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The Deep Roots of the Larderello Geothermal Field (Italy) from Heat Flux and ^{3}He anomalies

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Introduction: Several known geothermal areas in the world show heat flux (HF) anomalies positively related to the presence of ^{3}He enriched fluids in the upper continental crust, indicating a direct mass and heat input from the mantle. The Larderello geothermal field (Fig. 1) exhibits a surface HF locally around 1W/m^2 and geothermal fluids enriched in mantle-derived ^{3}He. The R/Ra ranges from 0.5 to 3.2 in present-day fluids and in fluid inclusions (Magro et al., 2003) indicating the upper mantle as the main active source for the crust thermal and ^{3}He anomalies. The R/Ra distribution at surface reflects the dynamic balance between crustal derived and mantle derived fluids.

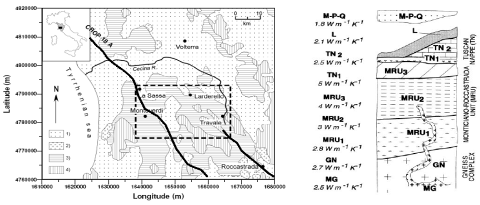

Fig.1 - Left: index geological map of the area. (1) Neoautochtonous sediments . (2) Igneous rocks. (3) Allochtonous flysch. (4) Potential reservoir formations (Tuscan Nappe, Tectonic Slices, Metamorphic Units). Dashed box: study area. Lines: deep seismic profiles. Right: Tectono-stratigraphic units of the Larderello area. Associated thermal conductivities in lab conditions on the left.

Geological setting. The Larderello geothermal field, one of the few vapor-dominated geothermal systems in the world, is considered as a single, large hydrothermal system recharged by meteoric waters and heated from deep magmas intruded into a thinned continental crust.
Pliocene-Present NE dipping normal faults characterize the structural setting of Larderello: according to various authors, the faults might coalesce at depth into brittle shear zones. Normal faulting was coeval to an uplift of the area of the order of 1 km.
In the last 10-15 years, the area was investigated by several seismic reflection profiles down to 4-5 km depth and by two deep crustal seismic reflection profiles (Figs. 1,2): CROP 18A and 18B. The CROP profiles show as the crust underlying the Tuscan area is characterized by a complex and structured upper part, an intermediate less reflective part and a highly reflective mid-lower portion, bottomed by a laminated Moho discontinuity at 22-24 km depth.
The bottom of the uppermost reflective part is marked by a discontinuous high amplitude reflector, (K-horizon), which tops at about 3-5 km in correspondence of the geothermal areas, and deepens moving outwards. A deeper reflector (K-2), was imaged at about 7-9 km depth on the basis of AVO analysis. The origin of the K-horizons reflectivity is still discussed, with two main possible interpretations: the upper K-horizon could be the top of the brittle-ductile transition, with presence of over-pressured fluids, or they could both top permeable reservoirs containing high pressure supercritical fluids.

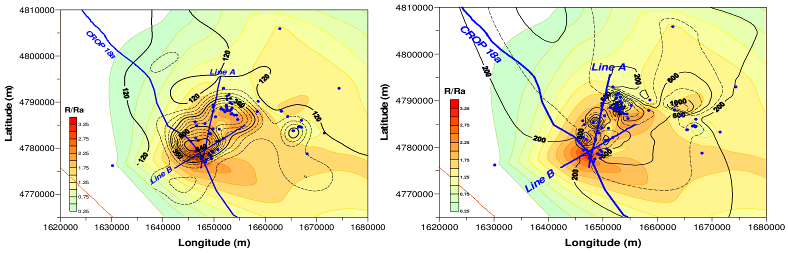

Fig.2 - a) Comparison of HF (black curves), b) He relative abundances (black curves) and R/Ra (color scale filled contours) contour maps. Blue lines: tracks of seismic profiles. Blue squares: gas sampling locations

Results and discussion: The Larderello–Travale area is covered by a wide set of borehole temperature data. A large data set of He isotopic composition (R/Ra) and He relative abundance (F(^{4}He)) are also available in fluids from Larderello geothermal wells and from free gases of the surrounding areas. All these data were used to produce contour maps of the HF density and of the He distribution at surface (Figs.2a-b).
The peaks of R/Ra and F(^{4}He) are shifted by about 8-10 km, indicating that high values of He relative abundance are isotopically marked by the lowering of R/Ra. The HF maximum almost coincide with R/Ra maximum with a slight shift (roughly 2-3 kilometers). The thermal anomaly is thus supported by upper mantle heat and mass flows, as clearly indicated by the highest R/Ra ratio of the whole Tuscan region.

