Characterization of deformation bands associated with normal and reverse stress states in the Navajo Sandstone, Utah: Discussion

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INTRODUCTION

In a recent article about deformation-band networks in Utah, Solum et al. (2010) present the thesis that deformation bands forming in the contractional regime are more areally extensive and not associated with discrete faults, whereas those forming in the extensional regime are generally limited to damage zones around faults. This is an attractive thesis and, insofar as it holds true, of great value for predicting deformation-band distributions in high-porosity sandstone reservoirs. We believe that Solum et al. (2010) touch on an important relationship between tectonic regime and strain distribution and, as geologists, we are constantly looking for simple relationships like this one. However, the authors base their suggestion on very limited data (two scanlines of 16 and 60 m [52 and 197 ft]), comparing localities that differ not only in tectonic regime, but also in tectonic style or boundary conditions as well as petrophysical properties. To add to the reflections of Solum et al. (2010) on how tectonic regime may control deformation-band distribution, we find it appropriate to discuss factors other than tectonic regime that may be at least as important for the characteristics and distribution of deformation bands in deformed porous sandstone reservoirs. Furthermore, their permeability considerations could be improved considering the anisotropic and architectural characteristics of deformation bands and deformation-band clusters.

THE FUNCTION OF IMPOSED DISPLACEMENT

The development of millimeter-thick deformation bands in highly porous sandstone is a fine-scale strain localization phenomenon that closely relates to the local state of stress and material properties at the time of deformation (e.g., Wong et al., 1997; Aydin et al., 2006; Schultz et al., 2010). This is a useful approach, particularly when dealing with deformation bands at the scale of laboratory samples and outcrops. However, the distribution of deformation bands on the hectometer to kilometer scale within a sandstone unit may, in many cases, be better viewed as the product of imposed displacement or velocity conditions (e.g., Tikoff and Wojtal, 1999), which can loosely be referred to as kinematic boundary conditions. In this perspective, stresses and the resulting structures that occur in a deforming sandstone unit arise from the material response to the imposed velocity and displacement field, as does the distribution of small-scale structures such as deformation bands.

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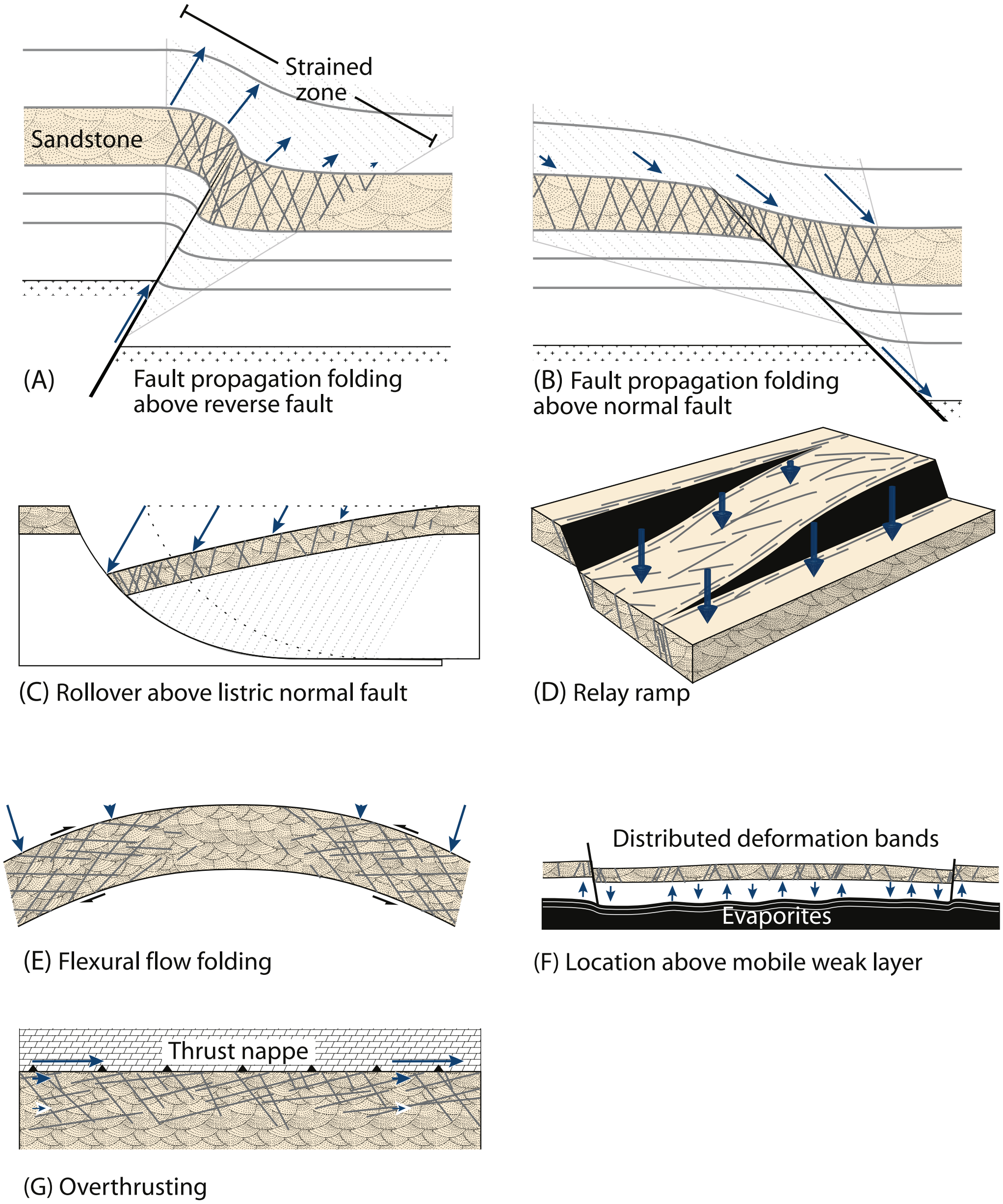


