“2-D thermal modelling in the geothermal areas of Tuscany, Italy

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The lithospheric extension affecting the Tuscan-Tyrrhenian domain represents one of the most relevant and recent tectonic processes within the entire Alpine-Mediterranean deformation area. The heat input from the mantle is responsible for the presence of large geothermal resources at accessible depths in the crust, as testified by temperature and heat flow anomalies, locally extremely high (Figs. 1-3). Despite intensive exploration and exploitation drilling programs carried out in Tuscany, mainly since the ‘70s, the nature, physical properties and structure of the intermediate and lower crust and of the upper mantle are still debated.

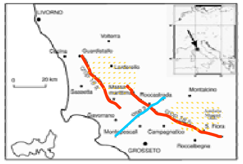

Fig. 1 – Location map

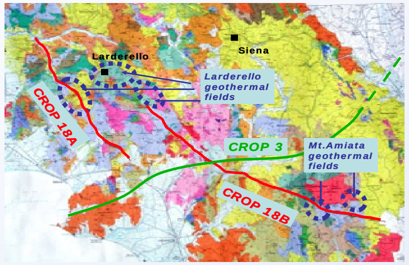

Fig. 2 – 1:200000 geological map and location of seismic profiles

The available dataset for the Tuscan area was significantly improved by the acquisition of the deep crustal seismic reflection profiles (CROP Profiles), in the mid ‘90s. The profiles CROP 18A (~42 km long) and 18B (75 km), crossing NW-SE wards the hgh enthalpy Larderello and Monte Amiata geothermal fields, and the CROP 03 profile (~70 km in its Tuscan part), intersecting with W-E direction the CROP 18B, were recently reprocessed to better characterize the crustal and upper mantle structures of the entire Tuscan geothermal area.

The results show new remarkable and interesting features, i.e.: the presence of extensional structures below the “K Horizon” (a regional high-amplitude reflector discontinuously underlying at a 3 – 8 km depth the whole region, with culminations in correspondence of the geothermal areas); a second deeper and more continuous similar horizon (“K2”); mantle intrusions; strong reflectors in the lower crust and a discontinuous crust/mantle transition with possible underplating. Accurate analyses of the seismic attributes suggest the presence of fluids/melts from the “K Horizon” down to about 10 km depth.

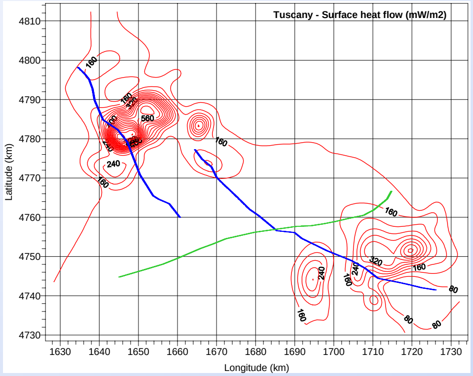

Fig. 3 – Surface heat flow map of Tuscany: data from over 350 gradient wells and deep geothermal wells since mid –’60s to late ’90s, digitized and re-processed.

These new data were put into a <u>simple and conceptual 2-D model</u>, aimed to provide a set of preliminary thermal models, to be compared with the experimental borehole temperature and heat flow data. <u>The 2-D numerical modelling followed a two-steps process</u>: first, modelling the regional conductive heat transfer in the upper 10-12 km of the crust and, secondly, superimposing local advection, in correspondence of the geothermal fields (Fig. 4; Table 1).

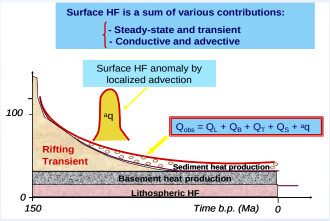

Fig. 4 – Contributions to surface heat flow

- Geometry from CROP transects, model base from R_P/R_S
- Forward modelling of MIN. – MAX. scenarios
- Finite differences scheme (RECTAN code)

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 – Thermal models: geometry and materials

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. The unknowns are the basal heat flow and the thermal properties of the crustal rocks, whereas the results are the temperature distribution with depth and the surface heat flow. To account for the uncertainties in the physical properties of the crustal rocks we produced <u>two sets of models</u>, using the parameters and assumptions which maximise and minimise, respectively, the surface heat flow output to be compared with the experimental data. <u>Local heat transfer by advection was introduced in the upper crustal structures of the geothermal fields, where the CROP seismic profiles were indicating presence of fluids</u>. (Figs. 5-9). The temperature, depth and extension of these reservoirs can explain most of the present extremely high surface heat flow anomalies.

