research article

Deformation bands and their significance in porous sandstone reservoirs

Haakon Fossen[1] and Jonny Hesthammer[2]

Introduction

Geologists and engineers in the oil industry are becoming increasingly aware of the importance of small-scale (sub seismic) faults and fractures in many reservoirs, but modelling of such structures is currently hampered by our limited understanding of these structures. The many fault parameters that, directly or indirectly, should be input to advanced reservoir simulation models include the number, distribution, orientation, geometry, displacement, length, and petrophysical properties of small-scale faults and deformation bands.

In porous sandstone reservoirs, which are the focus of the current contribution, deformation bands with displacements less than a few tens of centimetres are generally developed instead of slickenlined fault surfaces typical for less porous lithologies (Figs 1, 2, 3; see below). Deformation bands may show reduction in permeability by up to three orders of magnitude (Antonellini & Aydin 1994). This parameter needs to be estimated for each field or reservoir level, as it will depend on degree of lithification during deformation (for example, increasing depth during faulting implies increased influence of cataclasis and therefore stronger reduction of permeability across the deformation bands). Although of less importance at the exploration stage (Harper & Lundin 1997), deformation bands that significantly reduce permeability may be very important with respect to production from sandstone reservoirs. Displacement, as an isolated parameter, is of less importance, as it generally is too small for deformation bands to cause sealing by juxtaposition of sand and shale layers. Field studies have shown that deformation bands generally can be modelled as straight structures that are particularly numerous around larger faults, but may also occur as scattered structures between seismically resolvable faults (e.g. Antonellini & Aydin 1995). Much work is left to explore the relation between the distribution of micro faults and larger structures. However, the question of distribution must always be addressed in each case, for example by use of attribute maps and core data (e.g. Hesthammer & Fossen 1997).

In this work we will discuss the length vs. displacement of small-scale structures (deformation bands) in porous sandstones. It has been suggested that length and displacement can be scaled down from the size range covered by seismic data to the sub seismic domain (e.g. Yielding *et al.* 1992). The underlying assumption is that displacement and length are related through a power law and thus are fractal by nature. Down-scaling of fault length and displacement has already

Figure 1 Deformation band in highly porous sandstone near Goblin Valley State Park, SE Utah. The deformation band is a few mm wide, with a few cm of maximum displacement but more than 100 m long. Wild Horse Butte in the background.

[1]University of Bergen, Department of Geology, Allégt. 41, N-5007 Bergen, Norway (haakon.fossen@geol.uib.no)
[2]Statoil, GF/PETEK-GEO, N-5020 Bergen, Norway (jonhe@ln.statoil.no)

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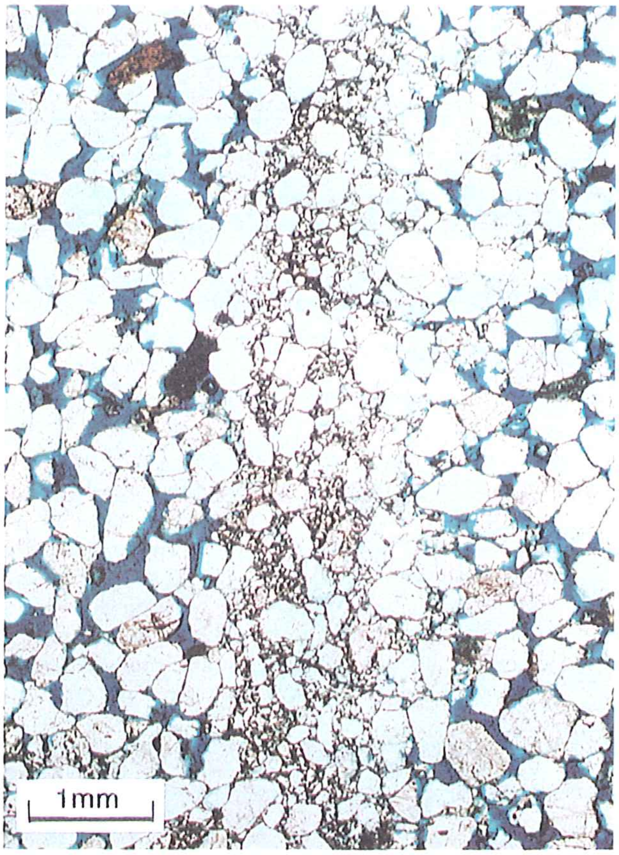

