Cataclastic bands in immature and poorly lithified sandstone, examples from Corsica, France

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ABSTRACT
Cataclastic bands with intense cataclasis formed in phyllosilicate- and clay-rich poorly lithified sandstone have been identified and characterized for the first time. This study indicates that intense cataclasis could occur at shallow burial depth regardless of mineralogy of the rock at the time of deformation. The study was performed on a series of listric normal faults (displacement up to 10 m) in the Aghione Formation at Aleria Basin, Corsica, France. In-situ measurements of permeability show a reduction in permeability up to two orders of magnitude in the damage zone (cataclastic bands), while permeability increases along the slip surfaces. The slip surfaces make conduits to fluid flow, which is also confirmed by the field observations. The permeability and porosity decrease within cataclastic bands is in agreement with an increase in P-wave velocity measured on the band possibly due to compaction, introducing anisotropy to the rock.

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1. Introduction

The process of deformation of high porosity sediments and poorly lithified rocks frequently involves formation of deformation bands (Aydin, 1978; Heynekamp et al., 1999; Sigda et al., 1999; Torabi, 2008 and the references therein). Deformation bands are kinematically classified as one of the three end members (e.g., Aydin et al., 2006 and Fossen et al., 2007) namely dilation band (volume increase in the band), compaction band (volume decrease in the band), and shear band (no volume change in the band) or a combination of dilation and shear or compaction and shear. However, deformation bands can be also classified based on the dominant deformation mechanism involved in the formation of bands and therefore different types of bands may form such as disaggregation band, cataclastic band and dissolution/cementation bands (e.g. Torabi and Fossen, 2009). It is generally believed that at shallow burial depths and in poorly lithified rocks deformation bands are commonly formed by particulate or granular flow mechanism (grain sliding or rolling) (Antonellini et al., 1994) resulting in disaggregation bands when the phyllosilicate or clay content is less than 15% (Fossen et al., 2007). Based on literature (e.g. Fisher et al., 2000; Fossen et al., 2007; Knipe et al., 1997; Torabi and Fossen, 2009), deformation of sediments or rocks with phyllosilicate and/or clay content between 15% and 40%, usually results in elongation of phyllosilicate and/or clay mineral aggregates along localized bands, which are commonly called phyllosilicate band or framework (e.g. Heynekamp et al., 1999; Knipe et al., 1997). The phyllosilicate bands involve disaggregation and usually are classified under the disaggregation bands category. If the phyllosilicate and/or clay content of the sediments or rocks increase to more than 40%, a phyllosilicate or clay smear will occur at shallow depth (e.g. Clausen and Gabrielsen, 2002; Clausen et al., 2003; Fisher et al., 2000). Cataclasis or grain breakage in deformation bands is commonly expected at deeper burial depth or higher confining pressure, but grain abrasion and low degree of cataclasis in deformation bands formed in poorly lithified sandstone at shallow burial depth have been previously reported in sediments and rocks with low content of clay and phyllosilicate, i.e. less than 15% (e.g., Balsamo and Storti, 2010; Cashman and Cashman, 2000; Rawling and Goodwin, 2003). Rawling and Goodwin (2003) report that the strength of grains (minerals) play a significant role in the deformation mechanism of poorly lithified sediments, in which a controlled particulate flow can form in immature sediments with high content of rock fragments and feldspar. In a controlled particulate flow, deformation of grains is selective, i.e. quartz grains are mainly deformed by abrasion, while feldspar grains break through transgranular fracturing and rock fragments by multi-cracking (Rawling and Goodwin, 2003).

