Lithofacies Controls on Deformation Band Development: Implications for Reservoir Quality*

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Abstract

This study examines the effect of lithofacies on the faulting and deformation band development within a mixed eolian – fluvial succession of the Sherwood Sandstone Group. Fieldwork, petrography and experimental work are utilized to investigate the textural controls on band development and the petrophysical effects of different faulted lithofacies. This provides a better understanding of the spatial variability of deformation bands in the reservoir, and the implications for fluid flow and hydrocarbon production

Introduction

Deformation bands are a major feature of fault zones in reservoir quality sands that have proven to affect negatively the fluid flow properties, leading to problems with exploration for, and production of, hydrocarbons. Although first identified in the early 1970s (Dunn et al., 1973), deformation bands have only been the subject of extensive research for the past two decades. Through this research, there has been a great deal of understanding of their occurrence, microstructure, petrophysical impacts and factors controlling their formation. However, these conclusions have been drawn from predominantly one lithofacies type, texturally mature sandstones of eolian (Antonellini et al., 1994) or marine origin (Saillet and Wibberley, 2010). This is in part due to the excellent exposure of fault zones in the western United States in formations such as the Aztec, Entrada and Navajo Sandstones, but also due to the preferential occurrence of deformation bands within high porosity well-sorted sands such as these. Although studies of sandstones of fluvial origin have been covered (Rotevatn et al., 2008; Torabi et al., 2013), they have not been studied in respect to lithofacies directly, nor have lithological parameters such as grain sorting, grain angularity and composition been quantitatively studied in detail. Current theory is that strain localization and deformation band formation is restricted to sandstones of high porosity and a narrow grain size distribution, and is inhibited in sandstones with wide grain size distributions. Instead, strain is accommodated through distributed cataclastic flow, and thus no deformation bands can form (Cheung et al., 2012).

The study will comprise outcrop exposure and core investigations, utilising the Sherwood Sandstone Group of the Cheshire Basin. The Triassic Sherwood Sandstone Group is chosen due to its good exposure throughout the UK. It represents a broad range of lithofacies recording the transition from a terrestrial eolian to fluvial environment, with the uppermost late Triassic formations offering plenty of lithofacies heterogeneity (Mountney and Thompson, 2002; Wakefield et al., 2015). The Sherwood Sandstone Group is also of economic importance as a major reservoir in the East Irish Sea, as well as an analogue to reservoirs in the North Sea and West of Shetland area. The Cheshire Basin offers some of the best exposures of these formations along its periphery, adding to that the extensive fault zones of which deformation bands are a major feature. The Cheshire basin itself lends petroleum context to the problem, providing a basin scale analog to many other tilted half grabens of extensional tectonic origin.

Method

Fifty-five samples of both undeformed host rock and faulted examples of these host units were obtained from seven localities within the Cheshire Basin. Samples were cut perpendicular to band orientation and thin sections 30 µm thick impregnated with blue resin were produced to display the deformation band and surrounding host rock. An initial petrographic analysis of the samples using optical microscope was used to obtain pictures for image analysis. Porosity measurements of samples were obtained using ImageJ analysis software. An 8-Bit palleted colour filter was first applied to optical images of both host rock and deformation band. A jPORv1.1 plug in for ImageJ is then used to identify, and quantify by area the pore filling blue resin. Grain size and grain size distribution were obtained using PetrogTM software and an automated microscope stage. Using a point counting technique in which the long and short axis of grains is measured, the long axis of the grains is used to calculate the mean grain size, and grain size distribution is classified using the Folk and Ward (1957) classification. A total of 250 grains were measured for each sample. Permeability measurements of undeformed host rock in both the field and core were obtained using a hand-held probe permeameter. An average of up to 10 measurements were taken per sample/unit. Due to sampling limitations of the deformation bands, in which the probe aperture is often much larger than the thickness of the bands, an accurate permeability measurement could not be obtained using this method. Therefore, permeability of deformation bands was calculated numerically using the Berg method (1970), with the following equation:

$$k = 5.1x10^{-6}\Phi^{5.1}d^{2}e^{-1.385p}$$

Where Φ is porosity, d is mean grain size and p is a sorting term.

Host rock permeability values were also obtained using this method for correlation with those obtained with the probe permeameter. Composition for a selection of the samples was obtained from diffractograms using X-Ray diffraction (XRD). Samples of 20-30 g were taken of undeformed host rock. Samples were ground in multiple stages and oven dried before going into a PANalytical X'pert Pro MPD X-ray diffractometer. The fault zone was characterized by measuring the density per unit area of deformation bands with distance. The density and thickness of deformation bands was also recorded through a succession displaying a number of lithofacies.

