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Deformation bands in chalk, examples from the Shetland Group of the Oseberg Field, North Sea, Norway

Ole Petter Wennberg [a,*], Giulio Casini [a], Ali Jahanpanah [a], Fabio Lapponi [a], Jon Ineson [b], Brita Graham Wall [c], Paul Gillespie [d]

[a] *Statoil ASA, PB 7200, 5020 Bergen, Norway*
[b] *Geological Survey of Denmark and Greenland (GEUS), Øster Voldgate 10, DK-1350 Copenhagen K, Denmark*
[c] *Statoil ASA, Martin Linges Vei 33, 1364 Fornebu, Oslo, Norway*
[d] *Statoil ASA, PB 8500, 4035 Stavanger, Norway*

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ABSTRACT

Deformation bands are described in detail for the first time in carbonate rock from the subsurface and in chalk from the North Sea. The samples are from 2200 to 2300 m below sea level, in upper Maastrichtian to Danian chalk in the Oseberg Field. The deformation bands were investigated using thin-section analysis, SEM and computed tomography (CT). There is a reduction in porosity from 30 to 40% in the matrix to ca. 10% or less inside the deformation bands. They have apparent thicknesses ranging from less than 0.05–0.5 mm and have previously often been referred to as hairline fractures. Their narrowness is probably the reason why these features have not previously been recognised as deformation bands. The deformation bands in chalk are very thin compared to deformation bands in sandstone and carbonate grainstones which have mm to cm widths. This is suggested to be due to the fine grain size of the chalk matrix (2–10 μm), and it appears to be a positive correlation between grain-size and width of deformation bands. The deformation bands are suggested to have been formed as compactional shear bands during mechanical compaction, and also related to faulting.

1. Introduction

Deformation bands were first described in porous sandstones (Aydin, 1978). Since then a large number of papers have described deformation bands in sandstone and discussed the mechanisms responsible for their formation. Deformation bands are a group of structures resulting from failure in porous granular rock in a narrow zone of localised strain (Aydin, 1978; Aydin and Johnson, 1978, 1983), and are among the most common structures in porous sandstones (Fossen et al., 2007). The offset of deformation bands in sandstones is normally not more than a few cm and their widths are typically of mm to a few cm scale (Aydin, 1978; Fossen et al., 2011). Deformation bands are commonly associated with a reduction in reservoir quality relative to the host rock, which is principally caused by pore collapse and cementation (Ogilvie and Glover, 2001; Fossen et al., 2007).

Based on the observations from sandstones, deformation bands in granular rocks have been divided into the following main types (see Fossen et al., 2007 and references therein): 1) ***Disaggregation bands*** develop in poorly consolidated sandstones as a result of grain rotation and sliding without breaking the individual grains. 2) ***Cataclastic deformation bands*** are developed when the mechanical breaking of grains is a significant deformation mechanism (Aydin, 1978). 3) ***Phyllosilicate bands*** or ***framework phyllosilicate bands*** (Knipe et al., 1997) form in sandstone when the content of clay minerals exceeds 10–15% and represent a particular type of disaggregation band where the platy phyllosilicate minerals promote frictional grain boundary sliding rather than cataclasis.

In terms of failure mechanism, deformation bands have been divided into three main end members (Borja and Aydin, 2004; Fossen et al., 2007): 1) ***Shear bands*** are characterized by displacement parallel to the band, and typically the slip across single shear bands is a few mm to a few cm. 2) ***Compaction bands*** are characterized by a volume decrease with no shear offset (Mollema and Antonellini, 1996). Pure compaction bands are rare in nature and reported hereunto only in Jurassic eolian sandstones of south-western USA, with porosity >26% and grain size >0.4 mm (Fossen et al., 2011). 3) ***Dilation bands*** are characterized by volume and porosity increase with no shear offset, although pure dilation bands have been documented in only one case (Du Bernard et al.,

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[*] Corresponding author.
E-mail address: oberg@statoil.com (O.P. Wennberg).

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2002). Hybrids between the shear deformation bands and the two others are common, and the most frequent type is ***compactional shear bands*** (Fossen et al., 2007).

Deformation bands do not exclusively occur in sandstones, and can develop in any porous granular rock. In carbonates, deformation bands were first documented in porous Cretaceous grainstones in the Maiella Mountains, central Italy (Marchegiani et al., 2006; Tondi et al., 2006). Since then, only relatively few other papers have described deformation bands in carbonate rocks at outcrop, of which the majority are from grainstone (Tondi et al., 2006; Tondi, 2007; Rath et al., 2011; Rustichelli et al., 2012). The highly reactive nature of carbonate rocks favours dissolution and cementation processes associated with development of deformation bands in such rocks (Cilona et al., 2012). Increasing degree of cementation of the host rock results in a transition from disaggregation bands, where grain rotation and compaction are the dominant mechanisms of deformation, to cataclastic deformation bands (Rath et al., 2011).

The chalk is a very fine grained sediment with micron sized particles. It is a highly porous carbonate rock that mostly consists of coccoliths (Surlyk et al., 2003). From a mechanical point of view it may be regarded as a granular material (Risnes et al., 2005). Because of its porous and granular character, chalk may deform through similar mechanisms as sandstone and grainstone and can develop deformation bands as demonstrated by experimental tests (Risnes, 2001). Natural deformation bands have also recently been observed in chalk and have been mentioned by Gaviglio et al. (2009) and by Gillespie and Graham Wall (2009). Natural deformation bands in chalk have not hitherto been described or analysed in detail in the literature.

