Subseismic-scale reservoir deformation: introduction

M. ASHTON1*, S. J. DEE2 & O. P. WENNBERG3

1Badley Ashton America Inc., 14701 St Mary’s Lane, Houston, TX 77079, USA
2BP Exploration and Operating Company Limited, Chertsey Road, Sunbury on Thames, Middlesex TW16 7BP, UK
3Statoil, Sandsliveien 90, Norway

*Correspondence: mikeashton@badleyashton-america.com

Abstract: This volume examines the current best practice and new challenges in reservoir characterization and modelling of small- to subseismic-scale deformation features through case studies, experimental results and modelling. The papers in this volume include contributions on four themes related to the small-scale deformation of hydrocarbon reservoirs: the characterization of deformation in porous sandstones; novel characterization techniques; quantifying and characterizing deformation in carbonates; and modelling small-scale features. It includes eight papers from the conference Small to Subseismic-Scale Reservoir Deformation, organized by the Petroleum Group of the Geological Society and held in London from 29 to 30 October 2014, plus two additional papers. The observations in this introduction reflect the authors’ experiences and opinions, presentations at the conference and the papers within this volume.

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In the current cost-constrained environment for hydrocarbon exploration and exploitation, increasing emphasis is being placed by major companies on robust subsurface description and a clear understanding of the range of uncertainties associated with models. Structurally complex reservoirs require subsurface models that capture structural heterogeneity to allow the prediction of subsurface flow characteristics. Constraining structural uncertainty early in the workflow by maximizing the value from all existing datasets also encourages a positive evaluation of the value of new additional information. In addition, knowledge of structural complexity gained in mature fields can be applied to the appraisal, sanction and development of new fields.

Small to subseismic deformation features can negatively impact reservoir performance and/or be stimulated to enhance field recovery. In many cases such features are controlled by, or interact with, similarly scaled sedimentological features, complicating conventional views of intra-reservoir connectivity and flow unit definition.

Although the intra-reservoir distribution of these small-scale features has traditionally been ‘modelled’ in the subsurface by applying data from analogue outcrop studies, recent advances in the acquisition and processing of both seismic and imaging techniques, such as helical computed tomography (CT) scans, have provided greater resolution of the subsurface than ever before.

This volume presents a collection of papers from a two-day international conference that brought together academic and industry geoscientists and engineers to discuss the current best practice and new challenges in reservoir characterization and the modelling of small- to subseismic-scale deformation features. Four themes were developed:

- **Theme I: characterization of deformation in porous sandstones**
- **Theme II: novel characterization techniques**
- **Theme III: quantifying and characterizing deformation in carbonates**
- **Theme IV: modelling small-scale features**

**Theme I: characterization of deformation in porous sandstones**

It has been realized for some time that highly porous media (commonly >15% porosity) form subseismic strain localization features – deformation bands (Aydin 1978; Davis 1999; Fossen et al. 2007) – which are in marked contrast with the fractures generated in low-porosity and non-porous rocks. Deformation bands differ from classical fractures in several ways. Their generally compactive nature leads to a loss of porosity and a reduction in permeability. In addition, the limited ability of individual bands to accumulate displacement results in the...
formation of large populations of bands or band clusters. These features, and other characteristic properties of deformation bands, relate to the high porosity of the host rock, which allows the reorganization of grains and grain fragments during deformation. Importantly, the fact that deformation bands commonly lead to a loss of porosity and a reduction in permeability in what are potentially high-quality reservoir rocks (Ballas et al. 2014 for review) makes their impact on fluid flow in hydrocarbon production of significant interest. Fossen et al. (2017) present an overview of how deformation bands can be classified; their origins understood, and how their characteristics differ depending on the tectonic regime in which they occur. These differences are exemplified in the papers by Rykkelid & Skurtveit (2017) and Zuluaga et al. (2017).

Fossen et al. (2017) refine the classification scheme for deformation bands, in which cataclasis is seen as the most important factor in the degradation of porosity and permeability, by means of a kinematic spectrum, which ranges from simple shear to pure compaction (simple shear bands, lacking cataclasis, to compactional shear bands, in which cataclasis is important, to shear-enhanced compaction bands to pure compaction bands). In addition, dilation bands have been reported from unconsolidated sand (Du Bernard et al. 2002), but are thought to be formed at shallow depths. The paper explains the factors affecting the formation of deformation bands, exploring the contrasting roles of burial and overpressure and, because of the intrinsic importance of grain realignment, how grain rounding (Cheung et al. 2012), sorting (Fossen & Gabrielsen 2005) and mineralogy are also significant. In this context, the phyllosilicates may play an important part (Knipe et al. 1997; Fossen et al. 2007), especially in degrading cross-band permeability (cf. Fisher & Knipe 2001).

