High Resolution Petrophysical Measurements of Deformation Bands in Sandstones

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Abstract. Sub-seismic scale deformation bands have an impact on production from hydrocarbon reservoirs since they have dramatically reduced porosity and permeability. These changes are commonly quantified using relatively low-resolution techniques, which invite host rock bias in measurement and inevitably underestimate the potential of these structures as fluid barriers. High-resolution petrophysical measurement within these discontinuities and the characterization of their variable microstructures are therefore critical in their incorporation into advanced reservoir simulation models. These have been carried out using pressure decay probe permeametry (PDPK) of slabbed sandstones containing a range of deformation band types combined with image analysis porosimetry of optical thin sections containing deformation bands. The higher resolution techniques show that much greater differences between host rock and deformation band petrophysical properties exist than when measured using conventional techniques. Cataclastic deformation bands in clean, highly porous sandstones have experienced the greatest reductions in porosity and permeability, increases in $S_{wi,}$ and reductions in sorting relative to their host. There is less contrast in these properties between clay-rich deformation bands and clay-rich host sandstones. This is due to an already low depositional porosity hence giving little opportunity to reduce the porosity further. The influence of lithology upon the formation of deformation bands does not apply to the same extent to cemented deformation bands, the cement of which is affective in modifying sandstones with high depositional porosity and permeability.

1. Introduction

Deformation bands are strain-hardened structures (Aydin, 1978; Aydin and Johnson, 1983), which show a significant reduction in porosity and permeability relative to their host sandstone, and hence are sites of restricted fluid flow in hydrocarbon and water reservoirs (Pittman, 1981; Underhill and Woodcock, 1987; Fowles and Burley, 1993; Hesthammer and Fossen, 2000). These discontinuities influence the production of most reservoirs, and their influence upon fault damage zones in high porosity sandstones has been extensively studied using relatively low-resolution techniques such as conventional core analysis and outcrop minipermeametry (e.g., Jamison and Stearns, 1982; Antonellini and Aydin, 1994; Antonellini and Aydin, 1995; Gibson, 1998). Many fault rocks have considerably lower permeability than 0.01 mD, the conventional resolution of traditional Hassler sleeve gas permeametry. Therefore, higher resolution data is required specific to the mm-thick deformation bands to support (i) a developing understanding of the relationship between the microstructure and petrophysical properties of deformation bands, (ii) their influence upon fluid flow, and (iii) their role in fault sealing analysis (Fisher and Knipe, 1998).

This paper reports high-resolution porosity and permeability measurements made on a range of deformation band types. Pressure-decay probe permeametry is used as it has a permeability resolution of 0.001 mD and a higher spatial resolution than Hassler-sleeve permeametry in measurements of much smaller rock volumes. It is therefore suitable for the measurement of very low permeability fault rock. Depending upon grid spacing, the micro-permeability of individual structures can be accurately depicted. There is no need to remove host rock or calculate the permeability of deformation bands based upon the harmonic mean of the sample.

In this work the samples are from southern North Sea reservoirs and from outcrop sandstones from the Inner Moray Firth, Scotland. The latter form the Permo-Triassic Hopeman Sandstone, which is host to cataclastic deformation bands (Edwards et al., 1993). These form by reductions in grain size and grain sorting. The subsurface samples contain clay-rich and cemented deformation bands. The clay-rich bands have formed through deformation induced mixing processes (Fisher and Knipe, 1998). The formation of deformation bands, and their resulting influence upon fluid flow, are shown to be highly dependent upon the primary composition of the host rock. For example, cataclastic deformation bands in highly porous sandstones are likely to have greater differences in petrophysical properties relative to their host rock compared to those hosted by immature, clay-rich sandstones. Hence, deformation bands in highly porous sandstones are more significant flow barriers than those in low porosity, clay-rich sandstones. Cemented deformation bands (e.g., Evans et al., 1998) are unrelated to host-rock composition, and will modify the flow characteristics of a sandstone where the depositional porosity and permeability is high.