The occurrence of intense cataclasis within a phyllosilicate- and/or clay-rich sand or sandstone is something that is not expected or has not been previously addressed. In the present work, we identified cataclastic bands with different degrees of cataclasis from low to intensive formed in a poorly lithified sandstone from the Aleria Basin Corsica, France. The studied sandstone contains more than 30% phyllosilicate...
and clay particles. The influence of such deformation on petrophysical (porosity and permeability) and acoustic properties (P-wave velocity) of rocks has been investigated. Previous studies have shown that phyllosilicate bands (because of the elongation of phyllosilicate grains along the band) and cataclastic bands (because of grain crushing and compaction) can impact the petrophysical properties of reservoir sandstones (e.g. Braathen et al., 2009; Fisher and Knipe, 2001; Torabi and Fossen, 2009; Torabi et al., 2013). By studying the variation in petrophysical properties of different types of deformation bands, Torabi and Fossen (2009) found that this variation depends on the degree of cataclasis in cataclastic bands and on the phyllosilicate content in phyllosilicate bands. Recently, Torabi et al. (2013) showed the impact of cataclastic bands within fault damage zone of faulted porous sandstones on fluid flow in petroleum reservoirs and on the capacity of reservoirs for CO₂ storage underground.

Torabi et al. (2013) indicate that a cluster of cataclastic bands (a zone of deformation bands in decimetre width) can be locally as efficient as a fault core in sealing fluid reservoirs (e.g. oil and CO₂) resulting in withholding up to ~1 m column of these fluids. However, this study and most of the previous studies report the importance of cataclasism in clean sandstone, while the significance of grain crushing in immature and phyllosilicate- and clay-rich sandstone has been undermined or less considered in the literature.

In this work, the deformation mechanism of immature and poorly lithified sandstone with high content of phyllosilicate and clay (more than 30%) is investigated. The fieldwork for this study was performed on a series of listric normal faults developed in poorly consolidated, high-porosity Aghione sandstone in the Aleria Basin, Corsica, France. Field measurements of geological structures and in-situ measurements of permeability are presented. In addition, microstructural analyses of thin sections, porosity and permeability measured on backscatter images (BSE) of thin sections, and ultrasonic measurements of samples that were collected from the outcrop, are investigated in order to further characterize cataclastic bands observed in these immature sandstones. Petrophysical properties (permeability and porosity) have been substantially decreased within these bands while acoustic properties (P-wave velocity) are increased inside the band due to compaction and porosity reduction, indicating anisotropy in the rock samples.

2. Methodology

In this study a series of measurements have been carried out in the field and laboratory. The field measurements include geometrical measurements of structural elements and in-situ permeability measurements. The laboratory work includes microstructural studies, petrophysical properties measurements (using image processing), density, and ultrasonic measurements.

In order to carry out the field measurements, a 43 metre scan-line was made along the outcrop almost perpendicular to the main orientation of faults in the studied locality. The structural analysis of the outcrop, measurements of faults orientations, deformation bands and fractures, and permeability measurements (using a Tiny-Perm II) were performed along the scan-line (Appendix A). Samples of outcrop were used for thin sections and ultrasonic measurements in the laboratory.

The ultrasonic analysis was performed on samples in the laboratory using a portable ultrasonic system by Geotron-Elektronik. In this device, the oven-dried sample is placed between two transducers. The length and bulk density of the sample are given by the user as input parameters, while the P-wave and S-wave velocities are measured by the instrument. Before performing the ultrasonic measurements, the bulk density of the samples was measured in the laboratory (Torabi and Alikarami, 2012).

Polished thin sections of the samples were studied by both optical and electronic microscopes. Porosity and permeability were estimated by image-processing of high resolution backscatter images of thin sections (Torabi et al., 2008, Appendix B).

XRD (X-ray diffraction measured on powder of rock samples in order to determine the average bulk composition of the rock) analysis was also performed on one of the sandstone samples in order to quantify the mineralogical composition of the sandstone. An energy-dispersive X-ray spectroscopy detector (EDS) for elemental analysis was used under electron microscopy for further identification of minerals that could not be captured by XRD analysis.

3. Geology of Aleria Basin and the studied area

The island of Corsica is located between the Liguro-Provençal back arc basin in the west and the Tyrrenhian Sea to the east. The island was part of the Iberian lithosphere which rifted off the main European continent during the Oligocene-Miocene (Alvarez et al., 1974).