Fossen et al. (2017) contrast the development of deformation bands in extensional and contractual regimes, explaining how the former is dominated by compactional shear bands, which develop in clusters that become the precursors to faults (Aydin & Johnson 1983; Shipton & Cowie 2001), at which point the deformation bands become the damage zone. Their distribution with respect to the fault core (cf. Johansen & Fossen 2008) is addressed, along with the relationship of band density to fault displacement and the propensity of these bands to form conjugate sets (Chemenda et al. 2014) with dihedral angles of 35–67° in compactional shear band occurrences. By contrast, observations of deformation bands in contractual regimes are rarer, but suggest more even distributions (Soliva et al. 2016) in both shear-enhanced compaction bands and compactional shear bands (Klimczak et al. 2011; Soliva et al. 2013) and an absence of the pre-faulting localization so typical of the extensional regimes. Conjugate set formation is prevalent in shear-enhanced compaction bands, although with higher dihedral angles (70–100°) (cf. Eichhubl et al. 2010); the angles are more modest (40–75°) in compactional shear bands.

Fossen et al. (2017) discuss how the inherent variability of the occurrence and make-up of deformation bands explains the observed variability in fluid flow behaviour, with the importance of cataclasis as a permeability degrader being emphasized. This leads naturally on to deformation band type and, ultimately, tectonic regime. The broad conclusion is that deformation bands promote permeability anisotropy, but do not have sealing capacity for compartmentalization alone.

The impact of deformation bands on reservoir quality and fluid flow is a topic that has been discussed in many papers over the last 30 years, including Aydin (2000) and Fossen & Bale (2007). Laboratory experiments are often used to investigate the deformation mechanism and products in porous rocks. Triaxial compression experiments on sandstone have been used to analyse the formation of deformation bands and the associated changes in texture and porosity (Louis et al. 2006). Triaxial experiments have also demonstrated that the formation of deformation bands is influenced by the confining pressure in combination with sand texture (Alikarami & Torabi 2015).

Rykkelid & Skurtveit (2017) used a triaxial strain box in the analysis of potential reservoir damage in rotated fault blocks. Their study was motivated by observations of small-scale deformation structures in the Fulla Structure in the northern North Sea, which represents a classical Upper Jurassic fault block of Brent Group sandstones with good reservoir quality. Core data show that high-porosity sandstones are present close to the main faults with no evidence of catalasis, only of soft sedimentary deformation. Shear bands are relatively thin with high offsets and have a texture comparable with that of the wall rock.

Synthetic sands with properties similar to the Brent Group reservoir were deformed in the triaxial plane strain box to improve our understanding of the controls on deformation processes and reservoir quality. The consolidation loading applied by Rykkelid & Skurtveit (2017) was in the range 100–8000 kPa, which corresponds to a depth in the range 10–800 m representing the burial depth at the time of active faulting. The experiments produced shear bands that were very thin, only a few grains wide, and with an insignificant imprint on the sand texture. The experiment suggested that the thin shear bands may remain weak through a rift phase, with sharp boundaries and limited wall
rock deformation. The experiments demonstrate that grain rolling and grain boundary sliding are the dominant deformation mechanisms at all the burial depths simulated and that this deformation has no impact on the reservoir quality of clean sandstone. The experimental results were in accordance with, and supported, the observations in core.

Our current knowledge about the deformation of sandstone comes mainly from extensional tectonic regimes and has largely focused on deformation bands, which were first described by Aydin (1978). Since then, many papers have characterized these structures in detail (e.g. Mollema & Antonellini 1996), discussed the formation mechanisms (e.g. Mollema & Antonellini 1996; Borja & Aydin 2004) and assessed their impact on local- and reservoir-scale fluid flow (e.g. Antonellini et al. 1994; Ogilvie & Glover 2001). As most of the studied deformation bands are formed during extension, it is a bias on the models and understanding of deformation mechanisms in porous sandstone. Soliva et al. (2013), Zuluaga et al. (2014) and Ballas et al. (2014) reported that the distribution of deformation band networks and the types of deformation bands are different in the contractional regime, which was suggested to be related to the stress state.

