Earth and Planetary Science Letters 461 (2017) 8–19

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

www.elsevier.com/locate/epsl

Static versus dynamic fracturing in shallow carbonate fault zones

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ARTICLE INFO

Article history:
Received 15 August 2016
Received in revised form 13 December 2016
Accepted 16 December 2016
Available online xxxx
Editor: P. Shearer

Keywords:
in-situ shattering
dynamic loading
earthquakes
quasi-static loading
carbonates
fractures

ABSTRACT

Moderate to large earthquakes often nucleate within and propagate through carbonates in the shallow crust. The occurrence of thick belts of low-strain fault-related breccias is relatively common within carbonate damage zones and was generally interpreted in relation to the quasi-static growth of faults. Here we report the occurrence of hundreds of meters thick belts of intensely fragmented dolostones along a major transpressive fault zone in the Italian Southern Alps. These fault rocks have been shattered *in-situ* with negligible shear strain accumulation. The conditions of *in-situ* shattering were investigated by deforming the host dolostones in uniaxial compression both under quasi-static (strain rate $\sim 10^{-5}\ \mathrm{s}^{-1}$) and dynamic (strain rate $>50\ \mathrm{s}^{-1}$) loading. Dolostones deformed up to failure under low-strain rate were affected by single to multiple discrete extensional fractures sub-parallel to the loading direction. Dolostones deformed under high-strain rate were shattered above a strain rate threshold of $\sim 120\ \mathrm{s}^{-1}$ and peak stresses on average larger than the uniaxial compressive strength of the rock, whereas they were split in few fragments or remained macroscopically intact at lower strain rates. Fracture networks were investigated in three dimensions showing that low- and high-strain rate damage patterns (fracture intensity, aperture, orientation) were significantly different, with the latter being similar to that of natural *in-situ* shattered dolostones (i.e., comparable fragment size distributions). *In-situ* shattered dolostones were thus interpreted as the result of high energy dynamic fragmentation (dissipated strain energies $>1.8\ \mathrm{MJ/m^3}$) similarly to pulverized rocks in crystalline lithologies. Given their seismic origin, the presence of *in-situ* shattered dolostones can be used in earthquake hazard studies as evidence of the propagation of seismic ruptures at shallow depths.

1. Introduction

Unstable fracture propagation and fragmentation are fundamental processes dominating brittle deformation of solid materials loaded upon and beyond their elastic limit (e.g., Scholz, 2002). The mechanics of fracturing is strongly controlled by the loading configuration (tensile or compressive) since in tension a single crack can grow unstably (i.e., accelerating) until sample failure, whereas in compression a population of small cracks propagates stably (i.e., steady growth rate) until stress interaction leads to instability and sample failure (Ahsby and Sammis, 1990). Fracture growth rates can range from stable quasi-static low velocities to dynamic ones comparable or higher than the Rayleigh wave velocity of the host material (e.g., Freund, 1990).

These considerations are particularly relevant when applied to rocks and fault zones in which fractures are widespread. Experimental deformation of both rocks and analogue materials (e.g., polymer composites) investigated the spectrum of propagation rates, from stable to dynamic, for growing shear and tensile single fractures nucleated under various loading configurations. As a result two major features, namely high angle tensile fractures and macro- to micro branching were recognized to be exclusively as-

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http://dx.doi.org/10.1016/j.epsl.2016.12.024

sociated to dynamic fracture propagation (e.g., Sagy et al., 2001; Griffith et al., 2009; Fineberg et al., 1992; Fineberg and Marder, 1999). High angle tensile fractures compare well with off-fault injection veins which are currently considered as clear evidence of earthquake ruptures in the field, especially when filled with pseudotachylites or fluidized fault rocks (Di Toro et al., 2005; Rowe and Griffith, 2015). Conversely this is not the case for branching fractures which can even be induced by quasi-static loading (Sagy et al., 2004). This means that besides investigating the growth velocity of single fractures, it is important to determine the loading conditions (e.g. loading and strain rates) responsible for the production of certain fracture patterns both in experiments and in nature.

The characterization of rock damage and the identification of dynamic signatures within fault zones have fundamental implications for earthquake mechanics and in particular for the constraint of energy budgets involved in seismic fracturing (e.g., Shipton et al., 2006; Pittarello et al., 2008). To date rock pulverization (i.e., fragmentation down to the crystal size scale with no shear strain accommodation) is the only large-scale macroscopic feature clearly relatable to dynamic off-fault damage induced during the propagation of earthquake ruptures. Indeed pulverized rocks have been reported in tens to hundreds of meters thick bands along major faults (Dor et al., 2006; Mitchell et al., 2011) and were produced in the laboratory under high strain rate loading conditions (Doan and Gary, 2009; Yuan et al., 2011). Fine-grained pulverized rocks (sensu Brune, 2001) seem to be exclusively formed at shallow depth (less than 3 km) within homogeneous stiff protoliths (mainly granitoids) while their occurrence was not frequently reported for heterogeneous sedimentary covers. The latter is the case for carbonates (i.e., limestones and dolostones), which are worldwide distributed lithologies dominating the upper crust of many seismically active regions where moderate to large magnitude earthquakes occur (e.g., 2008 Wenchuan Mw 7.9 and 2009 L'Aquila Mw 6.1 earthquakes; Burchfiel et al., 2008; Chiarabba et al., 2009). In particular, the occurrence of thick belts (10–100 s m) of low-strain, poorly distorted breccias (average size of rock fragments >1 cm) is common within carbonate fault zones of various kinematics exhumed from a few kilometers (e.g., Billi et al., 2003). These damage patterns were frequently interpreted in relation to the quasi-static growth of fault zones characterized by the sequential formation and activation of joints, pressure solution seams, veins, shear fractures during prolonged polyphasic deformations (e.g., Salvini et al., 1999; Billi et al., 2003; Agosta and Aydin, 2006).

