Earth and Planetary Science Letters 463 (2017) 81–91

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

www.elsevier.com/locate/epsl

High strain rate deformation of porous sandstone and the asymmetry of earthquake damage in shallow fault zones

F.M. Aben [a,*,1], M.-L. Doan [a], J.-P. Gratier [a], F. Renard [b]

[a] University Grenoble Alpes, ISTerre, Grenoble, France
[b] PGP, Department of Geosciences, University of Oslo, Oslo, Norway

ARTICLE INFO

Article history:
Received 29 September 2016
Received in revised form 11 January 2017
Accepted 18 January 2017
Available online xxxx
Editor: P. Shearer

Keywords:
fault zone damage
coseismic damage
rock pulverization
high strain rate experiments
sandstone compaction bands
earthquake rupture mechanisms

ABSTRACT

In contrast to coseismic pulverization of crystalline rocks, observations of coseismic pulverization in porous sedimentary rocks in fault damage zones are scarce. Also, juxtaposition of stiff crystalline rocks and compliant porous rocks across a fault often yields an asymmetric damage zone geometry, with less damage in the more compliant side. In this study, we argue that such asymmetry near the sub-surface may occur because of a different response of lithology to similar transient loading conditions. Uniaxial unconfined high strain rate loadings with a split Hopkinson pressure bar were performed on dry and water saturated Rothbach sandstone core samples. Bedding anisotropy was taken into account by coring the samples parallel and perpendicular to the bedding. The results show that pervasive pulverization below the grain scale, such as observed in crystalline rock, does not occur in the sandstone samples for the explored strain rate range (60–150 s^{-1}). Damage is mainly restricted to the scale of the grains, with intragranular deformation occurring only in weaker regions where compaction bands are formed. The presence of water and the bedding anisotropy mitigates the formation of compaction bands and motivates intergranular dilatation. The competition between inter- and intragranular damage during dynamic loading is explained with the geometric parameters of the rock in combination with two classic micromechanical models: the Hertzian contact model and the pore-emanated crack model. In conclusion, the observed microstructures can form in both quasi-static and dynamic loading regimes. Therefore caution is advised when interpreting the mechanism responsible for near-fault damage in sedimentary rock near the surface. Moreover, the results suggest that different responses of lithology to transient loading are responsible for sub-surface damage zone asymmetry.

1. Introduction

Intensively fractured rock or pulverized rock observed in fault damage zones are thought to be the product of transient coseismic loading and therefore have the potential to reveal past earthquake rupture conditions (Dor et al., 2006a, 2006b; Doan and Gary, 2009; Yuan et al., 2011; Rowe and Griffith, 2015; Aben et al., 2017). These rocks are pervasively fractured down to the micron scale, but lack any shear or rotation of fragments (Dor et al., 2006a; Rockwell et al., 2009; Mitchell et al., 2011). The vast majority of pulverized rocks are observed in crystalline lithologies, often igneous, along crustal scale faults (Dor et al., 2006b; Mitchell et al., 2011; Aben et al., 2017) and show intense pervasive damage, both inter- and intragranular.

In contrast, there are very few observations on pulverization in sedimentary rock. Dolomites and limestones, sedimentary rocks that are crystalline in nature, were labeled pulverized in some studies (Agosta and Aydin, 2006; Sagy and Korngreen, 2012; Fondriest et al., 2015). For more porous sedimentary rocks, only a few observations exist (Dor et al., 2009; Key and Schultz, 2011), of which the latter is related to a meteorite impact structure. Moreover, the interpretation as product of coseismic damage of these pulverized sedimentary rocks is ambiguous (Aben et al., 2017).

