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Microtectonics of low-P low-T carbonate fault rocks

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With the aim of deducing some general microtectonic processes responsible for the development of carbonate fault cores, rock samples were collected in ten of such structures, which are different in size, attitude, kinematics, displacement, and tectonic environment. Samples were thin-sectioned and analysed under an optical microscope. Microscopic evidence (i.e., at the scale of tens-to-hundreds of microns) shows that grain size reduction occurred mostly by cataclasis and, occasionally, by pressure solution. Cataclasis involved three main processes here named intragranular extension fracturing, chipping, and shear fracturing. Intragranular extension fracturing is more common in the early stages of cataclasis and produces a coarse breccia consisting of angular grains. In a few cases, pre-existing weaknesses and flaws control the fracture pattern associated with intragranular extension fracturing. Chipping is more common in the advanced stages of cataclasis and produces a gouge consisting of a few survivor rounded grains within a fine matrix. Shear fracturing seems less frequent than the other two processes and usually occurs in the advanced stages of cataclasis. By considering the microscopic and mesoscopic evidence, and the dissimilar frequency of dissolution structures in the analysed fault cores and damage zones, it is inferred that the studied fault zones probably acted as conduit–barrier permeability systems.

1. Introduction

Faults in low-pressure low-temperature carbonate rocks are known both as earthquake foci (Amato et al., 1998; Di Bucci and Mazzoli, 2003; Del Gaudio et al., 2007) and as complex permeability structures within hydrocarbon, water, and geothermal reservoirs (Eberli et al., 2004; Mancini et al., 2004; Mazzullo, 2004; Celico et al., 2006; Rossetti et al., 2007a,b). Their study, at all scales, is therefore relevant for structural geologists dealing with seismic faulting or working in the hydrocarbon, water, and geothermal industries.

Until about 1990, carbonate fault rocks were hardly studied (e.g., Turner et al., 1954; Rutter, 1974; Mimran, 1976, 1977; Friedman and Higgs, 1981) compared to fault-related crystalline and silicoclastic rocks (e.g., Engelder, 1974; Sibson, 1977; Sammis et al., 1986; Sammis and Biegel, 1989; Blenkinsop, 1991). In the last fifteen years, the study of carbonate fault rocks has significantly advanced and become systematic mostly because of its importance in the hydrocarbon industry (Burkhard, 1993; De Bresser and Spiers, 1993; Hadizadeh, 1994; Newman and Mitra, 1994; Babaie et al., 1995; Kennedy and Logan, 1997; Salvini et al., 1999; Graham et al., 2003; Kim et al., 2003; Storti et al., 2003; Llana-Funez and Rutter, 2005; Agosta and Aydin, 2006; Tondi et al., 2006; Agosta et al., 2007; Tondi, 2007). Studies of fault core permeability (Ghisetti et al., 2001; Agosta and Kirschner, 2003; Micarelli et al., 2006; Agosta et al., 2007), grain shape evolution with fault slip (Storti et al., 2007), and some earthquake indicators obtained in laboratory-simulated faults (Han et al., 2007a,b; see Billi and Di Toro, 2008 for a review) have recently improved our understanding of the mechanical and hydraulic behaviour of carbonate fault rocks. In particular, faulting simulations performed at seismic slip rates (about 1 m/s) in Carrara marble revealed very promising results and showed that the seismic (i.e., frictional) process and related indicators have to be investigated at the microscale (Han et al., 2007a,b). Unfortunately, the microtectonics of low-pressure low-temperature fault-related carbonate rocks is still poorly emphasized, and published microscopic images of these rocks are relatively rare (Wenk, 1985; Pieri et al., 2001a,b; Barnhoorn et al., 2004, 2005; Billi, 2005, 2007; Tondi et al., 2006; Tondi, 2007; Billi et al., 2008; Ferrill and Morris, 2008; Mort and Woodcock, 2008). This lack of knowledge prevents advances in the understanding of the processes responsible for the formation of carbonate fault cores and, therefore, in the understanding of the frictional and hydraulic behaviours of these structures.

