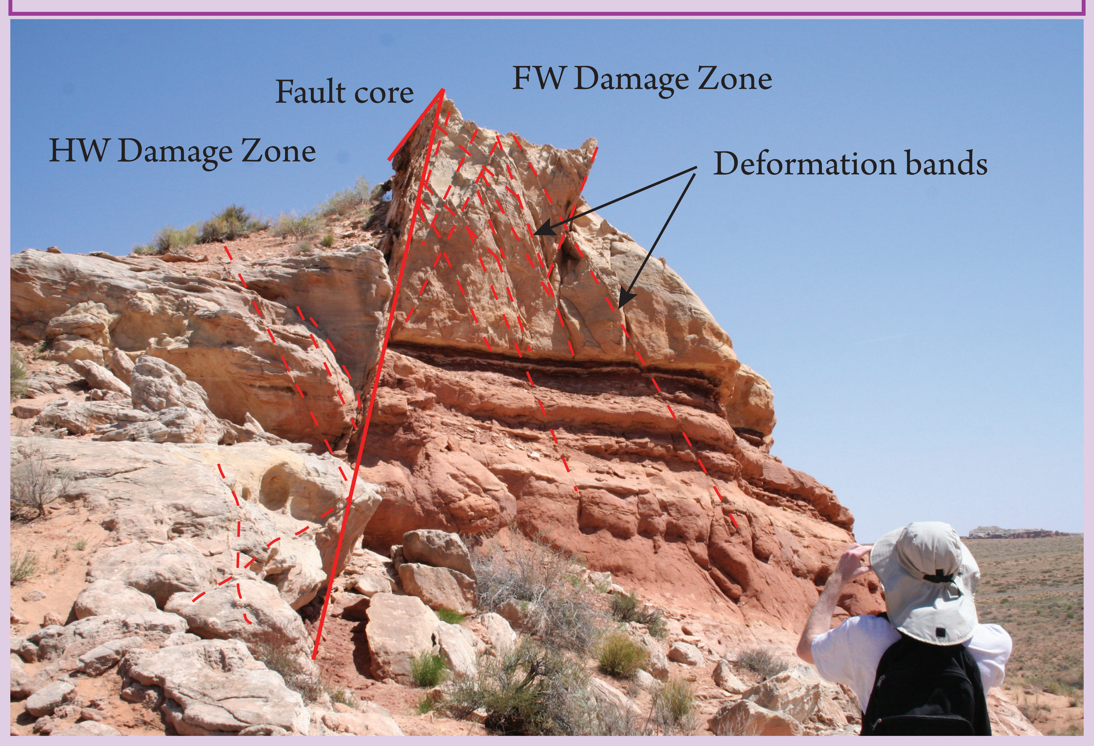
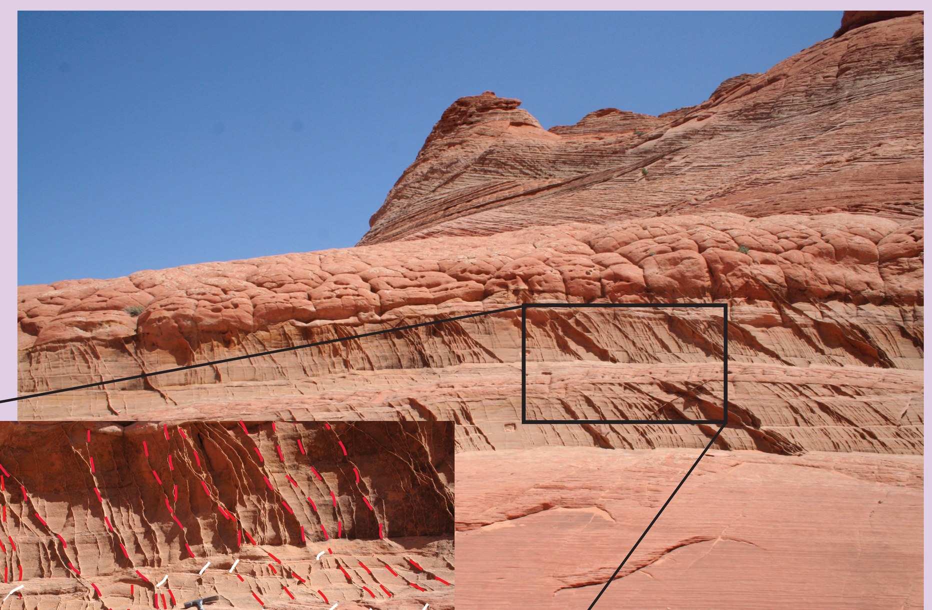
Summary

