Deformation of sandstone reservoirs

Insight from experiments and field studies

Elin Skurtveit

Dissertation for the degree philosophiae doctor (PhD)

at the University of Bergen

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Scientific environment

The research presented in this thesis is part of the Impact of fault rock properties on CO_2 storage in sandstone reservoir (IMPACT) project at the Center for Integrated petroleum Research (CIPR – Uni Research) in Bergen, Norway, where the PhD got funded and were officially performed. The Research Council of Norway and Statoil ASA funded the project. The candidate has been enrolled at the PhD study program of the Department of Earth Science at the University of Bergen. The main workplace was at the Norwegian Geotechnical Institute (NGI) in Oslo, Norway, where the experimental work was carried out. NGI also contributed with financial support through the internal research fund for education and sabbatical. A research stay was undertaken from October 2012 until June 2013 at the Stress and Crustal Mechanics Group, at the Department of Geophysics, Stanford University, USA and there has been a collaboration with the University of Montpellier, France.

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Professor Roy H. Gabrielsen (University of Oslo)

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First, I would like to thank all my supervisors for all the excellent supervision. Anita Torabi for encouraging me to start on this project, guidance trough all my work and all the nice discussion we have had. Roy H. Gabrielsen, Alvar Braathen and Haakon Fossen for all the fruitful discussion, field guidance and constructive comments to my work. I also like to mention Fabrice Cuisiat for his support and encouragement at the start of this work.

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Preface

This is an article-based dissertation and the work is divided into two main sections and two appendices.

Part I Background and synthesis: This first part describes the aim and motivation for the work, provides the background and stat-of-art for the research and synthesizes the main finding addressed in the various papers.

Part II Included Papers: This part presents the individual papers that are the main contribution of the PhD research.

Appendices: Appendix A includes three papers worked on during the PhD period as part of past and ongoing research activities linked to the main topic of the PhD work. Appendix B includes a list of conference contributions related to the PhD work.

Abstract

Sandstone reservoirs deform as a response to burial, tectonic stress and induced stress changes during reservoir injection or production. The deformation structures observed in reservoirs depend on the deformation mechanisms, lithological variations, degree of lithification and stress conditions. Deformation may be distributed within a reservoir or localized into deformation bands, fractures and distinct fault zones where the petrophysical properties are significantly different. The localization causes heterogeneities in the reservoir that are challenging for reservoir flow and geomechanical modeling. In this work macro- and microstructural analyses of deformation bands observed in field outcrops are combined with high quality mechanical testing to increase our fundamental understanding of sandstone deformation and its implications for reservoir properties.

Field observations from sandstone reservoirs with different degrees of lithification provide insight into different types of deformation structures. Multiple deformation events in the Navajo Formation, Utah show calcite veins forming along pre-existing cataclastic deformation implying temporal changes in flow properties within the fault zone. This study also shows that low permeable deformation bands could become preferential paths for fluid movements and calcite precipitation during fault reactivation. Cementation of the sandstone is found to have a significant impact on both permeability and strength of the rock.

Systematic high pressure triaxial testing is used to provide a better link between stress conditions, sand textural parameters, deformation mechanisms and the formation of microstructures in sand and poorly lithified sandstone from Provence, France. Visualization of deformation using pre-and post-test X-ray imaging and thin sections demonstrate localized deformation fabrics and grain damage. In addition, large inelastic compaction, porosity reduction and increasing P-wave velocity indicate grain rearrangement and grain sliding as important deformation mechanisms. This gradual transition in deformation mechanism from grain rearrangement to grain damage is an important and challenging mechanical characteristic for poorly lithified sandstone. Combining field observations, mechanical testing and detailed sand characterization

indicate that the preferential localization of shear-enhanced compaction bands in a coarse-grained unit is controlled by a combination of higher stress concentration on grain contacts, and faster compaction and increase in relative density compared to the finer grained and well sorted unit.

The findings discussed within this dissertation represent a contribution on integrating knowledge form geological observation with our understanding of mechanical processes and models. Linking the observed deformation structure with deformation mechanisms and conditions for strain localization is believed to provide useful input for flow simulation and geomechanical models for reservoir production and reservoir integrity during CO_2 injection.

List of publications

Paper I:

Skurtveit, E., Torabi A., Alikarami R., and Braathen A. **Fault baffle to conduit developments; reactivation and calcite invasion of deformation band fault in eolian sandstone.** Submitted to Petroleum Geoscience

Paper II:

Alikarami, R., Torabi A., Kolyukhin D., **Skurtveit E.**, (2013), **Geostatistical relationships between mechanical and petrophysical properties of deformed sandstone**, International Journal of Rock Mechanics & Mining Sciences, 63, 27– 38

Paper III:

Skurtveit, E., A. Torabi, R. H. Gabrielsen, and M. D. Zoback (2013), **Experimental investigation of deformation mechanisms during shear-enhanced compaction in poorly lithified sandstone and sand**, Journal of Geophysical Research: Solid Earth, 118(8), 4083-4100.

Paper IV:

Skurtveit E., Ballas, G., Fossen H., Torabi, A., Soliva R. and Peyret M. **Sand textural control on shear-enhanced compaction band development in poorly-lithified sandstone**. Submitted to Journal of Geological Resource and Engineering

Paper V:

Torabi, A. and **Skurtveit, E.** (2013) **Effect of initial grain size and packing on the evolution of elastic properties of poorly lithified sandstones**, American Rock Mechanics Association (ARMA), 47th US Rock Mechanics/Geomechanics Symposium, San Francisco, USA.

Appendix A

Paper A1:

Skurtveit, E., E. Aker, M. Soldal, M. Angeli, and Z. Wang (2012), **Experimental investigation of CO_2 breakthrough and flow mechanisms in shale**, Petroleum Geoscience, 18(1), 3-15.

Paper A2:

Bahman, B., **Skurtveit, E.**, Grande L., Titlestad, G.O., Børresen, M.H., Johnsen, Ø. and Braathen, A. **Geomechanical assessment of the Longyearbyen CO2 storage site based on laboratory experiments and injection tests.** Submitted to Norwegian Journal of Geology.

Paper A3:

Rykkelid, E. and **Skurtveit, E**. **Experimental testing of sands used to quantify deformation in a North Sea Jurassic trap**. Draft, ready for submission.

