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Low Angle Normal Fault (LANF)-zone architecture and permeability features in bedded carbonate from inner Northern Apennines (Rapolano Terme, Central Italy)

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ABSTRACT

Fault zones have the capacity to be hydraulic conduits within upper crustal levels, allowing migration of large volume of fluids through shallow and deeper geological environments. Low-angle normal faults (LANFs) crosscutting carbonate rocks produce damaged volumes that may have a relevant role in channelling or hosting geothermal fluids, therefore deserving of investigation to better predict mining targets. Deformation along LANFs zones, dissecting carbonate successions, produces permeable volumes presently exploited in the Larderello and Monte Amiata geothermal areas (Italy). In this paper, the architectural and permeability features of an exhumed LANF-zone exposed in the Northern Apennines, (Rapolano Terme, central Italy), affecting Cretaceous bedded limestone, are presented. Such a fault was not affected by circulation of geothermal fluids, but its features could reveal much on the potential impact on fluids migration in the active geothermal areas, therefore resulting an intriguing analogue. The study LANF-zone consists of faults, which enucleated at depth >4 km. During its earlier stage of evolution, dissolution seams, often arranged in s–c fabric, characterised the whole damage zone. Dissolution seams developed under very low-grade metamorphism (T = 100–150 °C) as indicated by illite crystallinity analyses. Fault zone architecture and permeability features changed during the fault growth and exhumation. Permeability heterogeneity and anisotropy characterised the LANF zone during its development. If geofluids circulated within the fault zone, it could be an effective barrier during its earlier evolution, being accompanied by dissolution seams. On the contrary, it could play as combined barriers–conduits during its later evolution (progressively at shallower levels) being characterised by intersecting fault planes, which define pipe-like conduits parallel to the direction of the tectonic transport. Such a configuration could have the capacity to impact on fluids migration for long paths across the upper crustal levels. This adds significant information for predicting deeper geothermal circuits and the location of potential exploitable reservoirs in active tectonic environments.

1. Introduction

Reconstructing faults zone architecture (i.e. geometry, intensity and distribution of fault-related fracturing, distribution of minor faults within damage zones, thickness, composition, lateral and vertical distribution of the core zone) is a primary goal for most geologists overall dealing with geofluids and georesources. It is well known that faults and associated structures may have a primary impact on fluids migration in the upper crustal levels (Agosta et al., 2009; Agosta and Kirschner, 2003; Bense et al., 2013; Caine et al., 1996; Curewitz and Karson, 1997; Sibson, 2000). In fact, it has been documented that fault-controlled damaged rock volumes play a fundamental role in hosting geothermal fluids (geothermal reservoirs; Barbier, 1998), ore bodies (Lattanzi, 1999; Person et al., 2008; Tanelli, 1983) and oil traps (Aydin, 2000; Sorkhabi and Tsuji, 2005; Van Dijk et al., 2000). In particular, carbonate successions could correspond to geothermal and hydrocarbon reservoirs, and can host significant ore deposits if affected by considerable brittle deformation that enhances the rock volume permeability (Caine et al., 1996). Permeability of rock volume depends upon many variables such as fracture length, height, anisotropy, spread, orientation, connectivity and, of course, intensity. On the other hand, it has been shown that brittle/ductile deformational features (e.g. pressure solution related structures) may also play a role in hydrocarbon migration and storage, for example due to their reactivation and consequent permeability increase during later deformational events (Graham Wall et al., 2006). In this view, faults zones can represent main targets for mining, geothermal and oil exploration/exploitation activities, therefore deserving of detailed studies for the better understanding of the reservoirs geometries and the processes driving the fluids migration and entrapment at shallow crustal levels, helping to reduce the mining risk.