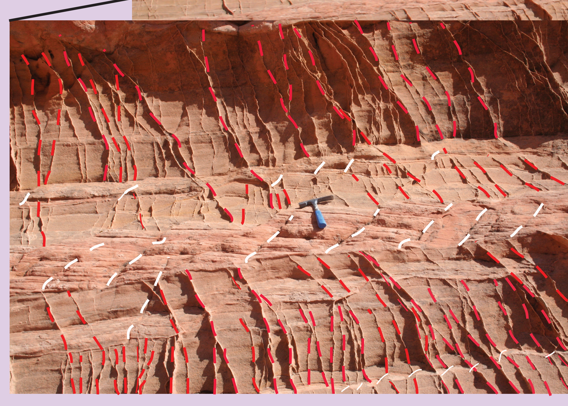
Main challenge in capacity estimation of reservoirs/aquifers for geological storage of CO2 is the geological heterogeneities within the reservoir, specially the presence of sub-seismic fractures, faults and other deformation structures such as deformation bands. An optimal CO2 storage reservoir needs to have high porosity and permeability and right communicational properties. Within sandstone reservoirs, deformation bands and faults may act as barriers, introduce compartmentalization and hence reduce the injection rate and the total capacity of the reservoir or compartments. In addition, CO2 injection in reservoirs creates a fluid pressure increase, which leads to changes in the stress state of the aquifer/reservoir and the surrounding sealing rocks. This might affect and reactivate faults both within and around reservoir, which might have undesirable consequences. The main challenge is to enhance our understanding of the processes and products of brittle deformation in porous sandstone in order to forecast the distribution and impact of faults on reservoir/aquifer performance and seal properties.This will contribute to improve risk assessment and optimized planning for the choice of reservoir for CO2 storage.
In the light of this, our main focus within our ongoing research have been to rise to the above challenge by an integrated, cross-disciplinary, comprehensive study which combines analysis of empirical outcrop and possibly subsurface data, experiments using physical analogues, microstructural analysis and numerical modelling. Our research based on natural and analogue examples reveal that faults and their associated deformation structures in sandstone reservoirs can reduce the petrophysical properties of porous sandstone considerably (Tveranger et al.2008; Braathen et al., 2009). Permeability is decreased up to 4 orders of magnitude within deformation bands (Torabi & Fossen, 2009). On the other hand, the thickness, microstructure, and hence the petrophysical properties of faults and deformation bands can change along them at short distances, changing and in most cases reducing the ability of faults and bands to act as barriers to fluid flow (Torabi et al., 2008; Torabi & Fossen, 2009).