The porosity and permeability mapping measurements across deformation bands obtained using image analysis and PDPK respectively are supported by a suite of conventional analysis; helium porosimetry, nitrogen permeametry, scanning electron microscopy (SEM), and mercury injection capillary pressure (MICP) analysis.

2 Methodology

A range of techniques was used to determine the porosities and permeabilities of the deformation bands and their host rock. The conventional core analysis methods provide measurements on 3D volumes, which can be combined usefully with higher resolution measurements made by more novel 2D image analysis and PDPK techniques.

2.1 Conventional methods

Core plugs were taken from 3 slabbed sandstone samples containing representative zones of deformation bands. Three plugs were taken through the zones of cataclastic, clay-rich and cemented deformation bands, and cut to separate the host rock from the deformation bands. Helium porosity and nitrogen permeability analyses were carried out on the resulting 6 plugs to characterize their mean porosity and permeability. Plug offcuts containing deformation bands were trimmed to separate the bands from the host rock and were subjected to mercury injection capillary pressure (MICP) analysis. This provided porosity, pore size distribution and irreducible water saturation (S_{wi}) data specific to individual deformation bands, hence avoiding a host rock bias inherent in whole-plug analysis. However, the deformation band sample inevitably contains some attached host rock and hence the porosity measured is not completely representative of the fault rock. Furthermore, the maximum pressure capabilities of the MICP instrument is 30000 psi, which is not high enough to inject mercury into some of the very reduced pore spaces in deformation bands. MICP was also carried out on related host rock specimens.

Scanning electron microscope-backscattered electron imaging (SEM-BSEI) of offcuts was used to observe textural and geochemical differences between the deformation bands and their host sandstone.

2.2 Image analysis porosimetry and PDPK

Plug offcuts containing deformation bands were impregnated with a blue epoxy in order to highlight the pore spaces. Thin sections were prepared from these samples and images were captured using a high quality digital colour camera connected to Sigma-Scan Pro™ image analysis software. The latter was used to separate porous areas from matrix areas and porosity values were obtained for 6 regions across the field of view of the thin-sections and high-resolution porosity profiles of 480×640 pixels were produced.

The pressure-decay profile permeameter of Jones (1992) was used in the measurement of permeability anisotropy of the slabbed surfaces prior to plugging. The pressure-decay of nitrogen gas through the rock is monitored and used to calculate a slip-corrected (klinkenberg) permeability at a given position. These are obtained using a modified Darcy's equation (Jones, 1992). Centimeter grids were pencilled onto the samples so that permeabilities could be measured at each node using a laser-guided probe. The resulting permeabilites were binned and plotted as 2D permeability contour maps (Ogilvie et al., 2000). This technique has proved particularly useful in the characterisation of deformation band permeability as it is effective in measuring permeabilities as low as 0.001 mD, and high resolution (<5 mm) permeability profiles of rock surfaces can be produced.

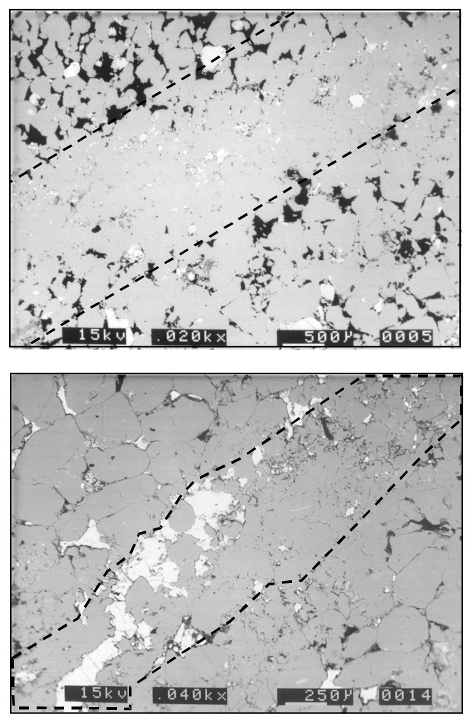

Fig. 1. SEM, backscattered electron images of deformation bands in sandstone. (a) Cataclastic deformation band hosted by a highly porous sandstone (porosity in black). This region of the sandstone has experienced significant reductions in grain size despite containing host rock size grains. (b) Anhydrite cementation in the reduced pore spaces of a reactivated cataclastic deformation band hosted by low porosity sandstone.