Figure 2 Microphotograph of deformation band (central vertical structure). Grain-size reduction by cataclastic deformation dramatically reduced the pore space (blue) within the zone. A marginal zone of compaction and little or no cataclastic deformation is seen. Entrada sandstone, Utah.

Figure 3 Photograph of core from the Gullfaks Field, North Sea, with deformation band offsetting the lamination by ≈ 2.5 cm. According to the displacement-width relation established from Utah (see text), this deformation band is more than 110 m long (assuming that the displacement of 2.5 cm is the maximum displacement of the structure). If properties of larger faults are assumed, its length can be estimated to ≈ 1 m. Width of core is ≈ 8 cm.

been applied as input to sandstone reservoir simulation models (e.g. Gauthier & Lake 1993). We here present new results from a population of deformation bands and discuss why properties of the seismically mappable part of a fault population cannot necessarily be extrapolated far into the sub seismic domain.

Fault development in porous sandstones: from deformation bands to more typical faults

The smallest visible shear fractures in porous sandstone are known as deformation bands (also called granulation seams, micro faults or shear bands) (Aydin 1978; Antonellini *et al.* 1994). Deformation bands are mm-thick sub planar structures (Fig. 1) that may be characterized by a central zone of smaller grains formed by mechanical fracturing of the original grains (cataclasis; Fig. 2). The central zone generally has very low porosity, and is surrounded by a zone of compacted grains which probably represents a preceding (pre-cataclasis) stage. Although individual deformation bands only have a few mm or cm of displacement (Fig. 3), reduction in permeability by two or three orders of magnitude has been estimated within such bands (Antonellini & Aydin 1994). These results prove their potential as important barriers to fluid flow in reservoirs during production (Harper & Lundin 1997).

Deformation bands are very common in sandstone reservoirs, e.g. in the North Sea (Gabrielsen & Koestler 1987) where core studies indicate that they not only cluster around larger faults to form a damage zone, but also occur throughout many reservoirs. Field studies of deformation bands have been carried out in great detail from the Jurassic Entrada and Navaho sandstones of the Arches National Park area of south-eastern Utah (Antonellini & Aydin 1994, 1995; Antonellini *et al.* 1994), and from the nearby San Rafael Swell area (Aydin 1978; Aydin & Johnson 1978, 1983).

Studies of deformation bands in Utah show that they occur as (a) isolated structures (Fig. 1), (b) linked systems, (c) complex zones of multiple interconnected deformation bands, and (d) in a zone at either side of faults, where the faults are defined by discrete, polished slip surfaces (Fig. 4). Aydin & Johnson (1978, 1983) suggested that this sequence represents the development through time from a single deformation band to an ordinary fault. During this process, displacement increases from the mm to cm scale at stage (a) and (b), to a few tens of cm at stage (c), and to several metres or more at stage (d). A dramatic change in accumulated displacement occurs as the slip surface initiates within or along the zone of deformation bands (stage c to d). In Utah this happens as the dense cluster zone exceeds ≈ 10–20 cm in thickness. From that moment, the structure behaves like any fault, with slip mainly accumulating on the striated slip plane.

In the following we shall make a distinction between deformation bands and ordinary faults. Deformation bands are described above, and differ from faults by the absence of a continuous slip surface. Slip surfaces occur in deformation bands only on the micro scale, where shear cracks may offset grain boundaries, but these slip surfaces are not much longer than the maximum grain size of the sandstone. In this sense, the deformation band classifies as a shear zone on the scale of outcrop or hand-sample, whereas ordinary faults are highly discontinuous structures at the same scale.

