Journal of Structural Geology 45 (2012) 38–51

Contents lists available at SciVerse ScienceDirect

Journal of Structural Geology

journal homepage: www.elsevier.com/locate/jsg

Fracture systems in normal fault zones crosscutting sedimentary rocks, Northwest German Basin

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ARTICLE INFO

Article history:
Received 30 September 2011
Received in revised form
11 June 2012
Accepted 12 June 2012
Available online 21 June 2012

Keywords:
Normal fault zone
Fracture systems
Fractured fluid reservoir
Sedimentary rocks
Outcrop analogue
Northwest German Basin

ABSTRACT

Field studies of fracture systems associated with 58 normal fault zones crosscutting sedimentary rocks were performed in the Northwest German Basin. Fracture orientations, densities, apertures and lengths, as well as fault zone structural indices, were analysed separately for fault damage zones and host rocks. The results show a pronounced difference between carbonate and clastic rocks: mainly in carbonate rocks we found presence of clear damage zones, characterized by higher fracture densities than in the host rocks. While the maximum aperture is similar for both units, the percentage of fractures with large apertures is much higher in the damage zones than in the host rocks.

Based on laboratory measurements of Young's moduli and field measurements of fracture densities, we calculate effective stiffnesses E_e, that is the Young's moduli of the *in situ* rock masses, within the normal fault zones. Compared with carbonate rocks, E_e computed for clastic-rock damage zones decreases significantly less due to lower fracture densities. We conclude that normal fault zones in carbonate rocks have more profound effects on enhancing permeability in fluid reservoirs than those in clastic rocks. The results are of great importance for modelling the hydromechanical behaviour of normal fault zones in subsurface fluid reservoirs.

1. Introduction

Normal fault zones are of great interest in terms of crustal fluid flow because they may be zones of increased permeability (e.g., Caine et al., 1996; Caine and Forster, 1999; Faybishenko et al., 2000; Sibson, 2000; Gudmundsson, 2001, 2011; Agosta et al., 2007; Meneghini et al., 2007; Faulkner et al., 2010) and therefore might have a high geothermal potential (Arnorsson, 1995a,b; Paschen et al., 2003; Philipp, 2007; Brogi, 2008). In the Northwest German Basin (NWGB) normal fault zones are of interest as possible geothermal reservoirs (Kehrer et al., 2007; Musmann et al., 2011; Schaumann et al., 2011; http://www.gebo-nds.de). To obtain high flow rates, as well as to minimise the risk in terms of borehole stability while drilling in the NWGB, it is important to assess in detail the fracture distribution within normal fault zones crosscutting sedimentary rocks. With the aim of gaining new insights on fracture orientation, density, aperture and length of NWGB-normal fault zones, we perform structural analysis of selected outcrop analogues. The studied outcrops expose rocks of comparable stratigraphy, lithology and facies to those found at depth.

The simplest description of a normal fault zone structure – and of fault zones in general – considers two major mechanical units, namely a fault core and a damage zone (cf., Caine et al., 1996; Faulkner et al., 2010). The fault core is a narrow zone, formed through repeated slip on the principal fault plane (Faulkner et al., 2010). Commonly it is brecciated, has a very low stiffness and rather deforms in a plastic manner (Lindsay et al., 1993; Gudmundsson, 2011), whereas cemented fault rocks may have high stiffnesses (Agosta et al., 2007). The damage zone surrounds the fault core and is a wider zone mechanically affected by slip. It is characterised by a high fracture density with still discernible former host rock fabric (e.g., Caine et al., 1996). This two-mechanical-units structure may be difficult to apply to all rock lithologies because different deformation mechanisms may be of importance in different rocks. For example, in porous rocks deformation bands may form (e.g., Aydin, 1978; Antonellini et al., 1994; Johansen et al., 2005), whereas in carbonate rocks there may be stylolites due to dissolution processes (Tondi et al., 2006). In this study, however, the simple damage-zone/fault-core model for normal fault description is convenient since the focus is on the fluid transport potential of normal fault zones, mainly through open fractures.

Depending on the relative displacement across the fracture plane, open fractures are either extension fractures or shear

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0191-8141/$ – see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.jsg.2012.06.002

fractures. For extension fractures, the relative displacement is perpendicular to the fracture plane, whereas for shear fractures the relative displacement is parallel to it (Hudson and Harrison, 1997; Jaeger et al., 2007; Twiss and Moores, 2007; Gudmundsson, 2011). However, in the field it is often difficult to distinguish clearly between the different fracture types. In the following text, we therefore use the general term 'fracture' if the distinction was impossible. Damage zone fractures have various sizes ranging from micrometre-scale to centimetre- to metre-scale. Fractures are typically either parallel or perpendicular to the main fault plane (Stewart and Hancock, 1991; Caine et al., 1996; Agosta and Kirschner, 2003; Agosta and Aydin, 2006; Gudmundsson, 2011). In the fault damage zone, the fracture density (as the number of fractures per unit length) commonly increases towards the fault core (e.g., Simmenes and Gudmundsson, 2002; Agosta and Kirschner, 2003; De Joussineau and Aydin, 2007; Gudmundsson et al., 2010; Gudmundsson, 2011).

To obtain high flow rates in a fluid reservoir, one very important fracture parameter is the fracture aperture. Based on the 'cubic law' (Eq. (1); De Marsily, 1986), a simplified model for flow rate Q [m^3/s] calculation where fracture roughness is not taken into account, the cube of the aperture value b [m] is considered:

$$Q = Cb^3 i \tag{1}$$

where C is a constant including the fracture width [m], the fluid density [kg/m^3], the dynamic viscosity [Pa s] and the acceleration due to gravity [m/s^2], i [−] is the hydraulic gradient. The aperture cumulative frequency commonly follows a power law (Guerriero et al., 2011). That is, most fractures have very small apertures and wider fracture apertures are rare. From Eq. (1), however, it follows that the apertures and lengths of microfractures are too small to have great effects on the resulting fluid flow through normal fault zones. This is the reason why we only analyse fractures with an aperture visible with the naked eye and a length of several centimetres.