The main goal of this paper is to contribute in knowing and understanding the microscopic processes that are responsible for the development of carbonate fault cores. To reach this goal,

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microscopic images from low-pressure (<∼100 MPa) low-temperature (<∼100 °C) carbonate fault rocks (i.e., fault cores) collected in Italy (Figs. 1–3) are shown and discussed. Insights into the microtectonic processes (i.e., cataclasis and pressure solution) are provided. As the main goal is to address the detailed mechanisms of fracture (or pressure solution) in carbonates, fault rocks in diverse settings were chosen in order to deduce the general processes in all such rocks (Table 1). It should be noted that observations and inferences provided in this paper are valid at the scale of analysis (i.e., tens-to-hundreds of microns; Figs. 4–6).

2. Geological setting

The analysed rocks were collected from exposures of Mesozoic shallow-water organic carbonates located in the central Apennine fold-thrust belt and in the northern Apulian foreland, central Italy (Fig. 1 and Table 1). The central Apennine fold-thrust belt mostly consists of Meso-Cenozoic carbonate thrust sheets accreted in Neogene time toward the Apulian–Adriatic foreland, in the east, during westward subduction of the foreland plate. In late Neogene time, the Tyrrhenian (i.e., western) side of the Apennine belt was extended under a backarc tectonic regime, while toward the east, tectonic accretion was still active at the front of the wedge (Malinverno and Ryan, 1986; Patacca et al., 1992; Faccenna et al., 2004). At present, reduced thickness of the lithosphere, volcanism, extensional basins, and high heat flow characterize the Tyrrhenian side of the Apennine belt and are the results of the Neogene–Quaternary backarc extensional process (Funiciello et al., 1976; Barchi et al., 1998; Jolivet et al., 1998; Billi et al., 2006; Nicolosi et al., 2006). In the central Apennines, thrust imbrication occurred mostly in a forelandward piggyback sequence, with a few out-of-sequence or backward thrusting episodes (Ghisetti and Vezzani, 1997; Cavinato and DeCelles, 1999). Post-orogenic normal faults and associated extensional basins of Miocene–Pleistocene age are widespread both in the Tyrrhenian side of the Apennines and in the axial sector of the fold-thrust belt (Keller et al., 1994; Lavecchia et al., 1994; Barchi et al., 1998, 2007; Jolivet et al., 1998; Cavinato et al., 2002). The locus of extension progressively migrated toward the east, parallel but west of the eastward-migrating locus of contractional deformation (Elter et al., 1975; Malinverno and Ryan, 1986; Carmignani and Kligfield, 1990; Patacca et al., 1992). The lag time between the onset of thrusting and initial extension at any given locality in the central Apennines is about 2–4 m.y. (Cavinato and DeCelles, 1999).

The Gargano Promontory (Fig. 1) is a structural high located in the Apulian–Adriatic foreland (Favali et al., 1993; Doglioni et al., 1994; Brankman and Aydin, 2004). The promontory consists of a thick succession of Mesozoic carbonates dissected by an active and complex fault array. Within this array, the strike-slip Mattinata Fault in the southern Gargano Promontory is the most prominent fault (Ortolani and Pagliuca, 1987; Funiciello et al., 1988; Salvini et al., 1999; Brankman and Aydin, 2004). Geological and geophysical evidence shows that the Mattinata Fault was activated during late Miocene time at the latest and is still active being the source of recent and historical earthquakes (Favali et al., 1993; Salvi et al., 1999; Patacca and Scandone, 2004; Tondi et al., 2005; Billi et al., 2007a).

