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The effects of rock heterogeneity on compaction localization in porous carbonates

Antonino Cilona [a], [*], Daniel Roy Faulkner [b], Emanuele Tondi [c], Fabrizio Agosta [d], Lucia Mancini [e], Andrea Rustichelli [c], Patrick Baud [f], Sergio Vinciguerra [g]

[a] Department of Geological and Environmental Sciences, Stanford University, Stanford, CA 94305, United States
[b] University of Liverpool, Liverpool, United Kingdom
[c] School of Environmental Sciences, University of Camerino, Camerino, Italy
[d] Department of Science, University of Basilicata, Potenza, Italy
[e] Elettra – Sincrotrone Trieste SCpA, SS 14, Km 163,5 in Area Science Park, 34012 Basovizza (Trieste), Italy
[f] EOST Strasbourg, Strasbourg, France
[g] Department of Geology, University of Leicester, Leicester, United Kingdom

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ABSTRACT

Recent field-based studies document the presence of bed-parallel compaction bands within the Oligocene-Miocene carbonates of Bolognano Formation exposed at the Majella Mountain of central Italy. These compaction bands are interpreted as burial-related structures, which accommodate volumetric strain by means of grain rotation/sliding, grain crushing, intergranular pressure solution and pore collapse.

In order to constrain the pressure conditions at which these compaction bands formed, and investigate the role exerted by rock heterogeneity (grain and pore size and cement amount) on compaction localization, we carried out a suite of triaxial compression experiments, under dry conditions and room temperature on representative host rock samples of the Bolognano Formation. The experiments were performed at confining pressures that are proxy of those experienced by the rock during burial (5–35 MPa). Cylinders were cored out from a sample of the carbonate lithofacies most commonly affected by natural compaction bands. Natural structures were sampled and compared to the laboratory ones.

During the experiments, the samples displayed shear-enhanced compaction and strain hardening associated with various patterns of strain localization. The brittle–ductile transition occurred at 12.5 MPa whereas compaction bands nucleated at 25 MPa confining pressure. A positive correlation between confining pressure and the angle formed by the deformation bands and the major principal stress axis was documented. Additional experiments were performed at 25 MPa on specimens cored oblique (parallel and at 45°) to the bedding. Detailed microstructural analyses, performed on pristine and deformed rocks by using optical microscopy, scanning electron microscopy and X-ray computed microtomography techniques, showed that grain crushing and mechanical twinning are the dominant deformation processes in the laboratory structures. Conversely, pressure solution appears to be dominant in the natural compaction bands. Experimental results highlight the strong influence exerted by bedding-parallel rock heterogeneity on both orientation and kinematics of deformation bands in the studied carbonates.

1. Introduction

Porous rocks form important reservoirs for water, hydrocarbons and, potentially, the storage of greenhouse gases. Post-depositional processes (i.e., mechanical, chemical, physical and biological) may strongly affect their fluid flow properties and, hence, are important to determine. For this reason, the analyses of both deformation mechanisms and flow properties of siliciclastic porous rocks have received a good deal of attention, both in the field (e.g., Aydin et al., 2006; Fossen et al., 2007) and in the laboratory (e.g., Wong et al., 1997; Wong and Baud, 2012). Less attention has been paid to porous carbonate rocks, which still constitute a large proportion of oil reservoirs.

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[*] Corresponding author. Tel.: +1 6507259355, +1 6502007418 (mobile).
E-mail address: cilona@stanford.edu (A. Cilona).

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In carbonates, as well as any other rock, strain localization on both small-scale laboratory samples and large-scale crustal fault zones, significantly influences the stress field (Paterson and Wong, 2005), strain partitioning (Olsson, 1999; Issen and Rudnicki, 2000) and fluid-transport properties of the deformed rocks (see Aydin, 2000; Faulkner et al., 2010a for full reviews). Previous studies accurately investigated the deformation mechanisms associated to the formation faults and fractures in carbonates by means of field and/or laboratory analyses (e.g., Baud et al., 2000; Agosta et al., 2007; Antonellini et al., 2008). Since these strain localizations are mainly associated with dilatancy, scientific attention has focused on the study of this phenomenon in tight carbonates. In contrast, systematic field and laboratory investigations of compaction-assisted strain localization have been carried out only in recent times.

Field-based studies (Tondi et al., 2006; Agosta et al., 2009; Cilona et al., 2012; Rustichelli et al., 2012; Tondi et al., 2012; Antonellini et al., 2014) described compaction localization within limestones characterized by a wide range of porosities ($15 < \phi < 45\%$). These authors documented strain localization occurring along narrow tabular bands oriented oblique and parallel to bedding (i.e. compactive shear bands and compaction bands, respectively; *sensu* Aydin et al., 2006). Bed-parallel compaction bands are characterized by a local porosity reduction and do not show any macroscopic shear offset (Aydin et al., 2006). Based upon the results of field and microstructural analyses, these compaction bands have been interpreted as burial-related structures which accommodate volumetric strain by the complex interplay of grain rotation/sliding, grain crushing, intergranular pressure solution and pore collapse. With the exception of intergranular pressure solution, these micromechanisms are analogous to those previously described in sandstones (e.g., Mollema and Antonellini, 1996; Aydin et al., 2006; Fossen et al., 2007; Aydin and Ahmadov, 2009; Eichhubl et al., 2010; Shultz et al., 2010; Deng and Aydin, 2012; Alikarami et al., 2013).