Examples of different deformation structures in siliciclastic rocks that affect the petrophysical properties of reservoirs/aquifers:

Fault core and damage zone in siliciclastic rocks, Goblin valley, Utah, USA



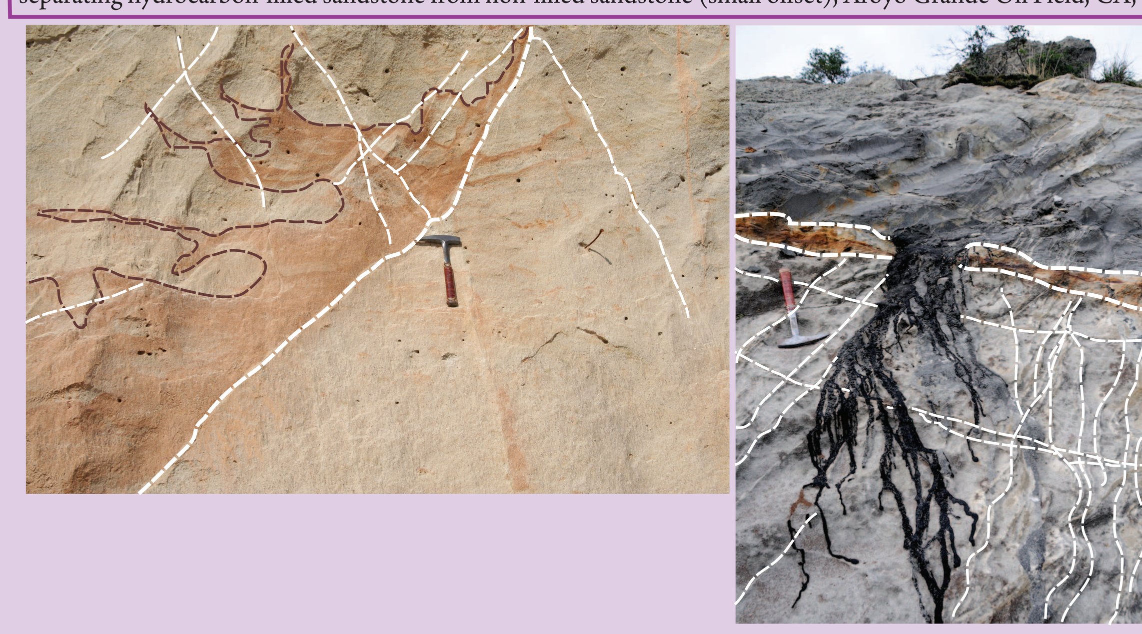




The interplay between compaction bands (red) and shear bands (white), Southern Utah, USA

Example of clay smear, Saline Tunnel, Utah, USA

Deformtion bands can hinder fluid flow: the picture to the left shows deformation bands that have influencd the staining pattern of sandstone (Southern France)and the picture to the right shows a deformation band zone separating hydrocarbon-filled sandstone from non-filled sandstone (small offset), Aroyo Grande Oil Field, CA, US.



Research background

Strain localization in geological materials occurs at all scales from intragranular to crustal scale structures. Understanding the process of strain localization and faulting and the resulted changes in the petrophysical properties of faulted/deformed rocks is essential when selecting candidate reservoir/aquifers for CO2 storage. Rudnicki and Rice (1975) proposed a bifurcation analysis based on localization theory to predict the onset of planar localization as a failure mode of brittle rocks. The bifurcation analysis allows sepcifying the strain type within a localized band. There exists a continuous evolution from pure extension bands to compaction bands via dilating and compacting shear bands, with respect to the constitutive parameters of the law (Besuelle, 2001).