Authorship Statement

As required by the regulations of the University of Bergen regarding cumulative PhD thesis, the following authorship statements are given to specify the contribution of the candidate and co-authors to each manuscript. The candidate, Elin Skurtveit, is the sole author of the Part I of this dissertation and the first author of three of five manuscripts in Part II. An overview of contribution of the candidate and co-authors to each manuscript in Part II is given below.

Paper I: **Skurtveit, E.**, Torabi A., Alikarami R., and Braathen A. **Fault baffle to conduit developments; reactivation and calcite invasion of deformation band fault in eolian sandstone**

The candidate was involved in the fieldworks including measurements and sampling and was responsible for further microscopic analyses and writing the manuscript. R. Alikarami participated in the field works, which included in situ measurements as well as sampling. He also contributed to the discussion of manuscript and performed manuscript review. A. Torabi guided the students in the field, participated in sampling and in situ measurements and advised on further analysis of data and samples, specially the microscopic studies, and reviewed the manuscript. A. Braathen was involved in one of the fieldwork with logging and mapping, discussions and review of manuscript.

Paper II: Alikarami, R., Torabi A., Kolyukhin D., **Skurtveit E.**, (2013), **Geostatistical relationships between mechanical and petrophysical properties of deformed sandstone**

The candidate participated in fieldwork and contributed on writing the geological setting for one locality. R. Alikarami did fieldwork, performed data processing and analysis, and wrote the manuscript. A. Torabi guided students during fieldworks, contributed on the data analysis and performed manuscript review and comments. D. Kolyukhin contributed on geostatistical analysis and writing of the corresponding results.

Paper III: **Skurtveit, E.**, A. Torabi, R. H. Gabrielsen, and M. D. Zoback (2013), **Experimental investigation of deformation mechanisms during shear-enhanced compaction in poorly lithified sandstone and sand.**

The candidate planned and perforemd the mechanical testing of the sand, analyzed the data and wrote the manuscript. A Torabi was involved in the planning of tests and discussion of the data and manuscript writing. R.H. Gabrielsen also contributed on the planning of the tests and did manuscript review. M. Zoback contributed with discussions on the data analysis and cap model.

Paper IV: **Skurtveit E.**, Ballas, G., Fossen H., Torabi, A., Soliva R. and Peyret M. **Sand textural control on shear-enhanced compaction band development in poorly-lithified sandstone**.

The candidate was involved in the sampling of material from the field, material characterization and performed the mechanical testing of the sand. The candidate is also the main author of the manuscript. G. Ballas has performed the field mapping and field characterization of the deformation bands, in addition he was involved in writing parts of the manuscript and reviewed the manuscript. H. Fossen contributed with discussions and manuscript reviews. A Torabi contributed with planning of tests, discussions and manuscript reviews. R. Soliva contributed with discussion on the field mapping. M. Peyret contributed with the grain angularity measurements.

Paper V: Torabi, A. and **Skurtveit, E.** (2013) **Effect of initial grain size and packing on the evolution of elastic properties of poorly lithified sandstones**.

The candidate performed the lab tests and the velocity interpretation, contributed with discussions on the analysis and did manuscript review. A. Torabi calculated and analysed the moduli data from the experimental measurements and wrote the manuscript.

Contents

Part 1

Part I Background and synthesis

1. Introduction and motivation

This dissertation is motivated by all the spectacular faults and deformation structures observed in field outcrops of porous sandstone (Figure 1) and a wish to understand more about their formation and how these kinds of structures affect reservoir flow and deformation. The current work benefits from the possibility to do field mapping of deformation bands within reservoir sandstone in Provence, France and study faults with multiple deformation events in Navajo and Page formations in the San Rafael Swell, Utah. Field mapping and sampling are combined with high quality mechanical testing, performed at the Norwegian Geotechnical Institute in Oslo, to increase our fundamental understanding of deformation mechanisms. Integrating knowledge from geological observations with understanding of mechanical processes and models is an interesting and fruitful approach for improving our understanding of reservoir deformation and faulting in sandstone reservoirs.

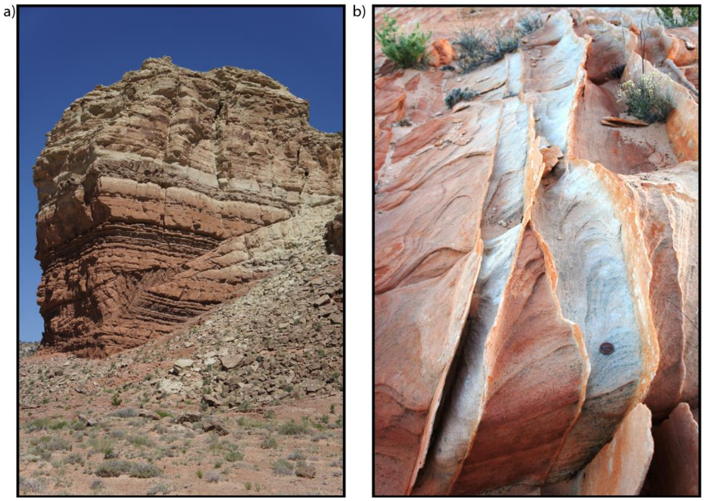

Figure 1 a) Small trust fault on the northwestern side of San Rafael Swell, Utah (height of cliff ca 30 m) and b) shear-enhanced compaction bands in the Valley of Fire, Nevada.

Aim and objectives

The overall aim of this work is to evaluate the relationship between observed deformation structures, implications for fault formation and development, and reservoir properties in porous sandstone. We approach this aim through establishing a better link between localization of deformation structures (microstructures), the deformation mechanisms, lithology variations, lithification and stress conditions (Figure 2).

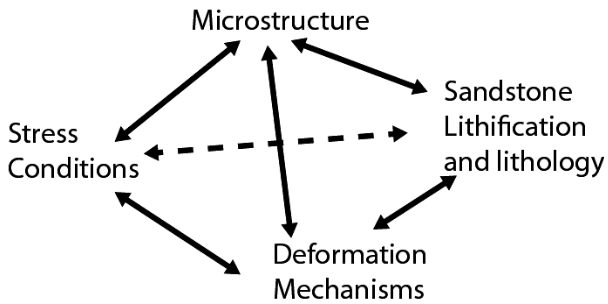

Figure 2 Microstructures (deformation structures) can be linked to the deformation mechanisms and are a function of both stress conditions (stress, temperature and fluid pressure) and the lithification and lithology of the sandstone.

