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Insights into the Larderello Geothermal Field: Structural Setting and Distribution of Thermal and ^{3}He Anomalies

S. Bellani*, G. Magro*, A. Brogi**, A. Lazzarotto**, D. Liotta***

* CNR-Istituto di Geoscienze e Georisorse, Pisa, Italy **, Dip.Scienze Terra, Siena, Italy***, Dip.Geologia e Geofisica, Bari, Italy

sbellani@igg.cnr.it, g.magro@igg.cnr.it, brogiandrea@unisi.it, lazzarotto@unisi .it, d.liotta@geo.uniba.it

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ABSTRACT

In the Larderello geothermal field, similarly to the other geothermal areas in the world (i.e. Yellowstone, The Geysers, Rhinegraben), heat flow at a regional scale anomaly corresponds to the presence of ^{3}He enriched fluids. At least in the last one million years in a typical crustal melting setting, high R/R_a values (ranging from 0.5 to 3.2) in present and inclusion fluids indicate mantle as the main source of the thermal and ^{3}He anomaly.

The combination of thermal and He data provide information on transport mechanism in upper and lower crust, which is strongly controlled by fault systems.

A targeted geological section of the Larderello field, integrating field, borehole and reflection seismic surveys data correspond to shear zones, where upward displacement of isotherms correspond to the NE-dipping normal fault system.

At surface, higher R/R_a values correspond to heat flow maxima, though slightly biased in space in the order of 1 - 2 km, and indicate that fault systems act as preferential pathways for mantle-derived fluids. The similar evolution in time and space of heat and ^{3}He anomalies, even though they differ by at least 1-3 orders of magnitude in diffusion time constants, indicate that they share sources and transfer mechanisms. Mantle-He transfer through the crust requires fluid advection or diffusion via fluid filled conduits while heat is more efficiently transferred by conductivity through the bulk rocks, enhanced by fluid circulation in the upper brittle crust. The local addition of an advective component to the regional background thermal anomaly caused by increased permeability along faults could explain the presence of maxima of thermal and ^{3}He anomaly at Larderello.

1. INTRODUCTION

The Larderello field (Fig. 1) is located in the inner side of northern Apennines belt (Tuscany, Central Italy), where extensional tectonics have been active since the early - middle Miocene, accompanied by a widespread Late Miocene-Quaternary magmatism. Magmas are derive from mixing of crustal and mantle sources (Innocenti et al., 1992). A wide thermal anomaly characterizes most of the Tuscany region, where more than 30% of Italian spas are concentrated. The background long wavelength heat flow anomaly has average values of 150-200 mW/m^2, by far higher than the average value of 50-60 mW/m^2 of surface heat flow in a continental area. The maxima of heat flow anomaly in the Larderello field reach up to 1000 mW/m^2. As a general rule, thermal anomalies are very often related to the presence of mantle-derived ^{3}He-enriched fluids, indicating the mantle as the main heat source that triggers convective and advective fluid movements in the upper crust.

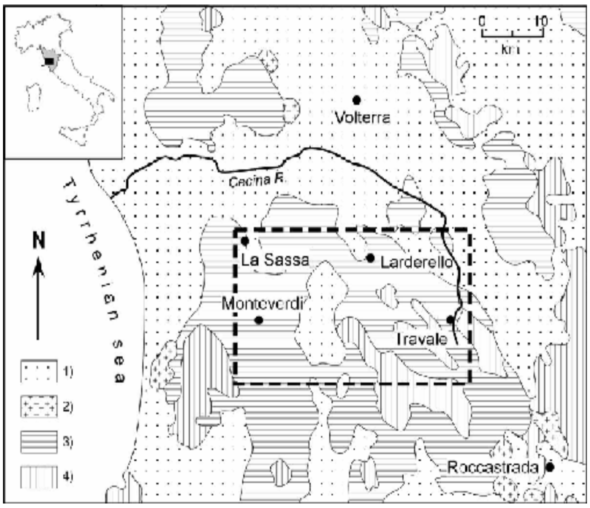

Figure 1. Location map and generalized geological map of the area: 1) Continental and marine sediments (Late. Miocene - Middle Pliocene); 2) Igneous rocks (Pliocene - Quaternary); 3) Jurassic oceanic crust and its Cretaceous - Eocene sedimentary cover; 4) Potential reservoir formations (Mesozoic Carbonatic rocks and, Metamorphic rocks).