Figure 1. Different styles of deformation caused by different external displacement conditions, each of which can result in a widely distributed deformation-band population. Examples cover the extensional (B, C, D, F) as well as the contractional (A, E, G) regime. Gray lines indicate deformation bands, and arrows indicate the externally imposed displacement field. The widths of these illustrations span from a few hundred meters to a few kilometers.

The reason why external displacement conditions are important in this discussion is that highly porous and poorly lithified sandstones, such as the Navajo Sandstone, which was even less lithified during the Sevier and Laramide phases, commonly behave as mechanically weak layers that deform passively in a kinematic framework that is controlled by the movement of basement blocks or other strong units exterior to the sandstone. In simple terms, the deformation of such layers is, to a large extent, forced upon them (hence, the term “forced folding”) by the behavior of adjacent and, particularly, underlying layers. This aspect of sandstone deformation is particularly relevant to the Sevier and Laramide phases of deformation of the Colorado Plateau, where the deformation of the Navajo Sandstone is mostly imposed through the relative movement of basement blocks (e.g., Davis and Bump, 2009).

We will illustrate that wide distributions of deformation bands are possible in both the extensional and the contractional regime, implying that not only the tectonic regime, but also the local tectonic setting or style, must be considered before a prediction can be made with regard to deformation band distribution in an area or a reservoir.

Fault Propagation Folding

Some relevant examples of settings where an external displacement or velocity field is imposed on a highly porous sandstone unit are shown in Figure 1. Fault propagation folding (forced folding) above a reverse fault (Figure 1A) or fault zone applies to the Buckskin Gulch site (Tindall and Davis, 1999), which is located at the easternmost flank of the East Kaibab monocline. The conditions imposed on the sandstone are here an upward-widening zone of distributed displacement that has been successfully reproduced by means of the trishear model (e.g., Erslev, 1991; Allmendinger, 1998). The dip of the underlying main fault (zone) is unknown but is thought to be a steep reverse fault with a certain dextral strike-slip component (Tindall and Davis, 1999; Doelling and Willis, 2006). The East Kaibab monocline is, similar to several other Laramide structures on the Colorado Plateau, a 5- to 10-km (3- to 6-mi)-wide zone of strained sandstones that, where the lithologic properties are right, can be expected to contain extensive zones of deformation bands (Fossen et al., 2011).

Similarly, areally extensive deformation-band populations can equally well form in fault propagation folds above more or less vertical faults. Along the northeastern margin of the Uncompahgre Plateau in Colorado, Jamison and Stearns (1982) demonstrated how deformation bands populate several hundred-meter-wide zones in the monocline structure, both where larger subvertical faults are (East Kodel's Canyon) and are not (North Canyon) present (Figure 2).