The paper by Zuluaga et al. (2017) contributes to an increased knowledge on deformation of sandstone in the contractional tectonic regime. The paper describes deformation of the Aztec sandstone in outcrops in SE Nevada in the footwall of a major thrust with >40 km displacement. The deformation was characterized by the early formation of networks of shear-enhanced deformation bands and pure compaction bands beneath and ahead of the thrust sheet. This was followed by a gradual increase in the effect of pressure solution and the formation of cataclastic shear bands. A decimetre to metre thick zone, dominated by cataclasite, is present below the thrust contact and characterized by low permeability (<50 mD) and porosity (<3%). Porosity and permeability were also reduced significantly due to cataclasite and pressure solution in a zone tens of metres below the thrust contact. The reservoir properties were largely preserved outside this zone with a porosity of 25% and permeability of up to 2D, except for the presence of local deformation bands that could potentially cause tortuous flow patterns and flow anisotropy.

**Theme II: novel characterization techniques**

The hydrocarbon industry constantly strives to improve both the reliability and predictability of its reservoir models, which therefore require improved description and data conditioning. Although some of this improvement may be gleaned from experience in applying standard techniques, there is a need to look for new techniques that can provide step changes in our ability to describe reservoirs. This theme covers two papers that offer novel approaches to different aspects of the reservoir description of subseismic tectonic features.

Cross-fault flow properties in subsurface hydrocarbon reservoirs are controlled by features below seismic resolution (Fisher & Knipe 1998, 2001) and therefore alternative strategies utilizing seismic data and reservoir stratigraphy have had to be derived to explain these properties. These tend to utilize the fault rock clay content, which is assumed to vary along a fault due to its changing throw and protolith clay composition. Various algorithms have been proposed for estimating the clay content from these parameters: the shale gouge ratio (Yielding et al. 1997; Yielding 2002), the clay smear factor (Yielding et al. 1997) and a weighted or effective shale gouge ratio (Freeman et al. 2010). However, the clay content algorithms describe different processes for forming the fault rock and it is not always clear which process actually controls the clay distribution in a specific geological setting: smearing, mixing or some more complex diagenetic or mechanical process. Relatively few studies have mapped the distribution of the fault rock clay content in sufficient detail (cf. Eichhubl et al. 2005) to provide analogue data to aid in the selection of the most appropriate algorithm.

Brown et al. (2017) address this issue by describing the fault rock and protolith relationships and clay compositions in the low-throw (c. 8 m, i.e. below seismic resolution) Salina Creek Fault in central Utah, USA, where it cross-cuts heterolithic fluvial deposits of the Cretaceous Castlegate Formation. The Salina Creek Fault is exposed in an old railway tunnel where minimal surficial weathering is present and the rock surfaces are readily cleaned. This is a key feature because Brown et al. (2017) described in detail the fabric and structural relationships of the fault rock and protolith, and used this framework to collect over 400 X-ray fluorescence elemental measurements from 203 stations, of which 123 were fault rock. These X-ray fluorescence measurements were calibrated with a smaller number of X-ray diffraction analyses to define the clay content and composition of the fault rock and protolith. A relatively simple mineralogy was recognized – quartz, kaolinite and illite – which gave confidence to the clay content estimates from the silicon, potassium and aluminium concentrations (for further details of the techniques applied, see Brown & Davies 2016). The mapped relationships and clay composition/content showed the fault rock to be an anisotropic, layered system with a heterogeneous distribution of clay. The overall
shear zone smearing produced both continuous and discontinuous layers, although mixing is evident, particularly at the microscopic scale. Comparison of these results with standard algorithms suggest that the clay smear factor algorithm might be preferred for the prediction of clay concentration and the associated permeability of low-throw to subseismic-scale faults in heterolithic reservoirs where smear is the dominant fault rock forming process.

