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Deformation features within an active normal fault zone in carbonate rocks: The Gubbio fault (Central Apennines, Italy)

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Abstract

The Gubbio fault is an active normal fault defined by an important morphological scarp and normal fault focal mechanism solutions. This fault truncates the inherited Miocene Gubbio anticline and juxtaposes Mesozoic limestones in the footwall against Quaternary lacustrine deposits in the hanging wall. The offset is more than 2000 m of geological throw accumulated during a poly-phased history, as suggested by previous works, and has generated a complex zone of carbonate-rich fault-related structures. We report the results of a multidisciplinary study that integrates detailed outcrop and petrographic analysis of two well-exposed areas along the Gubbio fault zone, geochemical analysis (fluid inclusions, stable isotopes, and trace elements) of calcite-sealed fault-related structures and fault rocks, and biostratigraphic controls. Our aims are: (i) the characterization of the deformation features and their spatial–temporal relationships, and (ii) the determination of the *P*/*T* conditions and the fluid behaviour during deformation to achieve a better understanding of fluid–rock interaction in fault zones.

We show that few of the observed structures can be attributed to an inherited shortening phase while the most abundant structures and fault rocks are related to extensional tectonics. The outcropping extensional patterns formed at depths less than 2.5–3 km, in a confined fluid system isolated from meteoric water, and the fault structures are the response to a small amount of cumulated displacement, 12–19% of the total geological throw.

Keywords: Fault rocks; Carbonates; Deformation mechanisms; Stable isotopes; Fluid inclusions; Displacement; Fluid–rock interaction

1. Introduction

The development of fault zone deformation features in carbonate rocks is related to *P*/*T* conditions, lithology, and fault displacement and conditioned by the presence of circulating fluids (Micarelli et al., 2005, 2006 and references therein). In recent years, research, coupling different methodologies, has revealed the role of these factors in fault-related deformation.

Recent works that combine microstructural analysis with paleothermometric analysis allow the characterization of the *P*/*T* (depth) behaviour during faulting (Micarelli et al., 2005; Benedicto et al., in press). Other works have focused on fault- and fracture-related calcites coupling microstructural, petrologic, and geochemical analyses; these works permit identification of different generations of calcite and investigations of fluid sources, flow pathways and fluid-driven mass transfer through faults (e.g. Travé et al., 1998; Boles and Grivetti, 2000; Sibson, 2000; Cello et al., 2001; Pili et al., 2002; Labaume et al., 2004; Benedicto et al., in press).

Our study integrates field macro and mesostructural analyses, microstructural analyses of thin sections by using classical, optical and cathodoluminescence microscopy, and paleothermometric analyses from fluid inclusions coupled with

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geochemical analyses (stable isotopes and trace elements) of syn-kinematic fault-related calcites. Furthermore, in the studied outcrops, we have performed some biostratigraphic controls that have been used as a tool to constrain fault displacement.

Here, we describe the deformation features and investigate their spatial organisation and their relative chronology. The influence of *P*/*T* conditions, lithology and fault displacement on the deformation mechanisms and related structures and fault rocks is also investigated in order to better constraint the evolution of the active Gubbio normal fault. Furthermore, geochemical analyses (stable isotopes and trace elements) of fault-related calcites provide a better understanding of fluid provenance and fluid–rock interaction within the fault zone.

2. Geological setting

The North-central Apennines chain is a NE-verging fold-and-thrust belt that resulted from the convergence between the Sardo-Corso block (European plate) to the west and the Adriatic block (African plate) to the east, since the Cretaceous (Dewey et al., 1989). The accretion process through the Adriatic continental margin (lower Oligocene–Pleistocene) has been accompanied by Tyrrhenian back-arc extension (Kastens et al., 1988) since the Miocene. The North-central Apennines presents two well-differentiated, adjacent domains (Fig. 1c; Alfano et al., 1982; Barchi et al., 1998). The Adriatic domain to the east (Fig. 1c) preserves compressional structures with Upper Miocene–Quaternary thrusting and related foredeep and/or piggyback basins (Collettini et al., 2000; Pauselli and Federico, 2003). To the west, the Tyrrhenian domain contains the inherited shortening structures of the chain overprinted by middle Miocene-to-Recent extensional deformation (Calamita and Pizzi, 1994; Cello et al., 1997). The extensional process has led to the formation of NW–SE trending normal faults and oblique-to-orthogonal strike-slip faults. Extensional features are progressively younger to the east and they controlled the development of Pliocene-to-Quaternary intramontane basins (Fig. 1). Normal and strike-slip faulting in the Tyrrhenian domain are coeval with active compression in the Adriatic domain (Elter et al., 1975).