Two-dimensional thermal modeling: A simple 2-D thermal model was constructed on the basis of the seismic data to provide a set of numerical models, to be compared with experimental borehole temperature and surface HF density data. We modeled the regional conductive heat transfer in the upper 8-10 km of the crust first and, secondly, superimposed local heat sources, to account for the advective heat contribution. Heat production from radioactive decay was neglected.
The 2-D regional conductive model was realized by means of a steady-state forward simulation, under the assumption of a purely conductive heat transfer (RECTAN finite differences code). We produced two sets of models, combining together the parameters and assumptions (Table 1) which maximize and minimize, respectively, the surface HF output to be compared with the experimental data.
The code was set to run for about 3.5 Ma, according to the age of the magmatic events in the area.
Since the simulated steady-state conductive surface HF was ranging between 120 and 150 mWm^{-2}, we superimposed local additional internal heat sources, to simulate the advective and/or convective HF components and to partly account for both the T borehole data and the surface HF anomaly.

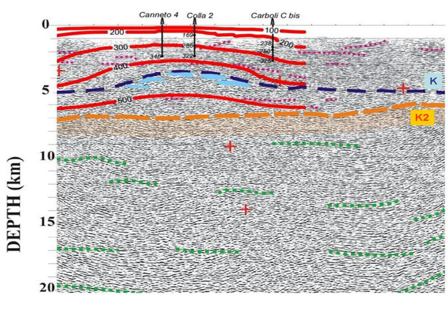

Fig.3 - Isotherms (°C) calculated with 2D modeling superimposed on pre-stack depth migrated section of the Larderello part of seismic profile 18A. Blue line: K-horizon; orange line: K2-horizon; light-blue areas: overpressured fluid traps; red crosses: magmatic intrusions. Dotted pink and dotted green lines: shallow and deep reflections, respectively. T data from three deep wells are shown for comparison.

Materials	*K (T=20°C) (W m^{-1} K^{-1})*	*T(z) (°C)*	*K (MIN) (W m^{-1} K^{-1})*	*K (MAX) (W m^{-1} K^{-1})*
Neogene sediments	*1.8-2.0*	*30-50*	*1.8*	*2.0*
Ligurian Units	*2.0-2.5*	*40-80*	*1.9*	*2.4*
Tuscan Nappes	*2.0-3.0*	*100+*	*1.6*	*2.3*
Evaporites	*5.0-6.0*	*100-150*	*3.8*	*4.5*
Verrucano Group	*3.5-4.5*	*150-200*	*2.8*	*3.6*
Pal. Phyllites	*2.0-3.0*	*250-300*	*1.7*	*2.2*
Pal. Micaschists	*2.6-3-2*	*300-350*	*1.9*	*2.15*
Upper basement	*2.6-3-2*	*400+*	*1.7*	*1.85*
Lower basement	*2.8-3.2*	*450-500*	*1.6*	*1.7*

***Table 1** – Physical properties and materials of the 2-D thermal model along the NW half of the CROP 18A profile. Temperatures from deep geothermal wells and/or downward extrapolations. K values corrected for temperature effect.*

The results of the 2-D modeling along the CROP 18A profile match reasonably well the temperature distribution within the upper few kilometers of the crust (Fig. 3), if we superimpose three relevant additional heat sources onto the modeled section (see profiles) :
1) a deep source at about the depth (7-9 km) of the base of the reflective layer below the K2-horizon; this source contributes up to 100-150 mWm-2 to the surface HF anomaly (long wavelength regional anomaly);
2) an intermediate source at about the depth of the upper "K" horizon reservoir (fluid reservoirs and magma bodies at about 3-4 km): it brings the total surface HF anomaly up to 300 mWm^{-2};
3) very shallow and spotty sources (fluid traps at about 1-2 km) that boost the total surface HF anomaly up to 700-800 mWm^{-2} (very short wavelength local anomalies).
In the Larderello geothermal field, the young and active igneous and tectonic activity is imaged in the wavelength of the surface HF anomalies; it suggests predominant advective/convective fluid and heat fluxes, creating very locally the complex and faulted geothermal field. This intense and short wavelength anomaly is sitting on top of a long wavelength regional HF anomaly, dominated by conduction.