The geological framework of the island includes two distinct structural terrains, Hercynian Corsica in the west and Alpine Corsica in the northeast of the island (Cavazza et al., 2007; Fig. 1). Hercynian Corsica is characterized by Palaeozoic granitoid rocks, volcanic rocks of Hercynian orogeny, some Palaeozoic sedimentary rocks, and Precambrian-Palaeozoic metamorphic rock units (Cavazza et al., 2007). The Alpine Corsica is part of the Alpine belt and is a nappe stack that was thrust on the Hercynian Corsica.

There are two schools of thought with regard to the tectonic evolution of the Alpine Corsica during the Neogene to Quaternary: a) continuous extension (Jolivet and Facenna, 2000; Jolivet et al., 1990, 1991) episodal extension and inversion (Fellin et al., 2005). According to the first group compression stopped in the late Oligocene and was followed by continuous extension. Continuous extension is suggested based on the regional significance of the extentional events which rule out the possibility of individual compressional structures (e.g. Jolivet et al., 1991).

The extension and opening of the Provençal-Ligurian back-arc basin led to the generation of different size sub-basins of different ages (Fellin et al., 2005; Zarki-Jakni et al., 2004). Examples are the Saint Florent Basin in the north and the Aleria and Marana Plains on the eastern coast of Corsica (Fig. 1). The borders of these basins are extensional faults which locally created accommodation space and post-sedimentary deformation has been recorded within the rock units (Cavazza et al., 2007; Fellin et al., 2005).

The Aleria Plain corresponds to the onshore portion of the greater offshore Corsica Basin (Mauffret et al., 1999). The sedimentary rocks of the Aleria Plain span from the Burdigalian to the Quaternary (Caron and Loye-Pilot, 1990). These rock units formed the youngest units of the Aleria Plain northwest of Casaperta (Fig. 2). Fig. 2 shows a geological map of part of the Aleria Basin around Casaperta. The outcrop is located on the eastern bank of the Corsigliese River before it joins the Tavignano River. The Miocene sedimentary rocks and Alpine Schist contact are faulted (Orszag-Sperber and Pilot, 1976). The regional fault system has a relatively simple trace further south but it is split into branches in the studied area. There are several sub-parallel extensional faults (dashed lines on the map in Fig. 2) which have displaced both Alpine units (e.g. Padoa et al., 2002) and the Miocene sedimentary rocks of the outcrop studied in this research. The oldest Miocene rock units in the area are the conglomerates and sandy marls of the Saint Antoine Formation that are exposed at the western bank of the Corsigliese River (Caron and Loye-Pilot, 1950). The Aghione Formation (Langhian) which overlies conformably the Saint Antoine Formation has three members (Fig. 2) including conglomerates with rhyolitic pebbles (m3-3), calcareous fossiliferous sandstones, (m3-2), and sand and sandy marls (m3-1). The m3-2 member is rich in micro-fauna and macro-fauna indicating a marine depositional environment. However, the fossiliferous calcareous sandstone beds of m3-2 member are only developed further to the north (outside of our studied area) between the conglomerate (m3-3) and sandy marl units (m3-1) (Caron and
Loye-Pilot, 1990). Within the m3-1 unit sandy channels have also been reported (Caron and Loye-Pilot, 1990; Orszag-Sperber and Pilot, 1976). Towards the top, the Aghione Formation becomes sandier (m3-1). The Aghione Formation is overlaid by the Alitzone Formation (sands and gravels). The contact between the Aghion and Alitzone Formations is gradual (Caron and Loye-Pilot, 1990).

4. Results

4.1. Outcrop description

The outcrop of the studied locality (Casaperta) consists of mainly poorly consolidated sandstones with thin coal beds (corresponding to m3-1 member) of the Aghione Formation and partly conglomerates (corresponding to the m3-3 member), Fig. 2. Fig. 3 illustrates a mosaic photo from the studied outcrop with a structural interpretation. Five samples from the damage zone close to the faults and two from the fault cores were carefully taken along the scan-line for the purpose of further analysis. Apart from one fault core sample from a conglomeratic unit, the rest of samples are from poorly lithified sandstone (Fig. 3).

