Journal of Structural Geology 45 (2012) 4–20

Contents lists available at SciVerse ScienceDirect

Journal of Structural Geology

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

Inner structure and deformation mechanisms of normal faults in conglomerates and carbonate grainstones (Granada Basin, Betic Cordillera, Spain): Inferences on fault permeability

Fabrizio Agosta[a,*], Patricia Ruano[b,c], Andrea Rustichelli[d], Emanuele Tondi[d], Jesús Galindo-Zaldívar[b,c], Carlos Sanz de Galdeano[c]

[a] Department of Geological Sciences, University of Basilicata, Via dell'Ateneo Lucano 10, 85100 Potenza, Italy
[b] Instituto Andaluz de Ciencias de la Tierra (IACT), Spain
[c] CSIC-University of Granada, Instituto Andaluz de Ciencias de la Tierra (IACT), Spain
[d] School of Science and Technology, Geology Division, University of Camerino, Italy

ARTICLE INFO

Article history:
Received 8 October 2011
Received in revised form
5 April 2012
Accepted 10 April 2012
Available online 21 April 2012

Keywords:
Normal faulting
Damage zones
Fault permeability
Granada Basin
Betic Cordillera
Spain

ABSTRACT

In the southeastern area of the Neogene-Quaternary Granada Basin, ~E–W trending normal faults crosscut ~80 m-thick clay-bearing conglomerates and ~30–40 m-thick carbonate grainstones containing centimeter-thick microconglomerate and sand interbeds. Three fundamental failure modes took place during fault nucleation: (1) phyllosilicate shear banding in the conglomerates, (2) jointing, mainly in the carbonate grainstones and (3) pressure solution in the carbonate matrix and grains of the microconglomerate and sand interbeds. Within the conglomerates, normal faults developed by pronounced clay smearing and, ultimately, cataclasis. Jointing also occurred within some of the pebbles surrounding the cataclastic rocks. In contrast, in the carbonate grainstones fault growth was characterized by predominant jointing and rock fragmentation, which localized in the extensional quadrants and/or releasing jogs of the evolving slip surfaces. Brecciation and cataclasis occurred only around the well-developed slip surfaces. Based upon their inner structure, we qualitatively assign a combined barrier-conduit fluid behavior to the tens of meters-throw normal faults juxtaposing the conglomerates against the carbonate grainstones. The inner fault cores inhibit fault-orthogonal fluid flow along their entire length. Instead, fault damage zones act as fluid barriers in the conglomerates, and as composite fluid conduits in the carbonate grainstones.

1. Introduction

Brittle faulting generally takes place in the uppermost few kilometers of the Earth's crust, at low confining pressures. In low-porosity rocks, fault nucleation and propagation occurs by linking of microfractures and formation/reactivation of mesoscopic joints (Segall and Pollard, 1983; Pollard and Fletcher, 2005; Martel and Langley, 2006). Within carbonate rocks faulting at shallow crustal depths may also involve localized dissolution (Marshak et al., 1982; Petit and Mattauer, 1995; Willemse et al., 1997; Kelly et al., 1998; Graham et al., 2003; Kim et al., 2003; Agosta and Aydin, 2006; Antonellini et al., 2008; Agosta et al., 2009; Aydin et al., 2010; Benedicto and Schultz, 2010). This process, which causes a volume reduction due to material removal and transport by fluids, forms stylolites, sub-tabular contractional features characterized by a tooth-like shape and presence of undissolved material (Arthaud and Mattauer, 1970; Alvarez et al., 1978; Fletcher and Pollard, 1981; Groshong, 1988). In high-porosity rocks, strain localization may take place by deformation banding, a process involving pore collapse, grain rolling and/or sliding, breakage of cements and, typically in porous carbonates, dissolution at grain-to-grain contacts (Aydin, 1978; Aydin and Johnson, 1978, 1983; Rawling and Goodwin, 2003; Aydin et al., 2006; Tondi et al., 2006; Fossen et al., 2007; Tondi, 2007). When the amount of clay is greater than 10–15% of the bulk rock, deformation bands rich in platy minerals may form (phyllosilicate bands, Knipe et al., 1997). Individual deformation bands are generally characterized by small amounts of displacement and thicknesses on the order of a few centimeters. Larger displacements are accommodated by tens of cm-thick zones of multiple deformation bands and, eventually,

* Corresponding author. Tel.: +39 3349104541.
E-mail address: fabrizio.agosta@unibas.it (F. Agosta).

0191-8141/$ – see front matter © 2012 Elsevier Ltd. All rights reserved.
doi:10.1016/j.jsg.2012.04.003

discrete slip surfaces (Antonellini et al., 1994; Mair et al., 2000; Shipton and Cowie, 2001; Tondi et al., 2012).

Well-developed faults are generally envisioned as discrete rock volumes made up of highly deformed fault rocks (fault cores), along which most of the displacement is accommodated, sandwiched between less deformed damage zones (Sibson, 1977; Chester and Logan, 1986; Cello et al., 2001). The fault cores are the site of grain/clast comminution, dissolution/precipitation, mineral reactions, and other mechanical and chemical processes that destroy the original host rock fabric. The damage zones are commonly characterized by numerous fractures and small faults that do not completely obliterate the host rock fabric. A good understanding of the faulting processes is key to building predictive models of fault permeability in fractured reservoirs (e.g., Caine et al., 1996; Aydin, 2000). Generally, high values of secondary porosity are associated with fault damage zones in low-porosity rocks, whereas fault cores made up of cataclastic rocks are considered barriers to fault-orthogonal fluid flow (Ghisetti et al., 2001; Rawling et al., 2001; Agosta and Kirschner, 2003; Agosta et al., 2007, 2008; Kim and Sanderson, 2010; Molli et al., 2010). Conversely, in high-porosity rocks, fault damage zones are also considered as seals to cross-fault fluid flow due to porosity reduction by deformation banding (Matthai et al., 1998; Walsh et al., 1998; Manzocchi et al., 2002).