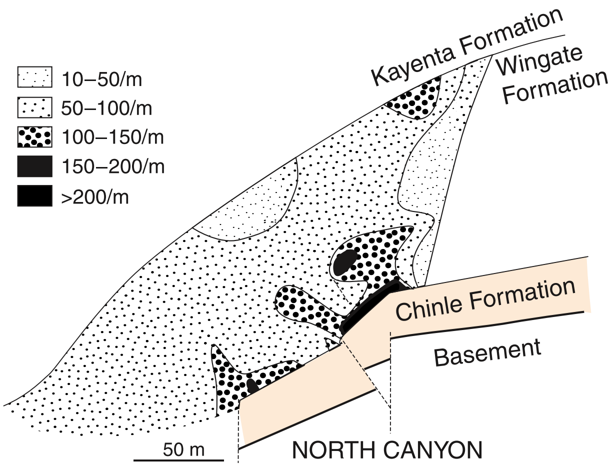


Figure 2. The distribution of deformation bands above a steep fault zone in the North Canyon of Colorado National Monument, as mapped by Jamison and Stearns (1982).

Interestingly, extensional faults also develop upward-widening fault propagation folds (Figure 1B) that can (but do not have to) be populated with deformation bands (Withjack et al., 1990). Examples include the North Sea Gullfaks field (Fossen and Hesthammer, 1998; figure 20.8 of Fossen, 2010), the northwest margin of the Red Sea rift system (Khalil and McClay, 2002), the Gulf of Suez (Sharp et al., 2000), and the Halten Terrace on the Norwegian continental shelf (Corfield and Sharp, 2000).

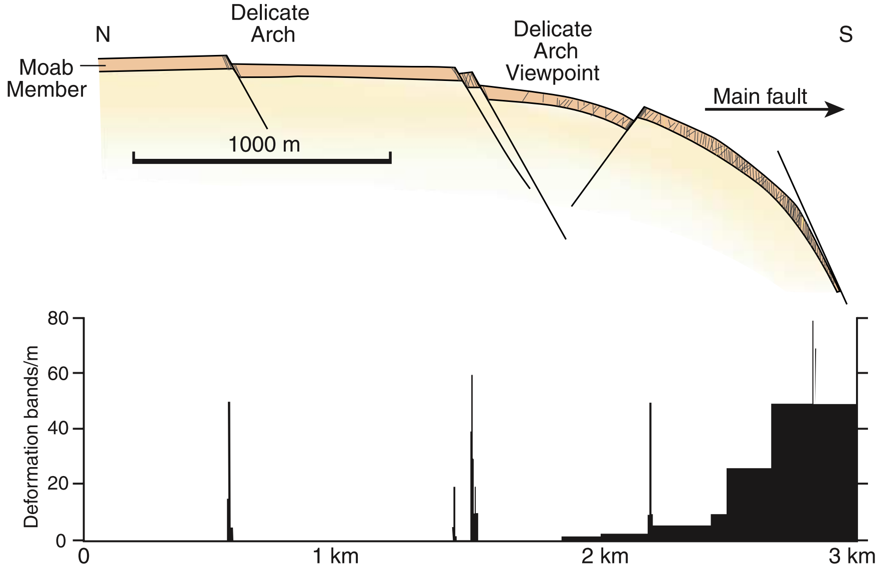
Rollover Structures

Two other situations in the extensional regime that create distributed strain are rollover structures above listric faults (Figure 1C) and relay ramps (Figure 1D). An outstanding example of a kilometer-wide zone of deformation bands in a rollover structure was reported by Antonellini and Aydin (1994) in Arches National Park, Utah (Figure 3). Strain in the exposed part of the highly porous Moab Member of the Entrada Sandstone was mostly accommodated through the formation of deformation bands. Mapping by Antonellini and Aydin (1994) showed that the deformation-band density increases with increasing dip, reaching frequencies of approximately 50 m (~164 ft) over an approximately 1-km (~0.6-mi)-wide zone (Figure 2). A detailed structural mapping in the same area demonstrated how an approximately 200-m (~656-ft)-wide relay ramp is populated with deformation bands as a response to the folding of the Moab Member between overlapping fault tips (Rotevatn et al., 2007).

Unstable Underlying Strata

Another example where external conditions impose displacements that generate distributed deformation bands is found in the Goblin Valley area, located in southern Utah, between the two sites described by Solum et al. (2010). In this area, large numbers of deformation bands are observed, not

Figure 3. Deformation-band distribution in a rollover structure to a normal fault in Arches National Park (modified from Antonellini and Aydin, 1994).



only in what can be defined as damage zones around small extensional faults, but also widely distributed between the faults (Aydin, 1977; Fossen and Hesthammer, 1997). The reason for this is probably the distributed displacement caused by the unstable and undulating nature of underlying semiductile evaporites (gypsum; Figure 1F).