Discussion

Host Rock Lithotypes

When considering the deformation of porous rock, it is essential to consider the microscale textural parameters that so strongly control the deformation behavior. Therefore, in order to investigate the link between sedimentology with structure, rock typing according to textural and petrophysical parameters is used to distinguish and group various facies. Five lithotypes are thus identified according to their grain size, grain size distribution, porosity, permeability, and composition (Figure 1).

- Lithotype L1 – Comprising of well-sorted fine sandstones with grain sizes in the range 146 - 230 microns, moderate to good porosity values of 16%, and mean permeability values of 1200mD. These lithotypes contain a variety facies such as horizontally bedded and trough and ripple laminated sands of eolian dune and fluvial bar top association (Miall, 1978).
- Lithotype L2 – Moderately sorted, fine- to medium-grained, 170 – 266 microns, average porosity of 11%, and an average permeability of 1600mD. These lithotypes comprise trough and horizontally bedded facies of fluvial channel and sheet flood associations.
- Lithotype L3 – Well-sorted, medium-grained sandstones with ranges of 256 – 500 microns. They record the highest porosity and permeability values of 21% and 7200mD. Comprised predominantly of trough cross-bedded and horizontally bedded facies of eolian dune association.
- Lithotype L4 – Well-sorted very fine sandstones with grain size range 81 – 130 microns. Low average porosity of 2.6% and low permeability of 110mD. Comprised of massive and laminated silt facies types of interdune and overbank association.
- Lithotype L5 – Poorly sorted, medium- to coarse-grained with size range of 348 – 636 microns. Moderately high average porosity of 17% and high average permeability of 3900mD. Comprised predominantly of fluvially derived trough and horizontally bedded, often pebbly sandstones.

Deformation Band Characteristics

Contrary to current theory and experimental findings, deformation bands can and do form in sandstones with what has been regarded previously as unfavorable textural characteristics. Bands form in four of the five lithotypes across the many localities of this study, and represent a broad range of grain sizes, size distributions, and porosity. Bands are most commonly found within lithotypes L1 and L3. Bands typically display thicker and straighter geometries, often with lenticular or lozenge shaped lenses along their length. These units have shown to develop complex and dense zones of conjugate deformation bands, often forming a thick core of amalgamated bands 20-30cm wide, which may have a principal slip plane developed. Although less common, possibly attributed to thinner successions and less abundant facies, bands also occur within lithotypes L2 and L5, of much coarser and wider grain size distribution. Bands are typically much thinner, with more complex geometries that anastomose and link throughout a unit. These observations can be seen through a single succession as bands strike through multiple lithotypes (Figure 1). Changes in these characteristics can be observed across bed boundaries, where thick lenticular bands thin and anastomose upon contact with much more poorly-sorted and coarse-grained facies (Figure 2), suggesting a strong lithological control.

Similar differences can be observed on a micro scale. While all band types show intense cataclasis and porosity reduction at their core (Figure 4 and Figure 5), differences are observed in their grain size distribution profiles (Figure 6 and Figure 7). Well sorted high porosity lithotypes reduce to a log normal distribution with a sorting of 0.6 Phi. Poorly sorted moderate porosity lithotypes reduce to a normal distribution with a sorting of 1.06 Phi. Deformation bands do not occur in lithotype L4, often terminating against these units. This can be attributed to their very fine grain sizes and low porosity values, making a mechanically very competent unit.

Deformation Mechanism

The anastomosis of deformation bands across boundaries of well to poorly sorted lithotypes, results in a localized increase in band density (Figure 3). The mechanisms of which may be explained by Hertzian fracture theory (Zhang et al., 1990) and grain comminution. Increase in grain size distribution within the core of deformation bands and various other fault gouge material may be explained by the constrained comminution model of Sammis et al. (1987), in which grain fracturing occurs amongst connected grains of similar grain size, leaving finer and coarser outliers undeformed. In a sandstone with narrow grain size distribution, the connected grain fraction makes up a larger portion of the total distribution, resulting in a wide zone of cataclasis. In contrast, samples with wide grain size distribution have a much smaller portion of similar grain size. Therefore, the Hertzian fracture network takes a more constrained route through the sample, resulting in much narrower zone of cataclasis and irregularly shaped deformation bands that anastomose through the unit (Figure 9). Volumetric strain is then maintained throughout the succession by localized density increase and anastomosis within poorly sorted lithotypes. The interaction of different mechanical units is complex and largely not understood, but the presence of deformation bands in what would be considered unfavorable sandstones may be due to the complex interaction of one localizing sand on another non-localizing. We hypothesize that the localizing sands have an over bearing mechanical control on the style of deformation throughout a succession, facilitating deformation band formation in what would be considered in isolation, a non-localizing sandstone.

