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Factors controlling permeability of cataclastic deformation bands and faults in porous sandstone reservoirs

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ABSTRACT

Improving the prediction of sub-seismic structures and their petrophysical properties is essential for realistic characterization of deformed sandstone reservoirs. In the present paper, we describe permeability contrasts induced by cataclastic deformation bands and faults in porous sandstones (766 data synthesized from field examples and the literature). We also discuss the influence of several factors, including tectonic regime, presence of a fault, burial depth, host sandstone porosity, and grain size and sorting for their initiation and permeability. This analysis confirms that permeability decrease is as a function of grain-crushing intensity in bands. Permeability reduction ranges from very limited in crush-microbreccia of compaction bands to high permeability reduction in cataclasites and ultracataclasites of shear-dominated bands, band clusters and faults. Tectonic regime, and especially normal-fault regime, with its tendency to localize strain and generate faults, is identified as the most important factor, leading to the formation of cataclastic bands with high permeability contrasts. Moreover, moderate burial depth (1–3 km) favors cataclastic bands with high permeability contrasts with respect to the host sandstone. High porosity, coarse-grain size and good grain sorting can slightly amplify the permeability reductions recorded in bands.

1. Introduction

Deformation bands are common features of sub-seismic scale structures developed in reservoirs composed of porous granular material such as sand and sandstone (Aydin and Johnson, 1978; Fisher and Knipe, 2001), carbonate grainstone (Tondi et al., 2006) or chalk (Wennberg et al., 2013). They accommodate mm- or cm-scale shear offsets, dilation or compaction (Aydin et al., 2006), and involve various micromechanisms of deformation, such as grain rearrangement (granular flow), cataclasis (grain cracking and comminution), or pressure-solution (Fossen et al., 2007 and references therein). In highly porous sandstone reservoirs, cataclastic bands showing a combination of compaction and shear are most common structures to result from localized deformation (Aydin, 1978; Underhill and Woodcock, 1987; Antonellini and Aydin, 1995; Wibberley et al., 2007; Tueckmantel et al., 2010). These structures can occur as individual strands, several tens of strands in tight deformation band zones or clusters, and generally occur around fault cores containing one or more localized slip-surfaces (e.g. Hesthammer and Fossen, 2001; Shipton and Cowie, 2001; Schueller et al., 2013 and references therein).

Cataclastic deformation bands can also be organized in pervasively distributed networks that appear not directly related to outcrop-scale faults (Solum et al., 2010; Saillet and Wibberley, 2010). In either case, they decrease porosity and permeability of the host sandstone (Fowles and Burley, 1994; Fisher and Knipe, 1998; Ogilvie and Glover, 2001; Fossen and Bale, 2007; Torabi et al., 2013). This decrease seems to be directly controlled by the intensity of cataclasis within the bands (Pittman, 1981; Crawford, 1998; Ballas et al., 2012). Cataclastic bands are therefore able to baffle or channelize fluid flow in reservoir settings (Harper and Moftah, 1985; Antonellini et al., 1999; Sternlof et al., 2006; Rotevatn et al., 2009; Tueckmantel et al., 2012). However, their quantitative and practical influence on reservoir performance remain unclear, and depends on both the geometry, distribution

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and petrophysical properties of the bands (Fossen and Bale, 2007; Brandenburg et al., 2012), of which the latter is the main focus of the present contribution.

Several factors influence the spatial distribution and petrophysical properties of cataclastic bands in porous sandstones (Schultz and Siddharthan, 2005; Fossen et al., 2007). Porosity, grain-size, grain sorting, grain shape, mineralogy, and lithification (mechanical compaction and cementation) represent internal sandstone characteristics controlling deformation initiation and mechanisms in porous and granular materials, whereas burial depth, tectonic regime and association with faults represent external controlling factors. Porosity determines the deformation behavior in granular material, from brittle regime and joint formation in low-porosity sandstone to macroscopically distributed ductile deformation and band development in high-porosity sandstone (Rutter, 1986; Wong et al., 1997; Du Bernard et al., 2002; Aydin et al., 2006; Rawling and Goodwin, 2006). Coarse grain-size favors initiation and localization of cataclastic bands (Schultz et al., 2010; Ballas et al., 2013) and seems to promote intense cataclasis (Chuhan et al., 2002; Balsamo and Storti, 2011). Good sorting (Antonellini and Pollard, 1995) and angular grain shape (Mair et al., 2002a) also promote cataclastic deformation. A high clay content favors disaggregation with the formation of phyllosilicate bands or clay smears (Fisher and Knipe, 2001; Fossen et al., 2007), whereas a large feldspar or lithic content promotes cataclastic processes (Antonellini et al., 1994; Chuhan et al., 2002; Rawling and Goodwin, 2003; Exner and Tschegg, 2012). Cementation may reduce sandstone porosity significantly, promoting brittle deformation (Swierczeska and Tokarski, 1998; Fisher et al., 2003; Balsamo et al., 2010). However, quartz-cemented sandstones with a high porosity are favorable sites for cataclasis (Johansen et al., 2005). Poor mechanical compaction or low packing density, increasing with burial depth, promotes diffuse grain rearrangement (Skurtveit et al., 2013) and the formation of disaggregation bands without any large change of permeability (Fossen, 2010), whereas compacted material favors cataclastic band formation (Kaproth et al., 2010; Kristensen et al., 2013). Burial depth also involves an increase in confining pressure, which may lead to more distributed deformation bands (Bésuelle, 2001; Mair et al., 2002b) and intense cataclasis (Antonellini et al., 1994; Crawford, 1998), and higher temperature, which promotes pressure-solution (Fisher and Knipe, 2001). Tectonic regime and presence of a large-scale fault also seem to influence the distribution of low-permeability cataclastic bands in porous sandstone reservoirs (Jamison and Stearns, 1982; Ballas et al., 2014), even if similar permeability reduction can be observed in bands formed in both normal- and thrust-fault regimes (Solum et al., 2010; Brandenburg et al., 2012).