The three main objectives of this study are:

- Data collection of deformation band and fracture characteristics in a fault zone to provide insight into deformation mechanisms and flow properties of faults with multiple deformation events. (Paper I and II)
- Perform experimental tests to establish a link between deformation structures, mechanisms and failure criteria's in poorly lithified sandsone and sand. (Paper III, IV and V)
- Establish a link between sand textural properties and strain localization by combining field observations, detailed material characteristics and mechanical testing. (Paper III, IV and V)

Connection of included papers

The papers included in this thesis are connected using a workflow chart that shows how the papers contribute to the link between deformation mechanisms, sandstone lithification and deformation processes using different approaches; field observations from outcrops, experimental investigations and reservoir characterization (Figure 3). Field observations from sandstone reservoirs with different degree of lithification provide insight into different types of deformation structures (Paper I, Paper II and Paper IV). Systematic experimental investigations are used to provide a better link between stress conditions, sand textural parameters, deformation mechanisms and the formation of microstructures in sand and poorly lithified sandstone (Paper III, Paper IV, Paper V and Paper A3) and in low permeable material (Paper A1). Further, some papers are included to show how subsurface reservoir characterization of deformation structures and implications for flow can benefit from integration with mechanical characterization (Paper A2 and Paper A3). Combining knowledge from different approaches gives a broader understanding of the formation of deformation structures, which is important for reservoir flow and geomechanical models predicting the reservoir behavior during production and/or injection of CO_2 or wastewater.

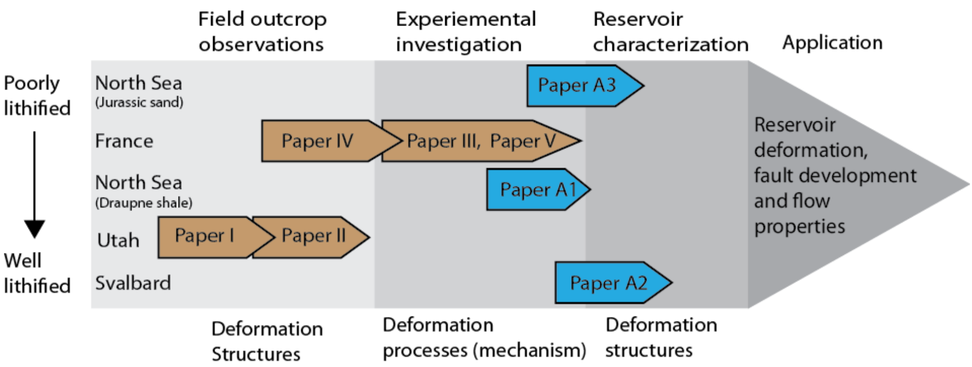

Figure 3 Schematic synthesis of the papers included in this PhD thesis and how they relate to the overall aim of increasing our understanding of deformation structures for reservoir applications. The figure illustrates a workflow where increased understanding of deformation structures is addressed using field outcrop observations, experimental investigation and

reservoir characterization. Paper I-V is included as the main part of this thesis and paper A1-A3 is part of Appendix A.

Terminology and definitions

Reservoir – a subsurface volume of porous and permeable rock in which oil and gas has been accumulated (AGI, 1974)

Shear-enhanced compaction band (SECB) – deformation bands with roughly equal amounts of shear and band-perpendicular compaction by grain rearrangement and porosity collapse (Eichhubl et al., 2010)

Cataclasis – brittle crushing of grains accompanied by frictional sliding and rotation (Fossen, 2010)

Cataclastic flow – flow of rock during deformation by means of cataclasis, but at a scale that make the deformation continuous and distributed over a zone (Fossen, 2010)

Fracture – a sharp planer discontinuity. It is a mechanical discontinuity with local reduction in strength (Fossen, 2010)

Fault - a surface or narrow tabular zone with displacement parallel to the surface (Fossen, 2010)

Deformation - The change of shape, position and/or orientation as a result of external forces (Fossen, 2010)

Deformation mechanism - process that lead to a change in shape or microstructure of rock, i.e. fracturing, cataclasis, frictional sliding, rotation, creep

Deformation band - millimeter thick zone of strain localization formed by grain reorganization and/or grain crushing (Aydin and Johnson, 1978)

Brittle deformation - deformation by fracturing at less than 3-5% deformation or strain (AGI, 1974)

Stress - force per unit area acting on a surface

Strain - change in the shape or volume of material as a result of stress

Lithification - the conversion of a newly deposited sediment into a solid rock, involving compaction, cementation and crystallization (AGI, 1974)

2. Background and State-of-the-art

In this section, I first describe the challenges of structurally complex reservoirs and implications of deformation structures for reservoir characterization and modelling. Then, I introduce the two field locations and the deformation structures that are the focus of this PhD work. I finally provide some background for the mechanical testing, failure criteria's and mechanical models discussed for the experimental results.

Challenges for reservoir modeling

Faults are present in a large variety of sedimentary basins and play a major role in the distribution of fluids, hydrocarbons and groundwater. Faults may be conduits or barriers to flow depending on their architecture, that reflects lithology, strain intensity, burial history and stress conditions. Structurally complex reservoirs (Jolley et al., 2007) are challenging since the reservoir models are sensitive to the uncertainty in geological input data (Manzocchi et al., 2008a). Faulting can include both small- and large-scale heterogeneities with a large variety of architectures and petrophysical properties (Faulkner et al., 2010). Within porous sandstone reservoirs, the most common strain localization feature is deformation bands (Fossen et al., 2007). Deformation bands can be classified based on their kinematics: dilation, shear or compaction; and by the deformation mechanisms responsible for their microstructures: disaggregation (grain rolling or slipping), cataclasis (grain crushing or splitting) or diagenetic processes (pressure-solution or cementation) (e.g., Fossen et al., 2007). For less porous rocks, faults may initiate as joints that link up by development of shear fractures and finally slip surfaces (e.g. Davatzes et al., 2003; Gabrielsen and Braathen, In Press; Peacock, 2001). Fracture corridors compromising both shear fractures and joints are observed in both fault damage zones and the fault tip process zones (Ogata et al., In Press), and may provide distinct flow paths within reservoirs.

