

Contractional deformation of porous sandstones

—

*Laramide and Sevier deformation of the Navajo
and Aztec sandstones in western USA*

Luisa F. Zuluaga



Dissertation for the degree Philosophiae Doctor (PhD)

The University of Bergen

2014

Dissertation date: 16.02.2015

© Copyright Luisa F.Zuluaga

The material in this publication is protected by copyright law.

Year: 2014

Title: Contractional deformation of porous sandstones:
Laramide and Sevier deformation of the Navajo and
Aztec sandstones in western USA

Author: Luisa F. Zuluaga

Print: AIT OSLO AS / University of Bergen

Contractional deformation of porous sandstones

—

*Laramide and Sevier deformation of the Navajo and Aztec
sandstones in western USA*

Luisa F. Zuluaga

Dissertation for the degree Philosophiae Doctor, PhD

Uni Research CIPR

Centre for Integrated Petroleum Research



University of Bergen

Department of Earth Science



Contents

Introduction.....	I
Preface	III
Acknowledgements	V
Scientific Environment	IX
List of Publications	X
Conference Contributions.....	XI
Authorship Statement	XII
Abstract.....	XIV
Chapter 1. Research Synopsis	17
Motivation	19
Objectives.....	21
Methods.....	22
Background and state of the art	27
Synthesis of main findings	39
Conclusions	53
Outlook and Future Work.....	55
Chapter 2. Manuscript Compilation.....	59
Progressive evolution of deformation band populations during Laramide fault-propagation folding: Navajo Sandstone, San Rafael Monocline, Utah, U.S.A.	61
Structural heterogeneity and fluid flow in porous sandstone reservoirs affected by contractional folding: a flow simulation study of the San Rafael Monocline, Utah U.S.A	80
Microstructural and petrophysical effects of overthrusting in highly porous sandstones: the Aztec Sandstone in the Buffington Window of Southeast Nevada, U.S.A.	113
Contractional deformation of sandstone: insights from the Aztec Sandstone in the footwall to the Sevier-age Muddy Mountains thrust, SE Nevada, U.S.A.	149
Chapter 3. Conference Contributions.....	180
Structural Reservoir Heterogeneity Induced by Forced Folding in Sandstone Reservoirs.....	182
Microstructural and Petrophysical Effects of Overthrusting on the Aztec Sandstone, Buffington Window, SE Nevada.	188
References	194

INTRODUCTION

*“Like all young men I set out to be a genius, but
mercifully laughter intervened.”*

— Lawrence Durrell

Preface

This dissertation presents the research I carried out as a doctoral student at the Department of Earth Science at the University of Bergen and Uni Research CIPR (the Centre for Integrated Petroleum Research), within the framework of the COPS project (Contraction of Porous Sandstones); the research was conducted between August 2011 and October 2014.

This thesis follows an article-based format in conformity with most Norwegian doctoral dissertations for natural sciences, with an introduction followed by three main chapters. The introduction includes the acknowledgements, a general overview of the research environment, a list of resulting publications and their corresponding authorship statements (in which my contribution and amount of involvement as a candidate is specified), and the thesis abstract. Following the introduction are the main thesis chapters; the first chapter is the research synopsis: the project overview (motivation, objectives, methods, background and state of the art) followed by the synthesis of key results, and a reflection for further work. The second chapter is comprised of four scientific articles published or submitted to peer-reviewed scientific journals, where the bulk of the work undertaken in this doctoral thesis is presented. The final chapter consists of additional contributions in the form of presentation abstracts and posters prepared for research dissemination at international conferences. For readers not accustomed to the paper-based format of the thesis, please note that since papers are stand-alone publications, there is some overlap between the different articles, particularly in terms of introductory/background material. There are also differences in spelling (American vs. British English), based on different journal editorial requirements.

Acknowledgements

This research project would not have been possible without the inspirational example of outstanding scientists I had as supervisors on the one hand, and the immense support of family, friends and colleagues on the other.

I am deeply grateful to my supervisors, Haakon Fossen and Atle Rotevatn, for productive discussions, constructive and comprehensive assessments of my work and manuscripts, as well as their patience, guidance and encouragement during my doctoral training. I value to have been influenced by their thorough methods of research and fieldwork, as well as their insight to make results interesting and concise.

For field companionship I thank Grégory Ballas and Tracy J. Thompson. The camping hacks and off-road driving techniques in such adventurous field campaigns in the Mojave and San Rafael deserts are among the most enjoyable transferable skills I gained during this process. Field explorations and discussions with Grégory Ballas and Roger Soliva resulted in valuable research collaborations that broadened perspectives of my research.

CIPR-Geo and UiB colleagues have provided an uplifting and supportive atmosphere full of empathy while facing and reaching common challenges and milestones, especially Anette Tvedt, Björn Nyberg, Andreas Rittersbacher, Dongfang Qu, Eirik Keilegavlen and the rest of the “fish tank” and Safari fellows.

I am grateful for the pleasant work environment, and the assistance with logistics and procedures given by Uni Research CIPR and UiB staff, especially by Inger S. Thorsen, Kristin Haug, and Caroline Ertsås Christie. Technicians Irina Dumitru from the thin-

sections preparation laboratory, Egil Erichsen and Irene Heggstad from the laboratory for electron microscopy provided me with useful tools to carry out my research.

Thanks as well to my friends in Bergen for the stress-relieving opportunities they provided along the road. I should also thank the city of Bergen itself, as I suspect the beautiful mountain trails and the less-beautiful grey sky have strengthened my muscles and character. At times when my research work was particularly isolating, volunteer work at the Haraldsplass hospital provided me with a unique sense of community and fulfilment, moments in which I gained further insight into Norwegian culture.

The love and encouragement from my family and friends back in Colombia, (constantly present with the amazing aid of current technology), truly motivated me and helped me to keep things in perspective.

Finally but above all, to my husband Alejandro, because as well as an adventure partner, he proved to be an excellent source of obscure bibliography, unconventional scientific discussions, and even field assistance. His suggestion of applying for this doctoral position and his gracefully endurance of the whole experience (presumably different to any newlywed expectations) are great reminders of my good fortune in this never-ending quest for knowledge and wisdom.

Luisa Fernanda Zuluaga Valencia
Bergen, Wednesday, 10 December 2014

Dedicated to my parents,

To my Mom,

My biggest inspiration, whose determination proved to me that getting a university degree, having a full time job and being a loving mother are not mutually exclusive endeavours,

&

To my Dad, who used to recite:

*“Estudia y no serás cuando crecido,
ni un juguete vulgar de las pasiones,
ni un esclavo servil de los tiranos”*

*“Study, so that in old age you will be
neither a mundane toy of the passions,
nor a servile slave of the tyrants”*

—Elías C. Pompa

Scientific Environment

The work presented in this thesis is part of the Contraction of Porous Sandstones project (COPS), conducted at Uni Research CIPR and the Department of Earth Science at the University of Bergen (UiB), Norway, in collaboration with the Laboratoire Géosciences at the Université Montpellier in France. The PhD scholarship was funded by Uni Research CIPR; travel grants from Statoil allowed international dissemination of research outcomes and discussions for progress.

While carrying out the research for this thesis, the candidate has been enrolled in the doctoral training program at the Faculty of Mathematics and Natural Sciences at the University of Bergen, Norway.



Supervisors:

Professor **Haakon Fossen** (Supervisor)

Department of Earth Science and Museum of Natural History, University of Bergen.

Professor **Atle Rotevatn** (Co-supervisor)

Department of Earth Science, University of Bergen.

List of Publications¹

Zuluaga, L.F., Fossen, H., & Rotevatn, A. 2014. Progressive evolution of deformation band populations during Laramide fault-propagation folding: Navajo Sandstone, San Rafael Monocline, Utah, U.S.A. *Journal of Structural Geology* **68**, 66-81.

Zuluaga, L.F., Rotevatn, A., Keilegavlen, E., & Fossen, H., *submitted*. Structural heterogeneity and fluid flow in porous sandstone reservoirs affected by contractional folding: a flow simulation study of the San Rafael Monocline, Utah (USA). *AAPG Bulletin*, *in review*.

Zuluaga, L.F., Ballas, G., Fossen, H., & Rotevatn, A., *submitted*. Microstructural and petrophysical effects of overthrusting in highly porous sandstones: the Aztec Sandstone at the Buffington Window of Southeast Nevada, U.S.A. *GSA Bulletin*, *in review*.

Fossen, H., Zuluaga, L.F., Ballas, G., Soliva, R., & Rotevatn, A., *submitted*. Contractional deformation of sandstone: insights from the Aztec Sandstone in the footwall to the Sevier Muddy Mountains thrust, SE Nevada, USA. Article submitted to the *Journal of Structural Geology*, *in review*.

¹ Reprints were made with permission from Elsevier, The American Association of Petroleum Geologists and the Geological Society of America. *All rights reserved*

Conference Contributions

Zuluaga, L.F., Fossen, H., & Rotevatn, A. 2012. Structural Reservoir Heterogeneity Induced by Forced Folding in Sandstone Reservoirs: Abstract and Poster presented at the Industrial Structural Geology Conference: principles, techniques and integration, The Geological Society. (November 2012). London, UK.

<http://folk.uib.no/nglhe/Papers/Poster-LZ.pdf>

Zuluaga, L.F., Ballas, G., Fossen, H., & Rotevatn, A. 2013. Microstructural and Petrophysical Effects of Overthrusting on the Aztec Sandstone, Buffington Window, SE Nevada. Presentation abstract for the GSA 125th Annual Meeting, Session No. 293 - T208: Hinterland, Retroarc Fold- Thrust Belt, and Foreland Systems. (October 2013). Denver CO, USA.

<https://gsa.confex.com/gsa/2013AM/webprogram/Paper230518.html>

Authorship Statement

As required by the regulations at the University of Bergen for the degree philosophiae doctor (PhD) in article-based dissertations, the following statement is given in order to specify the extent of the candidate's individual contribution and involvement in each publication of the present thesis.

PAPER I: Zuluaga, L.F., Fossen, H., & Rotevatn, A. Progressive evolution of deformation band populations during Laramide fault-propagation folding: Navajo Sandstone, San Rafael Monocline, Utah, U.S.A

The candidate undertook the majority of the data collection, processing and analysis, based on reconnaissance fieldwork by Haakon Fossen. The candidate was responsible for the preparation of the manuscript and all its figures. Co-authors engaged in discussions and contributed with manuscript reviews, especially contributing to improve the discussion of results.