Impact on Fluid Flow

Calculations of permeability for host rock were correlated with those obtained by probe permeameter in this study and from values published by Bloomfield et al. (2006). Calculated values correlate well with those measured by us and those published, and therefore offer a reasonable estimate of band permeability. The permeability of bands is said to be predominantly controlled by the amount of cataclasis (Fossen et al., 2018). This is due to the increase in grain size distribution within the band, resulting in porosity loss by reorganization of grains, with finer grain fraction blocking pore spaces and pore throats of larger grain fractions. It is therefore reasonable to assume that lithotypes with an already wide distribution will exhibit lower permeability with deformation band formation, due to an already less favorable texture. However, there is no significant clustering of the data to suggest that poorly sorted deformation bands are less permeable than those that are better sorted. Permeability calculations result in a wide range of values owed to the porosity and grain size distribution variation from which they are calculated. Permeability reduction is calculated to be between four and eight orders of magnitude (Figure 8), predicting a much lower permeability than those previously published. This is likely due to the low to negligible porosity values obtained for the bands, recording much lower values than previously published.

Conclusions

Our field and core observations show that deformation bands form in a variety of lithofacies, including those once thought unfavorable for deformation band formation. A strong lithological control is observed on the geometry and propagation of deformation bands throughout a mixed succession, in which the sands that are more favorable for band formation (clean, rounded, well sorted, high porosity) are suggested to be the controlling lithotype, where Hertzian fracture theory and constrained grain comminution model may be applied to explain their distribution and propagation from one lithotype to another.

Variations in host rock textures are also seen in deformation band textures, with well-sorted bands reducing to log normal distributions, and poorly sorted bands reducing to normal distributions. In both cases, grain size distribution is increased to such an extent that porosity is calculated to be negligible, with values as low as 1%. This results in permeability reduction of four to eight orders of magnitude, representing the lowest values recorded. Such low permeability values have huge implications for the fluid flow behavior of an already hydro dynamically complex reservoir. This work demonstrates that understanding the mechanical behavior of lithologically variable reservoirs is crucial to the prediction of the occurrence of deformation bands and their fluid flow properties.

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	DESCRIPTION
L1	Well sorted. Fine grained. Porosity: 16% +/- 7
L2	Mod Sorted. Fine - Med. Porosity: 11% +/- 5
L3	Well sorted. Med grained. Porosity: 21% +/- 4
L4	Well sorted. V fine grained. Porosity: 2.6% +/- 0.7
L5	Poorly sorted. M - C grained. Porosity: 17% +/- 2.4

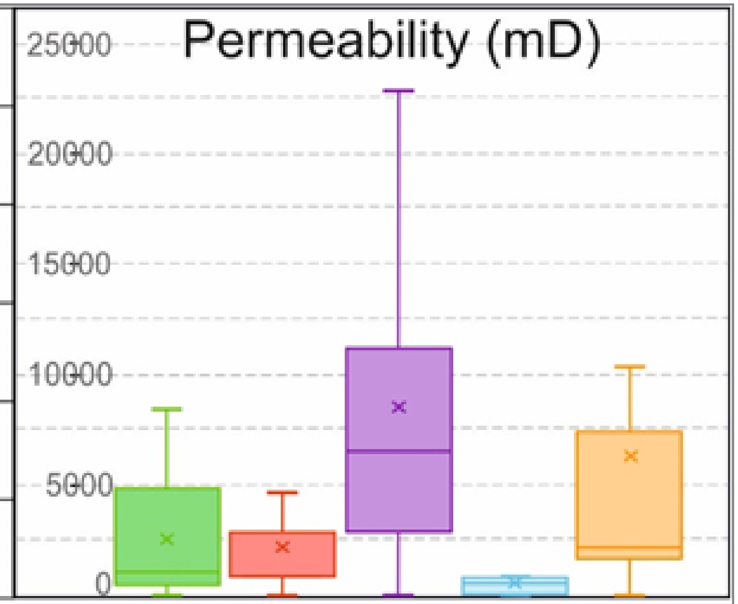
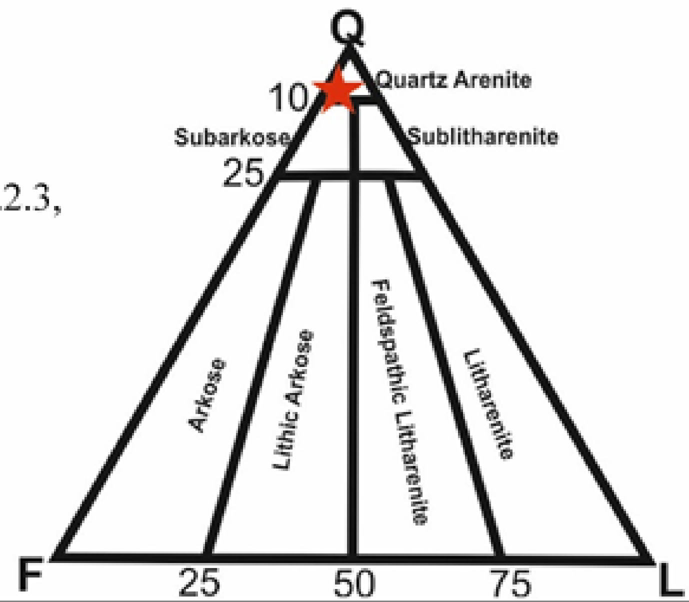


Figure 1. 5 lithotypes are identified according to several textural and petrophysical parameters.