The well-exposed part of the outcrop is 43 m long and comprises a set of synthetic listric NW–SE trending normal faults (faults F1 to 5 in Fig. 3). These synthetic faults join each other at the westernmost part of the outcrop towards a horizontal detachment with displacement up to 10 m (Figs. 3 and 4a). Fault F2 (Fig. 3) is traceable to the river floor providing a nice 3D view of the fault. The displacements of the synthetic faults vary between few centimetres to ten metres.

The synthetic faults are crossed by a set of antithetic faults (faults A1 to A4 in Fig. 3). The 5 synthetic and 4 antithetic faults mapped along the scan-line are considered here as main faults in this locality because of their larger displacements (up to 10 m). Several minor faults (with smaller displacement, which could also be called shear fractures or simply slip surfaces based on Fossen (2010) classification) cross the last synthetic fault, where it becomes horizontal along the section (Fig. 4a). These minor faults, which are mostly synthetic to the main faults have been also mapped through the scan-line. Displacement varies along the minor faults with the maximum about 0.5 m.

Most of the faults present open slip surfaces (Figs. 4a & 5a). Fault cores include crushed rocks and sometimes lenses of deformed rocks (Figs. 4a & 5a). In the damage zone of these faults, there are deformation bands crossing each other with different trends (Fig. 5b). In addition to deformation bands, fractures are present in the damage zone of the studied faults.

Geometrical measurements of faults, fractures, and deformation bands were plotted on lower hemisphere stereonet diagrams (Fig. 4). The main faults trend NW–SE with dips varying between 40° and 60° (Fig. 4b). The fractures dominant trends are similar to faults (Fig. 4c) and the deformation bands strike 100°, 142°, and 160° (Fig. 4d). In general, faults, fractures, and deformation bands show parallel trends (Fig. 4).

Based on field and microscopic observations the exposed sandstone has heterogeneous grain size. XRD and microscopic analyses of the samples show that the poorly consolidated sandstone contain abundant phyllosilicate and clay minerals (more than 30%, see Table 1) and is quite immature and very poorly sorted. In addition to the minerals identified by XRD analysis, coal, iron oxide and iron sulphide were observed in the BSE images examined by EDS during electron-microscopy (Figs. 6, 7). Coal was also observed as thin layers between sandstone layers that have been displaced by small faults (Fig. 7e). Previous work (Caron and Loye-Pilot, 1990; Orszag-Sperber and Pilot, 1976) has suggested shallow marine to fluvial depositional environment for these sediments, which has been confirmed by the present analyses and observations.
of some microfossils (e.g. foraminifera) in this study. The outcrop has been shallowly buried (probably around 100 m) at the time of faulting (Torabi, 2012; Torabi et al., 2007). The iron-oxide and iron-sulphide cementation (Fig. 6) appears to be a syn-deformation feature since we can find these cements in small pieces trapped inside broken and deformed phyllosilicate grains, where these grains are kinking. Further analysis is needed in order to prove this idea, which would be outside of the scope of this study.

4.2. Microstructural study of deformation bands

Two types of cataclastic bands based on the degree of cataclasis were identified through microscopic studies of thin sections of the Aghione sandstone. The cataclastic bands with high degree of cataclasis (Fig. 8a & c) are thicker (more than 1 mm, measured on BSE images), while the cataclastic bands with low degree of cataclasis and less grain crushing (Fig. 8b & d & e) are thinner (around 0.5 mm, measured on BSE images), Fig. 8. On BSE images, all of the bands contain deformed or broken phyllosilicate and clay particles, which is a new observation in such poorly consolidated sandstone with more than 30% phyllosilicate and clay (Fig. 8).

The cataclastic bands with low grain crushing are mineralogically divided into two sub-types: coal-dominated bands and iron-dominated bands (Fig. 8). Thin coal-dominated bands involve smearing of coal along the bands and a weak cataclasis (Fig. 8b & d), while iron-dominated bands are slightly thicker than the coal-dominated bands and can be observed both as individual bands as well as in the margin of the cataclastic bands with high degree of cataclasis (Fig. 8b & e). The iron-dominated bands show cataclasis to some extent and most of the pores have been filled with iron oxide and iron sulphide (Figs. 6, 8).