Recent publications provide quantitative data on the petrophysical properties of faults and localized microstructures, such as deformation bands (Antonellini et al., 1994; Fisher and Knipe, 2001; Fossen and Bale, 2007; Torabi and Fossen, 2009; Tueckmantel et al., 2012) and recently (Torabi et al., 2013) and more detailed separating deformation bands into compaction bands and shear enhanced compaction bands (Ballas et al., 2013; Eichhubl et al., 2010). Several works also provide details about the distribution and scaling of fault related structures (Caine et al., 1996; Peacock, 2001; Saillet and Wibberley, 2010; Shipton and Cowie, 2001; Shipton and Cowie, 2003; Yielding et al., 1997). These properties provide valuable input for fault models that are integrated into reservoir models (Braathen et al., 2009; Fredman et al., 2007; Manzocchi et al., 2008b), but also raise questions about the details of complex structures that can be included into reservoir models (Ringrose et al., 2008).

Recently, structural heterogeneities have received new interest in reservoir flow simulations related to CO_2 storage (e.g. Bachu et al., 2007) and for geomechanical modelling describing the effect of pore pressure during CO_2 injection (e.g. Cappa and Rutqvist, 2011). In order to use geomechanical modelling to enhance the understanding of the influence of fault architecture and dynamics on fluid flow models (Chadwick et al., 2009) and to define critical pressure to avoid fracturing within potential reservoirs/aquifers for CO_2 storage (Rutqvist et al., 2008), there is a need for better constitutive models describing the failure of the reservoir rocks as well as surrounding formations and faults. Rock strength (Cuisiat et al. 2010) and the structural complexity associated with strain accumulation are critical parameters when evaluating the effect of changing reservoir pressure on fault integrity.

Field location in Utah

The San Rafael Swell is one of a series of highly asymmetrical anticlines or monoclines (Bump and Davis, 2003), irregularly distributed within the Cordilleran foreland basin of the northern Colorado Plateau, Utah (Figure 4). Well-exposed faults and deformation structures are also previously studied in this area (Davatzes et al., 2003; Shipton and Cowie, 2001; Solum et al., 2010). Paleo-fluid flow is documented from bleaching of sandstones, mineralization of carbonates and celestine veins and minor hydrocarbon staining, in sum showing multiple phases of structurally controlled fluid flow (Dockrill and Shipton, 2010). The thick and widely distributed Navajo Sandstone in this area is an oil producing reservoir and is also considered as an excellent analogue for CO_2 sequestration (Parry et al., 2007).

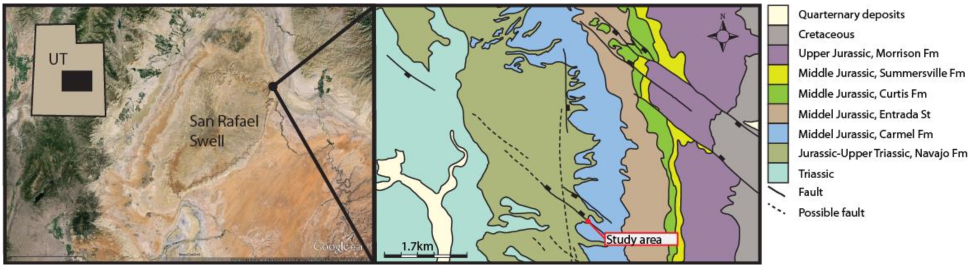

Figure 4 Location of the study area of the northeast San Rafael Swell, (Utah, USA), with map showing geological formations and faults in the study area. The map is based on the geological map by (Witkind, 1988).

The studied faults within the San Rafael Swell is located within the Navajo Sandstone Formation. The maximum burial depth for the Navajo Formation in this area is estimated to be around 3-4 km depth and there is several deformation events identified (e.g. Davatzes et al., 2003). Mapping of multiple deformation structures and calcite veins within faults in this area is used to describe the change in deformation mechanism and the temporal changes in flow along the fault during reactivation of deformation bands (Paper I). Mapping of permeability and strength around the fault is used to derive geostatistical relationships between mechanical and petrophysical properties of deformed sandstone (Paper II). Deformation bands are characterized by mm-thick tabular zones of continuous deformation with a small offset and no slip surface (Fossen et al., 2007). The impact of cataclastic, low porosity deformation bands on the permeability of faults have been extensively studied (Ballas et al., 2012; Shipton et al., 2005; Tueckmantel et al., 2012) identifying cataclastic bands as baffles or barriers to flow in porous reservoirs. However, the temporal development of low permeable deformation band faults into fractures and slip surfaces providing conduits for flow (e.g. Beitler et al., 2005; Boles et al., 2004; Chan et al., 2000; Eichhubl et al., 2009; Travé et al., 1998) still has many unresolved questions and there is a need for more data and analyses to understand how deformation bands develop and deform during changing pressure conditions such as tectonic events, exhumation or changing fluid pressure.

Field location in Provence, France

The Boncavaï quarry in the western part of the "Bassin du Sud-Est" in Provence, France is a poorly consolidated sandstone reservoir with a maximum burial of 400±100 m (Ballas et al., 2013) (Figure 5). Several Upper Cretaceous sand-dominated deposits crop out in this area, showing networks of deformation bands (Ballas et al., in press; Saillet and Wibberley, 2010; Soliva et al., 2013). Characteristic for this location is examples of intense cataclasis described in deformation bands formed within this shallowly buried sandstones (Ballas et al., 2012; Saillet and Wibberley, 2010) suggesting that factors other than burial depth influence the deformation mechanisms involved during deformatin of porous sand(stone). Further, shear-enhanced compaction bands (SECB) (e.g. Eichhubl et al., 2010) are observed to be specifically located in coarse-grained and less porous sand units (Ballas et al., 2013). The poorly consolidated material in this location gives excellent possibility for observation of shear enhanced compaction bands and their lithology dependent occurrence (Paper IV). Material from this location is used for the mechanical testing (Paper III, IV and V) and gives possibility for combining insight from mechanical testing with field observation of deformation (Paper IV) for a poorly lithified reservoir.