THE IMPORTANCE OF LITHOLOGY AND PETROPHYSICAL PROPERTIES

Nucleation and growth of deformation bands are extremely sensitive to even modest variations in petrophysical and lithologic parameters such as porosity, permeability, cementation, grain size, grain distribution, and grain shape (e.g., Wong et al., 1997; Fossen et al., 2007; Eichhubl et al., 2010). For example, porosity variations more than only a few percent can result in remarkably different deformation band density and distribution patterns because porosity plays such an important function during the grain reorganization processes that occur during deformation-band formation (Fossen et al., 2011). Although Solum et al. (2010) consider the two localities to be similar with respect to lithologic and petrophysical properties, the Navajo Sandstone in the Buck Springs site is generally more porous and permeable, with typical porosity values of approximately 25 to 30% in layers where deformation bands occur (Schultz et al., 2010; Fossen et al., 2011). In contrast, the sandstone affected by the Chimney Rock fault array has host porosities from 15 to 25% (Shipton and Cowie, 2001). Together with a significantly coarser grain size in Buckskin Gulch, this explains the higher permeability values obtained from Buckskin Gulch (1–35 d from unpublished data collected by the senior author in 2009, or 3.3–7.5 d according to Solum et al., 2010) than from the Big Hole site (0.66–1.1 d according to Solum et al., 2010). Hence, the higher porosity and permeability of the Navajo Sandstone may have caused or contributed to a more widespread deformation banding in Buckskin Gulch than in the Big Hole site.

In this context, note that the high porosity, poor lithification, and high population of reverse deformation bands and compaction bands of the Buckskin Gulch site are anomalous also within the East Kaibab monocline area. The compaction bands and shear-enhanced compaction bands that dominate the deformation-band population reported by Solum et al. (2010) seem to disappear as one moves north and south along the monocline. This anomaly may have a local geometric reason because the monoclinal structure makes a bend in this area. Recent numerical modeling by Schultz (2011) supports this view. With this information in mind, the scanline data from the Buckskin Gulch site are perhaps not the most representative choice of locality for the comparative study of Solum et al. (2010).

Solum et al. (2010) uses the lower porosity and permeability values reported from the Valley of Fire to argue that the lithologic and petrophysical differences between Buckskin Gulch and the Big Hole are not important in this context. This argument introduces another uncertainty: How much postdeformational compaction and cementation affected the Aztec Sandstone at the Valley of Fire? Sternlof et al. (2005) argue that very little cementation had occurred at the time of deformation. The average cement present in undeformed sandstone is now 3% quartz and 3% clay minerals, with increasing induration toward its base (Eichhubl et al., 2010). Furthermore, our own probe permeameter measurements from the Valley of Fire shows typical current permeability values of 1 to 10 d where compaction bands occur (porosity and permeability correlate reasonably well in the Navajo and Aztec Sandstones). Hence, postdeformational cementation may explain why porosity and permeability appear to be lower for the Aztec Sandstone in the Valley of Fire than for the Navajo Sandstone at Buckskin Gulch.

IMPLICATIONS FOR FLUID FLOW AND RESERVOIR PERFORMANCE

In cases where a significant population and distribution of deformation bands exist, their reservoir-scale influence on fluid flow, which by nature is a three-dimensional (3-D) problem, becomes an issue. Solum et al. (2010) present calculations of effective reservoir permeability and discuss the function of shear and compaction bands with respect to fluid flow. The authors base their considerations of effective permeability on a single scanline from each locality, which essentially assumes one-dimensional (1-D) flow along a random line through a reservoir. This way of considering how deformation bands affect fluid flow allows for simple calculations but is of limited value because of the variations and complexities associated with 3-D fluid flow in naturally deformed sandstone reservoirs, as discussed below.

Variations in Thickness, Microstructure, and Petrophysical Properties along Bands

Thickness variations along fault zones are widely known (e.g., Wibberley et al., 2008; Childs et al., 2009), and the concept applies to deformation bands also. This is discussed in a recent article (Fossen and Bale, 2007), which shows examples of significant thickness variations along deformation band cluster zones and individual deformation bands alike. Changes in thickness are locally more than one order of magnitude over a few centimeters of lateral or vertical distance, and such variations are also observed in the areas discussed by Solum et al. (2010) as shown in Figure 4. Furthermore, Torabi and Fossen (2009) identified variations in porosity by as much as 18% and permeability up to two orders of magnitude along individual deformation bands. Similar examples are found in sandstones in the Bassin du Sud-Est in Provence (France), where our own unpublished data show an abrupt thickness variability up to two orders of magnitude along deformation-band clusters with reverse-sense slip. The reason for these variations is not fully understood but may relate to the strain-hardening and strain-softening history of the band-internal material (microbreccia) and the formation of grain or stress bridges during shearing.

