# POSSIBLE MODELS OF THE DEEPEST PART OF THE LARDERELLO GEOTHERMAL FIELD

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**Key words** : Larderello geothermal field, geophysical techniques, magma-ambient geothermal systems

**Abstract**

The geological and geophysical data gathered so far at Larderello indicate the presence of a magmatic body, whose size, depth and volume are still a matter of debate. Granitic dikes as old as 3.8-2.9 Ma and a widespread contact aureole have been found in several wells. Heat flow data show positive anomalies, interpreted as the result of circulation of hot fluids above shallow magmatic bodies. The presence of low-density bodies is inferred by negative gravity values, often correlated with the positive heat flow anomalies. Reflection seismic surveys reveal the presence of a highly reflective horizon (named K) at a depth range of 3-12 km below the geothermal area; seismic tomography shows a low velocity body 30-40 km wide below the K horizon. Magnetotelluric surveys indicate the presence of a conductive body in good correlation with the other anomalies. These geophysical informations are used as "a priori" input data to test the reliability of various models: granite intrusion, geopressurized horizons below impervious layers, contact metamorphic aureole, listric faults or a combination of the four.

## 1. INTRODUCTION

The results of an entire spectrum of geophysical techniques are available in the Larderello geothermal field (Figure 1).

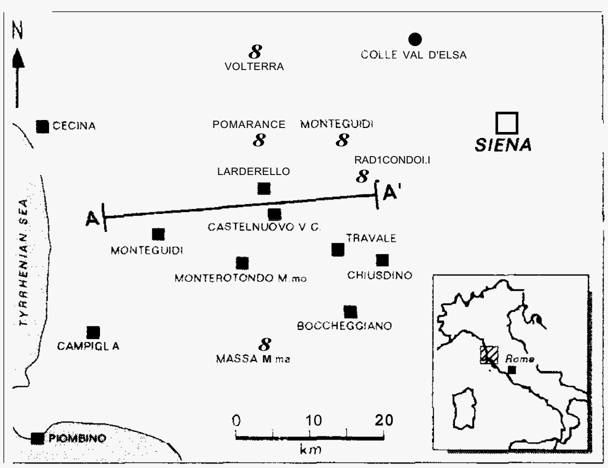


**Figure 1:** Location map of the Larderello geothermal field. The A-A profile refers to the cross section in Figure 2.

We conducted a comparative analysis of all available information to interpret surface-based geophysical data to infer the deep structure below the bottom of existing boreholes (reaching a depth of approximately 4.5 km below ground level). A brief description of all the available data is given, together with the main interpretations. In the conclusions the various models will be discussed in view of all possible observations.

## 2. GEOLOGICAL DATA

Granite intrusions and thermometamorphic minerals with ages between 1.3 Ma and 3.8 Ma are found in several wells at Larderello. Drillholes in the top **4.5** km encountered metamorphic rocks that are rarely present as outcrops in the Northern Apennines (Bagnoli *et al.*, 1980). Below flysch units (Ligurids) and Triassic to Tertiary allochthonous units (Tuscan Nappe) there is a zone of tectonic slices, involving Mesozoic rocks, Paleozoic formations that can be correlated with the Ordovician to Devonian sequences of the Apuan Alps or units referred to the Carboniferous (Pandeli *et ai.*, 1994). Deep wells at Larderello and Monteverdi reveal the presence of aplite and leucogranite dikes and granites. A remarkable and widespread post-tectonic high temperature-low pressure mineral assemblage has also been found in all geothermal fields. The attainment of temperatures as high as 600°C during this contact metamorphism is inferred from the presence of corundum + K-feldspar equilibrium textures (Batini *et al.*, 1983 a). The more widespread occurrence of biotite after Alpine chlorite and muscovite indicates a minimum temperature of 350°C. Granitic and contact metamorphic rocks found in drillholes have K/Ar ages of 1.6-3.8 Ma (Villa & Puxeddu, 1994). Hydrothermal metamorphism is present in the exploited geothermal systems (Cavarretta et *al.*, 1982; Bertini et al.. 1985) and reveals an age not older than 270,000 years (Enel, unpublished U/Th data; G. Bertini oral communication; see also Villa & Puxeddu, 1994). The hydrothermal minerals at Larderello formed in a wide range of temperatures and salinities, as shown by fluid inclusion data (Belkin *et al.,* 1985; Valori *et al.*, 1992; Cathelineau *et al.*, 1994). The minerals fill joints and fractures cutting all the pre-existing textures. In the exploited geothermal fields, there is evidence of brittle behaviour of rock with quartz and mica as major components even under past temperatures exceeding 550°C. Joints are found at measured temperatures of more than 420°C and open fractures are not rare in core samples of reservoir rocks with temperatures exceeding 300°C.