A well-connected fracture network is also of great importance to get high permeabilities and flow rates. For analyses of connectivity we distinguish between 'stratabound' fractures, that is, fractures that are restricted to individual beds, and 'non-stratabound' fractures which propagate through several beds generating fluid flow paths (Odling et al., 1999). In layered rocks such as those of the sedimentary succession in the NWGB, fracture propagation is commonly affected by the mechanical layering (Fig. 1) due to stiffness contrasts among adjacent sedimentary beds with different lithologies (Helgeson and Aydin, 1991; Hutchinson and Suo, 1992; Brenner, 2003; Gross and Eyal, 2007). Thus mechanical layering needs to be understood to predict fracture patterns in the subsurface. It is well known (e.g., Brown, 1981; Chang et al., 2006; Hoek, 2007) that well cemented sandstones and limestones have considerably higher values of strengths and stiffness than shales and marls. In the field, we use this relationship to distinguish soft (low Young's modulus) and stiff (higher Young's modulus) sedimentary beds based on lithology.

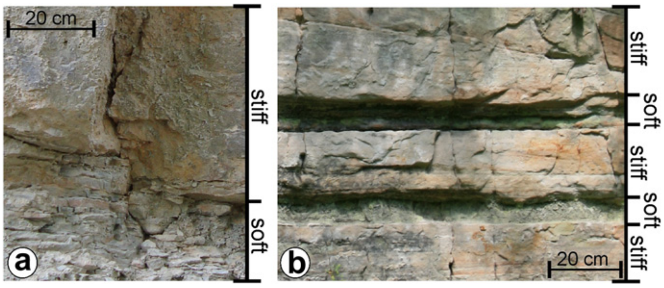

Fig. 1. Mechanical layering in sedimentary alternations due to different lithologies. a) Alternation of stiff massy limestones (top) and soft laminated marls (bottom) affecting fracture propagation (Lower Muschelkalk); b) Alternation of stiff sandstones and soft shales (back weathered beds) of Middle Bunter. Fractures mostly are restricted to individual sandstone beds.

This paper has two main aims. First, we present the results of structural geological field studies carried out in 58 normal fault zones in sedimentary rocks. Results are shown separately for carbonate- and clastic rocks. We consider the normal fault zone orientations in the context of local geological settings, and focus on damage zone widths, hanging wall and footwall widths as well as overall fault zone displacements. Differences between host rocks and damage zones in terms of fracture orientations, propagation, path, length and aperture are described in detail. In addition, we present the results of mechanical-property measurements of the intact rocks (host rocks) from outcrop samples. The second aim is to use the fracture data and mechanical rock properties to assess analytically the Young's moduli distribution in normal fault zones crosscutting the sedimentary rocks of NWGB. The results of this work will provide input parameters for future numerical models of the hydromechanical behaviour of normal fault zones. Due to normal fault's self-similarity (cf., King, 1983; Turcotte, 1989; Torabi and Berg, 2011), it should be possible to apply presented results to hydromechanical models of larger normal fault zones in fluid reservoirs.

2. Geologic setting

The NWGB (Fig. 2a), located in Northwest Germany and the southern North Sea, is part of the North German Basin (NGB) which belongs to the intracontinental Central European Basin (Walter, 2007). The NGB was initiated in the Late Carboniferous to Permian due to rifting processes with associated volcanism subsequent to the Variscan Orogenesis (Betz et al., 1987; Ziegler, 1990). Due to thermally induced subsidence, Rotliegend volcanism started, followed by the sedimentation of Rotliegend clastics and the deposition of several kilometres of sediments from the Upper Rotliegend to the Quaternary (e.g., Baldschuhn et al., 1996).

The Rotliegend is composed of continental redbeds (Schröder et al., 1995; Glennie, 1998) that are discordantly separated from the Zechstein evaporates. Red-coloured clastic rocks, typical for the Lower Triassic (Lower and Middle Bunter), are covered with shales and evaporites (Upper Bunter; Menning and Hendrich, 2005). In the Middle Triassic carbonate sediments were deposited (Lower and Upper Muschelkalk) alternating with evaporites (Middle Muschelkalk; Röhl, 1990). The Upper Triassic (Keuper) was characterised by terrestrial sediments (Betz et al., 1987). In the Lower Jurassic (Liassic), because of a worldwide sea level rise marine shales were deposited (Wehner et al., 1989). In the Middle Jurassic (Dogger), more sandstone layers intercalated the marine shales due to decreasing water depths (Menning and Hendrich, 2005). In the early Upper Jurassic, the NWGB began to subside and a marine carbonate succession was deposited (Kockel, 2002). During the Early Cretaceous, shallow marine carbonates and minor continental sediments (Wealden) formed. Subsequently, a change of the depositional environment towards open marine conditions occurred so that the resulting sedimentary succession consists, up to the end of the Cretaceous, of marls (Mutterlose and Bornemann, 2000).

The Permian thermal subsidence was replaced by an east–west extension during the Triassic. In the Jurassic, north–south (N–S) orientated grabens, such as the Leinetal-Graben, formed and, as a consequence, movements of Zechstein salt started (Ziegler, 1990). In the Upper Jurassic to Lower Cretaceous the tectonic regime changed to N–S compression causing uplift and reactivation of