STRUCTURE AND MECHANICAL PROPERTIES OF SEISMOGENIC FAULT ZONES IN CARBONATES

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Abstract

The study of exhumed fault zones allows to characterize the structure of potential seismic sources and earthquake-related processes. The Foiana Fault Zone (FFZ) is a sinistral transpressive fault cutting dolostones in the Italian Southern Alps. The fault zone is >350 m wide and consists of intensely fragmented dolostones which appear to have been shattered in situ. Such dolostones are locally cut by networks of faults with mirror-like surfaces which are demonstrated to form at seismic deformation conditions. Changes in both thickness of in-situ shattered dolostones and scattering/kinematics of mirror-like faults along the FFZ compare favourably with results of 3D rupture simulations and with the seismological structure of active seismic sources in carbonates. Since in-situ shattered dolostones might represent an indicator of seismic rupture propagation, the high strain rate deformation of dolostone has been investigated with shock-wave loading tests. Preliminary observations show similarities between natural and experimental in-situ shattered dolostones.

Introduction

Fault zones cutting carbonate rocks represent significant seismogenic sources in several areas worldwide, including Italy (e.g. Friuli earthquake (Italian Fore-Alps), 1976, Mw = 6.4; L’Aquila (Central Apennines), 2009, Mw = 6.1; Emilia (Po Plain), 2012, Mw = 6.0).

Earthquakes are traditionally studied using geophysical (e.g. seismic wave inversion) or remote-sensed methods (e.g. GPS, InSAR). These methods allow the retrieval of key parameters related to the earthquake source (e.g. seismic moment, static stress drop, radiated energy) (Kanamori and Brodsky, 2004) but typically lack sufficient resolution to constrain on- and off-fault processes (fracture energy, fault friction) at scales relevant for earthquake mechanics (Di Toro et al., 2012).

The seismogenic behavior of faults strongly depends on fault zone internal structure (geometry latus-sensu) and fault rock constitutive properties (Scholz, 2002). In the last few years increasingly high-resolution seismological techniques (e.g. high-precision hypocenters relocation, tomography based on different seismic observables) yielded new constraints on the geometry and velocity structure of active seismogenic fault zones down to length scales < 1 km (Di Stefano et al., 2011, Valoroso et al., 2013). Further information on the coseismic off-fault damage distribution are retrieved from 3D numerical simulations of seismic ruptures (e.g. Ma and Andrews, 2010). Nevertheless the study of exhumed fault zones remains the best tool to characterize the 3D structure of seismogenic faults both in terms of geometry, fault rock spatial distribution and physical (i.e. mechanical and transport) properties.

Rock deformation experiments performed under earthquake-like conditions (slip rates of m/s, slip up to several meters, stresses of tens of MPa and rupture speeds of km/s) provide direct information about the physical and chemical processes occurring on fault zones during the seismic cycle. One major advantage of these experiments is (i) the production of artificial seismic fault rocks that can be directly compared to natural ones, potentially leading to identify markers of earthquake ruptures in the field and (ii) the determination of several earthquake source parameters that are out of the range of the seismological investigation (e.g., friction).

This PhD project deals with the investigation of earthquake mechanics in carbonate host rocks, more specifically dolostones, by means of a multidisciplinary approach including:

- field description of dolostone-cutting fault zones exhumed from seismogenic depths
- rock mechanics experiments: (i) slow- to high-velocity rotary shear friction experiments; (ii) split Hopkinson Pressure Bar tests
- mineralogical and microstructural characterization of natural and experimental fault materials.

The principal aims of the project are (i) to characterize in detail the internal structure of ancient seismogenic fault zones in dolostones, (ii) to recognize mineralogical and microstructural indicators of
seismicity (e.g. coseismic slip and seismic rupture propagation), and (iii) to eventually estimate some earthquake source parameters.

The Foiana Fault Zone (FFZ) is a regional-scale transpressive fault zone cutting dolostones that was investigated during the third year of my PhD. Detailed field structural survey within the fault zone highlighted the presence of significant volumes of in-situ shattered dolostones, which are heavily fractured rocks lacking evidence of significant shear strain. Such dolostones are locally cut by dense networks of faults with mirror-like (light reflective) slip surfaces, which likely represent ancient seismic ruptures (Fondriest et al., 2013). Significant changes in both spatial distribution of the in-situ shattered dolostones, and scattering/kinematics of the mirror-like faults are reported within the FFZ moving along fault zone strike. These architectural features compare favorably both with predictions of 3-Dimension seismic rupture simulations and with the structure of active seismogenic sources in carbonates retrieved by seismological techniques.