XRD data classifies all lithotypes as quartz arenite with Qtz 90.8% +/.2.3, Kfs 7.8% +/.1.8, Brt 2% +/.1, Trace clays.



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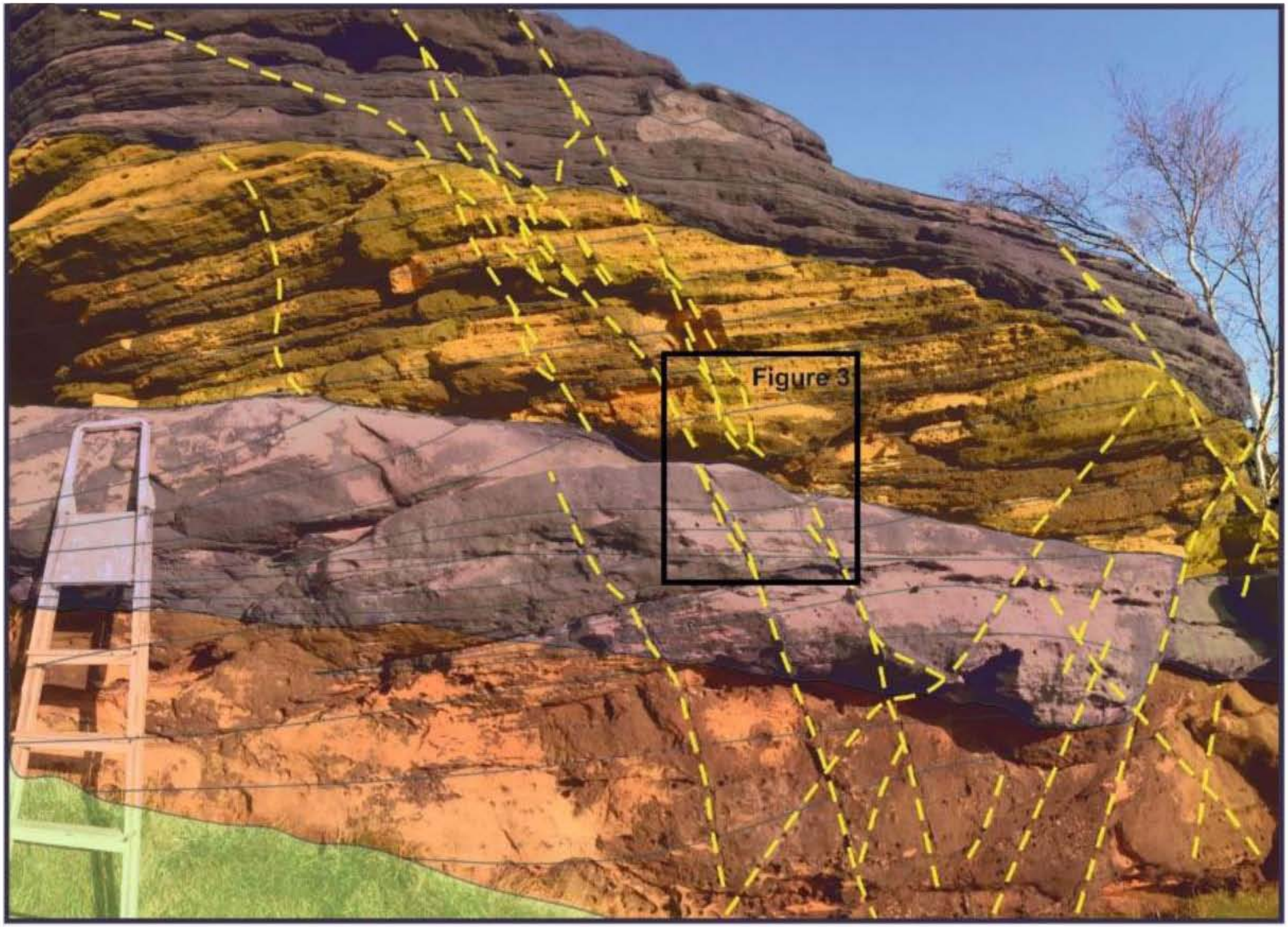

Figure 2. Outcrop at Helsby Hill shows deformation bands pervasive throughout three lithotypes from which comparisons in deformation band characteristics can be made across unit boundaries.