3 Results

3.1 Conventional methods

Scanning electron microscopy (SEM) of deformation bands in highly porous sandstone shows dramatic reductions in macropore size relative to the host rock (Fig 1a), correlating well with changes in sorting and grain size. However, despite reductions in grain size, rounded to sub-rounded host-sized grains account for up to 50% of the deformation band material. Host-sized grains occur in a groundmass of comminuted quartz, feldspar, rock fragment grains and clay (illite) in deformation bands, which are hosted by low porosity sandstones (Fig. 1b). Anhydrite cements are commonly observed along reactivated cataclastic bands in these samples, perhaps indicating that the nucleation of cement can be triggered more easily in the reduced pore spaces than in the macropores of the host rock (Berner, 1980). However, these cements are patchily distributed, and due to low host rock porosities are unlikely to have a significant effect upon the hydraulic properties of the rock (Fig 1b).

Table 1. Petrophysical data for deformation bands and their host sandstones obtained from conventional core analysis

Deformation band type	S_{wi} (%) MICP	Porosity (%) Helium	Porosity (%) MICP	Hassler-Sleeve permeability (mD)
Cataclastic	65.0	14.1	10.3	1324
Host rock	12.2	20.7	19.5	45.74
Clay – rich	62.7	10.6	11.1	0.49
Host rock	46.9	10.8	14.9	0.94
Cemented	76.9	5.6	6.6	0.19
Host rock	73.9	8.93	7.5	0.17

Table 1 shows that for a range of deformation bands, considerable differences are observed in conventional porosity and permeability values relative to the host rock. There are also differences in MICP and helium-derived porosity values for deformation band and host rock samples. The difference in helium derived porosities of sample pairs (deformation band and host rock) is less than for MICP measurements. This is a result of helium technique measuring the porosity of plugs which contain appreciably more host rock than deformation bands as opposed to MICP technique, which measures only the deformation band porosity.

The most significant differences in MICP porosities between sample pairs are for the cataclastic deformation bands relative to the host, where up to 50% reduction is observed (Table 1; Fig 1a). By contrast, the reduction in porosity in clay-rich and cemented deformation bands relative to host sandstone is no greater than 25% (Table 1, Fig 1b). These changes are mirrored in the S_{wi} trends, where the highest values characterizes the sandstone, which is host to cataclastic bands (Table 1).

Similar trends characterise the permeability measurements, with an order of magnitude reduction in permeability in plugs containing cataclastic deformation bands (relative to the host) compared to clay-rich and cemented deformation bands (Table 1).

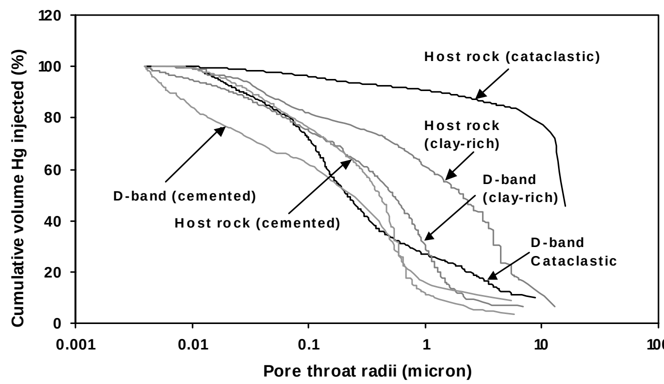

Fig. 2. Mercury injection capillary pressure (MICP) derived pore size distributions of cataclastic, clay-rich and cemented deformation bands together with their host rocks.