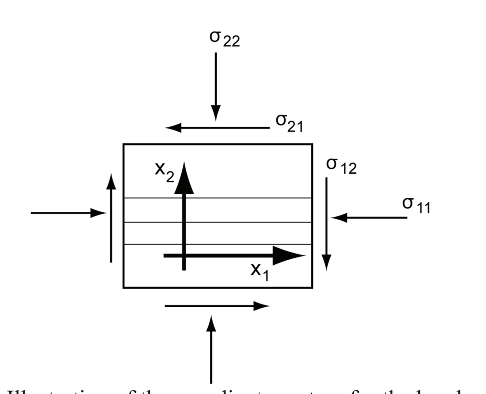
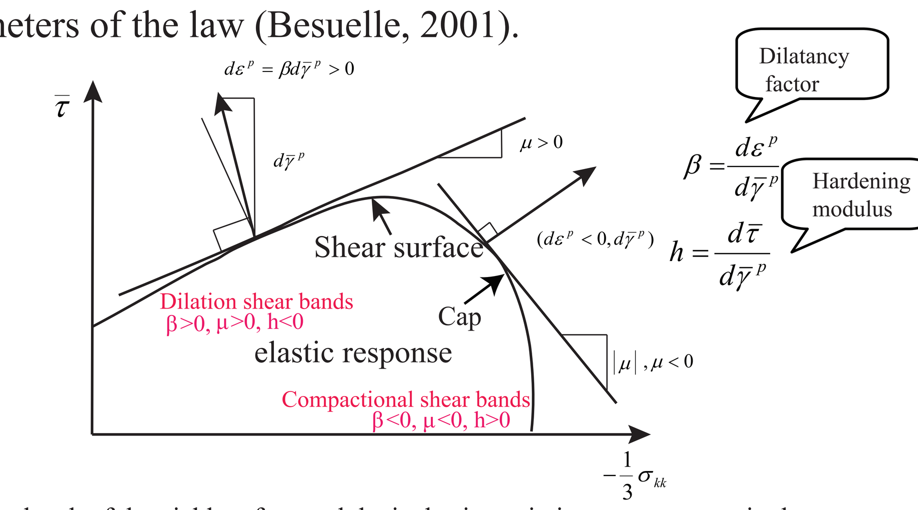


Illustration of the coordinate system for the band of localization, after Rudnicki and Rice, 1975.



sketch of the yield surface and the inelastic strain increment vector in the space of Mises equivalent shear stress versus mean compressive stress. The slope of the surface and the dilatancy factor can be positive or negative.

The Yield condition on the Cam-Cap model is:

$$F(\bar{\tau}, \bar{\sigma}, H) = 0$$

where H is a set of internal variables that keeps tracking the history of inelastic deformation such as microcrack density, dislocation density and inelastic porosity (Rudnicki, 2002).

Shear-driven local tensile cracking and dilatancy occurs on the shear surface.
Pore collapse and grain crushing occurs on the Cap.

However, the quantitative comparison between localization theory, experiments and natural examples of strain loclization in deformed sandstone is not straightforward (Paterson and Wong, 2005). Furthermore, data on compact porous rocks indicate that isotropic hardening model significantly overestimates the amount of softening required for the onset of shear localization (Wong et al., 1997). A constitutive model and localization analysis incorporating more phenomenological complexities (e.g. Chau and Rudnicki, 1990) may provide prediction on the onset of shear localization that are in better agreement with experimental and field observations.

Scope of the current project

1. Improve current understanding of strain localization and subsequent development of brittle deformation structures as a consequence of burial depth and stress level in porous sandstone;
2. Investigate the influence of impurities in quartz sandstone on strain localization and fracture development;
3. Study and identify spatial and temporal patterns in the textural and petrophysical properties of deformed sandstone.
4. Establish the dynamic relation between strain, texture, deformation mechanisms, petrophysical parameters (porosity, permeability, seismic velocity) and their impact on reservoir communication.
5. develop the existing CIPR database on faults and their associated structures within porous sandstone and apply this to risk assessment for CO2 storage.