4.3. Permeability and porosity measurements

Permeability was measured both in the field parallel to deformation structures using a Tiny-PermII (Fig. 9a) and on BSE images of thin sections using image processing (Torabi et al., 2008, Fig. 9b). The results
of permeability measurements from the two approaches show an agreement in reduction of permeability from host rock to deformation bands (for all kind of bands described in Section 4.2) and also to the fault cores.

The permeability reduction within the bands can be up to two orders of magnitude relative to the host rock, which is comparable to the permeability reduction in the fault core (Fig. 9). However, Tiny-PermII data show an increase of permeability around slip surfaces, which is confirmed with the field observation of remnants of fluid flow (reaction front) on open fault slip surfaces that have promoted fluid flow in the faults (Fig. 5). The variation in the permeability values of different types of bands (different symbols in Fig. 9b) can be attributed to the degree of cataclasis within these bands. In particular, thick cataclastic bands with high degree of grain crushing show higher permeability reduction relative to the host rock (solid symbols) in comparison to the two other bands in this study (thin coal-dominated and iron-dominated bands). When making a comparison between coal-dominated and iron-dominated bands, it appears that the iron-dominated bands show slightly higher permeability reduction than the coal-dominated bands. This could be due to the fact that many grains have been coated with iron oxide besides the pore-filling iron sulphide (Fig. 6), which is an early diagenetic effect, in addition to the slight cataclasis within these bands. Porosity is very high in the host rock with an average around 40% and is reduced within the bands to an average around 25% (Fig. 10).

4.4. Ultrasonic measurements

Ultrasonic measurements were performed on the deformed samples that were gathered either from the damage zone close to the faults (these samples include deformation bands) or from the fault core (five sandstone samples from damage zone and one from fault core plus an additional fault core sample from conglomeratic unit). Due to the irregular shape of the samples and the resulted uncertainty in Vs measurements because of the sample size, only Vp velocities are presented in this work. A plot of Vp versus bulk density of the samples is presented in Fig. 11. In general, the P-wave velocities are low for most of the samples (~1100 m/s for the conglomerate sample and ~1800 m/s for sandstone samples). The velocities measured in this study are lower than those previously reported for unconsolidated sand and sandstones (e.g. previous study by Wang, 2000); this could be related to the mineralogy and deformation of these samples and will be further discussed in the next section.

The highest velocity measurements belong to a deformation band. This is the only sandstone sample from damage zone with a shape that allowed velocity measurements in two different dimensions on the band (1810 m/s and 2402 m/s) and also perpendicular to the band (1742 m/s), see the solid squares on Fig. 11a and directions in Fig. 11b. The results show higher velocities on the band than outside the band (perpendicular to the band, Fig. 11a & b).

5. Discussion and conclusions

Based on previous studies (Cavazza et al., 2007; Fellin et al., 2005), faulting in the area has happened after sedimentation but when the sediments were still very porous (the porosity of the host rock is still around 40%). The main regional faults that have been previously mapped (dashed lines in Fig. 2) are NE–SW trending. These faults are either located at the boundary of the Alpine Corsica and Aleria Basin (Faults 1 and 3 in Fig. 2) or displace rock units in the Aleria Basin.
formed in quartz-rich sandstone in the Aleria Basin close to the studied et al., 2013). In addition, Rolseth (2008) reports on cataclastic bands supported by many authors before (e.g. recent studies by Balsamo and phyllosilicate and clay minerals in the host rock. Cataclastic bands reported for cataclastic bands measured parallel to the bands (e.g. Lothe et al., 2002; Torabi et al., 2013), and the degree of cataclasis in the present study seems to be more important than impurities such as coal and iron-oxide or iron-sulphide in reducing permeability of the bands (Fig. 9). Therefore, the cataclasis is considered to play a more significant role on fluid flow behaviour of these rocks when it comes to the movement of fluid or storage capacity of such a reservoir. On the other hand, evidence of fluid flow concentrated around slip surfaces is a good sign for the conductivity of the reservoir but needs to be taken with care if a risk assessment of possible leakage scenarios is the case when evaluating such reservoirs for the purpose of CO2 storage.