Clearly, thickness and permeability minimums along bands are leaky points that reduce the ability of the bands to impede fluid flow. The leaky points control or strongly influence the effective permeability in a reservoir, and random scanlines are therefore less helpful unless such variations are understood and considered. It is possible to model

Figure 4. Photograph of reverse-sense deformation band showing abrupt thickness variations, Buckskin Gulch, Utah.

such leaky points by means of stochastic distributions, as explored to some extent by Kolyukhin et al. (2009).

Three-Dimensional Geometry and Connectivity

The 3-D architecture of deformation-band populations is essential because it introduces a macroanisotropy to the reservoir that greatly affects the way reservoir fluids behave (e.g., Sternlof et al., 2004). Most populations seem to show conjugate sets, including those from the Big Hole site (Shipton and Cowie, 2001). As previously pointed out (e.g., Fossen and Bale, 2007), the permeability will be significantly higher parallel with the line of intersection of conjugate sets than perpendicular to this orientation. In the case of a faulted porous sandstone reservoir, this would mean that fault-parallel flow would be unaffected by deformation bands, whereas fault-perpendicular flow would be impeded. It would be interesting to know if the arrangement of deformation bands tends to be different for the extensional and contractional regimes.

Effects in a Producing Reservoir

The tendency for deformation bands to favor the most porous (and commonly the most permeable) stratigraphic units is independent of tectonic regime. To some extent, the deformation bands would then reduce the effective permeability in the most permeable layers more than they would in the less permeable reservoir units simply because bands in higher permeable layers are more numerous and involve more cataclasis and, therefore, more significantly reduce permeability. In such a setting, which is typical for eolian deposits where dune unit layers are interbedded with interdune layers of lower grain size and porosity, the presence of distributed deformation bands could improve sweep efficiency.

Interestingly, flow simulation studies have shown that deformation bands with up to three orders of magnitude permeability reduction (relative to host rock) may promote tortuous flow of injection fluids, thereby increasing sweep efficiency and total recovery (Rotevatn et al., 2009; Rotevatn and Fossen, 2011). Calculating the effective permeability based on a single scanline may be a useful first-pass exercise in the field, but it is unlikely to be a reliable indicator of the actual reservoir properties. Specifically, the aforementioned factors suggest that such 1-D models severely overestimate the effect of deformation bands in a producing reservoir. This is probably an important reason why deformation bands rarely, if ever, have been proven to negatively affect hydrocarbon production in producing oil and gas fields unless the oil is uncommonly heavy, as in the tar-filled Arroyo Grande field mentioned by Solum et al. (2010). For example, no convincing evidence exists that indicates that deformation bands in the North Sea Gullfaks Sør field "baffle flow and enhance fault seal" (Solum et al., 2010). Instead, unpublished data (Statoil, personal communication, 2009) suggest that flow complications in this field, where seismic data resolution is poor, are more likely the result of subseismic fault offsets, with or without a fault smear effect.

CONCLUDING REMARKS

We agree with Solum et al. (2010) that tectonic regime probably has an influence on deformation-band formation and distribution in porous sandstone. Compaction bands, for instance, are only reported from contractionally deformed sandstones (Mollema and Antonellini, 1996; Saillet, 2009; Eichhubl et al., 2010). However, lithology, petrophysical parameters, and tectonic style or boundary conditions can be even more important than tectonic regime. We believe that this may be the case in the comparative study done by Solum et al. (2010). We stress that (1) the kinematic boundary conditions for the two sites are fundamentally different (the Buckskin Gulch site is located in the lower part of a fault-propagation fold, whereas the Big Hole site is not related to folding at that scale); (2) the significantly higher grain size, porosity, and permeability at Buckskin Gulch may have caused or contributed to the more extensive formation and distribution of deformation bands at this locality; (3) two single transects from these two sites are not by far the amount of data required for this type of analysis; and (4) observations along the East Kaibab monocline indicate that the Sheet Gulch site is an anomaly. Furthermore, the influence of deformation bands and deformation-band cluster zones on fluid flow is poorly represented and generally overemphasized by 1-D calculations alone because of their variability in thickness and petrophysical properties and the importance of 3-D architecture.

It would be an interesting exercise to map and compare such architectures and variations in the two tectonic regimes so that differences and similarities could be deciphered and applied predictively during reservoir management. Solum et al. (2010) are thanked for putting focus on this aspect of porous sandstone deformation.

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