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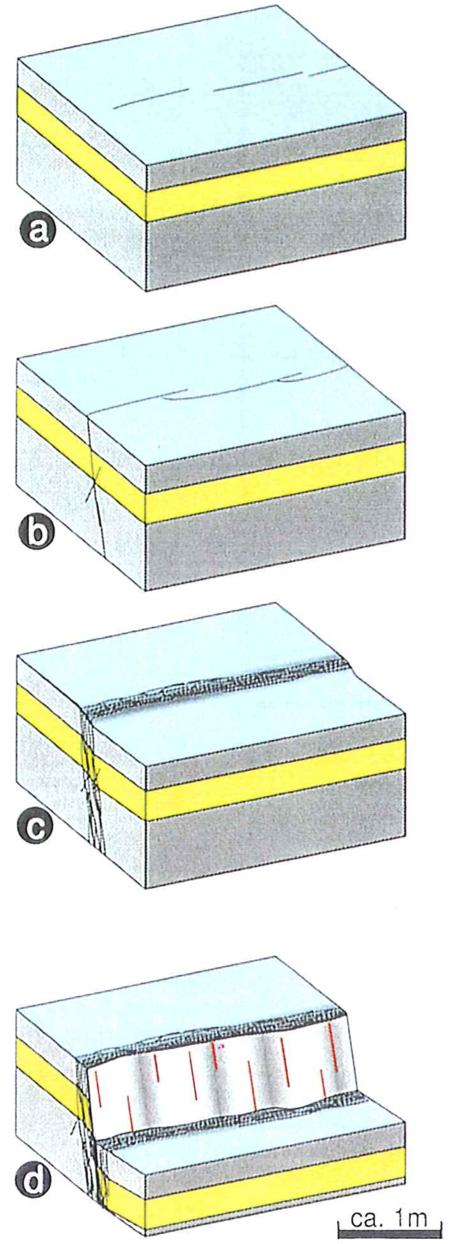

Figure 4 Development of a fault from deformation bands. Principal sketch, based on work by Aydin & Johnson (1983).

Relationship between displacement and length

In many ways, deformation bands are very similar to faults. This similarity includes the qualitative distribution of displacement on fault surfaces (central maximum displacement which decreases toward the margin) and complications caused by linkage or interference during growth (e.g. Walsh & Watterson 1987; Cowie & Scholz 1992; Peacock & Sanderson 1994). However, detailed quantitative analysis of a population of deformation bands in the San Rafael desert, Utah has unravelled important differences with respect to length vs. displacement. In this study, displacement and length was systematically measured for deformation bands exposed on a 100 × 200 m sub-horizontal surface. The data set spans more than three orders of magnitude for fault length (0.05–100 m) and more than two orders of magnitude for displacement (0.2–33 mm). This, as far as the authors are aware, is more than most previously published fault populations collected by use of a single method, and the only comprehensive analysis of deformation bands to date. A closer description of the data and the collection method will be given elsewhere.

Scaling relations

For faults with length in excess of ≈ 100 m, a power law (or fractal) relationship between length and displacement is generally accepted. In other words, the relation between displacement (D) and length (L) can be expressed as

$$D = aL^b,$$

where a is a constant. The value of the exponent b has been the matter of some debate. Workers who have analysed compiled data sets have suggested that $b = 2$ (Walsh & Watterson 1988) or 1.5 (Marrett & Allmendinger 1991, Walsh *et al.* 1991). Others, who have studied individual data sets, tend to obtain approximately linear relationships ($b = 1$) (see references and discussions by Cowie & Scholz 1992 and Clark & Cox 1996). Recent work on small-scale faults (not in porous sandstones) also indicates a linear relation between D and L (Schlische *et al.* 1996).