To investigate the origin of in-situ shattered dolostones uniaxial compressive tests (i.e., low strain rate) and Split Hopkinson Pressure Bar tests (i.e., high strain rate) were performed on solid rock cylinders. Experimental results indicate that in-situ shattering of dolostone occurs only at high strain rates (> 200 s⁻¹) whereas at lower strain rates the rock samples fractured by splitting or remained intact. Preliminary microstructural characterization of experimentally shattered dolostones highlights similarities with natural fault rocks of the FFZ. Further microstructural observations and theoretical considerations are needed to investigate the reliability to form in-situ shattered dolostones due to the stress perturbation associated to the propagation of an earthquake rupture.

**Methods**

Field work along the FFZ included systematic rock samples collection along structural profiles oriented parallel and perpendicular to the strike of the main faults. In the southern portion of the FFZ an aerial survey using an unmanned aerial vehicle (UAV; collaboration with Chartagena Srl) was also performed. The produced geo-referenced photomosaic was used for detailed structural mapping of the fault zone over an area of ~ 6*10⁴ m² with the aim to quantify the damage distribution within dolostones.

High strain rate deformation tests on dolostone solid rock cylinders were run with a Split Hopkinson Pressure Bar (SHPB) (also known as Kolsky bar) in Grenoble (IsTerre, Joseph Fourier University). This apparatus allows to deform materials at high strain rates (> 100 s⁻¹) under dynamic loading conditions. Such extreme deformations conditions are expected to occur in the fault wall rocks during the propagation of a seismic rupture.

Fault rock microstructures were studied by optical microscopy (OM), optical microscopy cathodoluminescence (OM-CL) and field emission scanning electron microscopy (FE-SEM). Mineral composition was determined by semi-quantitative X-ray powder diffraction (XRPD). Three dimensional fracture pattern of experimentally deformed samples (SHPB experiments) was retrieved by X-ray microtomography (xCT).

**Structure of a seismogenic fault zone in dolostones: the Foiana Fault Zone (FFZ)**

The Foiana Fault Zone (FFZ) is a ~ 30 km long NNE-SSW-trending sinistral transpressive fault zone cutting Triassic dolostones in the Italian Southern Alps (Val di Non area). Cumulative vertical throw is reducing from ~ 1.8 km to ~ 0.3 km moving from the northern sector of the fault zone toward the southern termination where a NE-SW-trending restraining fault bend occurs. Therefore the FFZ exposed in the northern sector might represent a deeper fault zone section compared to that exposed in the southern sector.

The FFZ is typically exposed in badlands areas and consists of heavily fractured dolostones reduced in fragments from few centimeters to few millimeters in size. Such dolostones appear to have been shattered in situ since they lack evidence of significant shear strain. The in-situ shattered dolostones are locally cut by dense network of very discrete faults with mirror-like slip surfaces. Mirror-like faults similar to these were produced in friction experiments at the deformation conditions expected during seismic slip along the FFZ (Fondriest et al., 2013). Microstructural observations up to distances of few centimeters from the mirror-like faults highlighted the presence of peculiar fault rocks characterized by: (i) lack of significant
shear strain (even at a few micrometers from the fault surface), (ii) pervasive extensional fracturing down to the micrometer scale, (iii) exploded clasts with radial fractures, and (iv) chains of split clasts (resulting from force chains) oriented at 60-80 degrees to the fault surfaces. Similar features have been reported in natural and experimental pulverized rocks, the latter produced under dynamic stress wave loading conditions.

Moving from the north to the south along FFZ strike the thickness of in-situ shattered dolostones increases from ~ 200 m to more than 350 m, the scattering in the attitude of the faults (even mirror-like) increases (i.e. fault attitudes are more dispersed to the south) and fault kinematics switches from dominant left-lateral oblique- to strike-slip to pure dip-slip reverse. Moreover the overall structure of the fault zone is strongly controlled by preexisting structures (i.e. the bedding) which are reactivated by faults, also during seismic slip (i.e. reactivation by mirror-like faults).

3-Dimension seismic rupture simulations along strike-slip faults predict (1) off-fault damage distributions with “flower-like” shapes (broad damage zone near the surface that rapidly narrows with increasing confining pressure, e.g., Ma and Andrews, 2010) and (2) formation of secondary faults/fractures with disperse attitudes and kinematics (reverse to normal) near the surface, with strike-slip at depth. Qualitatively, these theoretical results compare favorably with the structural features of the FFZ.

Moreover both the fault zone thickness (up to more than 350 m) and fault/fracture network complexity of the FFZ are well comparable with those retrieved by seismological techniques for recent seismic sequences hosted in carbonates (e.g. the L’Aquila seismic sequence of April 2009, Valoroso et al., 2013).

