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Permeability and hydraulic conductivity of faulted micaschist in the eastern Elba Island exhumed geothermal system (Tyrrhenian sea, Italy): insights from Cala Stagnone

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ABSTRACT

Estimating values of permeability (k), efficient porosity (P) and hydraulic conductivity (K) by analysing field outcrops as analogue of geothermal reservoirs, is a timely theme useful for predictions during geothermal exploration programs. In this paper we present a methodology providing k, P and K values, based on geometric analysis of quartz-tourmaline faults-vein arrays hosted in micaschist exposed in south-eastern Elba Island (Tuscan Archipelago, Italy), considered as the analogue of rock hosting the so-called "deep reservoir" in the Larderello geothermal field. The methodology is based on the integration among structural geology, fluid inclusions results and numerical analyses. Through a detailed structural mapping, scan lines and scan boxes analyses, we have reconstructed three superposed faulting events, developed in an extensional setting and framed in the Neogene evolution of inner Northern Apennines. Geometrical data of the fault-veins array were processed by reviewing the basic parallel-plate model equation for k evaluation. Fluid inclusion analyses provided those salinity and pressure-temperature values necessary for defining density and viscosity of the parent geothermal fluids. Then, permeability, density and viscosity were joined to get hydraulic conductivity (K). Permeability is estimated between 5×10^{-13} and 5×10^{-17} m^2 with variations among the different faults generation, while the hydraulic conductivity is encompassed between 1.31×10^{-8} and 2.4×10^{-13} m/s. The obtained permeability and hydraulic conductivity values are comparable with those from several geothermal areas, and in particular from the Larderello geothermal field. The main conclusion is that the proposed integrated approach provides a reliable methodology to obtain crucial values, normally obtained after drilling, for developing numerical flow models of geothermal fluid path in active geothermal systems by field and laboratory analyses of analogue, exhumed, geothermal systems.

1. Introduction

Hydraulic properties of rock volumes, in terms of permeability (k), hence efficient porosity (P) and hydraulic conductivity (K) are parameters describing the ability of the rock volume to channel fluids at crustal depth, where primary porosity is negligible and fluid flow is controlled by fracture networks (Sibson, 2000; Rowland and Sibson, 2004; Faulkner et al., 2010, for a review). Determination of such parameters and their variation through time are fundamental issues for both exploration and exploitation of geothermal reservoirs. These are key features to estimate the potentiality of a geothermal system and, consequently, to calibrate the investments and the economic plans (Barbier, 2002).

Hydraulic properties of reservoirs can be directly measured in laboratories (e.g. Preisig et al., 2015; Milsch et al., 2016) and/or extrapolated through boreholes tests (e.g. Peters, 2012; Stober and Bucher, 2014, 2015). The main results highlight that, in general, the permeability (k) decreases with depth, following an almost linear law, as documented in several geothermal fields (Stober and Bucher, 2007), even though local inversions may be found when rock volumes with different mechanical properties are encountered.

Permeability values in active geothermal areas have been directly measured in the range of $10^{-21} - 10^{-12}$ m^2 at depth (Stober and Bucher, 2014 with references therein), although reservoir rocks display

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permeability commonly encompassed between 10^{-14} and 10^{-17} m^2 (Rowland and Sibson, 2004). Nevertheless, it is demonstrated that permeability values are transient (Cox et al., 2001), being controlled by the interplay between tectonic activity (Sibson, 1987; Cox, 1999; Curewitz and Karson, 1997; Rowland and Sibson, 2004; Uysal et al., 2009) and fluid-rock interaction (Fyfe, 1987; Polak et al., 2003; Uysal et al., 2009; Alt-Epping et al., 2013). Generally, these two processes play in opposite directions: the former enhancing permeability, the latter sealing the fractures when precipitation of hydrothermal minerals occurs.

These opposite processes may coexist and/or occur in several repeated cycles implying that permeability in geothermal systems is overall time-dependent (Curewitz and Karson, 1997; Cox et al., 2001; Uysal et al., 2011; Brogi et al., 2012; Brogi et al., 2016). However, permeability evolution through time cannot be recorded by boreholes tests able only to estimate the present condition.

Generally, in hydrocarbon studies, determination of the hydraulic parameters of rock masses are derived from conventional 2D or 3D reservoir simulators (Long and Witherspoon, 1985; Cacas et al., 1990; Odling, 1992; Massonnat and Manisse, 1994; Lough et al., 1997; Bourbiaux et al., 1998; Min et al., 2004), whereas information on fracture array derives from fractal analyses (Miao et al., 2015 with references therein) and/or analyses of fracture data collected on analogue, exhumed, rock reservoirs (e.g. Hausegger et al., 2009; Agosta et al., 2010; Kim and Sanderson, 2010). It is therefore accepted that the results obtained from exposed outcrops can be considered representative even for rock volumes located at depth, although boundary conditions are different. Thus a statistical and/or numerical approach (Lisjak and Grasselli, 2014 with references therein) is commonly applied to foresee the distribution of fractures at depth.

Differently, in analogue, exhumed, geothermal systems, the fracture array that was present during fluid circulation is now defined by veins filled with hydrothermal minerals, indicating the original path through which fluids were channelled at the time and depth of their flow (McCaffrey et al., 1999).

In this paper we describe a methodological approach based on geometrical analyses of hydrothermal (tourmaline-quartz) veins hosted in micaschist belonging to the eastern Elba Island exhumed geothermal system (Fig. 1), and referred to the development of different faults generations. This area is considered the analogue of the about 3–5 km deep reservoir in micaschist presently exploited in the Larderello geothermal system (Batini et al., 2003; Bellani et al., 2004; Romagnoli et al., 2010).