As pointed out by Clark & Cox (1996), the disagreement is mainly a result of incorrect approaches to the problem. In particular, data sets should be analysed individually, and on a statistically sound basis. When this is done, the majority of the available fault population data sets exhibit an approximately linear relationship between displacement and length (i.e. an exponent of 1).

The present data set from the population of deformation bands from Utah also shows a relatively well-defined power-law relation between displacement and length (as identified by a straight line in log-log space; Fig. 5). However, the exponent b is not close to 1, but ≈ 0.5, and thus very different from any of the previously published fault data sets (Fig. 5). In other words, $D \approx c\sqrt{L}$ for deformation bands, whereas $D \approx cL$ most other fault data sets.

A lower b-value means that longer deformation bands have relatively smaller displacements than shorter ones, since D increases more slowly than L. For example, a fault with maximum displacement of 0.01 m can be predicted from Fig. 5 (using the line with slope of 1.0) to have a length of 0.5 m, whereas a deformation band with the same displacement should be 10–15 m long (line with slope of 0.5 in Fig. 5). The difference increases with size: a fault and deformation band with displacement of 0.05 m can be predicted to have lengths of ≈ 2 m and 600 m (!), respectively. This difference in length of up to three orders of magnitude may indeed have dramatic effects on models of reservoir performance.

Discussion

We believe that the difference in scaling relation is related to the fundamental differences between the development of deformation band populations and populations of faults with

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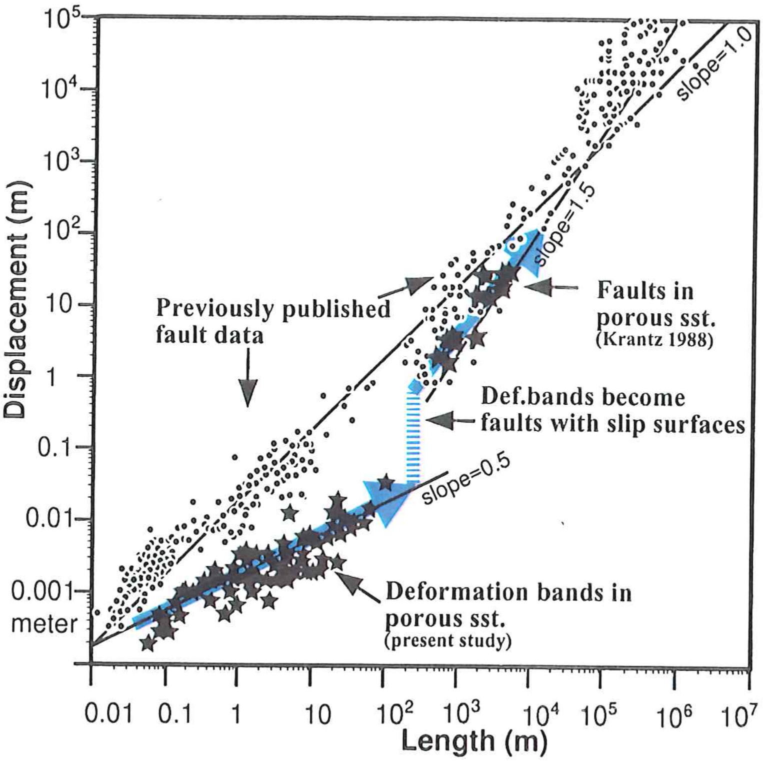

Figure 5 Displacement–length data for deformation bands and faults in porous Jurassic sandstones, San Rafael Swell area, Utah (stars) plotted together with data from other sources (cited in Schlische *et al.* 1996) (grey dots). Arrows outline a path which shows a break and a vertical shift at the transition from deformation band cluster zones to faults with slip surfaces. See text for discussion.