On a larger scale, pulverized crystalline rocks are often associated with an asymmetric distribution of sub-surface damage across a fault, where most damage is observed on the stiffer side consisting of crystalline rock (Dor et al., 2006b; Mitchell et al., 2011). The juxtaposed more compliant side of the fault often consists of a less damaged sedimentary rock (Dor et al., 2006b, 2008). Such asymmetric damage zone geometries have been linked to a bimaterial contrast at depth (Dor et al., 2006b, 2008; Mitchell et al., 2011) and subsequently to a preferred rupture direction related to so-called Weertman pulses (Weertman, 1980;

* Corresponding author.
E-mail address: f.aben@ucl.ac.uk (F.M. Aben).
[1] Now at: University College London, London, UK.

http://dx.doi.org/10.1016/j.epsl.2017.01.016

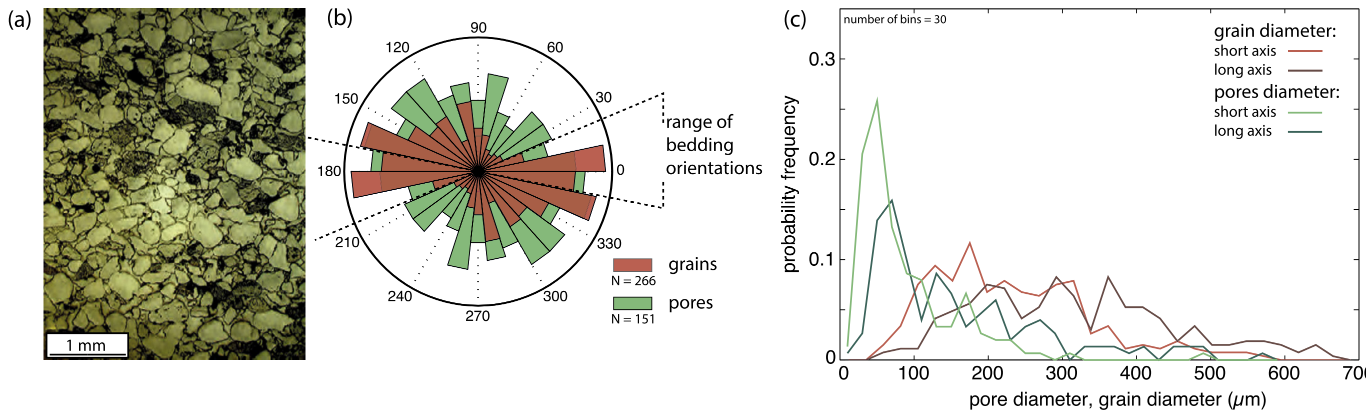

Fig. 1. (a): Optical microscope image (incident light) of undeformed Rothbach sandstone. (b): The approximate range of orientations of the bedding planes in Rothbach sandstone. The orientation of the longest axis of the grains (red) show a clear anisotropic fabric related to the sedimentary bedding. The orientation of the longest axis of the pores (green) indicates heterogeneity in pore orientation related to the sedimentary bedding. Grain and pore orientations have been obtained by semi-automatic image analysis on thin sections. (c): The grain size (red curves) and pore size (green curves) distribution for the shortest and longest axes. For (b) and (c), N = 266 and N = 151 for grains and pores respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Ben-Zion and Shi, 2005; Shi and Ben-zion, 2006). It is argued that such ruptures systematically produce more damage on the stiffer side of the fault, thereby explaining the lack of damage in the compliant lithology.

In this study, we propose another explanation of the discrepancy in damage between porous sedimentary rocks and crystalline rocks: the former respond differently to similar transient coseismic loadings than the latter. This response involves the deformation mechanisms that accommodate strain during transient loading conditions and the resulting microstructures. In the case of crystalline rocks, several laboratory studies have described the response to high strain rate loadings (Xia et al., 2008; Doan and Gary, 2009; Doan and Billi, 2011; Yuan et al., 2011; Doan and D'Hour, 2012; Aben et al., 2016). However, to our knowledge, the high strain rate response of porous sedimentary rocks has not been studied yet in the Earth's science community. Studies on porous rock in geotechnical literature [e.g. Yin et al., 2012; Wang et al., 2010; Christensen et al., 1972; Kim and de Oliveira, 2015] lack details on the microstructures of deformation and the deformation mechanisms.