PAPER II: Zuluaga, L.F., Rotevatn, A., Keilegavlen, E., & Fossen, H. Fluid flow across structurally heterogeneous aeolian sandstone reservoirs: Analog case study from the Navajo Sandstone, San Rafael Monocline, Utah U.S.A

The candidate was responsible for the preparation of the manuscript and all but one of its figures. She also carried out the majority of the data collection, processing and analysis. The candidate constructed the geocellular models and incorporated the small scale simulations done by Eirik Keilegavlen; the candidate performed the flow simulations of the geocellular

models. Atle Rotevatn and Haakon Fossen provided suggestions on model design. Atle Rotevatn and Eirik Keilegavlen contributed with manuscript reviews.

PAPER III: Zuluaga, L.F., Ballas, G., Fossen, H., & Rotevatn, A. Microstructural and petrophysical effects of overthrusting in highly porous sandstones: the Aztec Sandstone at the Buffington Window of Southeast Nevada, U.S.A.

The candidate was responsible for the preparation of the manuscript and all but one-half of its figures. Data collection on the field was made by the candidate and Grégory Ballas, based on reconnaissance fieldwork by Haakon Fossen. The candidate was in charge of data processing and analysis, as well as microscope observations and measurements. Haakon Fossen, Grégory Ballas and Atle Rotevatn participated in discussions and provided manuscript reviews.

PAPER IV: Fossen, H., Zuluaga, L.F., Ballas, G., Soliva, R., & Rotevatn, A. Contractional deformation of sandstone: insights from the Aztec Sandstone in the footwall to the Sevier Muddy Mountains thrust, SE Nevada

Data collection was performed by the candidate, G. Ballas, H. Fossen, R. Soliva and A. Rotevatn. The candidate prepared one of its figures (Figure 6), and participated in revisions and discussions to improve the manuscript.

Abstract

In response to stress, high porosity sandstones tend to deform and localize strain in the form of **deformation bands**, which form by rotation, sliding and potentially crushing of grains. Contrary to slip surfaces and fractures, these planar and tabular strain localization features are not discontinuities within the host rock volume in which they form; instead they maintain or enhance its cohesion, generally reducing porosity and permeability.

This research used outcrop analogs widely exposed in western USA to investigate deformation bands of highly porous sandstones formed under **contractional tectonic regimes**, evaluating their potential impact in terms of sandstone reservoirs in comparable settings, while comparing them with high porous deformation of sandstones in extensional regimes. This analysis included character, spatial distribution and evolution, as well as interpretation of controlling mechanisms of such deformation. Two particular settings were examined: fault-propagation-folding and footwalls of long distance overthrusts.

In both cases, a temporal evolution of deformation band formation is proposed, (Papers I and IV). For the fault-propagation fold, a flow simulation model was created using the field observations (Paper II), while for the overthrust system, a detailed description of the microstructure mechanisms, and resulting petrophysical properties of the sandstone layer is presented (Paper III).

Regarding tectonic regimes, this research provides additional evidences for the claim that contraction-induced deformation band arrangements are less prone to cluster and that such bands tend to be more broadly spaced than their extensional counterparts. Such anti-

clustering prevents them from becoming effective precursors for large offset faults, with the exception of meso-scale slip surfaces. The second major difference between deformation band formation in different tectonic regimes is that, in addition to the cataclastic shear bands (CSB) characteristic of extensional regimes, two types of deformation bands exist, apparently restricted to the contractional regime, namely pure compaction bands and shear enhanced compaction bands (PCB and SECB); pure compaction bands are posited as being the porous sandstone equivalent to stylolites, as they reveal consistent orientations perpendicular to the maximum principal stresses in our study areas.

Our analyses show that for reservoirs analogous to the contractional structures analysed, the effect of deformation bands is negligible for fluid flow at reservoir (km) scale, unless permeability contrast is equal or higher than three orders of magnitude between deformation bands and host rock and combined with long term production. In the latter case, the wider spacing of contractional arrangements of deformation bands allows for a better (albeit slower) sweep of reservoirs.

CHAPTER 1. RESEARCH SYNOPSIS

*“Nature is always more subtle, more intricate, more
elegant than what we are able to imagine”*

— *Carl Sagan*

Motivation

Deformation in porous sandstones is related to a range of processes that are unique to their granular nature; these processes usually lead to strain localization in the form of deformation bands (Aydin, 1977; Fossen et al., 2007). Studies and research on this subject in the last decades however, have mainly focused on the extensional regime, particularly related to fault damage zones, while deformation band formation in porous sandstones subjected to contractional deformation is a much less explored subject. A few studies have suggested that deformation bands are more broadly spaced, and less restricted to faults than deformation bands in extensional regimes (Solum et al., 2010; Brandenburg et al., 2012); motivated by these previous studies, this research aimed to achieve a better understanding of deformation of porous sandstones particular to contractional tectonism.

In addition to the fundamental motivations laid out above, porous sandstones are of interest because they constitute the most abundant type of petroleum reservoir and aquifer around the world (Ehrenberg & Nadeau, 2005; Margat & Van der Gun, 2013). Important hydrocarbon accumulations are located in contractional settings, where the structures in general are poorly imaged by seismic, and deformation bands (also below seismic resolution) introduce structural reservoir heterogeneities; thus their characterization and assessment with respect to the bigger-scale trapping structures is of great importance to obtain more realistic reservoir models, that result in better predictions and ultimately improvement of production, injection and even carbon storage strategies for comparable subsurface reservoirs.

Surface outcrops of sandstones subjected to contraction tectonism, such as the widely exposed Aztec and Navajo sandstones in western USA, and their impressive populations of contraction-related deformation bands, provided remarkably well-suited field areas for us to improve our knowledge of contraction of porous sandstones; including temporal evolution, spatial distribution and implications for fluid flow, as well as to draw comparisons with previous knowledge from extensional settings.

Objectives

This project aimed to i) explore how porous sandstones respond and evolve under contractional tectonism, ii) to determine properties and characteristics of deformation bands formed under contraction, iv) to evaluate effects of this deformation on fluid flow, and iii) to study the differences and similarities between deformation bands in the contractional regime compared to those of the extensional regime.

Particular objectives to address the aforementioned aims were as follows:

- Establishing which types of deformation bands can occur in highly porous sandstones deformed in the contractional regime (arrangements and orientations).
- Estimating how contractionally-induced deformation bands are distributed with respect to larger-scale structures (folds, reverse faults or thrusts, state of stress)
- Assessing the frequency of contraction-induced deformation bands with respect to larger structures (folds, thrusts etc.) and lithological parameters (sedimentary architecture, grain size, sorting etc.)
- Determining porosity/permeability reductions associated with contractional deformation of porous sandstones, assessing damage zone geometries and petrophysical properties.
- Evaluating effects of permeability/porosity reductions of deformation band arrays on reservoir-scale fluid flow for contractionally-deformed sandstone layers.

Methods

The methodology used in the present study mainly involved extensive fieldwork with detailed structural mapping; characterizing deformation bands, geometric description, mapping of spatial distributions with respect to larger structures such as folds and thrusts, collecting information about petrophysical properties, notably field permeability using a portable air permeameter (TinyPerm II), and rock sampling to estimate porosity and grain framework mainly via thin section analyses. To quantify and analyze the effects of the studied deformation bands on fluid flow at reservoir scale, tailor-made numerical simulations capturing the effect of deformation band networks on a small-scale were upscaled and incorporated into an industry standard geocellular reservoir model in order to simulate fluid flow across sandstone layers.

Fieldwork

The field areas selected for the present study are located in western USA, in the states of Utah and Nevada (Figure 1). These areas were selected due to their diverse and well-exposed examples of layers of porous sandstones involved in thick-skinned and thin-skinned contractional tectonism during the Laramide and Sevier orogenies, respectively. Lithologically, the Jurassic Navajo Sandstone and the correlative Aztec Sandstone were the primary units studied in this project; both represent highly porous, quartz-rich sandstones that for the most part are eolian in nature. Their widespread exposure in numerous locations allows for a detailed analysis of deformation bands within them.

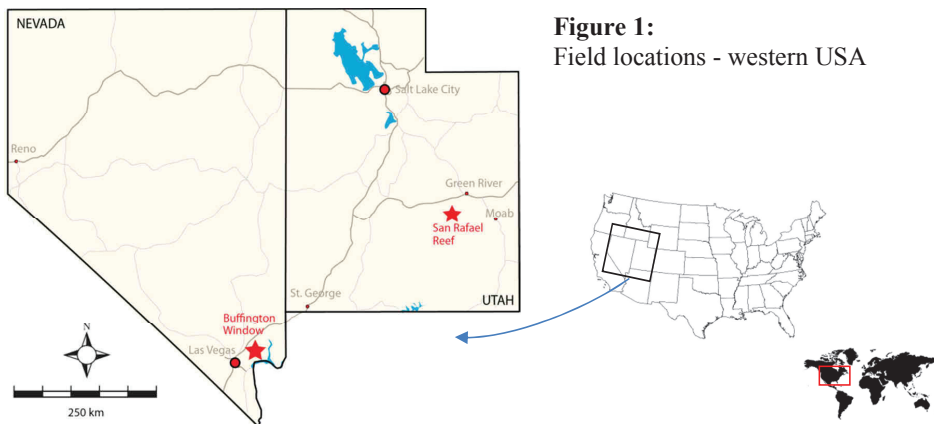
UTAH, San Rafael Reef: *Monoclinial fault-propagation fold - Cordillera Foreland Basin System, thick-skin tectonism.*

The San Rafael monocline is the eastern forelimb of the doubly-plunging asymmetric fold known as the San Rafael Swell, a basement uplift ~120 km long and ~60 km wide located in central Utah that exposes the Jurassic Navajo Sandstone in its steep limb, together with units as old as Permian toward its core. The San Rafael monocline is one of several monoclines located on the Colorado Plateau, formed during the Laramide orogeny. The San Rafael monocline is convex to the SE with changing interlimb angles along strike, resulting in variable fold tightness, which in turn is related to deformation band distributions in the Navajo Sandstone in the study area. A detailed mapping of deformation bands as well was carried out and their influence on reservoir quality was assessed developing numerical models for simulation of fluid flow). This fold structure was chosen because it is a good example of a fault-propagation fold that has not reached the stage of fault break-through (and hence small-scale structures can all be related to the folding process), because of its lateral variations in tightness and thus strain, and because of its exceptionally good exposures and simple setting as an isolated fault-propagation fold above a reactivated basement fault or fault zone.

NEVADA, Muddy Mountains, Buffington window: *Footwall of a large overthrust - North American Cordilleran orogenic belt, thin-skin tectonism.*

The Buffington window is a tectonic window exposing ~28 km² of the Aztec Sandstone of the lower plate of an eroded frontal thrust sheet (i.e. the Muddy Mountain thrust sheet) formed during the Sevier orogeny. Thrust sheets in the Buffington Window-Muddy Mountains area are mostly Paleozoic units overriding the porous Jurassic Aztec Sandstone.