References

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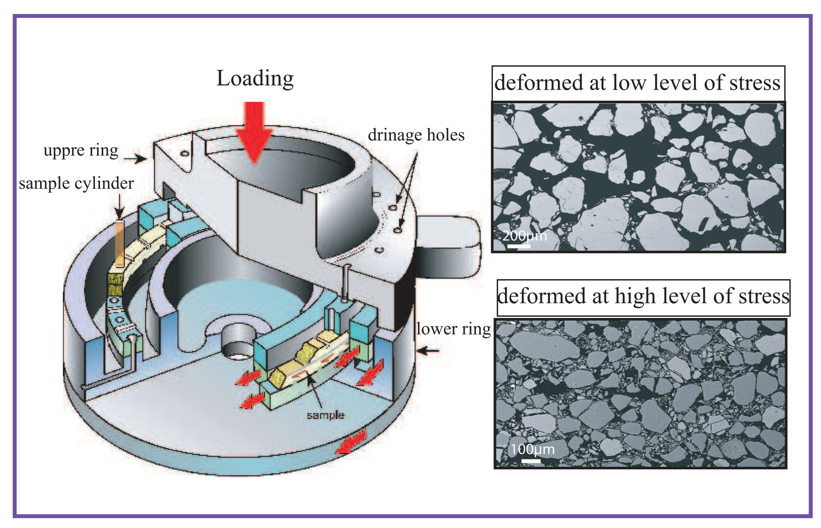
Research tasks and methods

a) The effect of burial depth and material properties on strain localization and development of deformaton/faulting

The impact of material properties on the localization and development of deformation in porous sandstone within a variety of stress levels comprising of about 100m to about 2 km burial depth is investigated through ring shear, triaxial and biaxial experiments supported by numerical back-calculations.



Ring shear experiment (Torabi et al., 2007)

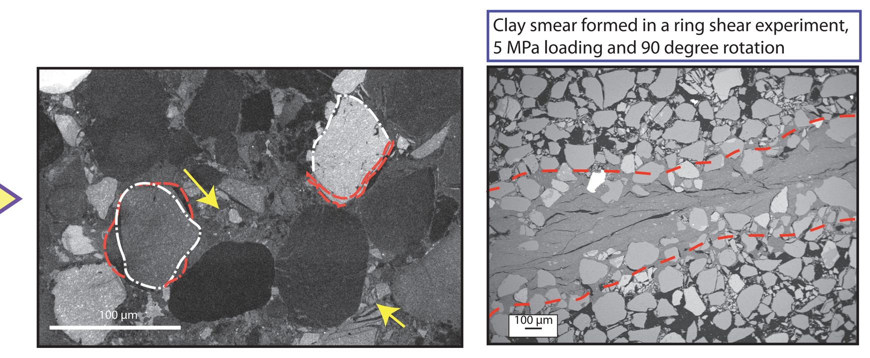
Triaxial/biaxial experiments (Rykkelid and Skurtveit, 2008)

b) The effect of impurities on localization and the process of faulting

The interaction between faulting and cementation with respect to their timing is investigated. The effect of other impurities, such as clay, on the condition for localization and development of deformation will be examined and quantified.

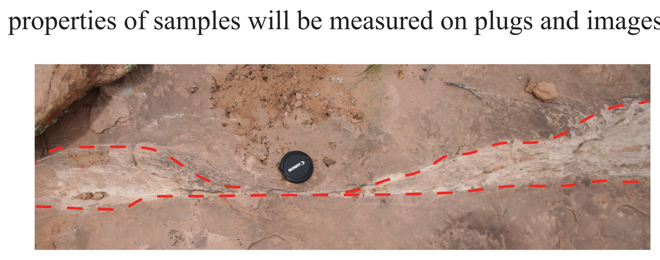
A cathodoluminescence image of a naturally faulted sandstone (Entrada Sandstone, Moab Fault) that shows the interaction bewteen quartz cementation and deformation (cataclasis).Yellow arrows show grain crushing (cataclasis), white dashed lines show the boundary of quartz grains that have been cemented. Red dashed lines show the quartz cementation around quartz grains.