The differences between sample pairs, and between deformation band types, are also seen in MICP-derived cumulative pore size distributions (Fig 2). The pore size distribution curve for the host rock of the cataclastic deformation band is reflective of well sorted pores and pore apertures, in marked contrast to the band itself, which shows reduced sorting. By contrast, the curves for the clay-rich deformation band and its host are morphologically similar, extending over a similar range of pore sizes. The effect of cemented deformation bands is unrelated to host rock composition but there is little difference in the pore size distributions of these cemented deformation bands and their host rock, which has a low depositional porosity.

3.2 Image analysis porosimetry and PDPK

Porosities for cataclastic and clay-rich deformation bands relative to their host sandstones obtained using image analysis are shown in Fig. 3. On the accompanying thin-section maps, porosity is white and the solid portion of the rock is black. The porosity maps imply a 75% reduction in porosity in the cataclastic deformation bands (Fig. 3a) and a reduction of 50% into the clay-rich deformation bands from a lower host rock porosity (Fig 3b). There is a ± 2% error introduced as a result of pixelation in the images.

Various deformation band types and their geometries in three sandstones are shown in Fig. 4. Pervasive zones of extensional, mm-thick, cataclastic deformation bands in a highly porous sandstone (Fig. 1a) are shown in Fig 4a.

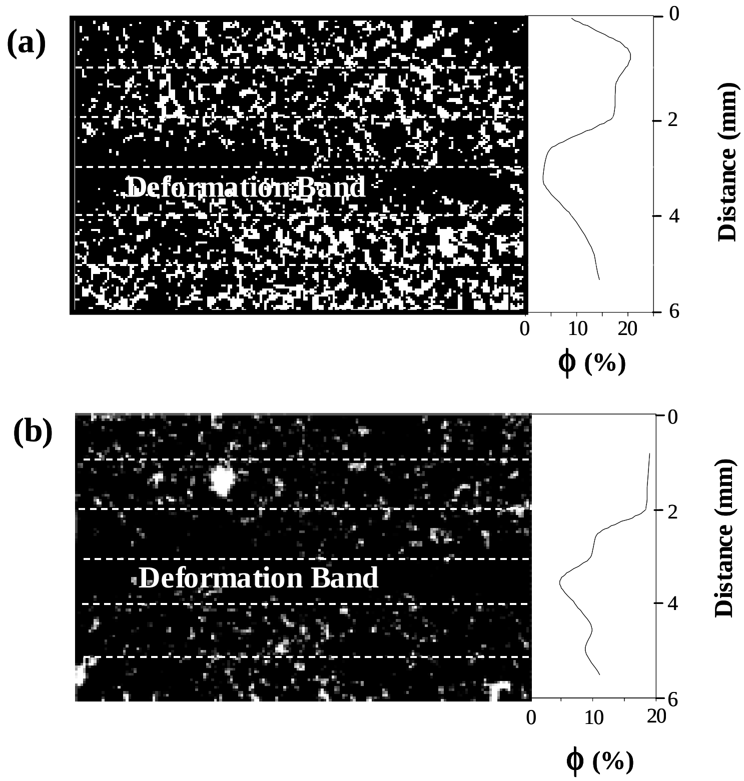

Fig. 3. Image analysed porosity maps of (a) cataclastic, and (b) clay-rich deformation bands together with porosity profiles, which document porosity changes over 6 rectangular regions of the image. The most drastic reductions relative to host rock are seen in (a).

The individual strands split and recombine forming isolated host rock pods. A less pervasive zone of slightly anastomosing clay-rich deformation bands displacing clay-rich laminae and separating a host rock pod is illustrated in Fig. 4b. In Fig. 4c, swarms of anhydrite-cemented cataclastic deformation bands with the appearance of quartz veins dissect a well-laminated sandstone into compartments of various sizes.