In this paper in order to investigate the relationship between crustal structures and deep fluid circulation, we compare the distribution at surface of R/R_a, which is a sensitive geochemical tracer of source, with heat flow and other geophysical and structural parameters like Bouguer anomaly and Pliocene, present normal fault distribution. These faults tend to sole out in a regional high-amplitude discontinuous reflector with local “bright spot” features, namely K-horizon, that mark the top of the reflective crust (Cameli et al., 1993). It is largely accepted that the reflectivity of this horizon is related to entrapped fluids in fractured levels. K horizon tops at ~ 3 km depth at Larderello and defines the upper boundary of an active shear zone located at the top of the brittle-ductile transition (Liotta and Ranalli, 1999).

More than one hundred He isotopic composition data of fluids from geothermal wells (Poliak et al., 1978; Nuti, 1984; Hooker et al., 1985; Magro et al., 2003), natural thermal manifestations (Minissale et al, 1997; Minissale et al., 2000) and thermal data from three hundred gradient wells and deep geothermal wells (Baldi et al., 1995) have been digitized and re-processed to cross-correlate the knowledge on the geothermal system.

2. DISCUSSION

On a regional scale, a correlation has been found between the R/R_a, heat flow, and Bouguer gravity anomaly spatial distributions. The iso-contour lines of R/R_a, constructed by adding the R/R_a values of Tuscany gas manifestations to the geothermal well data, are compared to the surface heat flow (HFD), the Bouguer gravity anomaly and the isobaths of the "K-horizon" (fig.2).

The correspondence among high values of R/R_a, heat flow and low Bouguer anomaly values indicate that the Larderello field is the area of preferential escape for mantle-derived fluids of the whole Tuscany. Although there are no outcrops of extrusive rocks in the Larderello geothermal field, felsic dykes and granitic bodies encountered in boreholes at different depths clearly indicate that magmas derives from mixing of mantle and crustal source. Moreover, the correspondence between heat flow maxima and Bouguer gravity anomaly minima accounts for the presence of a deep magma chamber (Gianelli et al., 1997).

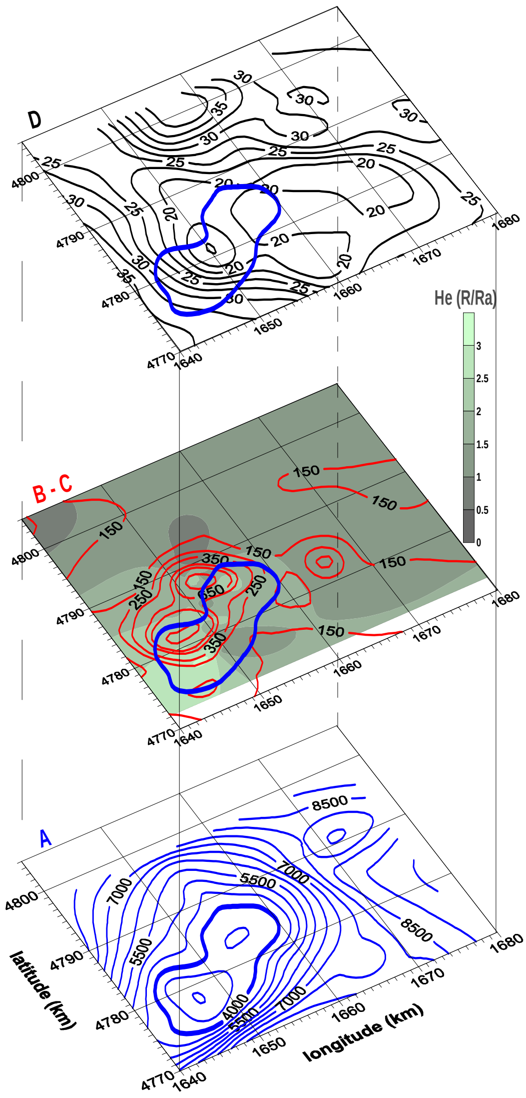

Figure 2 – Regional comparison among K-horizon seismic reflector isobaths in mbgl (A), R/R_a (B), surface heat flow in mW/m^2 (C), and Bouguer gravity anomaly in mgal (D) for Larderello and neighbouring areas. Heat flow and Bouguer anomaly data (modified) after Baldi et al. (1994, 1995); K-horizon isobaths after Barelli et al. (2000); R/Ra data after Magro et al. (2003).