5.1. P-wave velocity and anisotropy in the samples

P-wave velocity changes inside the cataclastic bands according to measuring direction on the band in three dimensions (Fig. 11). This could indicate anisotropy of the elastic properties in the measured dimensions in the sandstone sample. Torabi and Alikarami (2012) and recently Torabi and Zarafi (2014) report different values of M-modulus (the compressional P-wave modulus), Young’s modulus and Poisson’s ratio for cataclastic bands and their corresponding host rocks. This is expected from cataclastic bands since they usually show variation in their microtexture and physical properties along them, see e.g. Figs. 2 and 7 in Torabi et al. (2008), where they have examined a cataclastic band in three dimensions by studying two perpendicular thin sections. They report that permeability varies up to two orders of magnitude when measured in two perpendicular orientations on a single cataclastic band (Torabi et al., 2008). The ultrasonic measurements show higher P-wave velocities within the band and are in agreement with the results from image processing of thin sections that present lower porosity values in the bands. This could be an evidence of compaction and grain locking process which follows the grain crushing (cataclasis) within the bands. However, from the lower values of Vp and density for this study in comparison to previous published data in Fig. 11, one could predict that the relationship between density and velocity measurements does not correspond to those previously reported for unconsolidated sand, and sandstones with more than 15% clay (e.g. Wang, 2000), although our samples include more than 30% clay and phyllosilicates (Fig. 11). The reason for this discrepancy could be

<table>
<thead>
<tr>
<th>Illite/smectite</th>
<th>Illite + Mica</th>
<th>Kaolinite</th>
<th>Chlorite</th>
<th>Quartz</th>
<th>K feldspar</th>
<th>Plagioclase</th>
<th>Calcite</th>
<th>Dolomite</th>
<th>Siderite</th>
<th>Pyrite</th>
<th>Hematite</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>20.8</td>
<td>2.8</td>
<td>6.9</td>
<td>37.8</td>
<td>14.4</td>
<td>14.9</td>
<td>TR</td>
<td>2.5</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>100</td>
</tr>
</tbody>
</table>

Dolomite is Ferroan and Minor barite was observed. TR means trace.
Fig. 6. BSE images and EDS analyses of thin sections show of iron sulphide (a and c) and iron oxide in the samples (b and d).
Fig. 7. BSE images and EDS analyses of thin sections show evidences of coal (a–d). e) Field observation of coal layers displaced by small faults.
Fig. 8. a) Photomicrograph taken with optical microscope showing a cataclastic band with high degree of cataclasis; b) Photomicrograph taken with optical microscope showing iron-dominated and coal dominated bands. c) BSE image of a thick cataclastic band (band in a) with intense cataclasis. d) and e) BSE images of thin coal-dominated and iron-dominated bands with low degree of cataclasis.
related to two factors: (i) the presence of coal and abundant phyllosilicate and clay in the current samples and (ii) deformation in the samples, the presence of deformed and crushed grains; both of these factors would increase heterogeneity and bring anisotropy to the behaviour of the material when subjected to wave propagation. Low velocity and low density in coal-dominated sediments have been reported before (Yao and Han, 2008). In addition, phyllosilicates because of their platy shape can induce anisotropy to the sediments. The position and distribution of clay minerals influences the seismic velocity and density of the rock (Wang, 2000). Pore-filling clay does not change the wave velocity as such but increases the bulk density, on the other hand, the abundance of clay in the matrix of sandstone, which is the case in the current samples, will reduce seismic velocity but does not affect the density of the rock (Wang, 2000).

The following conclusions can be made from this study:

- Cataclastic bands can form in phyllosilicate- and clay-rich poorly lithified sandstone at shallow burial depth.
- This study indicates that cataclasis could occur at shallow burial depth regardless of mineralogy of the rock at the time of deformation. This suggests that mineralogy might not be an important factor for deformation mechanism of porous sandstone at shallow burial depth.
- Permeability is reduced up to two orders of magnitude within the studied cataclastic bands.
- Slip surfaces in this poorly lithified sandstone can form conduits to fluid flow around the faults, which might either enhance the conductivity of the reservoir in a desirable way or make leakage pathways in worst cases.
- Several factors have caused the discrepancy between the present velocity–density data and those previously published; these factors include the abundance of clay minerals and phyllosilicates and the presence of coal as well as deformed grains in the studied samples.