In this area it was possible to explore deformation structures in the sandstone associated with Sevier shortening and how the deformation altered the initial petrophysical properties of the sandstone from the thrust and down into the footwall. This area was chosen because it is an unusually well exposed example of highly porous sandstone being overthrust by a large thrust nappe at shallow crustal levels, which represents a contractional tectonic setting that is quite different from the San Rafael monocline in Utah.



Observations / Measurements / Rock Sampling

Observations and measurements were performed to obtain a robust structural mapping of the field areas that cover the character and spatial distribution of deformation bands, as well as their orientations. Stereographic projections were used to organize and display attitude measurements, integrating observations and data into GIS projects and/or Google Earth in order to relate observations spatially. Selective rock sampling of deformation bands and host rocks for thin sections was also performed.

Porosity and permeability analysis

Portable air permeameter measurements and profiling (TinyPerm II by NER), whose technical details are described in was executed to evaluate petrophysical variations in permeability of sandstones and deformation bands associated, see Rotevatn et al. (2008); Filomena et al. (2014) for a detailed methodology. Where possible, permeability was measured across deformation bands and compared to that of the adjacent host rock, from steep-dip reverse faulting (Utah) to sub-horizontal overthrusting (Nevada).

Analysis of Samples (Thin sections)

Thin sections were analyzed under the conventional optical microscope as well as under the electron microscopy (secondary and backscattered electrons and cathodoluminescence). Measurements included porosity estimation, micro-structural analysis, mineral identification, study of cementation/dissolution patterns and X-ray spectrometry analyses.

Numerical Modeling (San Rafael monocline)

Fluid flow simulation was undertaken in order to evaluate the effect of deformation band networks on fluid flow in porous sandstone reservoirs. Deformation bands are small-scale structural features that, given their low-permeable nature, alter reservoir properties and fluid flow patterns. These effects were captured using models and simulations at various scales, using conventional reservoir modeling software (Roxar RMS®) in combination with numerical simulation methods developed by the Department of Mathematics at UiB; the latter auxiliary domains allowed the capture and representation of deformation band effects in the direction perpendicular to the maximum heterogeneity, according to field observations (K_x and K_z , respectively), and the incorporation of resulting upscaled

permeabilities in the large scale model. The auxiliary domains covered a sufficient number of deformation bands to give a meaningful computation of upscaled permeability.

Kinematical modeling: for fold-scale strain considerations, a numerical two-dimensional modeling exercise using trishear was made to evaluate kinematic parameters for the San Rafael monocline. The model was run until the Navajo geometry in the model attained the maximum forelimb dip identified in the field, allowing us to compare strain ellipses and axis from the model to the sets of deformation bands measured in the field.

Data Basis, Methods and Statistics

The database consisted mainly of measurements and observations obtained during field work campaigns, although published available datasets were also used, especially geologic maps in GIS data format. Additionally, some measurements were compared to previous studies, especially for the Buffington Window, for which grain size distributions made for the Aztec sandstone were compared to previously published data.

Background and state of the art

This section provides a general overview of the knowledge foundations on which this project was built, including a synoptic survey of the state-of-the-art on deformation of porous sandstones and deformation bands research.

Deformation bands

Deformation bands are semi-brittle, tabular; mm to cm-thick strain localization features characteristic of deformation of porous granular materials and rocks (porosity $\phi \geq 15\%$). The term, first introduced by (Aydin, 1977; Aydin, 1978; Aydin & Johnson, 1978; Aydin & Johnson, 1983), has evolved over time to include cataclastic faults (Fisher & Knipe, 2001), microfaults (Jamison & Stearns, 1982), shear bands (Menéndez et al., 1996), Lüders bands (Friedman & Logan, 1973) and granulation seams (Pittman, 1981) among other terms, see Fossen et al. (2007) for a review. A significant amount of work has been dedicated to the understanding of deformation bands in the field, e.g., (Antonellini & Aydin, 1994; Davis, 1999); laboratory (Mair et al., 2000; Wong et al., 2001; Tembe et al., 2008; Charalampidou et al., 2011), and numerical simulations (Marketos & Bolton, 2009; Ahmad et al., 2010; Chemenda et al., 2012) yet our understanding of the range in expressions and occurrences of such structures is limited.

Individually, deformation bands accommodate millimetre-scale offsets, but can cluster into thicker inosculating arrays of various geometries (Davis et al., 2000; Schultz & Balasko, 2003; Okubo et al., 2006), displaying up to decimetre-scale cumulative offsets. Deformation bands generally involve pore collapse through grain rearrangement by frictional grain sliding, grain rotation and potentially, grain fracture (Aydin & Johnson,

1978; Antonellini et al., 1994; Fossen et al., 2007); deformation bands can be formed under many conditions, even in non-tectonic regimes (Fossen et al., 2007) such as glacial deformation (Hooke & Iverson, 1995) and gravity-driven collapse (Hesthammer & Fossen, 1999), hence the importance of its characterization for each setting.

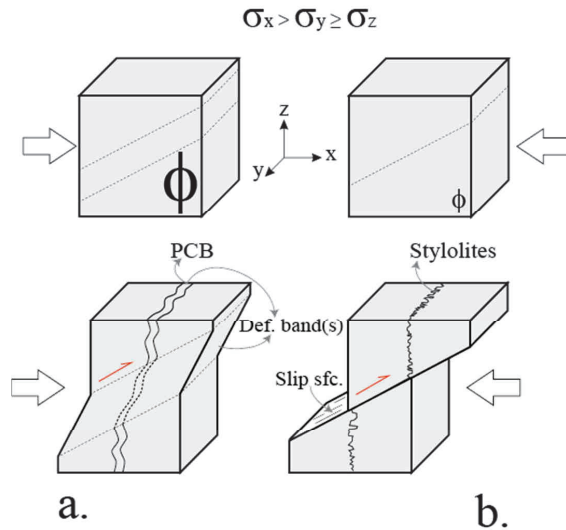
Figure 2: Difference in strain features for **a.** highly porous vs. **b.** non-porous sandstones.

a. Porous sandstones (porosity $\phi \geq 15\%$) accommodate shear in semi-brittle tabular zones, i.e. deformation bands. The sheared volume (dashed) can represent a single band or a cluster

b. Non-porous sandstones form discrete slip surfaces and/or fractures after deformation.

Rock cohesion is maintained by deformation bands, whereas is lost due to the discontinuities created by slip surfaces/fractures.

Under special conditions, vertical strain features (PCB and stylolites, respectively) can form perpendicular to the maximum stress (σ_x).



for both a. and b. timing and relationships between structures is approximate

What is common among all deformation bands, and what differentiates them from fractures, joints and any other comparable-sized strain features, is that across deformation bands, rock cohesion is for the most part preserved or enhanced, and porosity and permeability are typically reduced (Figure 2). Deformation bands are of additional interest, as their cohesive nature leads to strain hardening of the rock, and thus, a tendency to resist reactivation, which helps unravel the deformation history in areas of polyphased deformation (Davis, 1999).

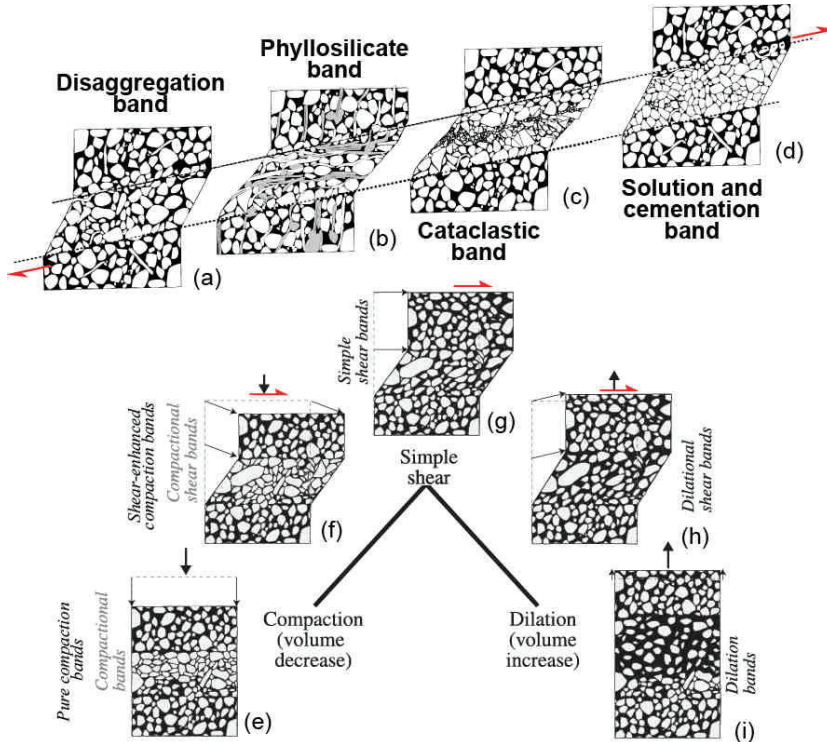


Figure 3: Deformation band types according to deformation mechanism (top) and kinematics (bottom) (modified from Fossen et. al., 2007). Except for dilational bands (h, i), rock cohesion is maintained (a, g) or enhanced (b, c, d, e, f) by deformation bands.

Fossen et al. (2007) proposed two different classifications for deformation bands, one in terms of deformation mechanisms (Figure 3, top); the other in terms of kinematics (Figure 3, bottom). Kinematically there is a range of deformation band types with three end members: compaction, dilation and shear, spanning from dilation bands to isochoric shear bands on one side, and further through compactional shear bands to compactional bands on the other, nowadays these are more commonly referred as to shear-enhanced compaction bands (SECB) and pure compaction bands (PCB), respectively (Figure 3 f, e).

Fossen's (2007) classification by deformation mechanism (Figure 3, top) relates to the interplay of grain framework and mineralogy, in addition to stress state. Spatial rearrangement of fragments dominate in the two first classes: disaggregation (a) and phyllosilicate bands (b), with minor changes in grain shape or size inside deformation bands; disaggregation bands form in compositionally mature rocks, whereas phyllosilicate bands form in rocks whose platy minerals are between 10-40%. For the last two types, cataclastic (c) and solution-cementation bands (d), grain shapes and sizes within bands are considerably smaller from those of the host rock, due to physical processes (grain crushing) for the former, and to chemical/diagenetical processes (dissolution/precipitation) for the latter.