The exact thermobaric regime experienced by each analysed fault is unknown; however, upper thermobaric boundaries for the central Apennines can be inferred from constraints obtained after organic matter maturity, clay mineralogy, stratigraphy, and structural geology studies. These results suggest that the investigated exposures experienced thermobaric conditions below the metamorphic regime (i.e., below a temperature of 200 °C and a pressure of 200 MPa) as also

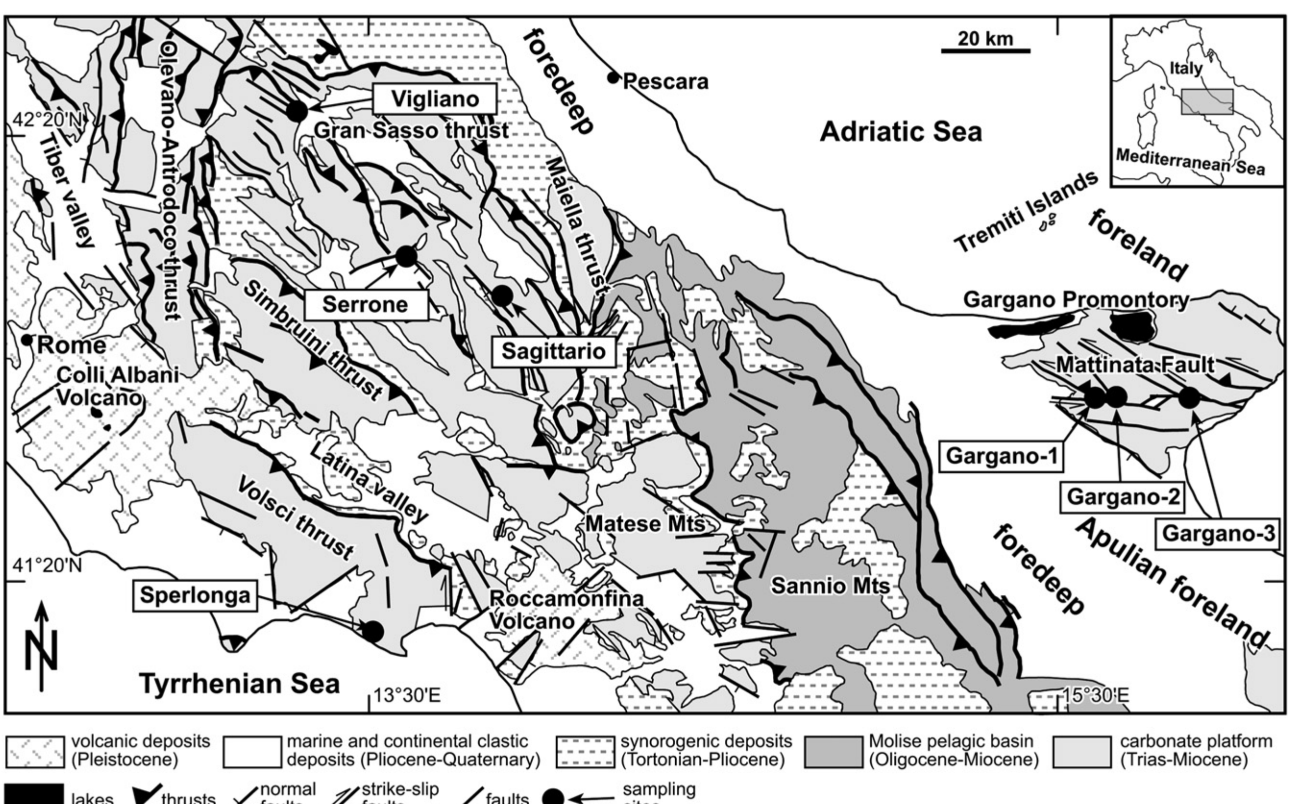

Fig. 1. Geological map of central Italy (modified after Bigi et al., 1991; Cavinato and DeCelles, 1999). Locations of the studied faults are displayed with black dots. See Table 1 for coordinates of fault locations and for fault main attributes.