The structural control on Heat and Helium anomalies: The HF, R/Ra and ^{4}He relative abundance trends are superimposed on the interpreted seismic sections of line A (fig.4a) and line B (fig.4b), where the isotherms are clearly influenced by hydrothermal circulation through the faults system (Bellani et al. 2004).
The highest R/Ra values were measured in fluids from wells intercepting the normal faults rooted into the culmination of the K-horizon, which confines the over-pressured fluids fed by upper mantle contributions. Intermediate to low values of R/Ra, corresponding to the maximum HF and to the increase of F(^{4}He) (fig. 4), image mostly the fluids from the wells tapping the shallower cataclastic reservoir (crossed by normal faults and likely in connection with meteoric recharge).
The ^{4}He excess must be related to long-term fluid circulation and water-rock interaction enhancing the extraction of ^{4}He derived from U and Th decay and entrapped in crustal rocks. The reservoirs capped by the K-horizons and the shallow cataclastic reservoirs act hence as structural traps for radiogenic He, accounting in this way for the R/Ra decrease, which becomes more significant moving away from the main network of discharging fractures.

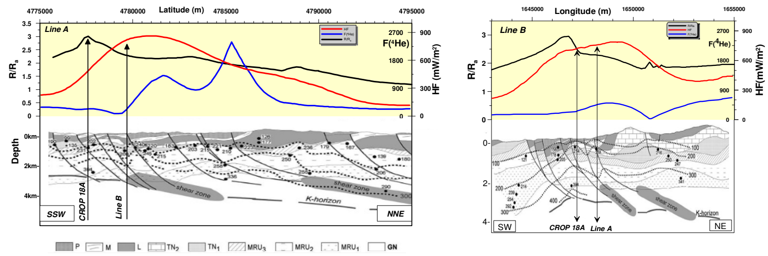

Fig.4 a-b - Bottom panel: Interpreted seismic line A and B (see Fig.2). Isotherms (dotted lines) drawn according to borehole T data (full dots with T values in °C; after Bellani et al., 2004). Top panel: Distribution of HF, R/Ra and F(^{4}He) along the profile. Arrows: interception of the seismic lines.

The R/Ra reaches the relative maximum of the entire Larderello geothermal field near the intersection between lines A and B and CROP 18A (fig.6). The reflective layer below the K2-horizon likely defines the brittle-ductile transition, that must be regionally located at 8-9 km depth in the Larderello and Mt. Amiata geothermal fields, where the temperature exceeds 500 °C (Della Vedova et al., 2008).
The K-horizons confine fluid-filled crustal zones and act as boundary layers, where ^{3}He enriched fluids rising from depth mix with crustal derived fluids enriched in radiogenic ^{4}He. Depending on secondary permeability, these fluids might spread laterally, invading larger rock volumes.

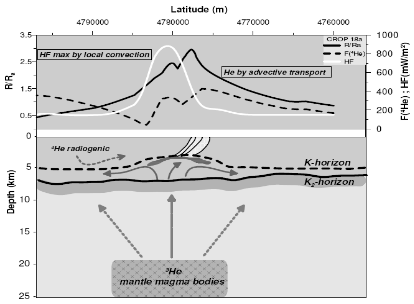

Fig.5 - Bottom panel: sketch map of Crop 18A profile, modified after Accaino et al., (2005). The K and K-2 horizons, as well as the reservoirs with overpressured fluids (dark grey areas below K-horizons) are shown. The fault system (black curves in light grey area) is drawn in correspondence of Crop 18A and line A intersection. Top panel: Distribution of HF, R/Ra and F(^{4}He) along the profile.

Remarkably, the highest R/Ra values are reached in the area of Larderello where extensional structures likely break through the K-horizon. Relatively high R/Ra values in regions with little or no recent extrusive volcanism imply differential uprising of mantle ^{3}He enriched fluids to the surface. This is an indicator of secondary crustal permeability, required to drive and sustain extensional geothermal systems.

Concluding remarks: The thermal modeling of the different surface HF components allowed to identify their source processes which, in turn, account also for the different fractions of He: ^{3}He-enriched fluids are related to long wavelength HF anomalies, whereas short wavelength thermal anomalies are related to ^{4}He enriched fluids derived from heating and degassing of crustal rocks.
The R/Ra distribution at surface is the result of a dynamic balance between crustal derived and mantle derived fluids, partially homogenizing at the K-horizons. The geometry, nature and vertical permeability of the K-horizons rule the deep hot fluid transfer towards the surface, creating fluid reservoirs that episodically escape through fault systems when the overpressure wins the sealing cap rocks.
This implies the He isotopic composition in the Tuscan area to be strongly dependent on the crustal fluid dilution and homogenization at the K-horizons, and to be highly influenced by the drainage depth of the feeding channels. The presence of fluid-homogenizing reservoirs introduces an important constraint for the extrapolation of the primitive signature of the mantle beneath central Italy.

References:
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