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In the last decade, many studies dealt with faults zones in carbonate rocks, overall describing: i) fault zone architecture and geometrical setting of the fractures network of the damage zones (Agosta and Aydin, 2006; Agosta and Tondi, 2010; Billi et al., 2003; Ferrill and Morris, 2008; Micarelli et al., 2005; Tondi, 2007; Van Gent et al., 2010); ii) the fault zone permeability features (Agosta et al., 2007; Breesch et al., 2009; Micarelli et al., 2006; Rotevatn and Bastesen, 2012) iii) microstructural and petrophysical features of the fault core zones (Billi and Storti, 2004; Billi, 2010; Tesei et al., 2013); iv) deformation mechanisms and seismic cycles (Bullock et al., 2014; Bussolotto et al., 2007; Fondriest et al., 2012; Smith et al., 2011); and v) results from high-velocity rock-friction experiments on calcite gouge, in order to define the faulting processes during coseismic ruptures (Di Toro et al., 2006; Han et al., 2007b; Fondriest et al, 2013; Smith et al., 2013). Nevertheless, most studies are focussed on fresh scarps of active and possible seismogenic structures, or on inactive faults zones exhumed from very shallow crustal levels (i.e. low pressure–low temperature), where their architectures are characterised by well-developed fracture network defining wide damaged zones and well developed fault cores (Agosta and Aydin, 2006; Agosta et al., 2008; Billi, 2005; Billi et al., 2007; Cello, 2000; Cello et al., 2000, 2001; Kim et al., 2004; Labaume et al., 2004; Micarelli et al., 2006; Peacock, 2001; Rossetti et al., 2007; Rustichelli et al., 2013; Storti et al., 2003). On the contrary, few data are available from the architectural features of fault zones affecting carbonate rocks that are exhumed from deeper levels, and are characterised by gently dipping attitudes (i.e. LANFs, Low-Angle Normal Faults), preventing advances in the understanding of their hydraulic behaviour. In southern Tuscany (Italy), it has been demonstrated that LANFs could have a big impact on the location and/or migration of geothermal fluids (e.g. Bellani et al., 2004). For example, geothermal resources hosted in carbonate reservoirs affected by LANFs are exploited at variable depths, ranging from 1 to 4 km down to the surface, in the: i) Larderello–Travale and Monte Amiata areas (Batini et al., 2003); ii) Torre Alfina area, Italy (Buonasorte et al., 1988); iii) Cesano area, Italy (Buonasorte et al., 1995); Denizly area, Turkey (Yılmazer et al., 2010). Similar features (i.e. fault controlled migration and storage of fluids) are from some oil fields (Cello et al., 2000; Shiner et al., 2004; Van Dijk et al., 2000) and ore bodies (Boni and Malafronte, 1983) around the world.

Unfortunately, information on fault zones architecture exhumed from deeper levels is often contrasted by the fact that LANFs are not so common at the surface, because they characterise only those areas affected by considerable uplift and exhumation. Southern Tuscany (Fig. 1a), just for its tectonic evolution (Barchi, 2010; Brogi et al., 2005; Carmignani et al., 2001; Molli, 2008), represents the exhumed hinterland (inner zone) of the Northern Apennines collisional belt. There, some of the most important geothermal fields in the world occur (Larderello–Travale, Monte Amiata; Batini et al., 2003), therefore offering the best opportunity to investigate fault zones that played at different crustal levels during the thinning of the previously over-thickened continental crust. LANFs in southern Tuscany were documented since the 60s (Baldi et al., 1994; Bertini et al., 1991; Brogi, 2004a, 2008, Brogi and Liotta, 2008; Calamai et al., 1970; Collettini et al., 2006; Lavecchia, 1988; Lazzarotto, 1967; Lazzarotto and Mazzanti, 1978; 2011; Mirabella et al., 2011). Unfortunately, studies of their architectural features in terms of fault zone geometry, composition, thickness, intensity and distribution of fault-related fracturing, lateral and vertical distribution of cataclasites are few, overall for those structures affecting carbonate rocks. In order to fill this gap, a LANF zone crosscutting carbonate rocks, exposed in an abandoned quarry located near the Rapolano geothermal area (inner Northern Apennines, southern Tuscany, Fig. 1B), has been studied in detail (Fig. 2). Such a structure was not affected by circulation of palaeogeothermal fluids but can be considered a useful analogue of LANFs crosscutting the carbonate geothermal reservoirs in southern Tuscany. Outcrop observation and results of the detailed studies are therefore discussed in terms of fault zone evolution and related permeability features.