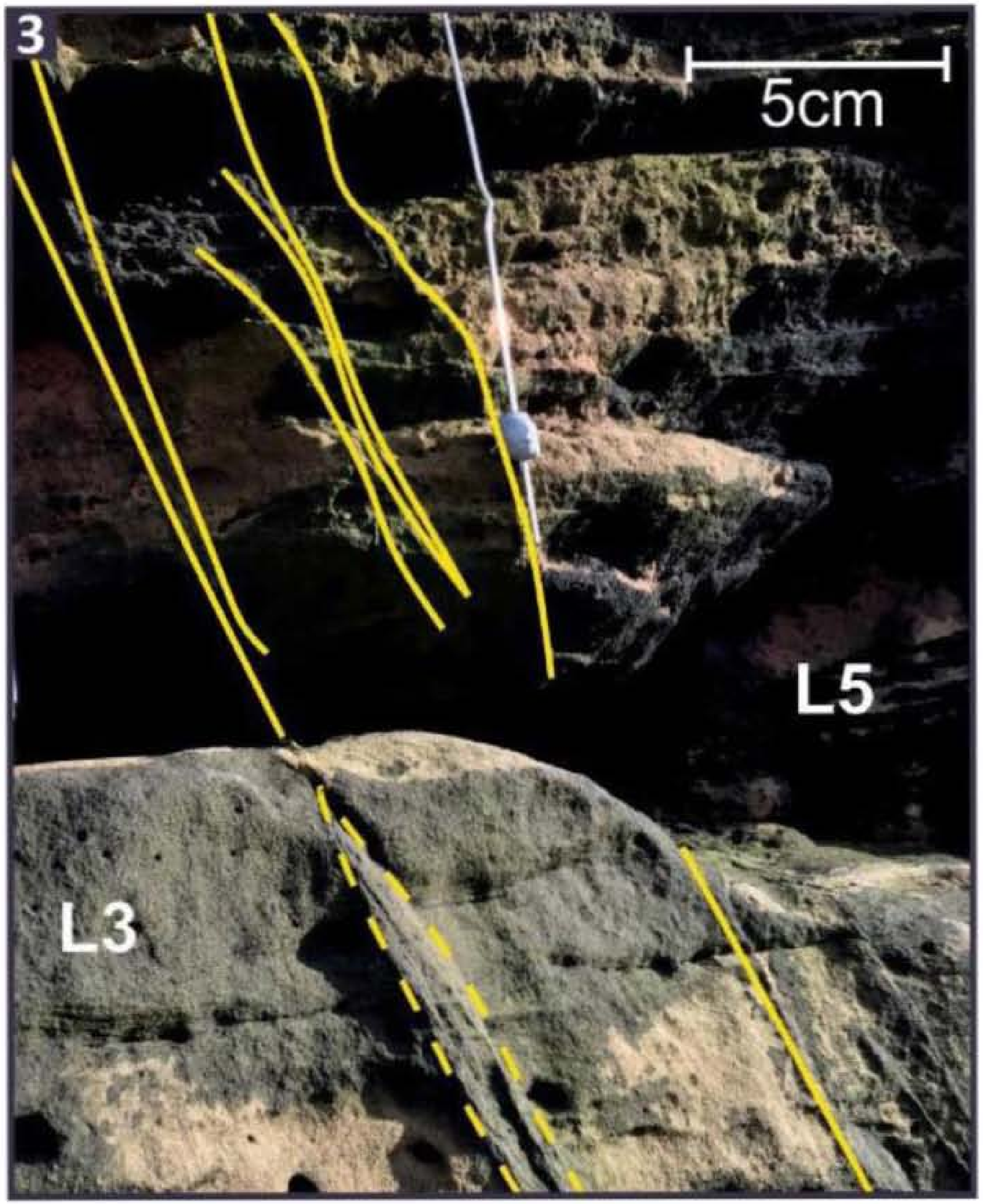

Figure 3. Deformation bands show localized density increase as bands thin and anastomose from L3 into L5 lithotypes.

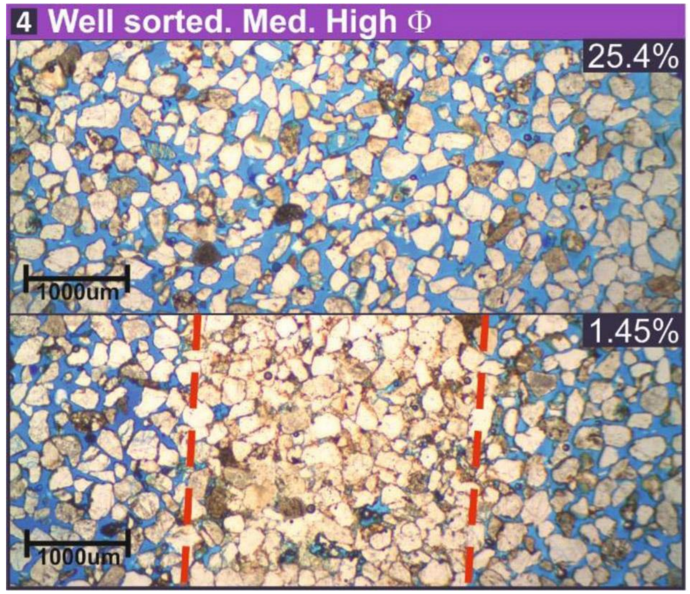

Figure 4. Deformation bands hosted in high porosity, well-sorted medium-grained sandstones form thick zones (2mm) of cataclasis, reducing to negligible porosity.