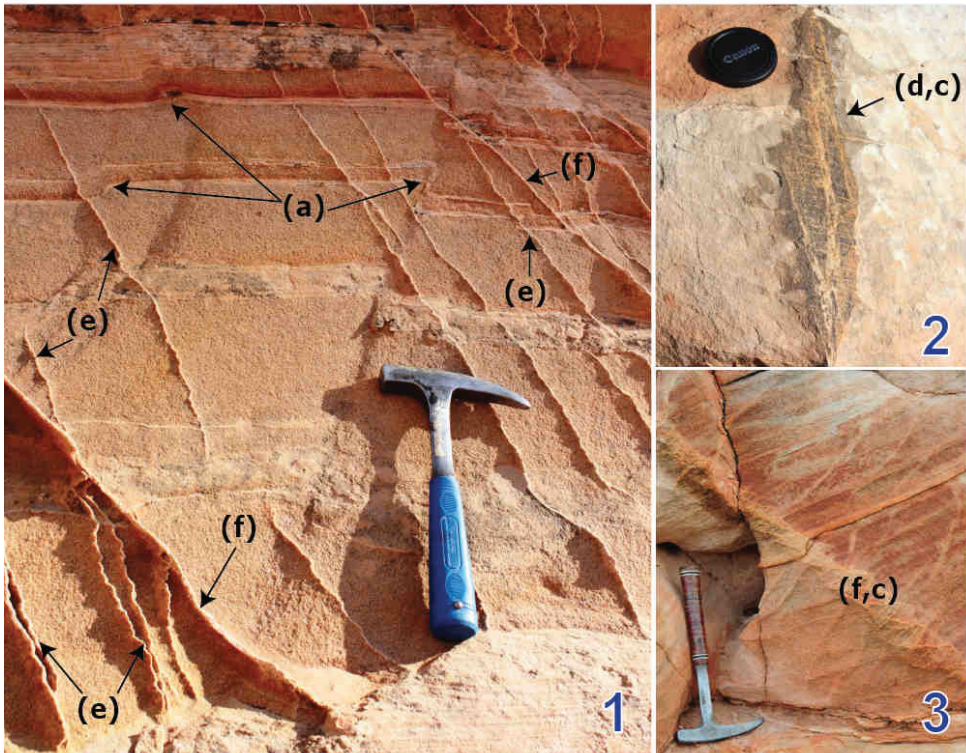


Figure 4: Examples of deformation bands in outcrop. **1.** Navajo Sandstone, Buckskin Gulch, Utah: (a) disaggregation bands, (e) pure compaction bands, and (f) shear-enhanced compaction bands. **2.** Aztec Sandstone, Muddy Mountains, Nevada: (d) solution/cementation band formed in an array of cataclastic bands arranged in ladder geometry (c) **3.** Aztec Sandstone, Muddy Mountains, Nevada: (c) cataclastic bands arranged in ladder geometry, formed along a cm-thick shear-enhanced compaction band (f). **2** and **3** show examples of one type of band being predecessor of other types.

Tectonic regime

The study of the deformation of highly porous sandstones has to a large extent been limited to extensional settings where deformation bands are associated with damage zones of normal faults (Aydin, 1978; Aydin & Johnson, 1978; 1983; Underhill & Woodcock, 1987; Antonellini & Aydin, 1994; Fowles & Burley, 1994; 1995; Fossen & Hesthammer, 1997; Beach et al., 1999; Hesthammer et al., 2000; Fisher & Knipe, 2001; Shipton & Cowie, 2001; Du Bernard et al., 2002a; 2002b; 2002; Bense et al., 2003; Davatzes & Aydin, 2003; Rawling & Goodwin, 2003; 2003; Evans & Bradbury, 2004; Berg & Skar, 2005; Davatzes et al., 2005; Johansen et al., 2005; Shipton et al., 2005; Wilson et al., 2006; Holcomb et al., 2007; Rotevatn et al., 2007; Johansen & Fossen, 2008; 2008; Torabi & Fossen, 2009; Exner & Grasemann, 2010; Tueckmantel et al., 2010; Nicol et al., 2013; Schueller et al., 2013; Awdal et al., 2014).

Areas where such studies have been undertaken include the Colorado Plateau (USA), Rio Grande Rift (USA/Mexico), North Sea Rift (England/Norway), Provence (France) and Sinai (Egypt), among others. Our present understanding of deformation bands and their occurrence in porous siliciclastic rocks are consequently built on studies from these areas and regimes, but also from laboratory experiments and numerical modeling (Wong et al., 1997; Zhu & Wong, 1997; Lothe et al., 2002; Mair et al., 2002; Schultz, 2009; Ahmad et al., 2010). Additionally, strike slip and contraction-related deformation bands have been the subjects of some analysis (Mollema & Antonellini, 1996; Wibberley et al., 2000; Eichhubl et al., 2004; 2007; Campbell, 2008; Eichhubl et al., 2010a; Sallet & Wibberley, 2010; Solum et al., 2010; Fossen et al., 2011; Aydin & de Jossineau, 2014). However, investigations of porous sandstones deformed under contractional tectonism are still

insufficient, both in terms of geographical coverage, as well as regarding to spatial distributions and evolution of deformation band arrays within large-scale contractional structures.

The present project focuses on the contractional regime, where deformation bands are associated with reverse faults and thrusts. During this doctoral period, however, some relevant works have emerged that explore the deformation of porous sandstones in the contractional tectonic regime, including comparative results for contraction and extension deformation of high porosity sandstones (Solum et al., 2010; Schultz, 2011; Brandenburg et al., 2012; Fossen & Rotevatn, 2012; Solum et al., 2012; Ballas et al., 2013; Soliva et al., 2013; Ballas et al., 2014). Laboratory studies and numerical modeling directed towards contractional deformation has also been the subject of present research (Chemenda, 2011; Klimczak et al., 2011; Chemenda et al., 2012; Cheung et al., 2012; Skurtveit et al., 2013).

For extensional regimes, it has been documented that as strain increases, tabular zones of deformation bands progressively form and cluster, until consequent rock hardening leads to slip and faulting. After this process, deformation bands become part of the fault's damage zone (Aydin & Johnson, 1977). For contractional regimes, although temporal evolution with respect to reverse faults and thrusts has not been explored in detail, it has been reported that contractionally derived deformation bands do not cluster very effectively, but rather develop more distributed populations in response to stress, Fossen et al. *in review*, (Solum et al., 2010; Soliva et al., 2013; Ballas et al., 2014).

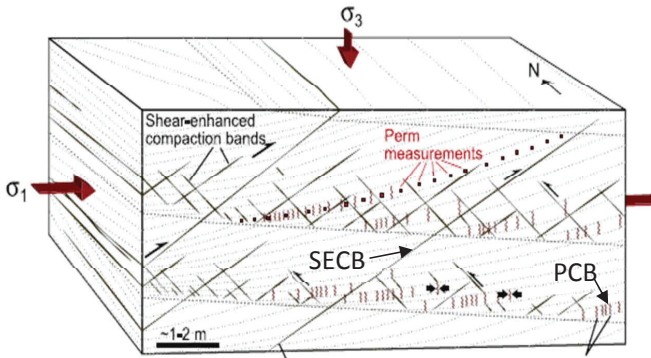


Figure 5: Schematic diagram of deformation bands found in a dune set of the Navajo Sandstone, related to the paleostress axis and host rock bedding (from Fossen et al., 2011), pure compaction bands in brown are perpendicular to maximum horizontal stresses, compactional shear bands or (shear-enhanced compaction bands, in black) are conjugate and at oblique angles to stress axis.

Additionally, it has been documented that different types of bands form at different orientations with respect to the principal horizontal stresses: PCB first described by Eichhubl et al. (2010a), form perpendicular to the maximum principal stress axis and are posited as being the porous sandstone equivalent to tectonic stylolites (Fossen et al., 2011). SECB form at angles to stress axes, typically as conjugate sets (Figure 5).

Furthermore, SECB and PCB have only been reported from contractional settings so far, notably in localities such as Valley of Fire, Nevada (Sternlof et al., 2005; Eichhubl et al., 2010), Buckskin Gulch, Utah (Mollema & Antonellini, 1996; Fossen et al., 2011), and Provence, France (Ballas et al., 2013). These compactive bands are typical for contraction, as in this setting the tectonic stress is added to the horizontal stress; and higher horizontal stresses are more likely to produce compaction.

PCB are the least common of the two, restricted to well-sorted sandstone layers with coarse/very-coarse grains ($>0.4\text{mm}$) combined with very high porosity and permeability ($\phi \geq 29\%$; $K \geq 10$ Darcy) (Schultz et al., 2010; Fossen et al., 2011).

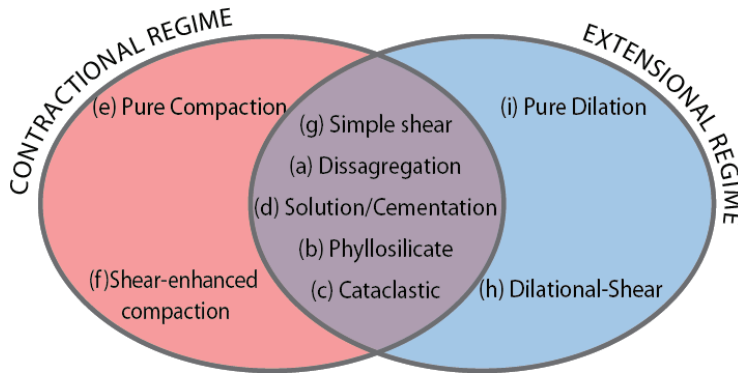


Figure 6: Deformation band types in relationship with tectonic regime. In addition to simple shear bands (g), all deformation band types in the classification by deformation mechanism can be found both in extension and in contraction (a-d), in contrast, only dilation/compaction end members of deformation bands from kinematic classification are exclusive to each tectonic regime, these end categories can be precursors to other types of deformation bands that can fall in the overlap area between regimes. (See classifications in Figure 3)

Structure and mechanisms

Theoretical and laboratory analyses of granular materials have been used to describe the mechanisms for deformation and shear localization of porous sandstones (Olsson, 1999; Mair et al., 2000; Schultz & Siddharthan, 2005; DiGiovanni et al., 2007; Rudnicki, 2007), after these studies, empirical laws and models relevant to porous sandstones and deformation bands have been derived.

The concept of bifurcation (Rudnicki & Rice, 1975), applicable to granular materials, refers to the change from a distributed strain homogeneously accommodated in the material, towards a heterogeneous strain localisation, concentrated and accommodated in a planar/tabular zone (i.e. a deformation band).