The accompanying PDPK profiles show dark swathes of low permeability coinciding with the deformation band zones, and lighter contours representing higher permeability characterise the host rock. In the highly porous sandstones studied there is a mean reduction of 4 orders of magnitude in PDPK permeability in the deformation band compared with the permeability of the immediately adjacent host rock pod and 5 orders of magnitude reduction compared to the bulk host rock (Fig. 4a). In the clay-rich sandstones the permeability profiles illustrate a mean reduction in permeability of 3 orders of magnitude for the deformation bands compared to the clay-rich host rock (Fig. 4b).

Increasing the grid spacing (and hence resolution) to 5 mm has the effect of more accurately constraining the permeability of the deformation band zone and host rock pod. It also shows that dark, fine grained laminae play an equally important role in providing low permeability barriers to flow in these sandstones. A mean reduction of up to 3 orders of magnitude characterizes the cemented deformation bands in Fig 4c. At 1 cm grid resolution, patches of low permeability have no intimate association with structural and sedimentological features of the sandstone. In fact, this grid resolution underestimates permeability in the sample and is therefore not considered to be useful in the depiction of micro-permeability. However, the 5 mm grid resolution is extremely effective at delineating the permeability of individual mm-thick deformation band strands.

4. Summary

Deformation bands are very common sub-seismic structures in sandstone reservoirs, and their effect upon the hydraulic properties of reservoirs is well documented. However, their grain-scale and lateral influences upon fluid flow are considerable, such that high-resolution petrophysical measurements are crucial in fault modelling studies. Pressure decay profile permeametry (PDPK) and image analysis porosity techniques used in this study have the advantage of providing deformation band specific values of small volumes of rock despite the 2D nature of measurement. By contrast, the conventional techniques (Helium porosimetry and Hassler sleeve gas permeametry) have a much lower spatial resolution and provide mean porosities and permeabilities of 3D volumes of deformation bands and host rock. Mercury injection capillary pressure (MICP) analysis provides useful deformation band specific, porosity, pore size distribution and S_{wi} data. It is therefore useful to combine these results for more robust fault seal analysis.

Image analysis and PDPK measurements are of particular value in characterising the petrophysical properties of deformation bands in clean, highly porous sandstones, where there are larger measured differences in host rock and deformation band porosity and permeability. Grain size reductions and primary mineralogy are the principle physical causes of this. Increased grain packing is aided by the reduction in sorting as observed in the experimental deformation bands of Mair et al. (2000). In clay-rich sandstones the differences in porosity and permeability are due to poor sorting and closer packing of grains. A grid spacing of 1 cm does not provide a high enough resolution to constrain the permeability of individual deformation bands and tends to underestimate permeability in the sample. However, the 5 mm grid resolution is very effective in representing the permeability of individual structures. Moreover, in the clay-rich sandstones increasing the PDPK grid spacing from 1 cm to 5 mm, certain dark sedimentary laminae are shown also to have significant reductions in porosity and permeability and also have a significant influence upon fluid flow. A much smaller grid in PDPK is expected to give greater permeability heterogeneity. Even in clay-rich and cemented sandstones, the novel measurements show a greater difference than the conventional measurements in porosity and permeability values between host rock and deformation band. Studies such as these are of importance in reducing the uncertainty regarding the role of deformation bands in fault sealing, and such data integrated with geometrical properties is important input into advanced reservoir models.