2. Geological outline

2.1. The inner Northern Apennines

The Northern Apennines (Fig. 1A) is a fold-and-thrust belt originated from the convergence and collision (Cretaceous–Early Miocene) of the African (Adria microplate) and the European plate, represented by the Sardinia–Corsica Massif (Boccaletti et al., 1971; Castellarin et al., 1992; Faccenna et al., 2001). This geodynamic process determined the eastward stacking of several tectonic units derived from oceanic and epicontinental palaeogeographical domains, composed of, from top to bottom: (a) Ligurian and Subligurian Units consisting of remnants of Jurassic oceanic crust and Cretaceous–Oligocene sedimentary cover involved in multiple thrust-sheets; (b) Tuscan Units including sedimentary (Tuscan Nappe) and metamorphic units ranging in age from Palaeozoic to Oligocene.

The Tuscan Nappe consists of, from the bottom: an evaporitic horizon (Late Triassic, TN_1 in Fig. 1B), a carbonate-siliceous succession (Early Jurassic–Early Cretaceous, TN_2 in Fig. 1B) and a terrigenous succession (Cretaceous–Early Miocene, TN_3 in Fig. 1B). This stratigraphic succession tectonically overlies the metamorphic units (MU in Fig. 1B). Both the Tuscan Nappe and the metamorphic units were imbricated in duplex structures (Brogi, 2004a; Pandeli et al., 1991) and thrusted eastwards over the Umbria–Marchigian units (Carmignani et al., 2001, and references therein). Since the Early/Middle Miocene (Carmignani et al., 1995), the inner zone of the Northern Apennines was affected by extensional tectonics (Barchi, 2010; Brunet et al., 2000; Jolivet et al., 1998) acting coevally with compression in the outer Northern Apennines (Barchi et al., 2006; Elter et al., 1975; Lavecchia et al., 1984) (Fig. 1A). The extension produced significant tectonic elisions within the tectonic pile, modifying the architecture of the Northern Apennines and giving rise to extensional duplexes (crustal boudins) where the collisional structures were preserved (Brogi, 2004b, 2008a). Although extension in the inner zone of the Northern Apennines was a continuing process, two main different styles were regionally recognised (Bertini et al., 1991; Carmignani et al., 1994, 1995). The first was characterised by extensional detachments and low-angle normal faults that gave rise to the crustal boudinage (Baldi et al., 1994; Carmignani et al., 1994) as well as exhumation of the deeper units (Brogi, 2008a). Miocene continental to marine basins developed in the gap between crustal boudins (Brogi and Liotta, 2008). Since Early Pliocene, high-angle normal and transtensional faults crosscut all the previous structures, forming younger tectonic depressions mainly filled by marine to continental sediments (Martini and Sagri, 1993). On the whole, the extensional tectonics produced: (a) thinning of the continental crust and lithosphere in the hinterland of the Northern Apennines (Tyrrhenian Sea and southern Tuscany), resulting in a thickness of about 20–22 and 30–50 km, respectively (Calcagnile and Panza, 1981; Locardi and Nicolich, 1992); (b) a positive regional Bouguer anomaly (Giese et al., 1981); (c) widespread magmatism (Dini et al., 2005; Peccerillo, 2003; Serri et al., 1993); (d) high heat flow (Della Vedova et al., 2001); (e) localised and regional uplift (Dallmeyer and Liotta, 1998).

2.2. Geological setting of the Rapolano area

The Rapolano geothermal area (Fig. 2) is located in the eastern shoulder of the Siena Basin (Costantini et al., 1982), a tectonic depression developed from Middle–Late Miocene to Middle Pliocene (Brogi, 2011). The Siena basin represents the central portion of a broader tectonic depression, about 90 km long and NNW–SSE trending, known as the Siena–Radicofani Basin (Bossio et al., 1993 with references therein) (Fig. 1B). Late Triassic–Early Miocene successions belonging to the Tuscan Nappe, strongly affected by contractional and extensional structures, are widespread exposed (Bambini et al., 2010). In particular, Late Oligocene–Early Miocene East-verging folds and associated reverse