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Recognizing the seismic cycle along ancient faults: CO_2-induced fluidization of breccias in the footwall of a sealing low-angle normal fault

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ABSTRACT

The Zuccale low-angle normal fault exposed on the island of Elba, Italy, is a crustal-scale structure which contains a strongly foliated fault core. In the immediate footwall of the Zuccale fault, cohesive fault-related breccias which were initially deformed by typical frictional deformation mechanisms experienced fluidization over areas of at least 10^{-2}–10^{-3} km^2.

Three internal variants of fluidized breccia are recognized, with each related to a separate fluidization event. Characteristics of the fluidized breccias include: (1) a highly irregular 'intrusive' boundary with the overlying fault core; (2) no grain-scale evidence for typical frictional deformation mechanisms; (3) an association with carbonate cements indicating that fluids contained CO_2; and (4) a clast-preferred orientation suggesting that fluids were moving vertically and spreading laterally as they encountered the foliated fault core.

Our observations suggest that the fluidized breccias are representative of the interseismic period along the Zuccale low-angle fault, and developed across small fault patches during build-ups in fluid overpressure. Attainment of a critical fluid overpressure triggered embrittlement and the formation of low-angle slip surfaces and sub-vertical tensile veins within the overlying fault core, which may account for the presence and the dimensions (10^{-1}–10^{-3} km^2) of rupture surfaces which produce microseismicity along active low-angle normal faults in central Italy.

1. Introduction

Fluids exert a fundamental control on the mechanical and chemical behaviour of all types of fault and shear zone. There is a voluminous literature detailing field, laboratory and theoretical work carried out in an attempt to understand the role of fluids in earthquake rupture, the formation of hydrothermal ore deposits, and the long-term evolution of faulted regions of the crust and lithosphere at all depths and scales (e.g. reviews by Hickman et al., 1995; Oliver, 1996; Sibson, 2000; Person et al., 2007). Increasingly it is recognized that cycling of fluid pressure, e.g. 'fault-valve' models (Sibson, 1990), within faults and shear zones strongly affects their mechanical behaviour, and can be intimately linked to the earthquake cycle (e.g. Parry and Bruhn, 1990; Sibson, 1992, 2007; Cox, 1995; Henderson and McCaig, 1996; Nguyen et al., 1998; Famin et al., 2005).

Low-angle normal faults, which dip less than 30°, have received considerable attention since standard 'Andersonian' frictional fault theory does not predict such orientations and because large earthquakes on low-angle normal faults are rare or absent (Anderson, 1942; Jackson and White, 1989; Wernicke, 1995; Collettini and Sibson, 2001; Axen, 2004, 2007). Low-angle normal faults may slip over prolonged periods of time if fault rock materials lining the fault surface possess a low friction coefficient (e.g. Numelin et al., 2007), or if high fluid pressures are generated within, or adjacent to, the fault zone (e.g. Axen, 1992). Attainment of tensile fluid overpressure ($P_f > \sigma_3$) is critical for reactivation and slip along low-angle normal faults, particularly in the upper 10 km of the brittle crust. For example, Collettini and Barchi (2002) applied frictional reactivation theory to study the conditions necessary for reactivation of the Altotiberina fault, an active low-angle normal fault in central Italy. They found that the Altotiberina fault can be reactivated for low values of differential stress ($\sigma_1 - \sigma_3 < 28$ MPa), relatively high values of tensile strength of the surrounding rocks (~ 10 MPa), and tensile fluid overpressure $P_f > \sigma_3$ (e.g. $\lambda_v > 0.93$). There is strong evidence from the footwalls of metamorphic core complexes and their associated low-angle normal faults, where vein and fracture networks are commonly observed, that tensile fluid overpressure is locally obtained (e.g. Reynolds and Lister, 1987). However, the factors leading to focused

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fluid flow and to the development of fluid overpressure at specific sites are unknown, and there is still a paucity of direct geological evidence for any form of fluid cycling along low-angle normal faults.

The aim of this paper is to describe in detail the geological setting, microstructural characteristics, and evolution of a suite of frictional fault rocks (breccias) which we believe to have experienced widespread fluidization beneath the Zuccale fault, a low-angle normal fault exposed on the Island of Elba. We focus our attention on a single coastal outcrop which contains 100% exposure in the immediate footwall of the Zuccale fault, and use our observations to develop a conceptual model for fluidization. We discuss our observations in the context of fluid cycling, the development of fluid overpressure associated with low-angle normal faults, and the recognition of fault rocks which represent particular phases of the seismic cycle.

2. Geological context

2.1. The northern Apennines

Elba lies ~20 km to the west of Tuscany in the northern Tyrrhenian Sea. This area has experienced two contrasting phases of deformation, both of which migrated progressively from west to east (Fig. 1a; Elter et al., 1975; Pauselli et al., 2006). An earlier phase of Cretaceous to Quaternary collision was followed by a later phase of Miocene to currently active post-collisional extension. Geological and geophysical studies have highlighted that a majority of post-collisional extension has been accommodated along shallowly east-dipping low-angle normal faults (Fig. 1a; Barchi et al., 1998; Jolivet et al., 1998; Pauselli et al., 2006; Collettini et al., 2006b; Chiaraluce et al., 2007). Active extension presently occurs along the Altotiberina low-angle normal fault, which produces abundant microseismicity ($M < 2.3$) at a rate of ~8.1 events day^{-1} km^{-2} (Chiaraluce et al., 2007) over a depth range of 4–14 km (Fig. 1a; Boncio et al., 1998, 2000). Microseismic activity occurs on rupture surfaces in the size range of 10^{-1}–10^{-3} km^2 (Sibson, 1989; Collettini and Barchi, 2002; Chiaraluce et al., 2007). The active regional stress field in central Italy is characterized by a sub-vertical σ_1 and an east–west to NE–SW trending, sub-horizontal σ_3 (Montone et al., 2004). Older, inactive low-angle normal faults are exhumed in western Tuscany and the Tyrrhenian islands, which includes the Zuccale fault exposed on Elba.