The evolution of the hydrothermal veins, in terms of their spatial distribution (array) and growth through time, was defined by a detailed examination of their crosscutting relationships, mainly based on geometrical analyses through scan line and scan box methodologies applied in selected outcrops, and by mineralogical and fluid inclusion studies. Reassessing the base algorithm for the permeability estimation (Gale, 1982; Cox et al., 2001), the maximum permeability values of the micaschist palaeo-geothermal reservoir have been calculated through time. Jointly, permeability values and pressure-temperature-salinity parameters derived from the fluid inclusion data, have been considered as the key parameters to estimate the palaeo-fluids viscosity, therefore contributing to better constrain several key chemical-physical parameters characterising the palaeo-geothermal field now exposed in the eastern Elba Island. The main results highlight the considerable role of fluctuant fluid pressure in maintaining the permeability within the reservoir. Furthermore, permeability and hydraulic conductivity of the micaschist reservoir estimated for the eastern Elba Island are comparable with those measured in the Larderello geothermal field.

2. Geological setting

The Elba Island (Tuscan Archipelago, Fig. 1) is part of the Northern Apennines inner zone. Northern Apennines is an alpine collisional belt (Cretaceous-early Miocene) deriving from the convergence and subsequent collision between the Adria microplate, representing the Africa plate, and the Sardinia-Corsica Massif of European pertinence (Molli, 2008 for a review). Collision determined the stacking and doubling of oceanic and continental tectonic units deriving from the palaeo-geographic domains of the Northern Apennines (Carmignani et al., 1994; Bianco et al., 2015). Since early-middle Miocene, inner Northern Apennines has been affecting by eastwards migrating extensional tectonics that can be described through two main events (Brogi and Liotta, 2008; Barchi, 2010): (a) the first one (early to late Miocene), characterized by an extension of at least 120% (Carmignani et al., 1994; Liotta et al., 1998; Brogi, 2006), gave rise to low-angle normal faults; this event produced the lateral segmentation of the previously stacked tectonic units and the exhumation of mid-crustal rocks (Liotta et al., 1998; Brogi, 2008; Barchi, 2010); (b) the second event (Pliocene to Present) is differently defined by high-angle normal faults, crosscutting the previous structures, and determining tectonic depressions where Pliocene to Quaternary continental and marine sediments deposited (Martini and Sagri, 1993). The amount of extension is here estimated in about 6–7% (Carmignani et al., 1994). The opening of the Tyrrhenian basin and the present crustal and lithospheric thicknesses, (20–22 and 30–50 km, respectively, Calcagnile and Panza, 1981; Locardi and Nicolich, 1992), are the clearest evidence of the extensional setting.

Since Langhian, the migration of extension is accompanied by magmatism, with an eastward younging direction (Fig. 1), mostly deriving from mixing of crustal and mantle sources (Serri et al., 1993; Peccerillo, 2003). Cooling of late Miocene-Pliocene plutons (such as the Monte Capanne and Porto Azzurro magmatic complexes at Elba Island, Westerman et al., 2004; Caggianelli et al., 2014) determined a widespread epithermal and mesothermal mineralization through Tuscany and Elba Island (Dini, 2003), where ore deposits were exploited for centuries (Fig. 1).

Hence, the high heat flow of Tuscany (regionally above 100 mW/m^2 with local peaks up to $1 W/m^2$, Mongelli and Zito, 1991; Della Vedova et al., 2001) and the presently exploited Larderello and Monte Amiata geothermal fields find a common explanation in this long-lasting active extensional and magmatic framework (Batini et al., 2003).

Thus, in the frame of the eastward extensional and magmatic migration, Elba Island (Fig. 2) is considered a precursor of the present Larderello geothermal system on the basis of the similarities in the geological settings (Trevisan, 1950; Puxeddu, 1984; Bortolotti et al., 2001), magmatic and tectonic evolution (Garfagnoli et al., 2005; Dini et al., 2005).

Furthermore, the structurally deepest rocks of Elba Island are micaschists affected by low-P metamorphism, crosscut by leucogranite dykes (Garfagnoli et al., 2005; Musumeci et al., 2011) and quartz-tourmaline veins (Dini et al., 2008; Viti et al., 2016). These features can be compared with the metamorphic basement drilled at depth (3.5–5 km b.g.l.) in Larderello, was micaschist with overpressured fluids (Cavarretta et al., 1983) were drilled at about 3 km depth.

Low-P micaschist (Garfagnoli et al., 2005) is widely exposed in the Monte Calamita Promontory (Fig. 2). This represents the host-rock of the Porto Azzurro monzogranite (5.9–5.4 Ma, Maineri et al., 2003), whose cooling was accompanied by the activity of a significant hydrothermal system, now exposed in the eastern side of Elba Island. This is testified by the notable variety of hydrothermal parageneses (Dini, 2003). Differently, the hydrothermal system connected to the western and older Monte Capanne plutonic complex (8–6.8 Ma, Dini et al., 2002, Fig. 2) is almost completely eroded.

3. Rock fabric

The Monte Calamita micaschist derives from a pelitic protolith of Cambrian to Ordovician age (Musumeci et al., 2011; Sirevaag et al., 2016). It is intruded by tourmaline-rich leucogranite dykes (Fig. 3a) and quartz-tourmaline veins, the latter related to the cooling stage of