Here, the mechanical and microstructural results are presented of uniaxial high strain rate loadings (strain rates between 60 and 150 s^{-1}) performed on Rothbach sandstone samples with a Split Hopkinson Pressure Bar (SHPB) apparatus. The sedimentary bedding anisotropy in the rock allows for a study on the effect of pore and grain geometry on the mechanical behavior and microstructures, by loading bedding-parallel and bedding-perpendicular samples. Also, water saturated samples in these two orientations have been tested to identify the influence of fluids during coseismic loading in porous rocks.

Next, the observed differences between the four series of samples are discussed by using the geometric parameters of the rock in combination with classic micromechanical models for deformation in porous rocks. The most noteworthy microstructures induced by transient dynamic loading are compaction bands, which usually form at higher confining pressures and at low strain rate (Fossen et al., 2007; Wong and Baud, 2012). The presented results suggest that the same microstructures form in both quasi-static and dynamic loading regimes. Therefore caution is advised when interpreting the mechanism responsible for near-fault damage in porous sedimentary rocks near the surface. Moreover, the results suggest that different responses of lithology to transient loading can explain sub-surface damage zone asymmetry.

2. Material and methods

2.1. Sandstone samples

Rothbach sandstone comes from the Vosges region in France, has a Lower Triassic age and consists of fine to coarse grained sand. The rock has been formed in a fluvial environment and contains cross-laminations, causing a scatter in bedding orientations of ∼30° (Fig. 1a). X-ray diffraction analyses from the sandstone block that was used for coring shows a mineralogical composition of 76.5% quartz, 13.4% feldspar (microcline), 3.4% mica (muscovite), 5.9% clay minerals, of which 4.9% smectite, and less than 1% of various oxides. There is slightly less feldspar (−3%) and more quartz (8%) in the block compared to the mineral content of Rothbach sandstone in literature (David et al., 1994). The porosity, obtained on five samples by water imbibition, is 20.3 ± 2.8%, similar to the value of 19.9 % porosity reported by David et al. (1994).

Some alternation between coarser and finer grained beds is observed in thin sections of undeformed Rothbach sandstone, similar to the structure reported by Louis et al. (2009). There is a higher abundance of feldspar in the finer grained beds. Image analysis reveals that the pores and grains are elongated, with the longest axis aligned along the bedding (Fig. 1a, b). Pore diameters range between 25–270 μm with a mean of 90 μm for the short axis and between 30–500 μm with a mean of 173 μm for the long axis (Fig. 1c). The grain diameters are between 50 to 600 μm with a mean of 240 μm for the short axis and between 70 and 800 μm with a mean of 330 μm for the long axis (Fig. 1c). These grain size values are similar to reported mean grain radii that vary between 110 μm (Louis et al., 2007) to 140 μm (Klein and Reuschlé, 2004) and 152 μm (David et al., 1994). P-wave measurements by (Louis et al., 2003) reveal a bedding-related anisotropy as well, with the faster velocities in the bedding-perpendicular direction. This effect increased when the pores were fluid-saturated (Louis et al., 2003). The sedimentary anisotropy causes mechanical anisotropy as well, as shown by quasi-static deformation experiments by Wong et al. (1997), Louis et al. (2009).

All samples were cored from the same block and are 1.5 cm in diameter and length. The length/diameter ratio is close to 1 to reduce inertia effects during SHPB-loading tests (Zhang and Zhao, 2014). Due to the laminations in the rock, the samples are technically oriented sub-perpendicular or sub-parallel to the bedding. In total, 16 perpendicular and 13 parallel samples were produced, labeled VS# and VSX#, respectively. Rectification ensured that the samples' top- and bottom surfaces were parallel within 80 μm or less. Next, they were dried in an oven at 60 °C for at least 48 h.