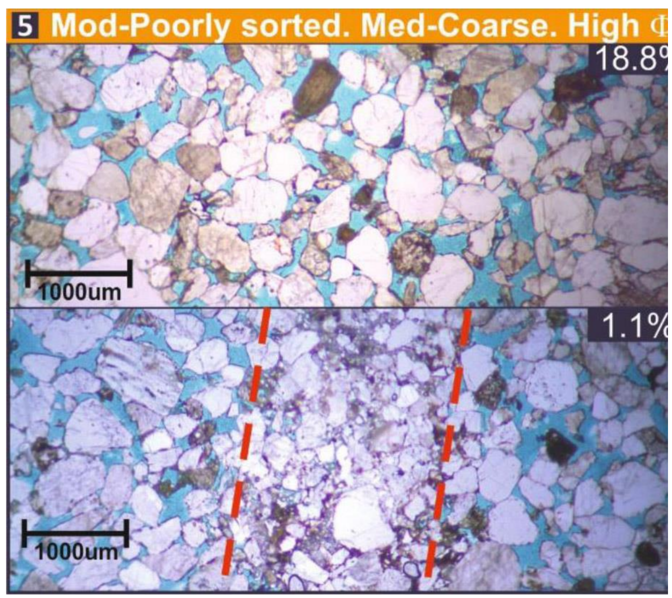

Figure 5. Deformation bands hosted in high porosity, poorly sorted coarse-grained sandstones form thinner zones (1mm) of cataclasis with negligible porosity.

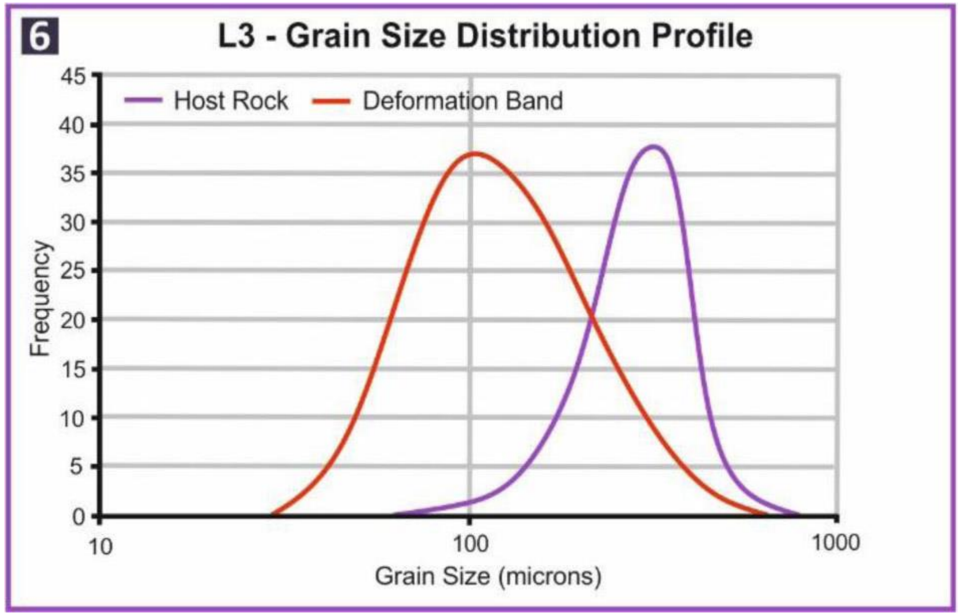

Figure 6. Grain size distribution reduces to a moderately sorted (0.6Phi) log normal distribution.