Here we investigate the alternative possibility that some of these fragmented rocks in carbonate fault zones may have a coseismic dynamic origin. We report the occurrence of thick belts of *in-situ* shattered dolostones along a major transpressive fault zone in the Italian Southern Alps and test the mechanical behavior of the dolomitic host rocks in compression over a wide range of strain rates (10^{-6}–10^{2} s^{-1}) to constrain the deformation conditions under which *in-situ* shattering occurs. We used image analysis techniques to discriminate between quasi-static and dynamic fracture patterns and inferred *in-situ* shattering as a dynamic coseismic process. We finally consider the implications of our experimental results for the mechanics of earthquakes and the scaling relationships of fault zones in carbonates.

2. *In-situ* shattered dolostones of the Foiana Fault Zone

The Foiana Fault Zone is a $\sim$30 km long major sinistral transpressive fault exhumed from <2 km depth in the Italian Southern Alps. The fault zone crosscuts Permo–Triassic igneous and sedimentary rocks, the latter including thick sequences of dolostones, with cumulative vertical throw of 0.3–1.8 km (Fig. 1a) (Prosser, 1998). The host rock (Mendola Formation – peritidal member) consists of light-gray sedimentary dolostones with cycles up to 0.6–1 m thick characterized by stromatolitic laminations and planar trails of *fenestrae* (Avanzini et al., 2001; Fondriest et al., 2015). The crystal size is in the range 20–300 μm, with the larger crystals filling diagenetic pores (see Fondriest et al., 2015 for full description). Measured acoustic/elastic properties of the host dolostones are: $Vp = 6.54 \pm 0.46$ km/s, $Vs = 3.64 \pm 0.15$ km/s, dynamic Young modulus $= 94.04 \pm 9.04$ GPa, while total Helium porosity is $1.7 \pm 0.8\%$ (see Supplementary Material).

The fault zone is exposed within badland areas and consists of >300 m thick belts of intensely fractured and fragmented dolostones which have been shattered *in-situ* with negligible shear strain accumulation (Fig. 1b, see Fondriest et al., 2015). This is documented by the preservation of primary sedimentary features (i.e., bedding surfaces, marly dolostone horizons and stromatolitic laminations; see inset in Fig. 1b) even in the most highly fragmented rock bodies. At the outcrop scale dolostones are reduced into fragments ranging from few centimeters down to few millimeters in size separated by joints and extensional micro-fractures. Joints are fault-related and are arranged in different sets (the most pervasive sets are parallel and perpendicular to fault strike; rose diagrams in Fig. 1a) displaying complex cross-cutting/abutting relations (Figs. 1a, b). At the meso- to micro-scale these rocks are affected by a pervasive and non-hierarchical fracture pattern with variable fracture orientations, locally resulting in the development of micro-fragmentation zones (fracture spacing <1 mm) (Figs. 1c–e). Fragment size distributions (FSD) (also named clast size distributions – CSD) measured in two dimensions by manual drawing on thin section scans (area $\sim$5 cm^{2}) cover a clast size range of 0.05–7 mm with average slopes of 1.2–1.3 in logarithmic plots (Figs. 1e–f) (see Supplementary Materials for details). The slopes were computed in the narrower range of 0.4–2 mm where the curves had a linear trend (Fig. 7), thus avoiding the external intervals. In fact, the latter are affected by bias related to the spatial resolution of the images (data truncation) and to the finite size of the analysis domain (data censoring). The clast size distributions determined on fault parallel and fault perpendicular orientations were comparable (Fig. 1f).

3. Methods

To understand the origin of the *in-situ* shattered dolostones of the Foiana Fault Zone low- to high-strain rate uniaxial compression experiments were performed on rock cylinders cored from the Mendola Formation. Low-strain rate ($\sim 10^{-5}$ s^{-1}) tests were performed with a uniaxial hydraulic test apparatus at the Rock and Ice Physics Laboratory at University College London and a uniaxial hydraulic press at the Geoscience Department rock deformation laboratory in Padova. High-strain rate (>50 s^{-1}) tests were conducted with a mini-Split Hopkinson Pressure Bar (SHPB) at the ISTerre laboratory in Grenoble (Aben et al., 2016a). Quasi-static uniaxial tests ($N = 16$) were run both in displacement and stress control mode on 20 and 25 mm in diameter rock cylinders with various length/diameter ratios ($\sim$1–2.4) (Table 1). Dynamic SHPB tests ($N = 29$) were run on samples with length/diameter ratio $\sim$1 to reduce inertia effects (Gama et al., 2004; Zhang and Zhao, 2014) and diameters of 10, 15 and 20 mm to explore a wide range of peak stresses and strain rates (Table 1). Applied strain (i.e., loading duration) was controlled by changing the length of the steel striker bar while striker impact velocity was kept fixed around 5 m/s. Cardboard pulse shapers were used to guarantee stress equilibrium conditions during the tests. Further details on the different apparatuses are summarized in Supplementary Material.

Some of the samples were wrapped with a heat-shrinkable plastic jacket to be recovered after the experiments (both quasi-