The general applicability of the aforementioned fault permeability structure is complicated in fault zones that crosscut mechanically layered sequences of beds. When a multi-layer rock is subject to strain, faults first form in the more brittle beds. Further strain allows faults to develop across the whole sequence, exerting a complex control on subsurface fluid flow (Peacock and Sanderson, 1991; Childs et al., 1996; Walsh et al., 1998, 2003; Ferrill and Morris, 2003; Schöpfer et al., 2006, 2007; Wilson, 2010; Roche et al., 2012). When clay is present in the multi-layer, it can be smeared into propagating slip surfaces, producing a continuous layer of clay capable of forming a membrane seal for cross-fault fluid flow (Knipe, 1992; Knipe et al., 1997; Fisher and Knipe, 1998; Van der Zee and Urai, 2005).

In this work, we take advantage of excellent road cut exposures (Tablate area, Granada Basin, Betic Cordillera, Spain) of normal faults crosscutting clay-rich conglomerates and carbonate grainstones to document the inner structures and deformation mechanisms developed in the two different lithologies. These normal faults were previously analyzed in terms of their geometry, orientation and kinematics (Sanz de Galdeano, 2008, and references therein). Moreover, a study of fault linkage processes was conducted along some of the normal faults cropping out in the Tablate area by Soliva and Benedicto (2004). In the present article, by integrating results of detailed structural analysis of selected outcrops with laboratory investigations of representative samples, we focus on processes of fault nucleation and growth in rocks characterized by different composition, texture, grain size and porosity. The results of this work are then discussed in terms of fault permeability to infer, qualitatively, the control exerted on fluid flow by normal faults that juxtapose conglomerates against carbonate grainstones. In particular, we focus on the variability of subsurface fluid flow induced by the fault damage zones that developed in the two different lithologies.

2. Methodology

Geological and fault maps (1:10,000 scale) of the Tablate area (Granada Basin, Betic Cordillera, Spain) were constructed by integration of field mapping and interpretation of topographic and ortho-rectified aerial photographs. Detailed documentation of the failure modes, distribution, crosscutting and abutting relationships of background fractures and fault-related deformation present

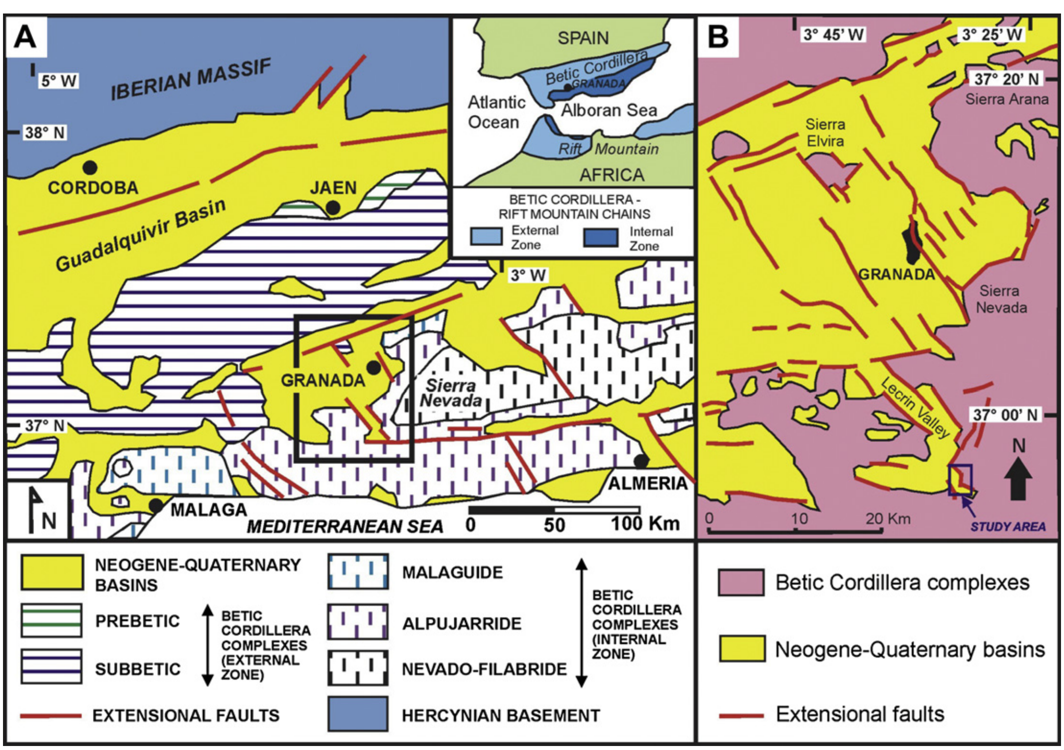

Fig. 1. Geological setting. (A) Geological framework of the Betic Cordillera and overlying Neogene-Quaternary basins. The black box highlights the area of Fig. 1B (modified by Sanz de Galdeano et al., 2003). The location of internal and external zones of the Betic Cordillera is reported in the inset (modified by Rodríguez-Fernández and Sanz de Galdeano, 2006). (B) Structural map of the Granada Basin showing both orientations and distribution of the main extensional faults. The blue rectangle indicates the location of the study area. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)