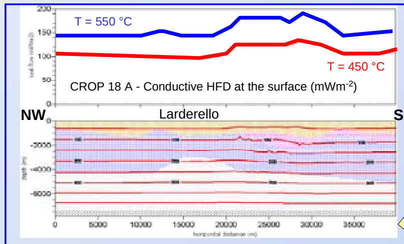

Fig. 5 – **<u>Crop 18 A profile</u>**: temperatures and surface heat flow calculated assuming a purely conductive heat transfer, with constant temperatures at base: 450 °C or 550 °C. Only the 550 °C isotherms set is shown.

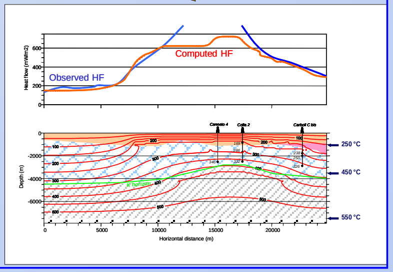

Fig. 6 – Temperatures and surface heat flow for the **<u>western part of the Crop 18 A profile (including Larderello area)</u>**, calculated inserting in selected areas of the profile (see right axis of the figure) temperatures from deep geothermal wells and from the literature (Liotta and Ranalli, 1999; Della Vedova et al., 2001; Bellani et al., 2004) to force the isotherms and the heat flow profile to simulate the advective and/or convective heat flow component. Thermal data from three deep geothermal wells are reported for comparison.

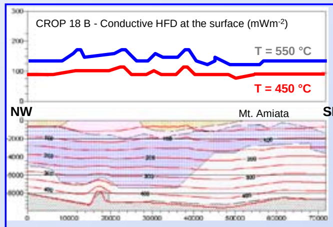

Fig. 7 - **<u>Crop 18 B profile</u>**: temperatures and surface heat flow calculated assuming a purely conductive heat transfer, with constant temperatures at base: 450 or 550 °C. Only the 550 °C isotherms set is shown.

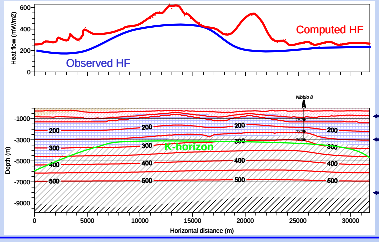

Fig. 8 – Temperatures and surface heat flow for the **<u>eastern part of the Crop 18 B profile (including Mt. Amiata area)</u>**, calculated using thermal data from deep geothermal wells and from the literature, as described in Fig. 6 caption. Temperatures from a deep geothermal well are reported for comparison.

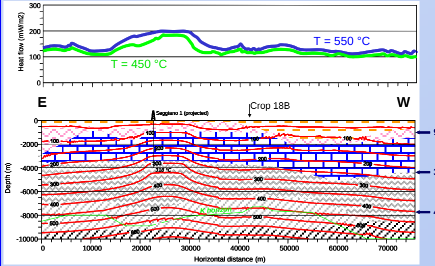

Fig. 9 – **<u>Crop 03 profile</u>**: temperatures and surface heat flow, calculated using thermal data from deep geothermal wells and from the literature, as described in Fig. 6 caption. Temperatures from a deep geothermal well from the nearby Mt. Amiata geothermal field (~ 8 km) are projected for comparison. Note the decrease of T gradients with depth and the deepening of the “K horizon” along this profile that does not cross the two main geothermal areas of Tuscany.

FINAL REMARKS:

- **Simple 2-D thermal modelling revealed to be useful to test conceptual models**
- **Three main heat sources are proposed to contribute to surface HF:**
  - **- deep source (7-9 km): → HF anomaly up to 100-150 mW m^{-2}**
  - **- source at “K” (3-4 km): → total HF anomaly up to 300 mW m^{-2}**
  - **- shallow source (1.0-2.0 km): → total HF anomaly up to 700 mW m^{-2}**
- **Wavelength + intensity of surface HF and borehole T data suggest changing T along “K horizon”**
- **A deeper “K2” at 7-9 km is likely more isothermal and might be closer to Brittle/Ductile transition**
- **Lack of thermal data below 4 km does not allow model validation**

REFERENCES:

- Bellani S., Brogi A., Lazzarotto A., Liotta D., Ranalli G. (2004): “Heat flow, deep temperatures and extensional structures in the Larderello geothermal field (Italy): constraints on geothermal fluid flow”. – Journal of Volc. and Geoth. Res., 132, 15-29.

- Della Vedova B., Bellani S., Pellis G., Squarci P. (2001): “Deep temperatures and surface heat flow distribution” In: Vai G.B. and Martini I.P. (Editors), “Anatomy of an Orogen: The Apennines and adjacent Mediterranean basins” – Kluwer Academic Publisher, Dordrecht, pp. 65-76.

- Liotta D.and Ranalli G. (1999): “Correlation between seismic reflectivity and rheology in extended lithosphere: Southern Tuscany, inner northern Apennines, Italy”. – Tectonophysics, 315, 109-122.