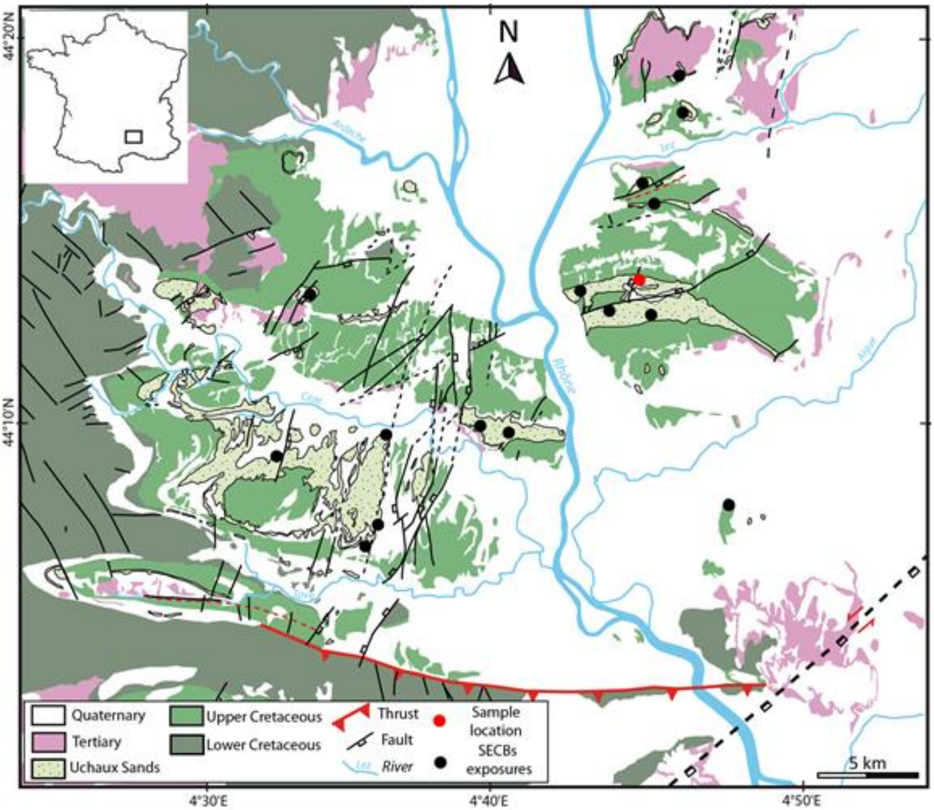

Figure 5 Geological map of the "Bassin du Sud-Est", Provence, France (after Ballas et al., 2013). The Boncavaï quarry study area is plotted as a red dot.

Failure criteria's and localization of deformation

The Mohr-Coulomb failure criterion represents a linear envelope obtained from a plot of the shear strength of a material versus the applied normal stress. This failure criterion is used to define the shear strength of soil and rock at different effective stresses. One of the limitations in this model is that the volumetric change of the material under a triaxial state of stress is not included. In order to describe the kinematic varieties of deformation bands, i.e., dilation, shear and compaction bands, the localized inelastic deformation could be described by a modified Cam-Clay cap model (Rudnicki, 2004; Schultz and Siddharthan, 2005). A simplified elliptical cam-cap model using a mean stress, P, versus differential stress, Q, is used to illustrate the failure criterion (Figure 6). The theoretical framework for these modified Cam-Clay cap models is based on models developed for soil mechanics, describing the transition from elastic to plastic deformation (Bésuelle and Rudnicki, 2003), and further were adopted to deformation bands observed in sandstone reservoirs (Aydin and Johnson, 1983; Rudnicki and Rice, 1975). Hence, Cam-Clay cap models are used to understand the deformation mechanisms involved in various types of deformation bands observed in the field (Wibberley et al., 2007).

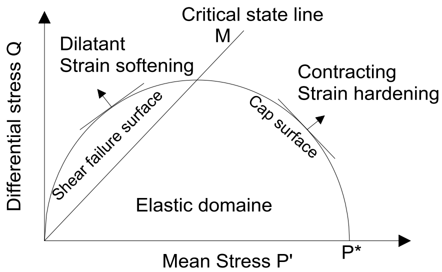

Figure 6 Example of elliptical yield cap for the modified Cam-Clay cap model. The shear failure surface and cap surface show the elastic-plastic transition associated with dilation and strain softening at the left side of the critical state line and contraction and strain hardening on the right side of the critical state line. The critical state line, with slope M, defines the state with frictional shearing and no volumetric change.

Factors controlling the large variation in textural composition, mode of deformation and shear displacement can be investigated in laboratory experiments using different experimental setups, loading conditions and materials. The transition from brittle faulting to cataclastic flow in porous sandstone have been treated in numerous theoretical studies (Bésuelle, 2001; Issen and Rudnicki, 2000; Rudnicki, 2004) and explored through mechanical testing with a broad range of effective pressures (Baud et al., 2004; Fortin et al., 2005; Tembe et al., 2008; Wong and Baud, 2012). The experimental data are used to identify initiation of shear-enhanced dilation in the brittle regime and shear enhanced compaction that results from cataclastic flow at high effective pressure in lithified sandstone. The results of the experiments are modelled utilizing the elliptical yield envelope comprising shear yield surface and cap. The size of the cap is found to be controlled by the yield stress along a hydrostatic loading path. Wong et al (1997) found that the yield stress, P*, is related to the onset of grain crushing and primarily controlled by the initial porosity and grain size. An interesting finding from these experimental results is that considerably higher pressures are required for the experimental formation of compaction bands than those suggested from field observations (Eichhubl et al., 2010; Schultz, 2009). Experimental work focusing on the deformation mechanisms in uncemented and poorly lithified sandstone, typical for shallow reservoirs conditions, is limited (Alikarami, 2014; Crawford et al., 2004; Kaproth et al., 2010). The experimental works (Paper III) in this PhD dissertation tries to fill this gap by performing a novel study of deformation mechanisms and conditions for shear-enhanced compaction for poorly lithified sandstone and sand using stress conditions higher than the typical 1-2MPa maximum pressure used within soil mechanical testing (Desrues and Viggiani, 2004; Hall et al., 2010).

3. Methods

The methods used within this PhD work are divided into two main categories; a) Field sampling, measurements and observation and b) mechanical testing and characterization. Details about the method are explained in each paper. Here I just give a short overview of the methods used:

Field investigation:

- Mapping of sedimentary layers and contacts
- Scanlines for fracture and deformation band density and orientation, permeability and strength
- Systematic sampling of sandstone and sand material for thin sections and experiments.