The rock mechanics of granular material is an area of active research (e.g. Wong et al., 1997; Bésuelle, 2001; Aydin et al., 2006), although most of the work has concentrated on sandstone. Under hydrostatic loading, there is distributed compaction and so we would not expect the formation of deformation bands. However, under non-hydrostatic stress, at high confining pressure, the failure mechanism is “shear-enhanced compaction”. This kind of failure is represented by the end cap in principal stress space, and may represent the typical stress state for the formation of shear bands.

Chalk has a failure surface with brittle shear failure at low confining pressures and an end cap at high stresses (Loe et al., 1992; Goulty, 2003). The end cap is associated with pore collapse, which can significantly reduce the pore space. However, there is a lack of microstructural observations tied to rock mechanical experiments, making it difficult to determine the exact stress paths under which shear bands may form in chalk.

Experimental results in sandstone indicate that a quantitative measure of the brittleness is given by the grain crushing pressure, i.e. the hydrostatic load at which grain crushing is the main deformation mechanism (Wong et al., 1997); the grain crushing pressure controls the scaling of the failure surface. The grain crushing pressure, P^*, increases with decreasing porosity and grain size (Zhang et al., 1990; Cuss et al., 2003), specifically

$$P^* \propto (\phi R)^{-3/2}$$

where ϕ is the porosity and R is the grain radius. Hence, the very fine grain size of chalk means that grain crushing is unlikely to be a significant deformation mechanism. Grain–grain disaggregation, pore collapse and shear/rotation are likely to be the main micro mechanisms, together with pressure solution.

In general, chalk rocks behave mechanically as frictional materials failing in a shear failure mode (Risnes, 2001). However, deformation of chalk is also typically associated with pore collapse which is caused by the initial very open pore structure (Risnes, 2001). The critical pressure for pore collapse is very low in chalk; <20 MPa, compared to other limestones, which range in values from 25 to 450 MPa (Wong and Baud, 2012). Shear failure between the grains seems to be the basic failure mechanism in deformation experiments of chalk samples, and shear bands are formed in addition to distributed pore collapse (Risnes, 2001). A special feature of chalk is that the strength depends strongly on the type of fluid in the pores and water-saturated chalk is mechanically weaker than dry or oil-saturated chalk (Risnes et al., 2005). This phenomenon is referred to as the water-weakening effect of chalk.

In this study natural deformation bands have been observed and described from the Late Cretaceous to earliest Paleogene chalk deposits of the Shetland Group in the Oseberg Field in the Norwegian part of the North Sea. The purpose of this paper is to provide a detailed description of the characteristics of deformation bands in chalk and to discuss their mechanism of formation.

2. Geological setting

2.1. North Sea Chalk deposits

The chalk of the North Sea was deposited from Cenomanian to Danian (Late Cretaceous to earliest Paleogene) and covers much of the southern part of the North Sea and onshore NW Europe including UK, France and Germany (Surlyk et al., 2003). The first oil discovery in the North Sea was in 1966 in chalk in the Kraka Field in the Danish Sector. Many major discoveries were subsequently made in the very fine grained chalk deposits of the Norwegian, Danish and UK sectors (e.g. Gautier and Klett, 2005). The largest of the North Sea Chalk fields is the Ekofisk Field, which was discovered in 1969 and has produced more than 430 million Sm^3 (2700 million barrels) oil since it started production in 1971 (www.npd.no). The porosity of the chalk reservoirs in the North Sea is high to very high with values typically in the range of 20–40% (Klinkby et al., 2005) and locally exceeding 50% in the Valhall Field (Barkved et al., 2003). The matrix permeability, however, is low and in general less than 10 mD (Surlyk et al., 2003) and production usually relies on the presence of open natural fractures (Fritsen and Corrigan, 1990; Dangerfield et al., 1992; Narr et al., 2006).

2.2. Fractures in North Sea Chalk

Fracture studies in the North Sea Chalk oil fields have focused on open fractures because of their major impact on oil production (e.g. Watts, 1983; Foster and Rattey, 1993; Agarwal et al., 2000). In particular, open fractures enhance production on the crest of the structures, where well test permeability is more than 10 times higher than the matrix permeability (e.g. Barkved et al., 2003). The impact of open fractures on oil production is variable, and oil fields with high structural relief caused by salt diapirs or structural inversion tend to be more influenced by open fractures than structures in a more passive tectonic setting (Klinkby et al., 2005).

Four main types of fractures have been described in North Sea Chalk (Toublanc et al., 2005):

- ***Tectonic fractures*** are well defined sets of planar, partly open fractures of dm to m length and sometimes developed as shear fractures with striations. These fractures are formed as a response to regional or local halokinetic stress. Tectonic fractures are considered responsible for the main reservoir permeability and to be most important for fluid flow in many North Sea Chalk fields, e.g. the Ekofisk Field (Agarwal et al., 1997; Surlyk et al., 2003; Toublanc et al., 2005)
- ***Stylolite-associated fractures*** are sub-vertical extension fractures with height up to 15 cm terminating at a stylolite on one