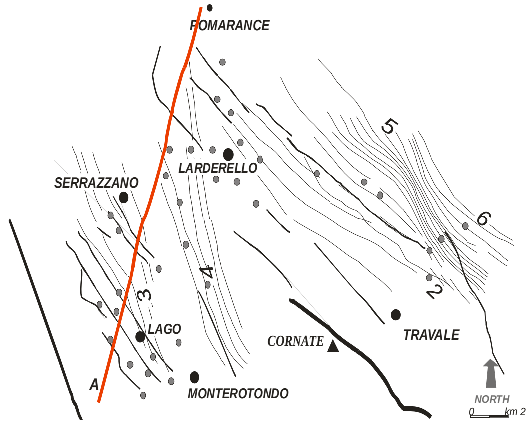

Figure 3: Generalized structural map of the Larderello geothermal area with isobaths of three extensional shear zones with depth values (km). Line A denotes the geological section shown in fig. 4.

The almost constant R/R_a values in the last 1 Ma (Magro et al., 2003) requires hot fluid refilling from the mantle as the most likely source of ^{3}He-enriched fluids and of the long wavelength component of the heat flow anomaly.

At the scale of the field (approximately 20x20 km, see Fig.2), the R/R_a distribution shows two relative maxima elongated in the NE-SW direction. A relative minimum follows the north-eastward maximum. A positive correlation has also been found between the R/R_a spatial distribution and the ''K horizon''. This may identify the areas inside the field where rapid uplift of fluids of mantle origin allows the existence of relatively high R/R_a values in a typical crustal melting environment. For the view of depth into the field, a profile of R/R_a and HF was drawn on a targeted geological section (line a in fig.3). The geometry of the normal faults down to depths of 4-5 km is constrained by field, borehole and reflection seismic data (Brogi et al., 2003). This NNE-SSW trending section crosses the Larderello geothermal field from Serrazzano and Pomarance Pliocene Basins, to the Lago geothermal area. Pliocene-Present N-E dipping listric normal faults characterize the structural setting of Larderello.

Reflection seismic data indicate the coalescence of faults into brittle shear zones (fig. 4). (Brogi et al.,2003). Three different extensional shear zones are recognizable in the Larderello area (fig. 3). The K-horizon loses its reflectivity at the intersection between these shear zones and the brittle-ductile transition. This accounts for fluid migration from the K-horizon toward the surface, along the brittle shear zones. Along this section, the R/R_a and heat flow trends at surface evidence a shift between the R/R_a and heat flow maxima. The R/R_a reaches the relative maximum of the whole Larderello geothermal field along this section (fig.4). The highest R/R_a values are found in fluids from wells intercepting the normal listric faults rooted in the shear zone in correspondence to the K-horizon culmination.

Intermediate to low values of R/R_a are recorded mostly in the wells tapping the shallower cataclastic reservoir (crossed by normal faults), where long term fluid circulation and water-rock interaction enhances the extraction of ^{4}He derived from U and Th decay and entrapped in crustal rocks accounting for the R/R_a decrease. Thus, the shallow cataclastic reservoir acts as a structural trap for He.

Mantle He transfer through the crust requires fluid advection or diffusion via fluid filled conduits, while heat is transferred both by conduction through the bulk rocks and by fluid circulation in the upper brittle crust. Hence, in areas where intense faulting increases secondary permeability, heat transfer is enhanced by fluid advective/convective circulation. The addition of an advective component to the regional background thermal anomaly could explain the presence of maxima of thermal and ^{3}He anomaly at Larderello. Roughly in correspondence to the shear zone, and the shift between He and heat flow maxima at the surface (fig. 4), it depends on the normal fault geometry governing the fluids pathways.

3. CONCLUSION

The high heat flow coupled with ^{3}He enriched fluids at surface indicates that in Tuscany in general and in Larderello field in particular the mantle is the main source of heat and He anomalies.

It has to be noted that the highest R/R_a values are reached in the area of Larderello where a shear zone breaks the K horizon. This suggests that the K-horizon could act as a boundary layer for He while being an important heat reservoir.