Mechanical testing:

- Triaxial testing with hydrostatic loading path under drained conditions
- Drained shearing at various confining pressure conditions
- Monitoring of sonic velocity during testing

Characterization of samples:

- SEM and optical microscope analysis of thin section
- Pre- and post-test CT scans
- Image analysis and sieving for grain size and textural analyses.
- Stable Isotope and fluid inclusion analysis
- X-ray spectrometry

4. Main results

This section presents a short summary of the main results from each paper included in Part II of this thesis.

Paper I – Fault baffle to conduit developments; reactivation and calcite invasion of deformation band fault in eolian sandstone

Paper I combines the field and microstructural observations of deformation bands and the interaction with calcite veins in order to provide a better understanding of fault zone development and temporal changes in the flow properties. The damage zone of three faults, located on the northern side of San Rafael Swell, Utah are described, focusing on multiple deformation events where cataclastic deformation bands are overprinted by fractures and filled with calcite cement. Scanlines across each of the faults are used to map deformation band and fracture density and orientation across the faults. Visible calcite crystals are observed within both fractures (veins) and deformation bands. Materials along the scanline are sampled for microstructural analysis with X-ray specterometry, optical and electron microscope. The examined faults reveal clear indications of multiple deformation episodes recognized along the faults: (1) an early formation of cataclastic deformation bands and (2) a later phase of fracturing, followed by (3) invasion of fluid with precipitation of calcite cement. The observation of calcite veins following along pre-existing cataclastic deformation bands shows that deformation bands found in the damage zone of a fault can become preferential paths for fluid movements and calcite precipitation during reactivation of the fault and fracturing.

Paper II – Geostatistical relationships between mechanical and petrophysical properties of deformed sandstone.

Paper II combines field measurements and geostatistical analysis of petrophysical and mechanical properties such as permeability, strength and Young's modulus of deformed rocks. The damage zone of faults exposed in Navajo and Entrada sandstones located in Cache Valley and San Rafael Swell, Utah, are studied. In-situ measurements of air permeability and mechanical strength using Tiny-perm and Schmidt hammer along scanlines are combined with registration of deformation band and fracture density.

Results indicate that permeability and strength/elasticity of deformed rock change in accordance with the density and type of deformation structures, i.e. fractures and deformation bands. Cluster of deformation bands shows the highest strength/elasticity and lowest permeability, whereas zones of fractures reveal the highest permeability and lowest strength and elasticity. Geostatistical analyses are used to support the correlation between permeability and strength as well as permeability and calculated Young's modulus for these sandstones. Cementation shows a high influence on both permeability and strength of the damage zone, especially in fractured zones where cemented veins are observed. The cementation decreases the permeability and increases the strength and the Young's modulus of rocks.

Paper III – Experimental investigation of deformation mechanisms during shear-enhanced compaction in poorly lithified sandstone and sand

Paper III gives a systematic presentation of all the mechanical tests performed on poorly lithified sandstone and sand from the same locality as Paper IV, the Uchaux sands in Provence, France. High pressure triaxial testing has been used to study deformation mechanisms involved during shear-enhanced compaction and controlling parameters for yield stress at varying confining pressure for sandstone/sand with different grain size, porosity, and packing. Sands with different packing have been used: 1) natural coarse-grained sandstone (2) densely packed fine-grained sand and (3) loosely packed fine-grained sand. Monitoring of deformation and ultrasonic velocity during deformation indicate porosity loss, compaction and strain hardening for most of the samples. Visualization of deformation using pre-and post-test X-ray imaging and thin sections demonstrate localized deformation fabrics and grain damage. Common characteristics for most of the tests were the large inelastic compaction and porosity reduction during loading. Yield stress during hydrostatic loading is discussed using methodologies from soil mechanics and found to be lower than predicted using empirical relationships for estimating yield stress related to pore collapse in well lithified and cemented sandstone. Comparison of the results with a modified Cam-Clay cap model shows that porosity loss during shear-enhanced compaction gives a reasonable fit with end-caps calculated from porosity loss during hydrostatic loading and demonstrates how end-caps change during compaction and increasing confining pressure for different types of material tested. The observed onset of grain fracturing at effective pressure of 5-10 MPa supports the idea that cataclastic shear-enhanced compaction bands might have been formed at shallow burial depth in the field.

Paper IV – Sand textural control on shear-enhanced compaction band development in poorly-lithified sandstone.

In Paper IV we study the selective formation of shear-enhanced compaction bands (SECB) within coarse-grained and less porous sand units in the Uchaux sands in

Provence, France. This is in contradiction to the deformation bands at Buckskin Gulch, Utah, where bands selectively form in layers with both coarse grain size and high porosity. We present textural characterization and mechanical testing in an attempt to understand the textural control on the formation of deformation bands in specific sand units. Textural characterization shows that the main difference between the two sand units is grain size and sorting, whereas they are similar with respect to the composition and grain angularity. Packing density is introduced as an important parameter for comparing the compaction properties independent of the textural variations between the two units. Better sorting of the fine-grained unit compared to the coarse-grained unit is found to control the porosity difference between the two units. The preferential localization of SECB in the coarse-grained unit is thought to be controlled by two factors: (1) higher stress concentration on grain contacts, mainly controlled by the grain size, initiating grain fracturing and (2) faster compaction and increase in relative density reducing the potential for distributed deformation.

Paper V – Effect of initial grain size and packing on the evolution of elastic properties of poorly lithified sandstones

The same tests as for Paper III are presented in Paper V, focusing on comparison of the static and dynamic elastic modules calculated from the experimental measurements. The paper discusses how grain size and packing influence the elastic properties of tested samples during deformation. The hydrostatic and triaxial tests in Paper III where accompanied with P- and S- wave velocity measurements in the axial direction that allowed for calculation of the dynamic moduli. Static bulk and shear moduli were calculated using the volumetric strain measurements from the tests. Dynamic and static M-moduli were calculated and compared for the shear phase of the experiments. The results show that static bulk and shear moduli vanish in the shear phase of the axisymmetric experiments due to substantial grain crushing in the samples. $M_{dynamic}$ and M_{static} are not in agreement, indicating that $M_{dynamic}$ increases along with porosity reduction, while M_{static} vanishes possibly due to large strain and grain crushing in the samples.

5. Synthesis

All the papers included in this PhD work are contributions towards a better understanding of formation and implication of localized deformation within structurally complex reservoirs (Figure 3). In this section, I first synthesize the results within a broad framework of how the individual papers contribute to various reservoir applications, then I discuss the contribution towards better understanding of strain localization and formation of deformation bands and linking of observed microstructures with the deformation processes, lithology and stress conditions.