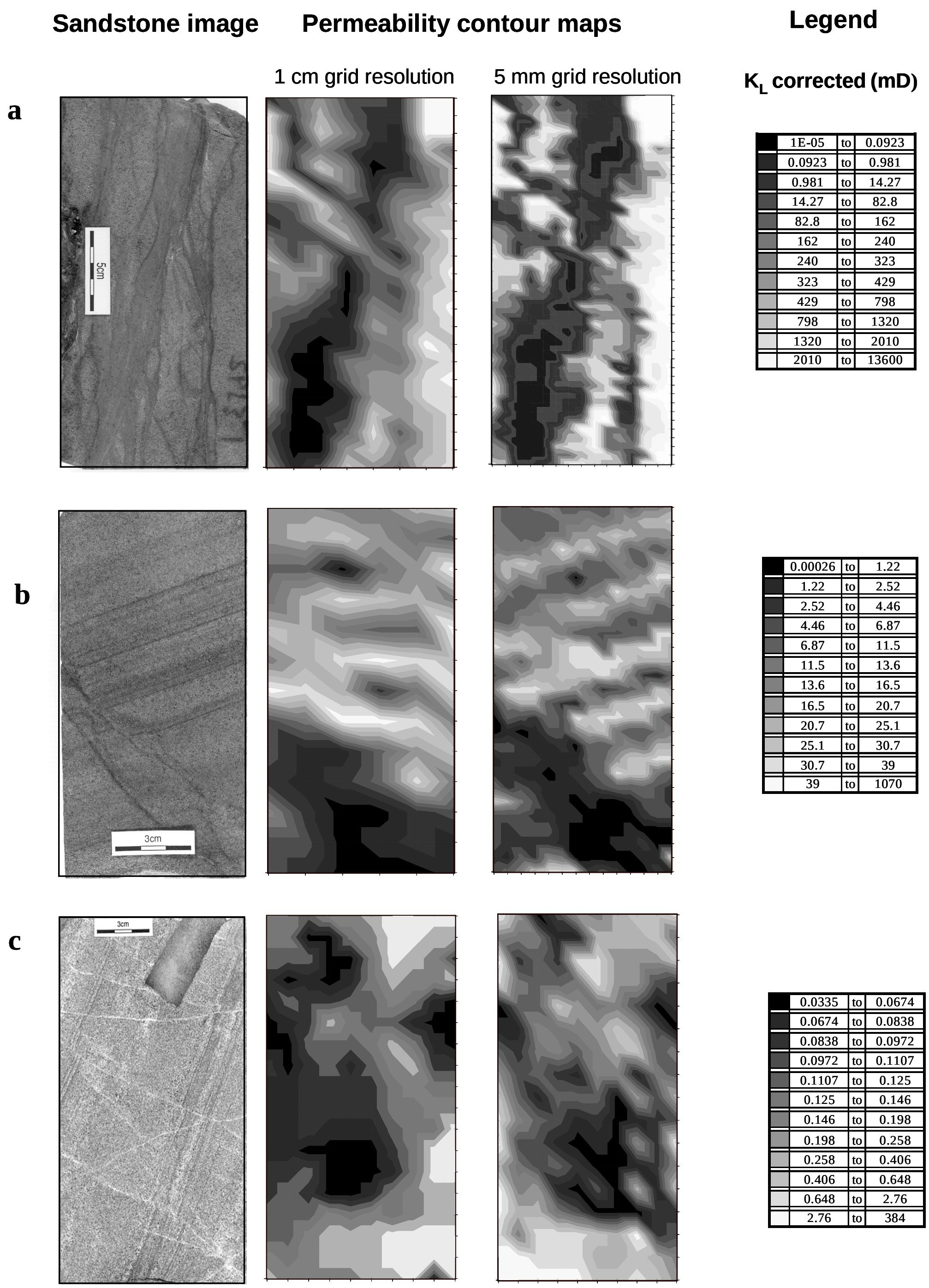

Fig. 4. Pressure-decay probe permeametry (PDPK) profiles of sandstones containing deformation bands and accompanying images and legends. (a) Reductions of 4 orders of magnitude in pervasive, cataclastic deformation bands relative to highly porous host sandstones. (b) Less severe reductions in clay-rich deformation bands (mean of 3 orders of magnitude) hosted by low porosity clay-rich sandstones. At a 5 mm grid resolution the interplay between sedimentary and structural permeability barriers is illustrated. (c) Swarms of Anhydrite- cemented deformation bands with a mean 3 orders of magnitude reduction in permeability relative to the well laminated sandstones of the host rock.

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