distinct slip surfaces. In a strict sense, faults are weak slip surfaces with associated narrow damage zones that may be formed by a single or, more commonly, repeated seismic slip events. Many deformation band populations show evidence for profound strain hardening without development of continuous weak slip surfaces until they reach an advanced stage, although strain hardening is not necessarily involved in the formation of deformation bands (see Harper & Lundin 1997 and references therein). The hardening process relates to locking of grain contacts as pore space collapses and grains get crushed, as described by Aydin (1978). The strain hardening effect causes a sequential formation of new deformation bands during deformation, resulting in a family of isolated, linked, and eventually zones of clustered deformation bands, as shown in Fig. 4. This evolution is different for other types of faults, where slip accumulates along more continuous slip *surfaces.* Although the exact faulting mechanism may change from fault to fault, the differences are probably less than those between deformation bands and ordinary faults. The differences in scaling law indicate that a different growth model applies to populations of deformation bands than to fault populations.

We suggest that growth of deformation band populations follow a *D–L* scaling law with exponent about 0.5 until a slip surface forms, i.e. after formation of ≈ 10–20 cm wide cluster zones with aggregate displacement up to a few tens of centimetres in the study area. The emerging population of faults with slip surfaces are expected to grow like any other population of large faults, and likely follows an approximately linear scaling relation ($b = 1$). Support for this interpretation was found by plotting displacement–length data from faults with slip surfaces that correspond to stage (d) in Fig. 4. These faults occur in the same porous Jurassic sandstones in the San Rafael Swell area as the deformation bands. The fault data were obtained from a previous study by Krantz (1988), and fall within the common range of faults as shown in Fig. 5, with an estimated slope (b) of ≈ 1.3.

This significant difference in scaling relation (Fig. 5) implies that displacement–length relationships established from interpretation of seismic data should not uncritically be scaled down to the size of deformation bands in a porous sandstone. To evaluate the application of these results to a specific case, it is necessary to utilize core data. If deformation bands are not present, and micro faults show well-developed striated slip surfaces, the ordinary (linear) scaling law is probably a good approximation. However, if deformation bands dominate, a change in scaling relationship is likely to occur for faults with displacements less than 0.1–1 m.

The consequence of the above-established scaling relationship between displacement and length for deformation bands, is that a deformation band with apparent offset of a few centimetres should not be neglected, as they are likely to be several hundreds of metres in length. If information about their orientation and distribution relative to larger, mappable structures is retrievable from cores (Fig. 3), seismic attribute studies, analogue models and/or field analogues, it should be possible to build a useful model of sub seismic structures.

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Conclusions

Deformation bands are typically ruled by strain-hardening processes, which cause the formation of deformation band cluster zones and eventually a throughgoing, weak slip surface which accommodates most subsequent strain. Prior to this stage, deformation bands do not follow the linear scaling relation between displacement and length which characterize ordinary fault populations, but obey a power-law relation with exponent close to 0.5, according to the new data presented here. Thus, deformation bands are very long with respect to their maximum displacements, as compared to faults with well-developed slip surfaces. This dissimilarity is increasingly present for larger deformation bands, and deformation bands and other types of faults with identical displacement may differ in length by up to three orders of magnitude.

A change in the scaling relationship between length and displacement is suspected to be a general feature for porous sandstones where faults develop from deformation bands, and down-scaling of ordinary fault populations into the size domain of deformation bands in porous sandstones is therefore potentially wrong. If subseismic faults are to be modelled numerically for porous sandstone reservoirs, information regarding frequency, distribution, orientation and petrophysical properties of deformation bands is required. If deformation bands are found to be common constituents of the subseismic part of the fault population, the scaling law presented in this work can be applied during modelling of reservoir performance. The ways in which deformation bands influence fluid flow in a reservoir depend on a number of factors, such as frequency, distribution, orientation and petrophysical properties (difference in porosity and permeability within and outside of deformation bands). These factors must be estimated individually and, together with the scaling law presented here, incorporated into a more complete reservoir simulation model.

Additional studies of deformation band populations and their scaling properties are needed to evaluate the generality of the results from Utah. However, the data presented here demonstrate that fault populations are not necessarily fractal over a wide range of scales – a fact which has also been noted for some larger-scale fault populations (e.g. Fossen & Rørnes 1996).