Contribution to reservoir applications

Reliable fault models are essential for geomechanical evaluation of fault integrity during both reservoir depletion and injection. In the San Rafael Swell, Utah, we mapped and described the deformation structures within a small, but complex fault zone with multiple deformation events and temporal changes in flow properties (Paper I). We identified an early phase of catalcastic deformation bands, later overprinted by fractures and calcite cement indicating fluid flow within the fault. These results provide evidence that existing cataclastic band, normally considered to be low permeable (e.g. Fossen and Bale, 2007) and strain hardening structures (Aydin and Johnson, 1978) could provide local pathways for flow during changes in stress conditions. Mapping of various relationships between the calcite cemented flow paths and pre-existing deformation structures along the fault indicates variation in host rock porosity due to quartz cementation and grain size as controlling factors for cementation along bands or within the host rock. This work contributes to the understanding of fluid flow during fault reactivation. Regional uplift of the area (Davatzes et al., 2003) is a likely stress change causing fracturing, but also high fluid pressure is observed to trigger flow along faults and fracture corridors in this area (Eichhubl et al., 2009; Ogata et al., In Press) providing this study area an interesting analog for CO_2 storage (Parry et al., 2007).

The initiation of fracturing along pre-existing defects with optimal orientation is well described in theoretical models (Paterson and Wong, 2005), but more observation of natural systems and implications for flow paths are needed to increase our understanding of natural systems. A case study from the Longyearbyen (LYB) CO_2 lab, Svalbard (Paper A2) indicates re-opening of favorable oriented fractures within the reservoir during water injection. The measured fracture pressures during water injection in the shallow LYB CO_2 storage site are strongly controlled by existing fractures and in-situ stress condition in the reservoir, with horizontal fractures most prone to re-opening in the overburden, whereas vertical fractures are most critical in the reservoir zone. On the micro scale, injection of CO_2 into low permeable shale in the laboratory, demonstrate the significance of stress dependent microfracturing as an important mechanism for flow (Paper A1). The stress dependent flow observed in the experiments gives flow rates much higher than expected from flow in the porous network for this low permeable material. The experiment show significant dilation of the sample during the injection of supercritical CO_2 that correlates with a fracture flow model, although there is no macroscopic fracture trough the sample.

In addition to the stress conditions, the microstructure and frictional properties of faults and deformation structures impose a significant control on integrity and deformation (Collettini et al., 2009; Kurz et al., 2008). This is demonstrated in a case study from the Statfjord Field evaluating the fault integrity during depletion (Cuisiat et al., 2010), where a critical input parameter for the fault model is the strength of the existing fault zone. Evaluating the strength of a fault zone for the individual deformation structures within a reservoir is a challenging task. The work presented in Paper II looks for an empirical correlation of strength and permeability within faults. A correlation between the two mentioned properties is observed and the cementation is identified as a parameter significantly influencing both permeability and mechanical properties.

Microstructures of deformation bands are discussed in Paper III, IV, V and A3. Common for these papers are the deformation within poorly lithified reservoir. The large number of tests presented in Paper III is a contribution to fill in on the gap in mechanical properties and deformation mechanisms for shallow buried reservoirs. Paper III provides a detailed discussion of the deformation mechanisms and observed microstructures during shear enhanced compaction. In Paper IV we study the shear-enhanced compaction bands observed within shallow buried sandstone units in Provence, France (Ballas et al., 2013) and demonstrate how textural differences like porosity, sorting, grain size and the packing density of the grains influence the compaction and localization of deformation into discrete cataclastic bands. Data on compaction and onset of grain fracturing (paper III) and the relationship between porosity, sonic velocity, dynamic and static modulus (Paper V) are important for the evaluation of potential CO_2 or waste water injection in shallow, poorly lithified reservoir like the Utsira Formation (Eiken et al., 2011). Oil and gas production from shallow and poorly lithified reservoir also requires more data in order to handle potential compaction and subsidence problems during production (e.g. Chan and Zoback, 2007).

Deformation structures observed within many North Sea reservoirs formed in poorly lithified sediments during syn-rift sedimentation (Fossen and Hesthammer, 1998; Færseth et al., 1995; Gabrielsen and Koestler, 1987). Experimental investigation of the microstructures and processes during deformation in poorly lithifed reservoirs can provide important contribution for understanding both reservoir and fault properties (e.g. Cuisiat and Skurtveit, 2010). In paper A3, experimental data on sand samples analog to the Brent reservoir is used for studying shear failure and microstructures within the Fulla Field. The dominating deformation mechanism for the tests is grain rearrangement with dilation and porosity increase during shear failure. The results are used to support borehole observation indicating limited damage to reservoir porosity from the faulting and shear deformation within this reservoir. It is also in agreement with the observation of limited cataclasis in deformation bands from Gullfaks area in the North Sea (Hesthammer and Fossen, 2001).

Contribution to the localization of deformation bands

The experimental work in Paper III provide insight into some very important and critical aspects of shear-enhanced compaction in poorly lithified sandstone; (1) the large inelastic deformation observed during testing (Hagin and Zoback, 2004) and (2) a change in deformation mechanisms from grain rearrangement (rotation and sliding) into grain damage (fracturing and crushing) (Chuhan et al., 2002; Mesri and Vardhanabhuti, 2009). The combined effect of both inelastic and elastic deformation during compaction is expressed as porosity reduction. Paper III presents elliptical end-caps for given porosities for each test series and show that the onset of shear-enhanced compaction do not map out a single end-cap as observed for sandstone (e.g. Wong and Baud, 2012; Wong et al., 1997). Rather, it relates to the observed porosity reduction during increasing total mean stress (p) and differential stress (q), mapping out elliptical end-caps increasing in size during compaction.