Instead of failing (fracturing), a granular material will yield (flow via granular or cataclastic flow) at progressive stresses. As a result, yield envelopes are used instead of failure envelopes; unlike the Mohr-Coulomb linear envelopes of failure, yield envelopes can account for the volumetric changes that take place in granular materials during deformation (Issen & Rudnicki, 2001; Borja & Aydin, 2004).

Yield surface envelopes are usually displayed in stress spaces with deviatoric stress q plotted against mean stress p (qp diagrams, Figure 7). This diagram has been widely used because it allows extracting information of sequential loading/unloading of materials, and because the stresses are already defined as effective, thus accounting for pore water pressure effects (Schultz & Siddharthan, 2005).

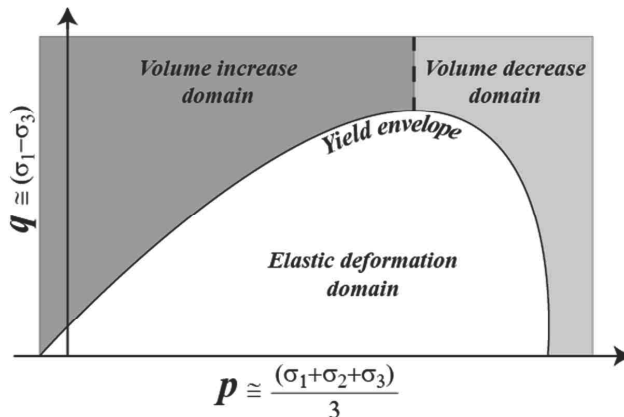


Figure 7: Generalized qp diagram, modified from (Schultz & Siddharthan, 2005). Different types of deformation bands will plot in different parts of the envelope after yielding: ideally, pure dilation bands and pure compaction bands plot along or near the horizontal axis, at minimum and maximum p values respectively; pure shear bands plot along the vertical boundary between volume increase and volume decrease (dashed line). In reality, most deformation bands have a mixed component of shear+dilation or shear+compaction.

Petrophysical properties: porous sandstones as reservoirs

The majority of the hydrocarbons currently extracted are located in sandstone reservoirs, which also constitute the most abundant type of aquifer around the world (Ehrenberg & Nadeau, 2005; Margat & Van der Gun, 2013). The interest in deformation bands in terms of petrophysical properties and influence on reservoirs lie in their tendency to reduce porosity and permeability after pore collapse, creating petrophysical heterogeneities with the potential to redirect or baffle fluid flow (Sigda et al., 1999; Rotevatn et al., 2009b; Rotevatn et al., 2013); the interest to characterize them is mainly for predictive purposes due to their small size, well below seismic resolution (Gabrielsen et al., 1998).

The main control behind deformation band formation in sandstones is the primary porosity of the host rock, hence, processes that alter porosity are also controlling factors affecting deformation band formation; these processes can be inherent to the host rock (grain size and shape, grain sorting, mineralogical composition etc.), as well as external to the host rock (burial/lithification, diagenesis, applied tectonic loads, mechanical contrast between layers etc.). Some studies explicitly exploring the influence of these factors in porous sandstone deformation include: for diagenesis (Labaume & Moretti, 2001; Ogilvie & Glover, 2001); for grain size distributions (Cheung et al., 2012; Torabi et al., 2013) for grain shape (Mair, 2002), and for burial (Karner et al., 2005).

In terms of permeability, the main control behind band permeability is degree of cataclasis (Fossen & Bale, 2007; Ballas et al., 2012b). Deformation bands have been reported to have permeabilities that range from values comparable to those of the adjacent host rock (i.e. disaggregation bands, PCB and SECB), up to contrasts of 5 orders of magnitude reduction

deformation include: for diagenesis (Labaume & Moretti, 2001; Ogilvie & Glover, 2001); for grain size distributions (Cheung et al., 2012; Torabi et al., 2013) for grain shape (Mair, 2002), and for burial (Karner et al., 2005).

In terms of permeability, the main control behind band permeability is degree of cataclasis (Fossen & Bale, 2007; Ballas et al., 2012b). Deformation bands have been reported to have permeabilities that range from values comparable to those of the adjacent host rock (i.e. disaggregation bands, PCB and SECB), up to contrasts of 5 orders of magnitude reduction with respect to the host rock (generally for dense clusters of cataclastic bands or cementation bands).

In addition to the aforementioned properties and relations, as deformation bands are small-scale features, their effect at reservoir scale depends on their spatial distribution (length, thickness, density and 3-dimensional connectivity) combined with the dynamic properties and fluid interactions within reservoirs containing them (capillary pressures, flow phases etc.). Studies that explore fluid flow across deformation band networks in reservoirs include (Antonellini & Aydin, 1994; Sternlof et al., 2006; Jolley et al., 2007; Kolyukhin et al., 2009; Rotevatn et al., 2009a; Exner et al., 2012; Rotevatn et al., 2013). Most of these studies are two-dimensional simulations across a single damage zone, or in outcrops no larger than a square kilometre. The only one of these studies that consider a contractionally derived deformation band array is that by (Sternlof et al., 2006), who did a 2-D simulation study of a model less than 1km².

Synthesis of main findings

This research provides further contributions towards a better understanding of how porous sandstones deform under contractional tectonic regimes. Our research analysed two eolian sandstone layers and their associated deformation band populations, formed as a result of thick-skinned (basement-involved) contractional folding and thin-skinned overthrusting, respectively.

Our analyses in both locations link multiscale observations, from microscale via outcrop to kilometric (reservoir) scale, allowing the creation of models for temporal evolution of deformation band networks, as well as investigations of their associated petrophysical effects and potential applications.

The following is a generalized account of our main findings and their implications in the frame of the existent knowledge of deformation of porous sandstones.

Development of deformation bands in the contractional regime

The study of deformation bands in the San Rafael monocline allowed us to propose a model for the evolution of deformation bands in fault propagation folding (Ch.2, Paper I). Results show that deformation band arrangements, (formed as a result of increasing stresses), can be chronologically assessed; the sequence of deformation band evolution for sandstone layers in fault-propagation folds can be associated with different stages of folding, establishing a close relationship between limb dip, which appears to be closely related to strain, and deformation band geometry, arrays and density, as shown in Figure 8.

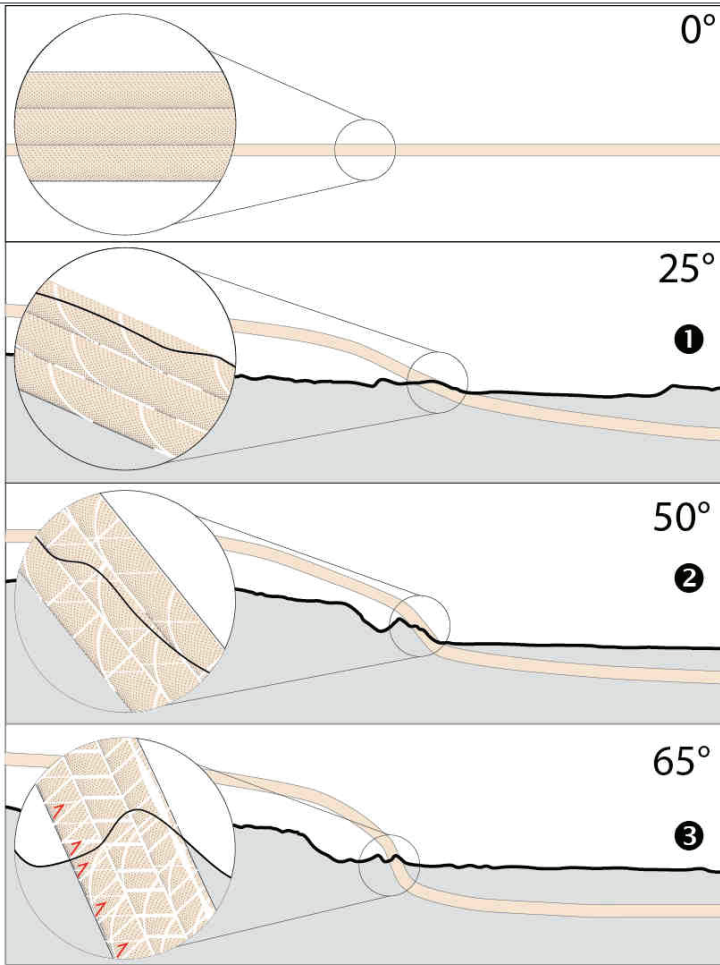


Figure 8: Proposed evolution of deformation bands in the San Rafael monocline (Navajo interval constructed above and below present day topography in gray). Bedding-parallel and crossbed-parallel deformation bands begin forming at gentle dip domains (❶), ladder structures, cutting across bedding occur as folding progresses (❷). Deformation bands continue to develop, increasing in thickness and number. At final stages, clusters aggregate at the top of the unit, whereas slip surfaces form at the base of the formation (❸).

The Buffington window example represents a very different setting because stress builds up from a horizontal push, not by the reactivation of a buried basement structure. The study of the Buffington window suggests that for long distance overthrusting, deformation bands first develop in response to rear-push forces, prior to or at early stages of the thrust sheet

emplacement, leading to different types and orientations of deformation bands as the upper plate emplacement and motion over the sandstone progresses (see Figure 9 and Ch. 2, Paper IV). Additional variables such as and properties will be discussed in the following section.

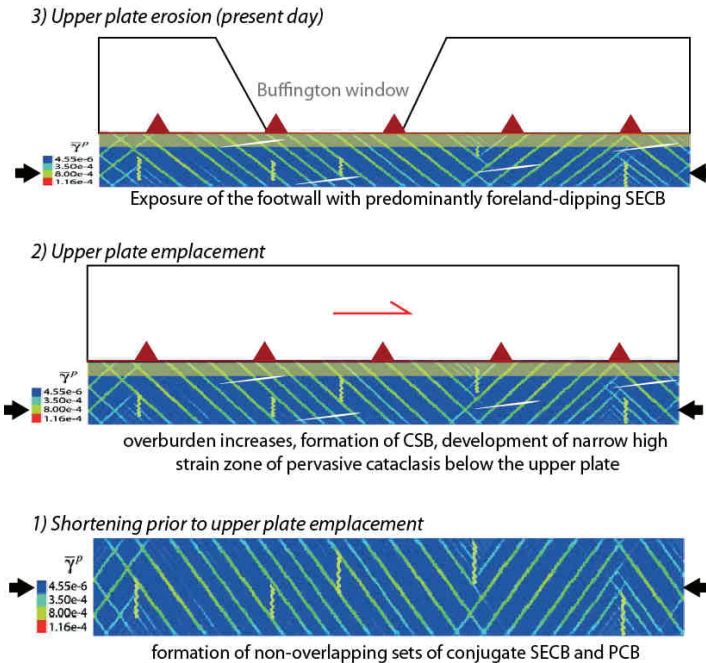


Figure 9: Proposed evolution of deformation bands in the Aztec sandstone at the Buffington window, Nevada (simplified, not drawn to scale. $\bar{\gamma}^p$ = shear deformation). After Fossen et al., *in review*. Modified from Chemenda et al. (2014).