Hence, several factors influence cataclastic band initiation and characteristics. However, influence on the permeability can be directly estimated for only few of them. A better knowledge of the relationships between the cataclastic band characteristics and factors influencing them is therefore necessary for understanding the influence of such sub-seismic structures on reservoir behavior. In the present paper, we analyze permeability contrasts induced by deformation bands and faults as a function of cataclasis intensity and discuss their potential control on fluid flow in porous sandstone reservoirs. To this end, we synthesized 766 permeability data of cataclastic bands and faults from literature (see Table 1, Table 2, and Supplementary Materials for spreadsheet) and new field examples (see Appendix for detailed description of these new data). We discuss also the influence of tectonic regime, presence of a large-scale fault, burial depth, and host sandstone porosity, grain size and grain sorting on this permeability contrasts induced by cataclastic deformation bands and faults in sandstone reservoirs. We believe that these data are representative for deformation band permeability in porous sandstone, at least for the factors discussed in the present contribution.

2. Methodology

The present paper is based on a synthesis of permeability data (766 data) from cataclastic deformation bands and faults formed in porous sandstone (Fig. 1). The major portion of these data is from the following references: Pittman (1981); Harper and Moftah (1985); Fowles and Burley (1994); Antonellini and Aydin (1994); Gibson (1998); Fisher and Knipe (1998); Ogilvie et al. (2001); Ogilvie and Glover (2001); Lothe et al. (2002); Shipton et al. (2002); Flodin et al. (2005); Keehm et al. (2006); Fossen and Bale (2007); Al-Hinai et al. (2008); Rotevatn et al. (2008); Torabi et al. (2008); Aydin and Ahmadov (2009); Torabi and Fossen (2009); Balsamo et al. (2010); Balsamo and Storti (2010); Medeiros et al. (2010); Solum et al. (2010); Tueckmantel et al. (2010); Balsamo and Storti (2011); Fossen et al. (2011); Sun et al. (2011); Tueckmantel et al. (2012); Ballas et al. (2013); Saillet and Wibberley (2013); Torabi et al. (2013); Ballas et al. (2014); Zuluaga et al. (2014) (see Tables 1 and 2). Previously unpublished permeability data from different sets of deformation bands in western US (Arches National Park, Buffington Windows, Pismo Basin, San Rafael Desert and San Rafael Reef) were also added to complete the data set, especially from structures formed in a thrust-fault regime (see Appendix). Only permeability data measured perpendicular to deformed bands are included in the present dataset.

Because the different methods of measurement introduce some variation in absolute permeability value (the TinyPerm permeameter, pressure-decay profile permeametry, air and nitrogen permeametry, numerical image analysis from thin-section or tomography, probe permeameter, Kozeny-Carman laws and more), we only considered the permeability contrast between the bands and faults vs. the host sandstones. The choice of methods for permeability quantification may also influence the permeability contrast value, but to a smaller extent. The *average value* ($\overline{X}$) of permeability contrast and the *standard deviation* were calculated for each type of cataclastic structures (from compaction band to fault core) and for each class defined according to factors such as tectonic setting, burial depth and host rock properties (for example, structures formed in coarse-grained sandstones being treated separately from structures formed in fine-grained sandstones). To limit the influence of the measurement variability between different studies, we used the average value for each study site in each paper (or each band set in the case of various band generations from the same site) for statistical analysis of external factors (tectonic regime, presence of fault and burial depth), and also for each host sandstone unit for statistical analysis of internal factors (porosity, grain size and sorting). We also calculated the minimum (*Min*) and the maximum (*Max*) permeability contrast for the different classes of bands relative to each factor.

All permeability data are plotted in Fig. 1. The proportion (%) of each type of cataclastic structure (from compaction band to fault core) was quantified for all defined classes with respect to the various factors. Graphs of distribution and frequency were extracted from this data set according to the different types of bands and factors. The proportion of bands inducing more than two orders of magnitude of permeability reduction was also calculated. Described as a permeability threshold between barrier and non-barrier structures for water flow under vadose conditions (Ballas et al., 2012), this proportion was used as a proxy to discuss the role of bands and related faults in reservoir behavior. We quantified also the proportion of sets containing bands involving permeability reductions greater than three orders of magnitude. This proportion