Central Italy is characterized by an anomalously high flux of non-volcanic CO_2, focused specifically within the area which has experienced widespread post-collisional extension (Fig. 1a; Chiodini et al., 2004). The flux of CO_2 reaches ~0.8 tonnes day^{-1} km^{-2}, whereas to the east of the active extensional front, the flux of CO_2 decreases rapidly. Based mainly on $^3He/^4He$ and $\delta^{13}C$ isotopic analysis, it appears that around 40% of the CO_2 gas discharged in central Italy is derived from the upper mantle, which acts as an important source of CO_2-bearing fluid to the base of the brittle crust (Chiodini et al., 2004; Minissale et al., 2000; Minissale, 2004). Two deep boreholes (Santo Donato at 4750 m below sea level and Santo Stefano at 3700 m below sea level) which penetrated the active Altotiberina fault encountered fluid overpressures which were ~85% of the lithostatic load ($\lambda_v = 0.85$), induced by trapped CO_2-bearing hydrous fluids in the footwall of the fault (Chiodini and Cioni, 1989). Several authors have suggested that deeply derived CO_2-bearing fluids play a critical role in the nucleation of crustal earthquakes and the time–space evolution of aftershocks in central Italy (e.g. Collettini and Barchi, 2002; Miller et al., 2004; Chiaraluce et al., 2007).

2.2. The Zuccale fault on the island of Elba

Elba consists of a series of 5 stacked thrust sheets (Complexes I–V) which formed during late Cretaceous–early Miocene shortening (Fig. 1b). All of the thrust sheets currently dip moderately to the west and are crosscut and displaced by the shallowly east-dipping Zuccale fault (Fig. 1b; Trevisan et al., 1967; Keller and Pialli, 1990; Bortolotti et al., 2001). Shear sense along the Zuccale fault is

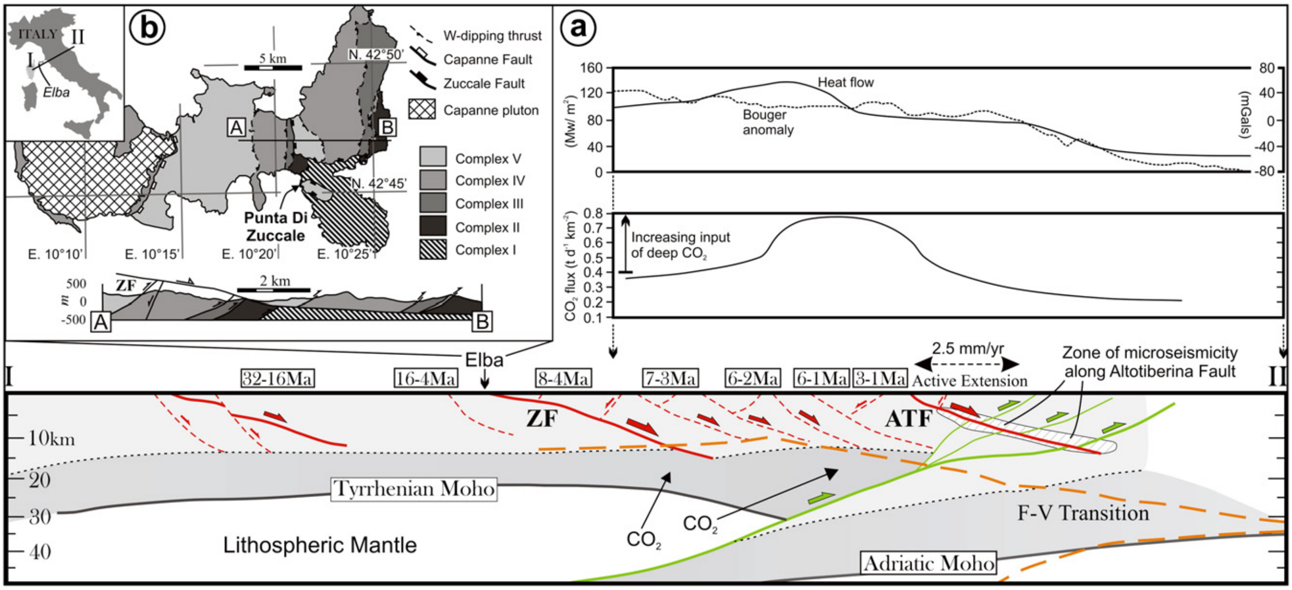

Fig. 1. (a) Crustal-scale cross section from Corsica to the Adriatic coast based partly on the CROP03 deep seismic reflection profile (Barchi et al., 1998). Location of the cross section is shown in part (b). The age ranges of syn-tectonic extensional basins are shown in white boxes. Extensional processes in the Tyrrhenian Sea and Tuscany have caused high average heat flows, a regional positive Bouger gravity anomaly, and a shallow Moho (after Collettini et al., 2006b). Additionally, the area is associated with high fluxes of deeply-derived CO_2. Location of the frictional–viscous (F–V) transition after Pauselli and Federico (2002). Zone of microseismicity along the Altotiberina Fault (ATF) after Chiaraluce et al. (2007). ZF, Zuccale fault. (b) Simplified geological map of Elba (after Trevisan et al., 1967) and cross section through central and eastern Elba highlighting the geometry of the Zuccale fault. Complex I, Paleozoic basement schists; Complex II, Tuscan metamorphic sequence; Complex III, Tuscan limestone sequence; Complex IV, Ligurian ophiolite sequence; Complex V, Cretaceous flysch.