The combination of geophysical, structural and geochemical data provides information on transport mechanism in upper and lower crusts.

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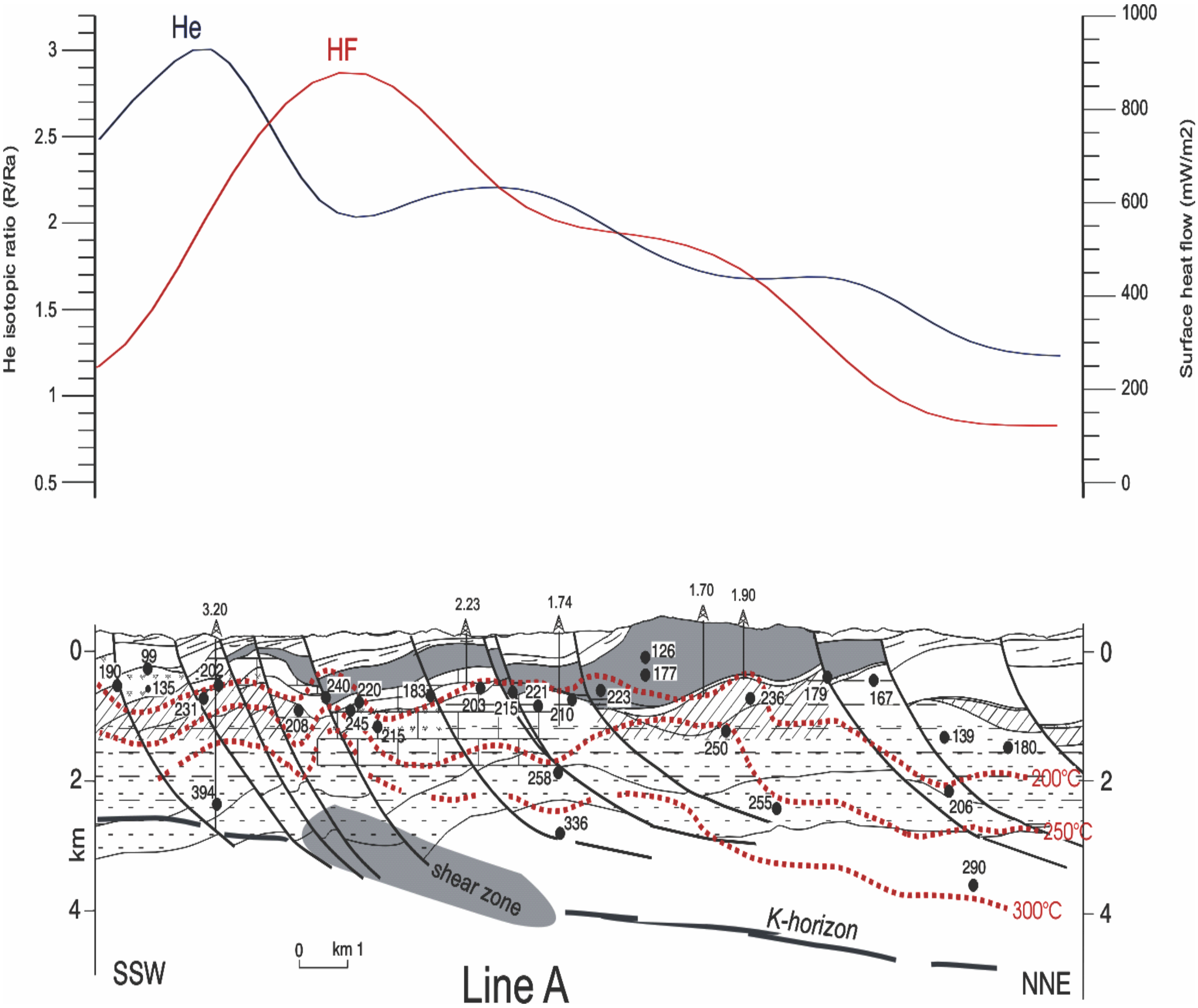

Fig.4 The R/R_a and HF patterns are overlaid on the cross section (line a in fig.3) from SSW (Lago area) to NNE (Serrazzano and Pomarance basins) drawn to the K-horizon depth. Red dotted curves are isotherms in °C. Cross section and isotherms after Bellani et al. (2004).