The Umbria sector, where the Gubbio structure is located, can be considered as the transition between these Adriatic and Tyrrhenian domains (Boschi et al., 1997; Barchi et al., 2000; Collettini et al., 2003) and is characterized by NNW–SSE trending, SW dipping active normal faults (e.g. the Norcia earthquake, 1979, Ms = 5.9; the Gubbio earthquake, 1984, Ms = 5.2; the Colfiorito earthquake, 1997, $M_{max} = 5.9$; Boschi et al., 1997; Cello et al., 1997; Boncio and Lavecchia, 2000). These features overprint the thrust edifice built up since the late Miocene and involve the sedimentary succession (Umbria–Marche succession; Fig. 1b) and the underlying basement. The sedimentary succession is from bottom to top: evaporitic rocks (*Anidriti di Burano Fm*, Upper Triassic; about 1500 m thick); carbonate multilayers composed of Upper Triassic to Lower Liassic carbonate neritic sequence of massive limestones (*Calcare Massiccio Fm*; about 700–800 m thick), Middle Lias to Miocene well-bedded calcareous and calcareous-marly–cherty pelagic and hemipelagic sequence (900–1400 m thick); and siliciclastic turbiditic syn-orogenic deposits (*Marnoso-Arenacea Fm*, up to 4000 m thick) of lower Miocene–Pleistocene age that are progressively younger from the west to the east (Deiana and Pialli, 1994).

In this sector, seismic profiles show the presence of a regional east-dipping, low-angle normal fault, the Alto Tiberina fault (Fig. 1), which is interpreted as the basal detachment onto which outcropping normal faults, i.e. the Gubbio fault, connect with a listric geometry (Boncio et al., 1998, 2000; Barchi et al., 1999; Collettini et al., 2000; Boncio and Lavecchia, 2000). Modern seismicity is localized between the Alto Tiberina fault and the antithetic Gubbio fault (Boncio et al., 1998).

The Gubbio structure is one of the typical kilometre-scale folds cropping out in the external zone of the North-central Apennines (Figs. 1 and 2), where the Mesozoic–Paleogene sedimentary succession crops out between the terrigenous Miocene successions. The Gubbio fold axial plane strikes N135° and the fold's western limb is cut by a normal fault (Fig. 2), which strikes N110–N130° and juxtaposes the folded Mesozoic marine limestones in the footwall against the Plio-Quaternary lacustrine deposits in the hanging wall (Menichetti and Minelli, 1991; Boncio and Lavecchia, 2000).

Recently, the Gubbio fault has been the subject of numerous studies focused on seismic activity (Boncio and Lavecchia, 2000; Collettini and Barchi, 2002), fault geometry at depth and relations with inherited thrusting and folding (Menichetti and Minelli, 1991; Collettini et al., 2003; Mirabella et al., 2004), related basin geometry, and morpho-tectonic and sedimentary patterns (Collettini et al., 2000). Mirabella et al. (2004) describe the Gubbio fault as a multi-phase major fault with more than 2000 m of cumulative displacement that accommodated a geological throw of 850 m during the Lower Miocene extension and 1350 m during the Quaternary extension. They also suggest that during Upper Miocene NW–SE compression, the deeper part of the Gubbio fault was reactivated as reverse fault generating the Gubbio anticline.

3. Methods

Fault-related features such as slip planes, calcite-sealed veins, calcite-cemented breccias, and/or cataclasites (see below) are described in the field at outcrop scale (Figs. 3 and 4). Microstructural characteristics and cross-cutting relationships were defined by analyzing about 50 thin sections, using polarizing and cathodoluminescence microscopy. For cathodoluminescence analysis we used a Cold Cathodoluminescence Model (Technosyn 8200 M411) at 12–16 kV and 450–550 μ gun current and 0.05 Torr vacuum.[1]

After a preliminary petrographic examination of 21 double polished sections for fluid inclusion analyses, 12 samples were selected for fluid inclusion microthermometric analysis. This was performed by a U.S.G.S. heating–freezing stage.[2] The thermocouple was calibrated using synthetic standards with pure water (0 and 374.1 °C) and pure CO_2 (−56.6 °C). Sample

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