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References

Antonellini, M. and Aydin, A. [1994] Effect of faulting on fluid flow in porous sandstones: petrophysical properties. *American Association of Petroleum Geologists Bulletin* 78, 355–377.

Antonellini, M. and Aydin, A. [1995] Effect of faulting on fluid flow in porous sandstones: geometry and spatial distribution. *American Association of Petroleum Geologists Bulletin* 79, 642–671.

Antonellini, M. A., Aydin, A. and Pollard, D. D. [1994] Microstructure of deformation bands in porous sandstones at Arches National Park, Utah. *Journal of Structural Geology* 16, 941–959.

Aydin, A. and Johnson, A. M. [1978] Development of faults as zones of deformation bands and as slip surfaces in sandstones. *Pure and A pplied Geophysics* 116, 931–942.

Aydin, A. and Johnson, A. M. [1983] Analysis of faulting in porous sandstones. *Journal of Structural Geology* 5, 19–31.

Aydin, A. [1978] Small faults formed as deformation bands in sandstone. *Pageoph* 116, 913–930.

Clark, R. M. and Cox, S. J. D. [1996] A modern regression approach to determining fault displacement scaling relationships. *Journal of Structural Geology* 18, 147–152.

Cowie, P. A. and Scholz, C. H. [1992] Displacement-length scaling relationship of faults using a post-yield fracture mechanics model. *Journal of Structural Geology* 14, 1133–1148.

Fossen, H. and Rørnes, A. [1996] Properties of fault populations in the Gullfaks Field, northern North Sea. *Journal of Structural Geology* 18, 179–190.

Gabrielsen, R. H. and Koestler, A. G. [1987] Description and structural implications of fractures in late Jurassic sandstones of the Troll Field, northern North Sea. *Norsk Geologisk Tidsskrift* 67, 371–381.

Gauthier, B. D. M. and Lake, S. D. [1993] Probabilistic modeling of faults below the limit of seismic resolution in Pelican Field, North Sea, offshore United Kingdom. *American Association of Petroleum Geologists Bulletin* 77, 761–777.

Harper, T. R. and Lundin, E. R. [1997] Fault seal analysis: reducing our dependence on empiricism. In: *Hydrocarbon seals – importance for exploration and production*. Elsevier, in press.

Hesthammer, J. and Fossen, H. [1997] Seismic attribute mapping for structural interpretation of the Gullfaks Field, northern North Sea. *Petroleum Geoscience* 3, 13–26.

Krantz, R. W. [1988] Multiple fault sets and three-dimensional strain: theory and application. *Journal of Structural Geology* 10, 225–237.

Marrett, R. and Allmendinger, R. W. [1991] Estimates of strain due to brittle faulting: sampling fault populations. *Journal of Structural Geology* 13, 735–738.

Peacock, D. C. P. and Sanderson, D. J. [1994] Geometry and development of relay ramps in normal fault systems. *American Association of Petroleum Geologists Bulletin* 78, 247–165.

Schlische, R. W., Young, S. S., Ackermann, R. V. and Gupta, A. [1996] Geometry and scaling relations of a population of very small rift-related normal faults. *Geology* 24, 683–686.

Walsh, J. J. and Watterson, J. [1987] Distributions of cumulative displacement and seismic slip on a single normal fault surface. *Journal of Structural Geology* 9, 1039–1046.

Walsh, J. J. and Watterson, J. [1988] Analysis of the relationship between displacements and dimensions of faults. *Journal of Structural Geology* 10, 239–247.

Walsh, J., Watterson, J. and Yielding, G. [1991] The importance of small-scale faulting in regional extension. *Nature* 351, 391–393.

Yielding, G., Walsh, J. and Watterson, J. [1992] The prediction of small-scale faulting in reservoirs. *First Break* 10, 449–460.

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