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Deformation bands in porous carbonate grainstones: Field and laboratory observations

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ABSTRACT

Recent field-based studies documented deformation bands in porous carbonates; these structures accommodate volumetric and/or shear strain by means of pore collapse, grain rotation and/or sliding. Microstructural observations of natural deformation bands in carbonates showed that, at advanced stages of deformation, pressure solution helps to reduce the grain size, enhancing comminuted flow and forming narrow cataclastic zones within the bands. In contrast, laboratory studies on the mechanics of deformation bands in limestones identified grain crushing, pore collapse and mechanical twinning as the micromechanisms leading to strain localization.

Here, we present a multidisciplinary field and laboratory study performed on a Cretaceous carbonate grainstone to investigate the microprocesses associated to deformation banding in this rock. A quantitative microstructural analysis, carried out on natural deformation bands aimed at defining the spatial distribution of pressure solutions, was accompanied by a force chain orientation study. Two sets of triaxial experiments were performed under wet conditions on selected host rock samples. The deformed samples often displayed a shear-enhanced compaction behavior and strain hardening, associated with various patterns of strain localization.

We constrained the pressure conditions at which natural deformation bands developed by reproducing in laboratory both low and high angle to the major principal stress axis deformation bands. The comparison among natural and laboratory-formed structures, allowed us to gain new insights into the role, and the relative predominance, of different microprocesses (i.e. microcracking, twinning and pressure solution) in nature and laboratory.

1. Introduction

The inelastic deformation of porous rocks is a widely studied problem among the scientific community. The specific failure modes, faulting processes and overall strain rates are all aspects that are currently investigated by both field and laboratory studies with the purpose of better assessing the control exerted by deformation on the petrophysical properties of porous rocks in geotechnical engineering and reservoir management applications (see Fossen et al., 2007; for a full review). In fact, both natural and laboratory-induced modifications of pore volume, shape and, hence, interstitial pressure in the subsurface may cause variations of the effective stress possibly leading to faulting and/or inelastic deformation, as well as alter the original fluid flow paths in the shallow crust (see Faulkner et al., 2010 for a full review). In recent years, Tondi et al. (2006) and Tondi (2007) described a new faulting mechanism characteristic of porous limestones. By means of detailed field and microstructural observations, four main deformation processes representative of increased stages of deformation were identified: (i) compaction and shear strain localization into narrow bands (Aydin, 1978; Antonellini et al., 1994; Antonellini and Aydin, 1994; Shipton and Cowie, 2001; Aydin et al., 2006; Rath et al., 2011), (ii) pressure solution at the grain contacts, with development of discrete pressure solution seams, within the already compacted bands (Rutter, 1983; Groshong, 1988; Liteanu

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and Spiers, 2009; Croizé et al., 2010c; Zhang et al., 2010), (iii) subsequent shearing of the pressure solution seams (e.g. Alvarez et al., 1978; Agosta and Aydin, 2006; Agosta et al., 2009) and (iv) cataclasis localized along the sheared pressure solution seams (e.g. Engelder, 1974).

In the laboratory, the mechanical behavior of carbonate rocks of a wide range of porosities has been documented by many studies (Fruth et al., 1966; Teufel et al., 1991; Renner and Rummel, 1996; Fabre and Gustkiewicz, 1997; Baud et al., 2000, 2009; Vajdova et al., 2004; Risnes et al., 2005; Zhang and Spiers, 2005; Baxevanis et al., 2006; Croizé et al., 2010a, b; Zhu et al., 2010; Dautriat et al., 2011; Vajdova et al., in press). These studies investigated the distinct mechanical responses of carbonates to different stress conditions and various level of plastic strain. By monitoring the evolution of deformation, the aforementioned authors deduced that carbonates with intermediate values of porosity (3–18%) display dilatancy and shear localization in dry conditions and at low confining pressure. Differently shear-enhanced compaction and strain hardening are the prevailing mechanisms at higher confining pressures. After a certain amount of strain hardening (this amount typically increases with confining pressure), a switch from compaction to dilatancy is observed (Baud et al., 2000; Vajdova et al., 2004). The high-porosity carbonates ($\varphi > 30\%$) studied in Baud et al. (2009) show similar behavior to the less porous ones, but no dilatancy occurs at low confining pressures. The results of microstructural analyses performed, on the laboratory deformed samples, by previous authors highlighted microcracking and plastic/cataclastic pore collapse as the main deformation micromechanisms. Moreover, since calcite requires relatively low shear stresses to initiate mechanical twinning and dislocation, these latter mechanisms play also a significant role in particular at high levels of plastic strain (Vajdova et al., 2010, in press). The complex interplay between pore collapse, microcracking and crystal plasticity hence controls the carbonates macroscopic compactive yielding (Vajdova et al., 2004, 2010, in press; Zhu et al., 2010).