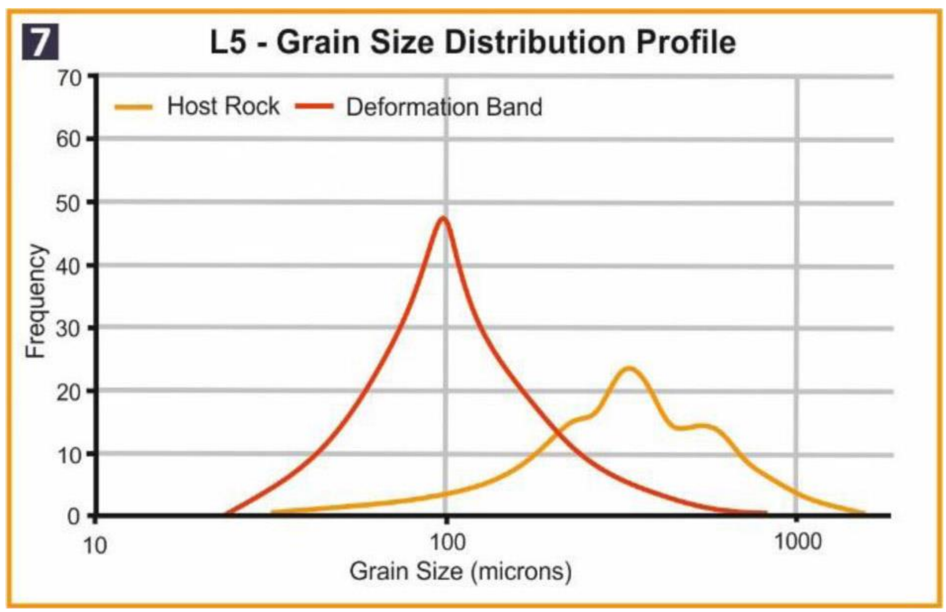

Figure 7. Grain size distribution reduces to a poorly sorted (1.06Phi) normal distribution.

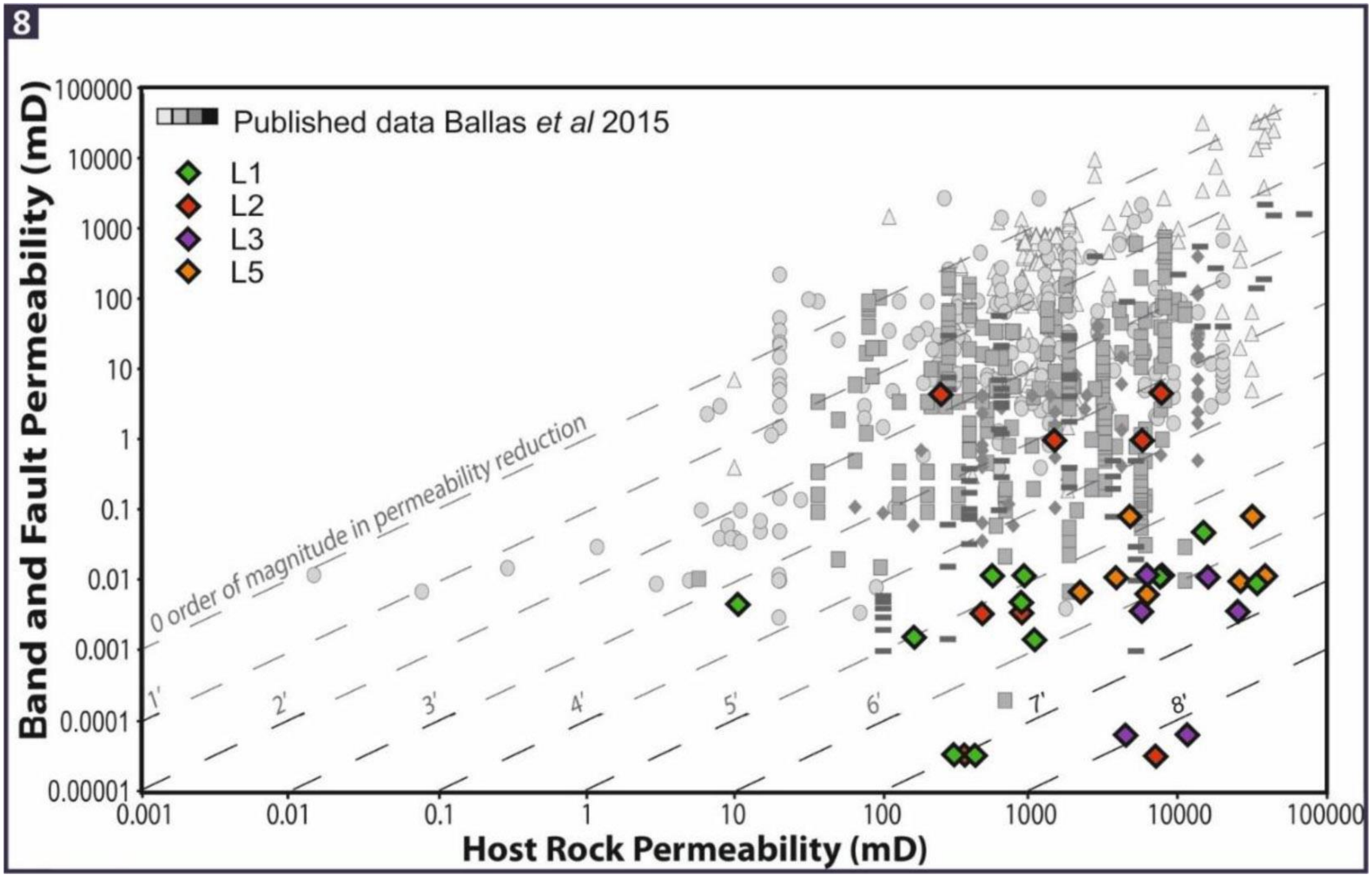

Figure 8. Permeability contrasts between host rock and deformation band are between 4-8 orders of magnitude. Slight clustering of L3 and L5 suggest they are the worst affected lithotypes.