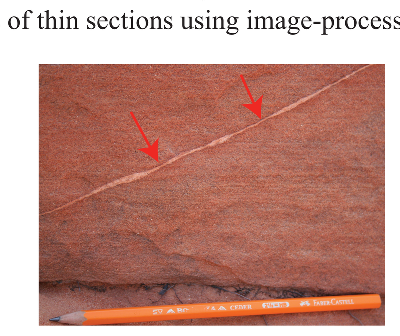
Clay smear formed in a ring shear experiment, 5 MPa loading and 90 degree rotation

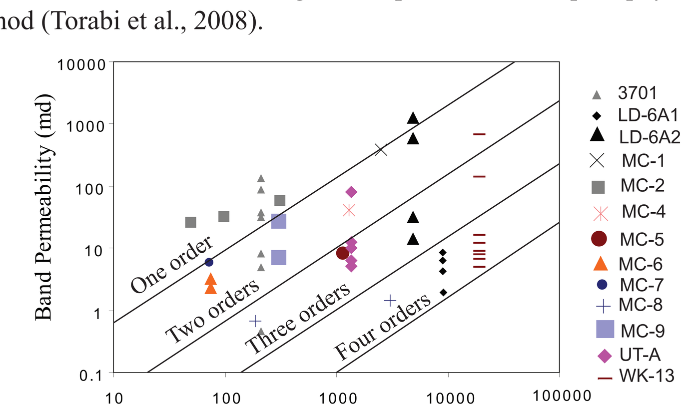


c) Geometric and textural variations along deformation bands and faults within homogeneous sandstone

Natural deformation bands (compaction and shear bands) and faults show significant geometric and textural variations along them. Microstructural study of deformation bands reveal important changes not only in the thickness, but also in the petrophysical properties along them (Torabi and Fossen, 2009). This kind of variation has been observed in outcrop and also through microscopic studies, but has not been appreciated by the theory of localization or the Cam-Cap model or the experimental works. In order to understand the mechanical causes for these variations, a series of triaxial tests supporetd by detailed field investigations and numerical modelling will be performed. The petrophysical properties of samples will be measured on plugs and images of thin sections using image-processing method (Torabi et al., 2008).





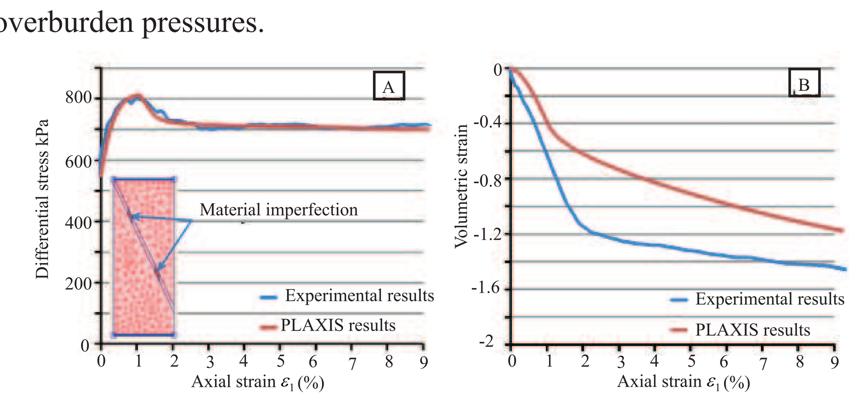


d) Localization of compaction

Observation of natural compaction bands in outcrops does not conform to the Cam-cap model in the sense that the sandstone does not exhibit evidences of high stress (they form in unconsolidated sandstone). Some of the bands show grain crushing (cataclasis). In this project, the condition for localization of compaction in porous sandstone is investigated through the empirical relationship between crushing pressure and initial porosity and grain size by running triaxial experiments at different stress levels comparable to the natural overburden pressures.

e) Numerical modelling

Combining the results of experiments and field observations with numerical modelling gives a unique possibility to develop advanced material constitutive models for the initiation and development of shear failures in soft sediments. A better understanding of mechanisms involved in the development of shear bands will enhance the ability to evaluate the actual properties of fault rocks without direct measurements.



Numerical modelling of plane strain compression test with PLAXIS using a hypoplastic constitutive model for sand. Comparison of global behaviour between experimental and numerical results (NGI, internal report)