While previous studies have shown that natural and laboratory deformation bands have comparable characteristics (i.e. pore and grain sizes reduction), many discrepancies among the mechanisms responsible for their development have been found. The comparison between field and laboratory failure processes remains to date limited by the fact that most experimental studies on carbonates have been performed on dry rocks whereas the natural deformation (i.e. compaction, pressure solution) likely happens in presence of fluids.

In this paper we present the results of a multidisciplinary work, which integrates field and laboratory studies on the porous carbonate grainstones belonging to the Orfento Formation (Vecsei, 1991; Mutti et al., 1996). The goal is to gain a new knowledge on the micromechanics of deformation bands in porous carbonates.

2. Geological setting, lithological description and rocks characterization

The Majella Mountain is an East-vergent, thrust-related anticline located in the external zone of the central Apennines, in central Italy (Fig. 1; Vezzani and Ghisetti, 1998). The stratigraphic succession includes a 2 km-thick sequence of Cretaceous to Miocene carbonate units, which are related to different depositional settings (platform and slope/ramp) originally pertaining to the northernmost sector of the Apulian Platform realm. The Apulian carbonate units are overlain by siliciclastic deposits of Messinian-to-Pleistocene age originally deposited within the Peri-Adriatic foredeep basin of the central Apennines fold-and-thrust belt (Scisciani et al., 2002). According to Ghisetti and Vezzani (2002) and Agosta et al. (2009), the development of the Majella thrust-related anticline occurred during the Middle-to-Late Pliocene. The internal deformation of this box-shaped fold, characterized by two highly-steeping to overturned limbs, mainly consists of high-angle normal, strike-slip and oblique-slip faults, small folds and different sets of fractures (e.g. Marchegiani et al., 2006; Tondi et al., 2006; Antonellini et al., 2008; Agosta et al., 2010; Aydin et al., 2010).

This study focuses on natural and laboratory deformation bands of the Upper Campanian to Maastrichtian Orfento Fm. (Vecsei, 1991). This formation consists of white, high porosity and friable bioclastic grainstones rich of rudist fragments interpreted as a package of proximal bioclastic turbidites (Mutti et al., 1996). The study area corresponds to a small quarry named Madonna della Mazza, which is located in the inner part of the Majella anticline's forelimb nearby the town of Pretoro (Fig. 1; see also Tondi et al., 2006). By means of stratigraphic and sedimentological analyses, of different parameters (e.g. measurement of bed thickness and lateral extension, grain size estimation by comparison charts), we were aimed at better defining the depositional architecture of the studied rocks. Samples collection of the most representative strata (see Fig. 2 and Table 1) was carried out for: thin section observations, porosity measurements (i.e. water saturation method and helium pycnometer) and rock mineralogical composition by means of x-ray diffraction analysis. Sclerometric testing, performed by using a Proceq L/LR-type Schmidt Hammer, allowed us to estimate the mechanical properties, namely the unconfined Uniaxial Compressive Strength (UCS), of the sampled strata (Table 1). Even if the provided results are only an estimation of UCS, on the other hand this instrument is a very expeditious test that can be directly performed in the field by applying the standard measurement procedure (http://www.abbeyspares.co.uk): twenty rebounds are measured in correspondence of each station. The twenty obtained values are subsequently computed by discarding both the five higher most and lowermost readings, and then hence by averaging the 10 remaining values.

Our detailed stratigraphic/sedimentological loggings (Fig. 2) showed that the bulk of the Orfento Fm., exposed at the Madonna della Mazza quarry, is made up of poorly-cemented, whitish bioclastic carbonate grainstones (*sensu* Dunham, 1962; Table 1).

The studied carbonate grainstones are arranged into normal graded, planar beds gently dipping toward NE with dip angle of about 18° showing erosional bases, lateral extensions up to 10 s of meters and thickness of tens of decimeters (Fig. 3; Rustichelli, 2010). Centimeter-thick, strongly cemented layers of whitish calcilutites (mudstones, wackestones and packstones, *sensu* Dunham, 1962) are often present at the top of individual carbonate beds. Intraformational carbonate breccia horizons, up to tens of meter-long and reaching tens of centimeters of thickness, consist of sub-angular-to-sub-rounded rudist fragments (mainly *Radiolitidae*) and intraclasts dispersed into a fine- to very fine sand-grained bioclastic matrix.

According to the facies model proposed by Mutti et al. (1996), the large-scale planar geometry of beds, as well as the erosional bases and normal gradation of individual beds, represent the diagnostic elements that allowed us to interpret these carbonate rocks as a package of proximal bioclastic turbidites (Fig. 4). The lower portion of each individual turbidite bed is broadly constituted by decimeter-thick normally-graded grainstones, which gradually evolve upwards into centimeter-thick calcilutites.

Both bioclastic carbonate grainstones, which range in size from fine sand to silt, and intraformational carbonate breccias are constituted by predominant rudist fragments and intraclasts (Table 1; Fig. 4a and b). Rudist shells can be partially replaced by either micrite or detrital sparry calcite; on the contrary, intraclasts and calcilutites consist of micrite mixed to detrital microsparry