Properties and Characteristics: Types, spatial distribution and orientations

In terms of orientation, attitudes of deformation bands for the Buffington window show good consistency with horizontal maximum stresses (Figure 9 and Ch.2, Paper IV). On the other hand, the progressive rotation of layers in the San Rafael monocline forelimb results in a more dispersed distribution of structural attitudes. It was possible however, to identify

the passive rotation of deformation band arrays during folding to correlate the orientations to east-west contraction (see Ch.2, Paper I).

For the Navajo sandstone in the San Rafael monocline, contractional deformation bands are almost exclusively mm-thick cataclastic shear bands (CSB, Figure 3-c), arranged both as individual bands, as well as members of higher order arrays, (ladders and tabular clusters), occasionally developing slip surfaces with meter-scale offsets (Figure 8).

The Aztec sandstone at the Buffington window is characterized by its populations of cm-thick shear-enhanced compaction bands and pure compaction bands. As stated in the previous sections, PCB and SECB were formed prior or at early stages of upper plate emplacement, in response to rear-push forces, whereas cataclastic shear bands (CSB) are subordinate and subsequent to the previous two types, most likely related to additional loading by the upper plate and resulting increase in stress across grain contact points (see Figure 9).

Pure compaction bands and shear-enhanced compaction bands were not identified in our analysis of the Navajo sandstone. Although Navajo and Aztec sandstones are both eolian sandstones and considered to be laterally equivalent, they are involved in two very different types of contractional deformation. It is therefore more natural to explore the reasons behind the absence of PCB and SECB with a comparable fault-propagation structure, the East Kaibab monocline, for which both PCB and SECB have been documented (Fossen et al., 2011; Schultz, 2011; Brandenburg et al., 2012); It is also worth noting that the majority of the SECB are much thinner in the East Kaibab monocline than in the Aztec Sandstone in Nevada (see Figure 4), although the reason for this is not obvious.

The lack of pure compaction bands and shear-enhanced compaction bands in the San Rafael monocline could be explained in two manners: first, in terms of host rock grain framework, differences in compaction due to deeper burial of the Navajo in the San Rafael monocline (Nuccio & Condon, 2000), or due to subtle differences in granulometry, PCB/SECB are characteristic of layers with highest porosity PCB especially restricted to coarsest-grained layers (Schultz et al., 2010; Fossen et al., 2011). Figure 10 shows that the Navajo sandstone in the east Kaibab monocline is indeed slightly coarser than the Navajo at the San Rafael monocline, denoting suitability for PCB/SECB.

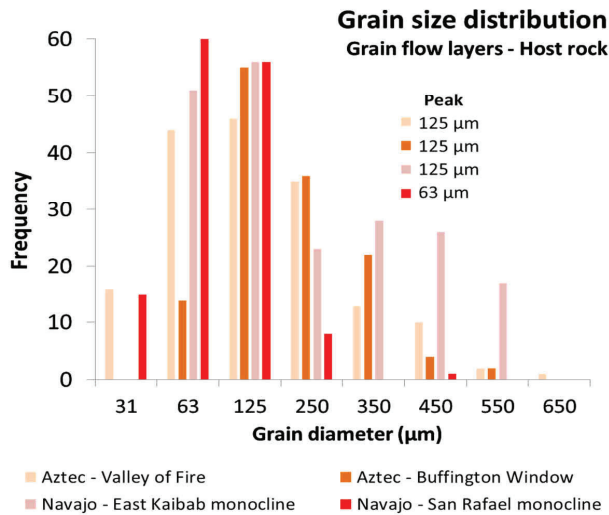


Figure 10: Grain size distribution of samples from the Aztec Sandstone in Nevada (Valley of Fire and Buffington Window), and Navajo Sandstone in Utah (East Kaibab and San Rafael monoclines). All from grain flow layers (layers with highest porosity and coarsest grains). Incidentally, PCB/SECB in the East Kaibab are thinner than those of the Aztec, correlating with finer grain sizes for the Navajo Sandstone and coarser for the Aztec Sandstone.

A second explanation relates to the location of the outcrops with respect to the fault propagation fold for each structure analyzed, as shown in Figure 11. The Navajo outcrops in the middle of the triangular trishear zone of the San Rafael monocline (i.e. the interlimb of the monocline), whereas in the East Kaibab monocline, it outcrops in the transition zone

between the interlimb and the lower limb (see red stars in Figure 11). According to trishear modeling by Brandenburg et al. (2012), strain decreases in this zone. If this is the case, PCB and SECB could possibly be found in the buried Navajo layers of the San Rafael monocline, towards the outer limb of the fold, segments for which layer parallel shortening could be more pronounced.

Another factor to consider (albeit much less constrained) is the kinematics and slip behavior of the controlling basement faults; there is a strong component of oblique-slip for the East Kaibab monocline (Tindall & Davis, 1999), whereas the San Rafael monocline fault is dominated by dip-slip (Fischer & Christensen, 2004), this could also result in differences in the way strain localizes above a propagating reverse fault tip.

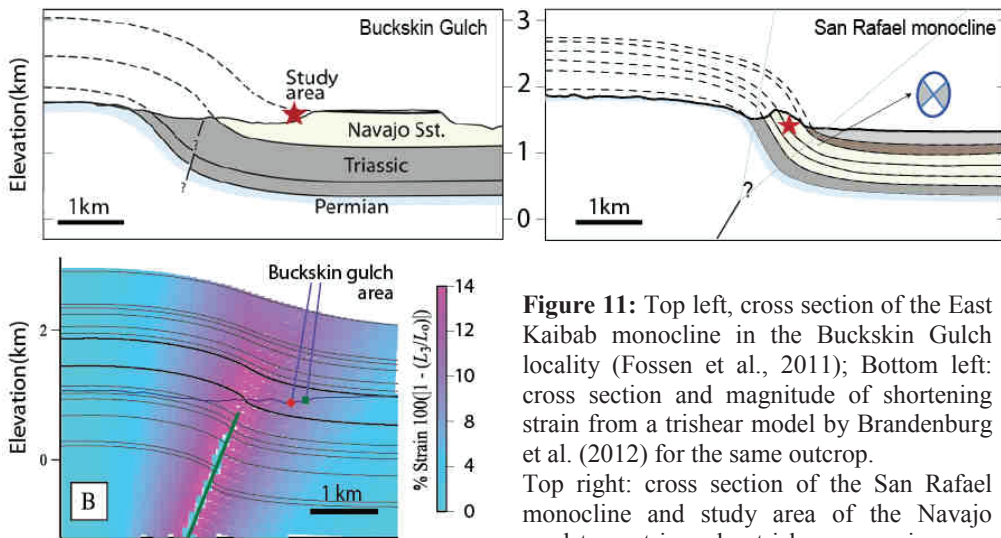


Figure 11: Top left, cross section of the East Kaibab monocline in the Buckskin Gulch locality (Fossen et al., 2011); Bottom left: cross section and magnitude of shortening strain from a trishear model by Brandenburg et al. (2012) for the same outcrop.

Top right: cross section of the San Rafael monocline and study area of the Navajo sandstone, triangular trishear zone in gray, and strain ellipse adjacent to it indicating (horizontal) layer-parallel shortening, from Zuluaga et al. (2014).

Our observations in both the Aztec sandstone in Nevada and in the Navajo sandstone in Utah reveal that strain localization is related to the stress concentration for each structure; in fault propagation folding, the development of deformation bands appears to be restricted to the trishear triangular zones, whereas the regional shortening of the overthrust in Nevada allowed a much more widespread deformation of the sandstone layers in the footwall, less restricted by the overthrust fault and more closely related to far-field stresses, at least at early stages of shortening.

This is also evidenced in the spacing of networks, as spacing between deformation band arrays are variable in both settings: at the Buffington window, SECB were usually spaced 3 m^{-1} on average (Ch.2, Fig. 4 of Paper IV), whereas CSB arranged in ladder structures at the San Rafael monocline (in the steepest sector of the monocline forelimb), averaged 1 m^{-1} (Ch.2, Fig. 8 of Paper I).

Reservoir implications

Deformation band arrays have some capabilities of redirecting flow (Antonellini & Aydin, 1994; Antonellini et al., 1999; Chuhan et al., 2002; Eichhubl et al., 2004; Eichhubl & Flodin, 2005; Fossen & Bale, 2007; Ballas et al., 2012a; Tueckmantel et al., 2012). The wide areal exposure of the San Rafael monocline allowed us to construct a model and to develop a flow simulation model at a scale significantly larger than previous simulation studies so far, which for the most part have been two-dimensional and across a fault damage zones in outcrop (metric) scales, in contrast, the three-dimensional reservoir model built in this study from the San Rafael monocline is considerably larger (80 km^3), comparable in dimensions to mid-size hydrocarbon fields.

According to our studies and numerical simulations of the Navajo Sandstone in the San Rafael monocline, the contrast in permeability between pervasive deformation band arrays and the host rock permeability needs to be at least of three orders of magnitude to have a noticeable impact in large scale production: when the difference is of at least three orders, our simulation shows a positive effect of sweeping efficiency, as deformation bands become less permeable with respect to host rock, allowing for a higher fluid path tortuosity, that resulted in delayed water breakthroughs, less bypassed oil and ultimate higher recoveries, hence, larger final produced volumes. In any case, long term production is needed in order to detect the effect of deformation bands in a comparable subsurface reservoir. (Ch. 2, Paper II).

For large-scale overthrusting, reservoir quality from petrophysical studies suggest that high porosity sandstones can endure extensive overthrusting and largely preserve good petrophysical properties (Ch. 2, Paper III). However, for the overthrust analysed, the timing of migration relative to the thrust zone development would be critical for successful fluid entrapment. In other words, a reservoir experimenting a comparable deformation history will trap a fluid only after the low permeable-low porous zone has been formed (product of the friction on the Muddy Mountains thrust), thus constituting a top seal for the sandstone, (Figure 12).

In both sandstone units and settings, the wider spacing and anti-clustering tendencies of contractional arrangements of deformation bands allows for a better (albeit slower) sweep of reservoirs, when fluids traverse zones with deformation bands. Compartmentalization is most effective for arrays of cataclastic deformation bands such as the ones in the San Rafael monocline for the Navajo Sandstone, as opposed to the SECB and PCB in the Aztec

Sandstone, as the porosity and permeability of PCB and SECB are very similar to the host rock; as such, effective reservoir compartmentalization will not likely take place for porous sandstones whose majority of deformation bands are not cataclastic, unless pressure gradients are sufficiently low.