Laboratory-based studies have investigated the parameters controlling the mechanics of compaction of porous carbonates ($10 < \phi < 46\%$). Among these parameters, attention has been drawn on fluids type and/or chemistry (e.g., Homand and Shao, 2000; Risnes et al., 2005; Zhang and Spiers, 2005 Croizé et al., 2010b), temperature (e.g., Croizé et al., 2010a) and pore size/type (e.g., Zhu et al., 2010). Other studies described the evolution of failure modes, microstructures and micromechanism at different confining pressures (Vajdova et al., 2004; Baxevanis et al., 2006; Baud et al., 2009; Dautriat et al., 2011b; Cilona et al., 2012; Vajdova et al., 2012). In contrast to sandstones for which compaction localization has been reproduced in laboratory (e.g., Bésuelle, 2001; Cuss et al., 2003; Vajdova and Wong, 2003; Baud et al., 2004; Fortin et al., 2005; Louis et al., 2006, 2009), porous carbonates mainly showed homogeneous deformation associated with the ductile regime (e.g., Vajdova et al., 2004, 2010; Baud et al., 2009; Zhu et al., 2010; Dautriat et al., 2011b; Vajdova et al., 2012). A recent pilot study described compaction bands formed during laboratory experiments performed on a carbonate grainstone under wet conditions (Cilona et al., 2012). These authors suggested that a more systematic work was needed to understand fully the parameters controlling compaction localization in these rocks.

In this paper we perform a systematic set of triaxial compaction experiments on specimens cored from the Bolognano Fm. (Crescenti et al. 1969) to constrain the conditions at which natural compaction bands nucleate and to investigate the role of rock heterogeneity on compaction localization in porous carbonates. The study rocks crop out at the Majella Mountain (central Italy) and have been lately investigated by Rustichelli et al. (2012) and (2013). The authors correlated compositional, sedimentological and pore network characteristics to development and distribution of bed-parallel compaction bands. In this work, an attempt to replicate in the laboratory these natural features is performed. Dry experiments, conducted under a range of confining pressures (5–35 MPa) on samples cored in different orientations with respect to the bedding (i.e., perpendicular, parallel and at 45° degree), are aimed at evaluating the role exerted by primary rock constituents (e.g., grain and pore size/shape and cement amount/type) on any compaction localization. The effect of rock heterogeneity and anisotropy on the strength and failure modes of sandstones has been previously studied by Louis et al. (2009) and Baud et al. (2012).

Both intact and deformed samples are characterized by means of detailed microstructural analyses, performed by integrating optical microscopy, Scanning Electron Microscopy (SEM) and X-ray computed microtomography (μCT) techniques (Baker et al., 2012). The results of microstructural analysis of experimentally-deformed rocks are then compared with those obtained from natural structures.

2. Methodology

2.1. Laboratory experiments

The experiments were carried out at the Rock Deformation Laboratory of Liverpool University. Nine cylindrical specimens (20 mm diameter and 50 mm length) were cored, perpendicular to bedding, from a boulder-sized hand sample. Moreover, two additional specimens (same shape) were cored parallel and oblique (45°) with respect to bedding. Each specimen was ground, to make its bases parallel to each other, and then oven-dried for 48 h at 80 °C to eliminate any residual humidity. The starting porosity values were determined by means of helium multipycnometer measurements using Quantachrome Instruments (MVP D150E). The pore-throats distribution of one intact sample was computed by mercury injection. The specimens were then placed in a 3.4 mm-thick PVC jacket, in order to isolate them from the confining medium (silicon oil). Eleven specimens were deformed in a conventional triaxial conuration, under dry conditions and at room temperature, at confining pressures ranging from 5 to 35 MPa (cf. Faulkner et al., 2010b for details on the experimental apparatus).

The axial force applied on the sample was measured by an internal force gauge with a ±0.02 kN resolution. The axial displacement was measured using a linear variable differential transformer (LVDT) attached, outside of the pressure vessel, to the electromechanical servo-controlled ram for axial loading. The axial load was applied at a fixed rate of 0.5 $\mu m\ s^{-1}$ that corresponds to a nominal strain rate of $10^{-5}\ s^{-1}$. Since the studied rock was too porous to enable the use of strain gauges, the volumetric strain of the samples was recorded with a confining pressure volumometer with a ±0.1 mm^3 resolution. The volumometer was calibrated by loading a steel blank specimen up-to 20 kN while keeping the confining pressure constant.

2.2. X-ray microtomography (μCT)

A selection of samples (i.e. deformed and pristine) was vacuum impregnated with epoxy resin and imaged at the Elettra synchrotron light laboratory in Basovizza (Trieste, Italy) by two different instruments. Each cylindrical sample (diameter of 20 mm) was cut in two parts: one half-cylinder was imaged by conventional microfocus X-ray μCT at the TomoLab station (Zandomeneghi et al., 2010). A smaller parallelepiped-shaped sample was cut from the remaining half cylinder to be investigated by using phase-contrast synchrotron radiation (SR) μCT at the SYRMEP beamline (Tromba et al., 2010). Details about samples investigated by X-ray μCT are reported in Table 1.