The description and acquisition of reliable hard data derived from small-scale tectonic structures in conventional cores and outcrops has always been essentially two-dimensional, even when whole-core surface ‘mapping’ has been undertaken. With the advent of X-ray computed tomography (CT) and its widespread use and development in the medical sciences, the opportunity to investigate these structures in three dimensions has become increasingly prevalent. This technique is particularly valuable because it is non-destructive and has received wide attention in the description of sedimentary rocks in terms of depositional structures and diagenetic textures (e.g. Coles et al. 1994; Orsi et al. 1994), facies analysis (Mena et al. 2015), and porosity distribution and network modelling (e.g. Akin et al. 1996; Sok et al. 2010; Bultreys et al. 2015, 2016; Teles et al. 2016). It has also been routinely used to check sample integrity in plugs used for reservoir engineering data (Hicks 1996) and for imaging and analysing single and multiphase flow in porous and fractured media (e.g. Barbu et al. 1999; Berg et al. 2016).

Wennberg & Rennan (2017) primarily address the use of CT for the static imaging of small-scale tectonic structures, with a focus on reservoir-related uses, and offer a review of earlier work. They briefly describe the CT method and the types of equipment available, guiding the reader to more detailed publications where appropriate. Importantly, the uncertainties and limitations of the method are discussed, both from the viewpoint of acquisition and processing (e.g. artefacts such as beam hardening) to structural interpretation (resolution to operator dependency issues) to the state of the core in tectonically damaged zones. The core of the paper deals with the use of CT in analysing the main structural features, from fracture characterization to fault recognition in core, to deformation band description (in chalks as well as sandstones) and to stylolites. Emphasis centres on how to improve the images and maximize the value of the technique, especially through the use of visualization software. An important side issue is the recognition of the value of integrated CT and borehole imaging methods in the determination of fracture orientation. This fits well with the authors extolling the value of integrating the ‘new’ qualitative and quantitative CT data with more traditional thin section and scanning electron microscopy observations. Wennberg & Rennan (2017) point out that there is still much to do to exploit the value of this technique fully.

Theme III: quantifying and characterizing deformation in carbonates

Carbonate reservoirs are commonly fractured and this normally receives much attention in reservoir characterization. Relatively little, however, has been published about the nature of carbonate fault cores, their microstructure and how these features might influence fluid flow within the reservoir. Michie et al. (2017) demonstrate a range of fault core properties using analysis of outcrop data from Malta to highlight the important considerations when attempting to calculate fault transmissibility for inclusion in reservoir simulation models. Fault rock types in carbonates clearly vary considerably and the principal controls appear to be the variation in the host lithofacies, displacement and juxtaposition. More data are required to understand fully the range of uncertainty associated with fault transmissibility in carbonate reservoirs before an effective predictive algorithm can be established.

Fractured reservoirs are heterogeneous at all scales, from the micro-scale to full field, and an understanding of the spatial distribution of fractures is necessary to predict fluid flow and to develop drainage strategies. A large part of the fracture population is below the resolution of seismic data. In addition, several key fracture parameters for reservoir modelling are difficult or impossible to quantify from well data, e.g. fracture length and cross-cutting relationships. Therefore outcrop studies have been used to improve our understanding of fracture formation and the spatial distribution of fractures (e.g. Aydin 2000; Sharp et al. 2006; Awdal et al. 2013).

Gutmanis et al. (2017) present an outcrop study of Cretaceous carbonates in anticlines in the foreland of the Catalan Pyrenees. The paper illustrates the importance of heterogeneity and the variable connectivity of open fractures. More specifically, the paper describes the challenge of capturing the fracture characteristics from the seismic to subseismic scale, discusses the relationship between in situ stress, mechanical anisotropy and fracture distribution, and the importance of fault damage zones. In addition, the uncertainties associated with the interpretation of subsurface (seismic and well) data are addressed. The outcrop study illustrates the difficulties involved in using curvature analysis to predict fracture distribution in reservoirs where layers have large contrasts in mechanical properties and where flexural slip has been the main mechanism of folding. The paper agrees with previous studies
that outcrop data are of great value for the evaluation of the fracture parameters that cannot be quantified in the subsurface data, i.e. fracture length, connectivity and their relationship to mechanical units.

Discontinuities, where material has been dissolved, are commonly present in carbonate rocks as pressure solution surfaces or stylolites, which also occur in sandstones. Stylolites are, in general, associated with compaction of the reservoir and a reduction in reservoir quality (e.g. Ehrenberg 2006). They are reported to reduce permeability and represent local seals and baffles in a reservoir (e.g. Nelson 1981). Stylolites can also form along earlier faults, increasing their sealing capacity (Peacock et al. 1999) and they may also represent flow pathways in carbonate rocks when reactivated by shearing (Graham Wall 2006).