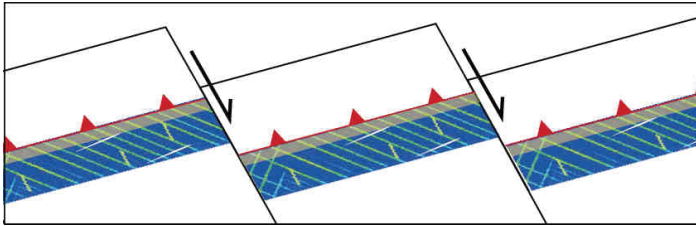


Figure 12: Hypothetical scenario for successful fluid entrapment in an overthrust eolian sandstone analogous to the Aztec Sandstone at the Buffington Window. Top seal provided by the low permeable-low porous zone at the thrust contact (formed during Sevier overthrusting), combined with lateral seals from fully-sealing normal faults (Basin and Range extensional tectonism)

The relatively lesser clustering of contraction-induced deformation bands can potentially have better effects on long term recovery of fluids and sweep than the extensionally derived counterparts, for which channelling and bypassing of fluids can be more common. With the exception of fault interferences in normal-fault systems that impede extreme clustering, such as the relay zones investigated by (Rotevatn et al., 2009b), which also reported good sweeping effects.

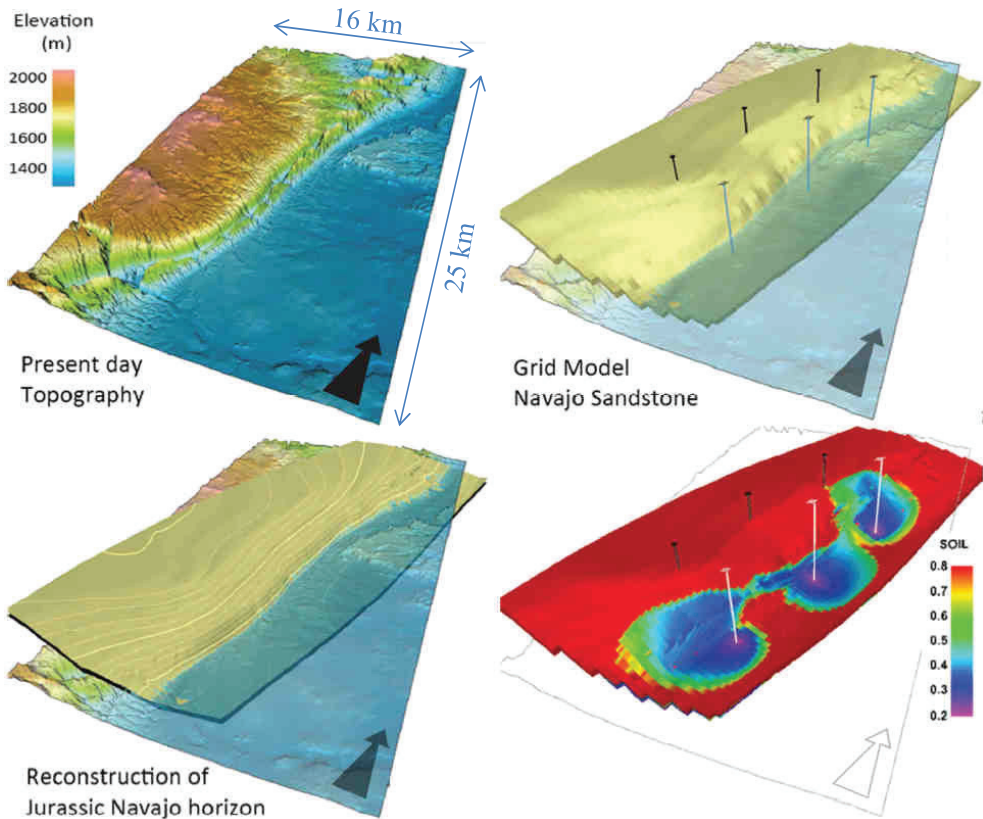


Figure 13: Construction and flow simulation of the reservoir model for the Navajo Sandstone in the San Rafael monocline. Bottom right shows simulation results for contrasts of 5 orders of magnitude (reduction in permeability of deformation bands with respect to the host rock), showing redirection of fluids along strike. (Vertical exaggeration 2x. SOIL=Oil saturation).

Comparison with extensional regimes

Spatial distributions and evolution: This research supports the claim that contraction-induced deformation band arrangements are less likely to cluster and tend to be more broadly spaced than their extensional counterparts (Solum et al., 2010; Soliva et al., 2013; Ballas et al., 2014; Zuluaga et al., 2014) Fossen et al. *in review*. Such anti-clustering prevents them from forming nucleation sites for large-offset faults, with the exception of meso-scale slip surfaces; the second major difference between regimes, is that in addition to the cataclastic shear bands (CSB) typical of extensional regimes, two types of deformation bands appear to be restricted to contraction tectonics, namely pure compaction bands and shear-enhanced compaction bands (PCB, SECB), In our study areas, they reveal consistent orientations perpendicular to the maximum principal stresses (See Ch.2, Figs. 1 and 4 of Paper IV).

Deformation bands formed in the contractional regime have been shown to be less localized and more broadly spaced. Such anti-clustering prevents them from becoming effective precursors for large offset faults like extensional deformation bands. For the San Rafael fault-propagation folding, however, cataclastic shear bands closer to the fold core (i.e. near the fault termination at depth) were found to develop meso-scale slip surfaces.

Contraction-induced deformation bands can also form over longer time or strain intervals prior to faulting, as compared with extensional deformation bands, i.e. from early folding ahead of fault tips (as shown by our study of the San Rafael monocline), and as our analysis of the tectonic Buffington window showed, from far-field stress responses of shortening, prior to or at early stages of overthrusting.

Contraction vs. extension in porous sandstone reservoirs: Permeability studies from porous sandstones deformed under contractional regimes suggest a more constant relationship between permeability and porosity trends (Figure 14), as well as less scattering of permeability values than the extensional counterparts (Figure 15). At present, predictably, no contractional deformation bands have been reported with an increase of permeability with respect to the host rock.

Figure 14 shows that porosity vs. permeability trends in sandstones under contraction result in a preservation of petrophysical properties of the host rock, comparable to sandstones with only burial vertical loading. This can be attributed to the broader networks of deformation bands having an overall small effect in the host rock reservoir properties. Additionally, PCB and SECB tend to reduce only slightly porosity and permeability. In extensional regimes, preservation of porosity and permeability only occurs by dilation and disaggregation bands, these bands are very rare compared to PCB and SECB.

Figure 15 shows that contrast in permeability between host rocks and deformation bands in the contractional regime ranges from none to five orders of magnitude, whereas the range of contrast for extensional regimes is much broader. Nonetheless, it is important to notice that these observations might change when more studies of shortened sandstones arise.

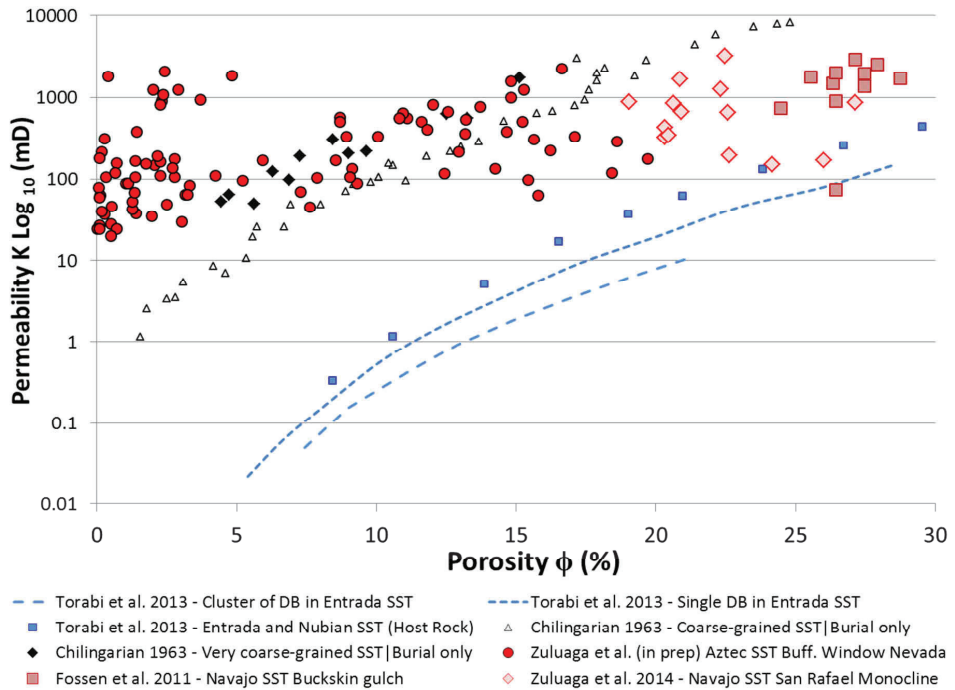


Figure 14: Permeability-porosity relationships of various porous rocks modified after (Fossen et al., 2011; Torabi et al., 2013). Black colors represent sandstones with no tectonic loading (burial only), Blue colors correspond to host rocks (squares) and deformation bands (lines) affected by extension tectonism, red colors are from sandstones deformed under contractional tectonism.