Yield stress, describing the transition for elastic to plastic strain (pore collapse and onset of grain crushing) is well defined form cemented sandstone (Baud et al., 2004; Fortin et al., 2005; Wong et al., 1997), whereas for the tests on poorly consolidated sandstone and sand in Paper III, the yield is less well defined. This could be attributed to the poor lithification and packing of the samples tested, making room for grain rearrangement and denser packing of the sand during compaction. The gradual transition in deformation mechanisms from grain rearrangement into grain fracturing and crushing might also make the yield less defined. Another factor influencing the yield is the strain rate (Hagin and Zoback, 2004), where higher rate gives higher yield stress. The gradual transition in deformation mechanisms is largely controlled by increasing stress, but also the grain size and shape, as discussed in both Paper III and IV. Stress path can also influence the deformation mechanisms. Mechanical testing at similar consolidation stress as in Paper III, but with an unloading stress path, show well defined localization where the dominant deformation mechanism is grain rolling, rotation and frictional sliding (Paper A3).

Hydrostatic yield stress interpreted from bulk modulus and maximum curvature (Paper III) is low compared with empirical models derived from mechanical testing of sandstone and Hertzian fracturing theories (Zhang et al., 1990). The empirical relationship of Zhang et al. (1990) used in Paper III relate the yield stress to porosity and grain size, and thus it is natural to ask the impact of other textural parameter like sorting (Cheung et al., 2012; Wang et al., 2008) and grain shape (Alikarami, 2014; Mair et al., 2002) on yield stress in order to explain the lower yield observed for poorly consolidate sandstone and sand (Alikarami, 2014; Crawford et al., 2004). The preferential localization of shear-enhanced compaction bands in the coarse grained, but low porosity unit in France (Paper IV) is an excellent example for comparison of textural characterization and natural examples of shear-enhanced compaction band formation. Detailed textural characterization in combination with mechanical testing of compaction and discussion of the Hertzian fracture model (Sammis et al., 1987; Zhang et al., 1990) and forces on grain contacts (Mavko and Dvorkin., 2009), suggests that porosity difference between the units are largely controlled by grain shape and sorting, whereas the grain size controls the onset of fracturing. In Paper IV we introduce the relative packing density (Cornforth, 1973) in order to separate the initial porosity variations due to textural variations between different sands and the porosity variations due to loading and compaction. Faster initial reduction in packing density (compaction) of the coarse sand, together with the coarser grains favoring higher stress concentration on grain contacts, both contribute to the preferential localization in the coarse grained unit (Paper IV).

Well-defined localization of shear bands were not observed in the tests in Paper III, rather the localization of cataclastic deformation is distributed. Several factors may influence on this. First, typical field characteristics of cataclastic compaction and shear-enhanced compaction bands describe this type of bands as typical wider and less localized (Ballas et al., 2013; Eichhubl et al., 2010) than classical shear bands observed in the field (e.g. Ballas et al., 2012; Lothe et al., 2002) and in experiments (Mair et al., 2000). Further, in soil mechanic, the yield for sand and clay is related to the pre-consolidation pressure or maximum in-situ stress in the sample. Crawford et al. (2004) tested sand with a pre-consolidation pressure and showed that the yield was controlled by pre-consolidation for some sands, whereas for others it was better related to the grain crushing pressure. For the lab tests in Paper III, localization versus distributed deformation is controlled by the stress path distance from the critical state line in the cam cap plot and the initial porosity or packing density of the sand. The latter, likely controlling the freedom for distributed grain rearrangement.

6. Conclusion

The overall aim of the current work is to increase our knowledge of the formation of deformation structures, and their implications for fault development and reservoir flow. Further, this dissertation focuses on combining field mapping of outcrop data with mechanical testing for quantification of deformation mechanisms during strain localization. The following main conclusions can be drawn from this PhD work:

- Multiple deformation events show that cataclastic deformation bands could become flow paths during re-activation and fracturing of a deformation band fault.
- Changes in stress condition and deformation mechanisms are found to give temporal changes in permeability from fault baffle, to conduit and back to baffles again.
- Mechanical testing of sand and poorly lithified sandstone using triaxial testing is dominated by large inelastic deformation and porosity reduction showing significant strain hardening and mostly distributed deformation.
- The yield stress marking the onset of shear-enhanced compaction is not found to map out a single end-cap as for sandstone, but relates to the observed porosity reduction.
- The preferential formation of shear-enhanced compaction bands in the coarse and low porosity unit is attributed to the combination of compaction and faster reduction in packing density of this unit together with the larger grain size and initiation of grain fracturing and crushing.
- Microstructural imaging shows grain crushing as an important deformation mechanism for pressures from 5-10 MPa. The large compaction, porosity reduction and increasing P-wave velocity indicate that grain rearrangement like grain rotation and slip, is important deformation mechanisms. This gradual transition in deformation mechanisms from grain rearrangement to grain damage is an important and challenging mechanical characteristic for poorly lithified sandstone.

Outlook

During the course of this PhD thesis several suggestions for future work are identified. For the mechanical testing of poorly lithified sandstone and sand the following gaps are seen:

- More data is needed on the mechanical properties of poorly lithified units, specially the effect of creep and strain rate on localization.
- Mechanical testing could also be extended to include permeability measurements during localization to better describe the effect of porosity reduction on permeability during compaction and cataclastic deformation. This requires a setup for permeability measurements in high permeable sandstone.
- The procedure for sampling of undisturbed poorly consolidated sandstone in the field needs to be improved in order to perform tests with correct initial porosity.
- Imaging of deformation and localization could be improved by using triaxial testing within a CT scanner to see the porosity development and grain fracturing during localization of deformation (Alikarami, 2014).

For the application of the cam-clay cap model there are some gaps identified:

- In order to describe the full cam-cap model, tests with strain softening and dilation should be included in the same series; more focus on the transition from softening to hardening is needed.
- Yield stress during hydrostatic loading is related to pre-consolidation pressure for most soils, whereas for sandstone the yield stress is linked to an empirical relationship for porosity and grain size derived from the Hertzian fracturing theory. What controls the yield stress for poorly lithified sandstone is still unclear.

For the application to reservoir modelling the main challenges identified are:

- Implementation of cam-clay cap model as failure criteria in reservoir modelling tools may provide a better hydro-mechanical coupling since the volumetric changes during failure are considered in this model. This requires dedicated mechanical testing and careful interpretations in order to provide the data needed.
- Mechancial testing should preferably be on material from the reservoir considered, as degree of lithification, compaction history and stress path is important for the mechanical behavior and mode of failure.
- Most mechanical testing is done with loading until failure, whereas the most likely stress path during injection (CO_2, wastewater) is unloading due to the increasing pore pressure. There is little data available comparing microstructure of localized deformation during an unloading versus loading condition during testing.

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