The paper by Martín-Martín et al. (2017) illustrates a case where stylolites behave like baffles for fluid flow at an early stage and as conduits at a later stage. The presented outcrop study from the Cretaceous platform carbonates of the Maestrat Basin in Spain discusses the impact stylolites have on the distribution of dolostones and the subsequent hydrothermal mineralization. The dolomite and calcite cements were studied by a combination of field geology and standard petrographic and isotopic analyses. The dolostones are indicated to be closely associated with seismic-scale syn-sedimentary faults, which acted as the main distribution channels for the magnesium-rich fluids. The dolostones preferentially replace grain-dominated facies where the dolomitizing fronts mostly correspond to bed-parallel stylolites. The dolostones are corroded and contain bed-parallel pores that are filled with hydrothermal saddle dolomite and late blocky calcite cements. The calcite cement commonly envelopes clasts of the host dolomite, implying that hydraulic brecciation took place during overpressure. It is suggested that stylolites acted as baffles for the dolomitizing fluids during the replacement stage, resulting in the strata-bound distribution of dolostone. Stylolites became the preferred pathways for overpressured hydrothermal corrosive and mineralizing fluids during the post-dolomitization stage, which generated bed-parallel stylolitic porosity.

Theme IV: modelling small-scale features

A large part of the global hydrocarbon reserves is in naturally fractured reservoirs (e.g. Nelson 2001; Narr et al. 2006), which are most common in carbonates, but are also found in sandstones and basement rocks. Open fractures in reservoirs represent high-capacity conduits and are associated with a high contrast in permeability between the matrix and fracture system. The presence of open fractures has a large impact on well rate and ultimate recovery; special attention is needed when analysing such reservoirs and generating static and dynamic models (e.g. Reiss 1980; Nelson 2001; Narr et al. 2006).

Our understanding of the subseismic subsurface configuration of the fractures, their connectivity and impact on flow is typically limited and we rely on modelling techniques to aid in the population of flow models. A number of approaches are used, including the geostatistical methods often represented in discrete fracture network models (Odling & Webman 1991; Manzocchi 2002), but these methods are unable to represent the mechanical interaction between fractures and its influence on connectivity. Alternative approaches, such as geomechanical forward models implementing linear elastic fracture mechanics, can be computationally expensive (Gale et al. 2010; Wu & Olson 2015). Gillespie et al. (2017) describe a novel approach for simulating fracture growth and interaction using a simplified stress field representation and the implementation of fracture mechanics. The resulting model is able to produce a wide range of fracture network characteristics from a relatively simple input, and allows the evaluation of alternative scenarios in an efficient manner.

A considerable challenge for fractured reservoirs is the construction of realistic flow models that honour the topology of the fracture network and allow the evaluation of uncertainty. This process typically involves upsampling the fracture properties derived from discrete fracture network models, seismic data and density maps (Lefranc et al. 2011). Milliotte et al. (2017) use an alternative to this approach based on a technique called discrete fracture and matrix homogenization, which captures the effects of fractures and matrix properties in the near-wellbore region and interpolation between wells (Matthiï & Nick 2009). This technique is applied to the problem of modelling fractured carbonate reservoirs where reservoirs with intrinsically low matrix permeabilities are nonetheless significant producers. In addition, this technique allows the evaluation of fracture interactions across multiple layers and highlights the importance of connective fractures on the resulting pressure distribution within fractured reservoirs.

Conclusions

Considering the volume as a whole, the understanding of small- to subseismic-scale deformation features has been enhanced. The refined descriptive terminology for deformation bands (Fossen et al. 2017) provides a common language for the geoscience community to utilize, as well as setting these features in their broader tectonic environments, a
theme supported by the more rarely reported occurrences in compressional regimes. New techniques now allow these small-scale features to be imaged better and therefore superior descriptions to be generated from which models can be built. In this context, the modelling papers outline novel methods and highlight some of the pitfalls in representing the effects of small-scale structures in predictive subsurface models. However, the value of traditional fieldwork allied to thoughtful analytical study still has a valuable part to play in providing both crucial datasets and conceptual understanding. This is demonstrated in a number of the papers covering clastic and carbonates rocks and their deformation features. This small, but eclectic, mix of papers meets the goals of the original conference, demonstrating the importance of subseismic-scale deformation features to the realistic description of hydrocarbon reservoirs and fluid flow behaviour. They also show that niche subjects are able to populate conferences and provide worthwhile texts.

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