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**Appendix A. Modified after Tiny-PermII User’s Manual, NER**

In-situ permeability measurements were performed by a Tiny-PermII manufactured by New England Research (NER). In order to perform the measurements, a rubber nozzle is pressured against the sample and the device is vacuumed by pulling a plunger. When the device is ready, the air is sent to the sample with a single stroke of a syringe. The plunger is held until the measurement is completed and the result displays on the monitor. The result (TP) is related to permeability (K) using Eq. (A.1):

$$TP = 0.8206 \log(K) + 12.8737$$  \hspace{1cm} \text{(A.1)}$$

where TP is the Tiny-PermII reading. When performing the tests in the field, the weathered surface was cleaned using a geological hammer.
Measurements on cracks and open fractures were avoided. For each sample point, 3 measurements were made and an average value of them was used as the representative value for that point.

Appendix B. Image processing

In the backscatter images, the sandstone grain and pore phases occupy different spatial positions. In such a two-phase (grain–pore) system of volume \( v \) each phase occupies a subvolume, \( v_1 \) (for grains) and subvolume \( v_2 \) (for pores), and a characteristic or indicator function can be defined as follows:

\[
f(r) = \begin{cases} 
0 & r \in v_1 \\
1 & r \in v_2.
\end{cases}
\]  

(B.1)

Each image includes a matrix of \( M \) by \( N \) pixels. In order to be able to use the indicator function to characterize the microgeometry of the samples, the colour intensity range should be limited to two pixel values representing the two phases of the medium (binary image). For a binary image we define a function \( f(i,j) \) that is zero for grains and one for pores, and \((i,j)\) indicates the position of pixels in the image. The pore one-point correlation function, Eq. (B.2), \( S_1 \), gives information about the volume fraction of the pores in an image consisting of \( M \) by \( N \) pixels (Garboczi et al., 1999), which is the porosity \( \phi \).

\[
S_1 = \phi = \langle f(i,j) \rangle = \frac{1}{MN} \sum_{j} f(i,j)
\]

(B.2)

\( i = 1, 2, 3, \ldots M \) and \( j = 1, 2, 3, \ldots N \).

For permeability estimation through the image processing approach (Torabi et al., 2008), a pore–pore two point correlation function was used on binary images of thin sections using Eq. (B.3).

\[
S_2(x,y) = \langle f(i,j)f(i+x,j+y) \rangle = \frac{1}{MN} \sum_{j} f(i,j)f(i+x,j+y)
\]

(B.3)

Using Eq. (B.4), the specific surface area of the pores is calculated and finally the permeability is estimated utilizing a modified version of the Kozney–Carman relation (Eq. (B.5), Walsh and Brace, 1984; Blair et al., 1996), where \( F \) the formation factor has an exponential relation with

Fig. 11. a) P-wave velocity measurements versus estimated density for the corresponding samples; square and diamond symbols are from this study. Solid diamonds are sandstone samples from damage zone, open diamonds are fault core samples, the greyish open symbol is from conglomerate, while the solid squares are the deformation band samples. The data from the current study are compared with the reported velocity–density data by Wang (2000). Both density and P-wave velocity values are lower for the deformed samples in this work, even smaller than those of unconsolidated sand previously reported by Wang, 2000. b) P-wave velocity measurements were performed on 3 dimensions on a sample with a deformation band, two measurements on the deformation band (1810 m/s and 2402 m/s) and one perpendicular to deformation band (1742 m/s).
porosity and $r$ is a constant that is considered to be equal to 2 for porous materials with circular pore geometry.

$$S_c(0) = \frac{s}{4} \quad (B.4)$$

$$k = \frac{q^2}{CF^2} \quad (B.5)$$

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