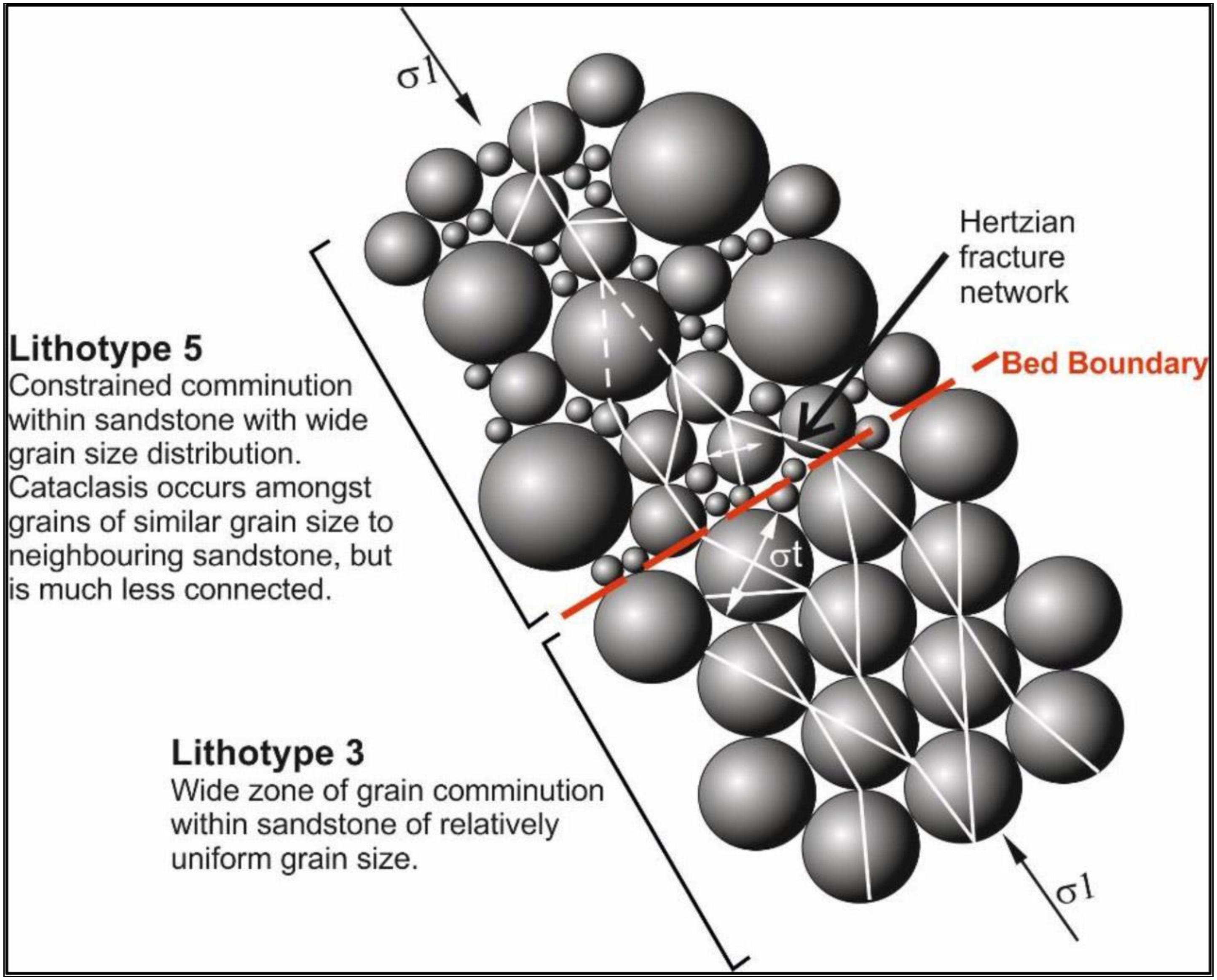

Figure 9. Grain to grain interactions between two lithotypes can be explained by grain comminution model (Sammis et al., 1987) and the connection of Hertzian fracture networks from sample to sample (Zhang et al., 1990). Comminution of grains becomes narrowed in lithotypes with wide grain size distribution.