**The origin of in-situ shattered dolostones**

**Results**

The origin of in-situ shattering in dolostones has been investigated by performing uniaxial compressive tests (i.e. at low strain rates ~10⁻³ s⁻¹) and Split Hopkinson Pressure Bar tests (i.e. at high strain rates > 100 s⁻¹) on dolostone solid rock cylinders. Experimental results indicate that in-situ shattering occurs only at high strain rates (> 200 s⁻¹) whereas at lower strain rates the rock samples fractured by splitting or remained intact. Experimental in situ-shattered samples consist of rock fragments of few millimeters to hundreds of micrometers in size (the sample diameter was 10 mm) with a small amount of rock fragments with grain size 1-10 µm. Microstructural (SEM) observations of experimental in situ-shattered samples cut parallel to the loading direction highlighted the presence of an up to 1 mm thick layer of fine-grained material (fragment size down to 1 µm) at one of the sample edge (that which is loaded at first). Such microstructures compare fairly well with those described in the fault rocks of the Foiana Fault Zone (see section above).

**Ongoing work and open questions**

Further microstructural observations are needed to compare both experimental and natural in-situ shattered dolostones, basing on SEM observations of oriented thin sections, 3D reconstruction of the fracture network by x-Ray microtomography, and particle size distribution analyses.

Moreover since under comparable high strain rate (> 100-150 s⁻¹) other lithologies, such as granites, were observed to pulverize (i.e. in situ-shattering with much smaller average fragment size: 10-100 µm; Doan and Gary, 2009), the high strain rate damage of dolostone need to be further investigated. At the end, the reliability to produce in-situ shattered dolostones due to the stress perturbations associated to the propagation of a seismic rupture (i.e. at which rupture propagation velocity?; at which maximum distances from the rupture tip?) has to be determined by theoretical calculations.

**References**


SUMMARY OF ACTIVITIES

Courses attended during 2013:

- R. CARNIEL: Analisi spettrale e dinamica di serie temporali, Dipartimento di Geoscienze, Università degli Studi di Padova, Padova (IT), Giugno 2013.
- M. PETERNELL and J. H. KRUHL: Anisotropy and Inhomogeneity Quantification of Rock Fabrics, workshop of the VI International Conference on Fractals and Dynamic Systems in Geoscience, Perugia (IT), 26 September 2013.
- T. BLENKINSOP: Fractals and Natural Resources, workshop of the VI International Conference on Fractals and Dynamic Systems in Geoscience, Perugia (IT), 27 September 2013.
- C. SUTEANU: Fractal-Geometry-Based Treatment of Geohazards, workshop of the VI International Conference on Fractals and Dynamic Systems in Geoscience, Perugia (IT), 28 September 2013.

Oral communications of the three years (conference talks and seminars):


SMITH, S. A. F., FONDRIEST, M., DI TORO, G., NIELSEN, S., Invited Talk, Dynamic recrystallization and mirror-like slip surfaces: potential coseismic microstructures in shallow crustal carbonate faults, to be presented to AGU Fall Meeting, December 2013, San Francisco, USA.

Posters of the three years:
FONDRIEST, M., SMITH, S. A. F., ZAMPIERI, D., DI TORO, G., Field and microstructural investigations of an exhumed fault zone in dolostones (Southern Alps, Italy), EGU Annual Assembly, Vienna, AUT, April 2011.

Publications of the three years:

Co-tutoring

Teaching activities of the last year:

Grants and Awards of the three years:
(*) “Premio miglior presentazione orale giovani non strutturati”, GIGS Annual Meeting 2012, October 2012, Modena, Italy.

European Science Foundation, Conference on Continuing Challenges in Earthquake Dynamics: New Methods for Observing and Modelling a Multi-Scale System, conference fees covered (EU 730.00).
40th Workshop of the International School of Geophysics Properties and Processes of Crustal Fault Zones, workshop fees covered (EU 600.00).
GSA travel grant for attending GSA short course: Modern Digital Geologic Mapping Techniques. US $ 102.00.

Other activities of the last year:
April 2013, INGV; Rome (IT): Low- to high-velocity rotary friction experiments on mixed calcite-dolomite gouges; in collaboration with Steven Smith.
June-October 2013, Val di Non (TN, IT): Field work in the outcrops of the Foiana Line, in collaboration with Stefano Aretusini.
August 2013, Campo Imperatore (AQ, IT): Field work in collaboration with Matteo Demurtas and Giulio Di Toro.

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