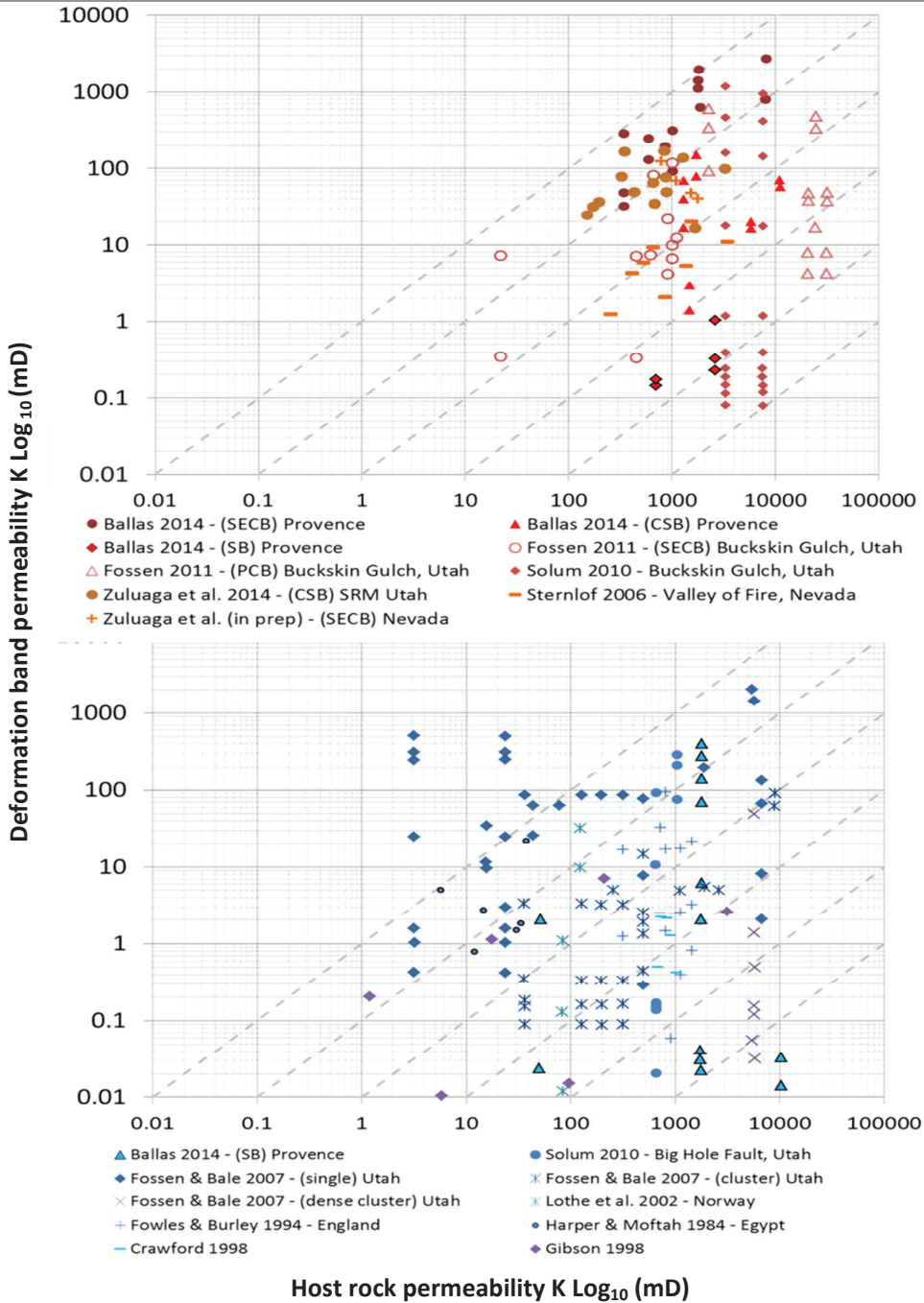


Figure 15: Permeability contrasts between deformation bands and host rocks in contraction (top) and extension (bottom) regimes, from published data and measurements from this study. Localities and deformation band types stated where available. Modified from Fossen and Bale (2007); Solum et al. (2010); Ballas et al. (2014).

Conclusions

- Tectonic regime has an important influence on the character of sandstone deformation, mainly in terms of spatial distributions of deformation bands within contractional structures. Deformation bands in contractional settings are more broadly distributed compared to extensional deformation band populations.
- Because of their tendency to not develop clusters, contractional deformation bands are not effective fault precursors, with the exception of meso-scale slip surfaces formed at advanced stages of deformation band development.
- Although broadly-spaced distributions of deformation band are characteristic of contractional structures, strain localization within each contractional structure can vary: high-angle reverse basement faults are more likely to localize strain in sandstone layers within or adjacent to their trishear triangular zones, whereas far-field shortening related to long distance overthrusts can distribute stress in a much wider area of the sandstone footwall, and only start to localize deformation pervasively (and very close to the fault contact) in late stages of overthrusting, due to friction between thrust plates.
- By comparing the two study sites, the amount of tectonic transport does not appear to be a factor controlling intensity of deformation band networks, as densities of deformation bands were higher for fault-propagation folding which has substantially less fault movement than the Muddy Mountain thrust (hundreds of meters for the former vs. tens of kilometres for the latter). Hence, the boundary conditions appear to be more important than the total strain involved.

- Deformation bands have fluid baffling effects, but do not effectively compartmentalize reservoirs; this baffling impact on reservoirs is limited, and only evidenced for cases involving high permeability contrasts and at mature stages of production.

Outlook and Future Work

This research has contributed to a better understanding of how deformation of highly porous sandstones occurs under contractional tectonic regimes, and their implications for fluid flow and reservoir performance. While carrying out the project, and in light of our observations and results, new research possibilities arose for expanding and improving this knowledge.

- *Contractional regime:* This research examines deformation of porous sandstones related to the Sevier orogen and the Laramide foreland of western USA. Expanding this line of research to different geographical locations with additional areas of contractional deformation, such as collisional orogens and deep-water thrust-and-fold belts is relevant.
- *Structures:* studies of additional types of contractional structures would broaden the knowledge of how porous sandstones deform during contractional tectonics (e.g. fault-bend folds, detachment folds, accretionary wedges, duplexes, restraining stepovers of strike-slip systems etc.). Such expansions should ideally include data from subsurface structures of reservoirs in which contraction-related deformation band populations have been recognized.
- *Deformation bands particular to contractional regimes:* According to our results as well as those of other scientist who worked in comparable settings (Eichhubl et al., 2010b; Ballas et al., 2013), it appears that shear-enhanced compaction bands and pure compaction bands (SECB and PCB) are exclusive of deformation of porous sandstones under contraction. In order to strengthen this claim, more evidence needs to be obtained, via investigation of the points aforementioned: i.e. more contractional examples and additional contraction structures.

- *Geomechanical modeling and analyses*: Some rheology considerations were explored in this research; however, numerical modeling exercises accounting for mechanical properties, interlayer slip and contrasts between adjacent layers at larger scale, as well as their boundary conditions, have the potential to further elucidate the controls on deformation band formation in porous sandstones in contractional regimes.

- *Interplay and controls of sedimentary architecture*: although some controls of sedimentary structures at early stages of deformation were observed in our analyses, it would be of interest to investigate in greater detail how sedimentary architecture and heterogeneity influences the style and distribution of deformation bands.

- *Mechanical paradox of overthrusting*: the Aztec sandstone remains essentially undeformed despite the magnitude in size and amount of transport of the upper plate that rode over it, the question remains open, whether the granular nature of the sandstone (saturated with relatively freely moving fluids) could be an effective lubricant that compensated for the absence of overpressured fluids and décollement layers in the Muddy Mountain thrust, and also how was it able to accommodate most of the deformation near the thrust and only slightly underneath, expressed in deformation bands.

- *Deformation band waves*: In both the Aztec and Navajo sandstones at the two field areas investigated, arrays of cataclastic bands organized in concentric/radial geometries were recognized, informally called by the author “waves”, due to its resemblance to surface dispersion waves (Figure 5); seemingly these have not been analyzed or reported previously. The author speculates that they could represent focal points of deformation and energy release, travelling radially across sand(stone), when or if highly saturated with fluids

(liquefaction?). The mapping and analysis of these features in depth is potentially very interesting.

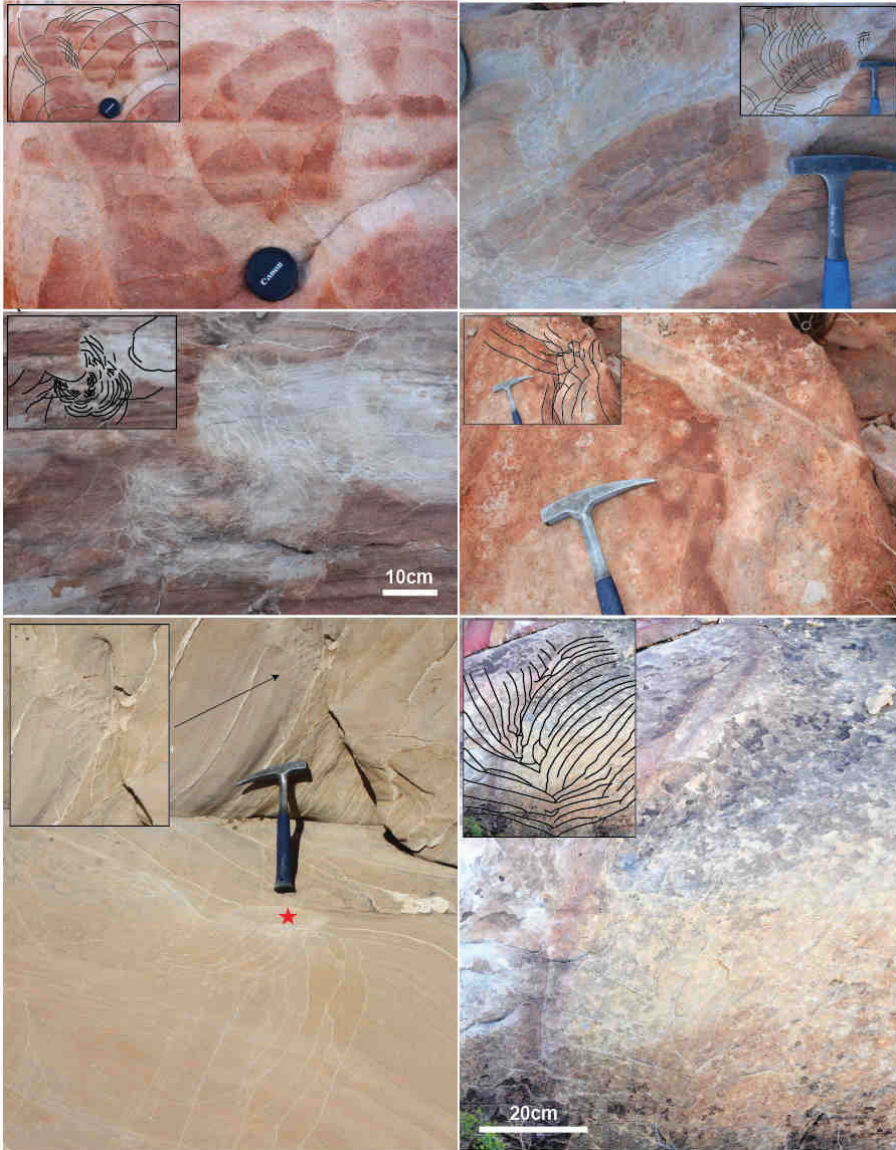


Figure 16: photographs of cataclastic deformation bands arranged in concentric geometries or “waves”. All photos from the Aztec Sandstone in the Buffington window, except for the bottom left photo (red star), from the Navajo sandstone in the San Rafael monocline.