FRACTURES AND MINERALIZING FLUID PATHS IN THE EASTERN ELBA ISLAND EXHUMED GEOTHERMAL SYSTEM (ITALY)

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The circulation and storage of geothermal fluids in the continental crust is mainly controlled by structures associated to the brittle deformations in the upper part of the crust, particularly during extensional processes accompanied with magmatism. This study aims to reconstruct the relationships between continental structures and hydrothermal fluids flow at different structural levels in a thinned continental crust, from levels located nearby the brittle-ductile transition (4-6 km) to the shallower ones.

The study area is the eastern side of the Elba Island, corresponding to an exhumed crustal sector of inner Northern Apennines (Carmignani *et al*., 1995), that experienced lithosphere thickening (see Molli, 2008 for a review) up to HP-LP conditions (late Oligocene-early Miocene, Jolivet *et al*., 1998; Rossetti *et al*., 2002; Bianco *et al*., 2015) and subsequent thinning since Miocene, due to the development of post-collision extensional tectonics (Carmignani *et al*., 1994). Extension, from late Miocene to Pleistocene, is joined to magmatism (Serri *et al.*, 1993; Pertusati *et al*., 1993; Dini *et al*., 2002, 2005, 2008b; Brogi *et al*., 2005a, 2005b; Liotta *et al*., 2015).

In this framework, the geological evolution of Elba Island is characterized by two main magmatic bodies (Monte Capanne and Porto Azzurro plutonic complexes), emplaced at 6-7 km depth, whose cooling favoured the circulation of hydrothermal fluids (Tanelli, 1983; Dini *et al*., 2002, 2008b).

The emplacement of these magmatic bodies was favoured by the contemporaneous extensional tectonics that gave rise to normal faults and associated transfer-zones, mainly consisting of SW-NE trending sub-vertical transtensional faults (Dini *et al*., 2008b; Liotta *et al*., 2015).

The Porto Azzurro monzogranite (5.9 Ma, Maineri *et al*., 2003) is partly exposed, in limited outcrops, in the eastern side of the Elba Island, whereas its thermometamorphic aureole, affecting micaschist deriving from a Palaeozoic protolith (Duranti *et al*., 1992; Garfagnoli *et al*., 2005; Musumeci *et al*., 2011), is broadly exposed especially in the southeastern part of the island (*e.g.*, Monte Calamita). The hosting micaschist belongs to the deeper unit described for the Elba Island (Garfagnoli *et al*., 2005), which is overlain by other tectonic units of continental and oceanic pertinence (Pertusati *et al*., 1993; Bortolotti *et al*., 2001a, 2001b; Bianco *et al*., 2015). Biotite isopleths derived from SEM analyses of a sample of micaschist collected in the Cala Stagnone area, show that the micaschist equilibrated at a temperature ranging between 540 and 580 °C and at a pressure comprised between 1600 and 1900 bars. Considering these values, the basement outcropping at Cala Stagnone area was originally located at a depth in the order of 6-7 km.

During the emplacement and cooling of the Porto Azzurro pluton, the whole tectonic pile was permeated by geothermal fluids, which were mainly channelled along fault zones. These fluids gave rise to the well-known Fe-ore deposits (mostly pyrite and hematite; Benvenuti *et al*., 2001; Maineri *et al*., 2003; Dini, 2003) and quartz-tourmaline veins, mainly developed within the micaschist nearby the intrusive body (Dini *et al*., 2008a; Mazzarini *et al*., 2011).

Given this geological setting and its analogy with the one described for Larderello geothermal area (Puxeddu, 1984; Gianelli & Ruggieri, 2002), eastern Elba Island is considered the exhumed analogue of the Larderello active geothermal field.

In this view, the research activity has been addressed to the reconstruction of structural (geometry and kinematics of faults, fracture network) and hydraulic parameters (secondary permeability, efficient porosity) and fluids features (temperature and salinity) characterising the palaeo-geothermal system by analysing five key areas. These latter have been selected as follows, being representative of different structural and geothermal features: *i*) areas located nearby the Porto Azzurro magmatic body, characterized by tectonically controlled

tourmaline-quartz mineralization (Cala Stagnone and Morcone areas); *ii*) areas located nearby structural conduits at shallower levels, mainly characterized by hematite/pyrite mineralized low- and high-angle faults (Terra Nera, Topinetti and Valle Giove areas).

In all selected areas, analyses of mineralization and hosting rocks and detailed structural and kinematic analyses have been carried out. Key outcrops were also identified for the reconstruction of the fracture network and associated hydraulic parameters. Fluid inclusions analyses of quartz and adularia single crystals and/or mineralized veins, have been done in order to get information on the main chemical-physical properties of the parent fluids, and to define the evolution of geothermal fluids in terms of their salinity and temperature, both largely influenced by their origin (magmatic, meteoric, or a mixing of both).

The structural and kinematic study has been based on the classical approach of the structural geology and detailed structural maps (1:100 scale) were performed for each study area. The mineralized veins network, associated with the main structures, was reconstructed through scan-lines and scan-boxes measurements, opportunely collected in key sectors of the analysed outcrops. The palaeo-permeability reconstruction was obtained by means of geometrical parameters (*i.e.*, length, minimum and maximum width, and frequency of each mineralized shear veins) measured through the scan-box (area 40×40 cm^2) methodology. The secondary permeability was computed using a theoretical approach, tested in this thesis, and deriving from the revision of the algorithms of Gale (1982), Nicholl *et al*. (1999), Zimmerman & Bodvarsson (1996). The main results indicate that the geothermal fluids producing the main mineralizations (tourmaline and Fe-ore deposits) were controlled by fracture systems associated to three different faults generations. These latter are characterized by different geometrical and kinematics features but can be reconciled in a common extensional tectonic framework characterising the Elba Island and the northern Tyrrhenian Sea during the Neogene.

Secondary permeability (k) values from the analysed areas range from 10^{-17} m^2 and 10^{-12} m^2, with the majority encompassed between 10^{-14} and 10^{-13} m^2. These values are comparable with those obtained for active geothermal systems worldwide.

Fluid inclusions analyses highlighted that differences of salinities and temperatures characterize the geothermal palaeo-fluids in the different areas and are representative of the different structural levels. At the deepest level (Cala Stagnone), Th values indicate a range between 250 and 540 °C with salinity encompassed between 10 and 47 wt.% NaCl eq. (Image Periodic Report, 2015; Rimondi *et al*., 2015a; 2015b; Zucchi *et al*., 2016, 2017). Differently, moving on the shallow structural levels, the Th tends to decrease (< 400 °C) with a variable salinity that does not exceed 31 wt.% NaCl eq.

These features may suggest primary fluids of magmatic origin that were progressively contaminated by fluids with low-salinity (probably of meteoric origin).

The permeability and related geothermal fluids circulation, independently by fluids origin and chemical-physical properties, were guaranteed by a continuous tectonic activity that operated at the different structural levels. This is supported by evidence of syn-tectonic mineralization recognised in the whole area and, in addition, by evidence of paleoseismicity as documented for the normal faults representative of the deeper structural level. These faults show traces of frictional heating at seismic slip rate, indicating thermally-activated processes, and involving both interstitial goethite and tourmaline. Tourmaline clasts were furthermore included in a partial decomposition at grain boundaries. The results of this study are published in Viti *et al*. (2016).

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