## 3. GEOPHYSICAL DATA

### 3.1 Thermal regime

Estimates of vertical heat flow are determined from temperature gradients in shallow borehole and thermal conductivity. These allow us to estimate temperature at greater depth, assuming a pure heat conduction model. The heat flow map of the geothermal fields (Baldi *et al.*, 1993) shows a strong positive anomaly, with values reaching 1000 $mW/m^2$. These values decay rapidly away from the geothermal region to 200 $mW/m^2$. The peak values are concentrated around Larderello, Lago and Travale, i.e., the most productive areas. A model of Mongelli *et al.* (1989) proves that the thermal anomaly requires an important convective component induced by fluid circulation in the uppermost 2-3 km of the crust.

### 3.2 Gravity

While the main regional gravimetric anomalies show a NW-SE trend, the geothermal area exhibits a subcircular-shaped gravity low (Bouguer anomaly values < 20 mgal). Since this area has outcrops of older and denser terrains (Tertiary Flysch units and Triassic dolostones) than the surrounding areas (Neogene sediments), it can be inferred that this **low** must be of deep origin. This mass deficit, corresponding quite well to the zones with highest heat flow, would imply the presence of a low density body at depth. Since there is no evidence of such a body in the drilled area (Puxeddu, 1984), this body should occur below 4.5-5 km. Results of 2D modelling showed that a light body at a depth of 7-8 km would give rise to such an anomaly. In the Travale area 3D modelling revealed a connection between the lowest gravity values and the most productive wells. This was explained by the fact that the productive areas of the reservoir are filled with fluid in the vapour phase (Toro *et ai.*, 1994). However this would not explain the whole anomaly of the area.

### 3.3 Seismic

Seismic reflection data revealed the presence of sub-horizontaland sub-parallel events inside the basement at different levels. The most evident is the so-called K horizon, defining **a strong** amplitude and frequency anomaly due to a high reflection coefficient (Batini et al., 1983 a, Batini *et al.*, 1985). This marker is characterized by a good horizontal continuity but also subvertical discontinuities. It was recognized in most of the geothermal region, at depths varying from 3 to 7 km, and also outside the geothermal fields, in relatively cold areas like Siena Graben, where it shows at a depth of 10 km. In the nearby Amiata geothermal area, a K horizon can **also be** recognized at a depth of 4-5 **km.** The very low acoustic impedance, which produces reflections of the "bright spot" type characterizing this marker, was explained by the presence of a high degree of fracturing and possible presence of geopressurized fluids inside the fractures. **A** different interpretation is proposed by Cameli *et al.* (1993), who assume the presence of mylonites along listric fault planes. In this model the K horizon would represent the transition between the brittle and the ductile crust. The San Pompeo 2 well reached the K horizon and recorded a bottomhole temperature of 420°C, corresponding to a strongly fractured micaschist horizon with highly pressured (>240 bars) fluids. Blow-out of the well prevented further analysis. The acoustic impedance variation due to lithological change inside the metamorphic formation was computed for the other wells at the same depth: but it is much lower than that required to produce such a strong marker. In some places the K horizon consists of multiple reflections, mainly in the southernmost part of the field. One of these reflections was reached by the well San Pompeo 2, and revealed the presence of a biotite, tourmaline-rich metamorphic rock. Below the K horizon some other minor reflecting horizons were recognized as well as a decrease of S-waves. The distribution of hypocentres of the Larderello seismic network shows a concentration of hypocentral depth around 3-5 km (Foley *et al.*, 1992; Cameli *et al.*, 1993). Some events are located deeper but rarely exceed a depth of 8 **km,** thus indicating a ductile behaviour below this depth, owing to high temperatures. The inversion of local earthquake arrival time **data** allowed us to reconstruct a P-wave velocity model below Larderello **area** (Block *at al.*, 1991). Three main low velocity anomalies were detected below the geothermal area: two of them occur at a depth of 4 and 7 km, with a width of 5 to 10 km corresponding in space to two structural *peaks* of the K horizon. The third and widest anomaly occurs at 8 km depth and deeper. associated with an increase in the $V_p / V_s$ ratio, This would be consistent with partial melting conditions at those depths.

The analysis of teleseismic travel time residuals also **led** to the same conclusion (Foley *at al.,* 1992). The anomalous body would extend to a depth greater than 20 km.

### 3.4 Conductivity structure

**A** recent magnetotelluric (MT) survey revealed the presence of a large conductive body below Larderello geothermal field (Fiordelisi *et al.*, 1994). The MT data were the first to provide a detailed definition of the conductivity structure at great depths beneath the area. since conductive covers and strong environmental background noise had prevented us from using geoelectric and less refined electromagnetic techniques at those depths. The inversion modelling results indicated the presence of a main conductive body at a depth of 5-6 km, in the same location as the anomalous **low** velocity body defined by tomography.

The resolution *of* this method is linked horizontally to the distance spanned by the stations on the surface - 2 km in this case - and decreases exponentially with depth. The conductive body would have its largest extent in the southern part of the geothermal area. extending to 12-15 km depth.

Results of the geophysical surveys are represented in Figure *2,* along a transect crossing Larderello area (see Figure 1).

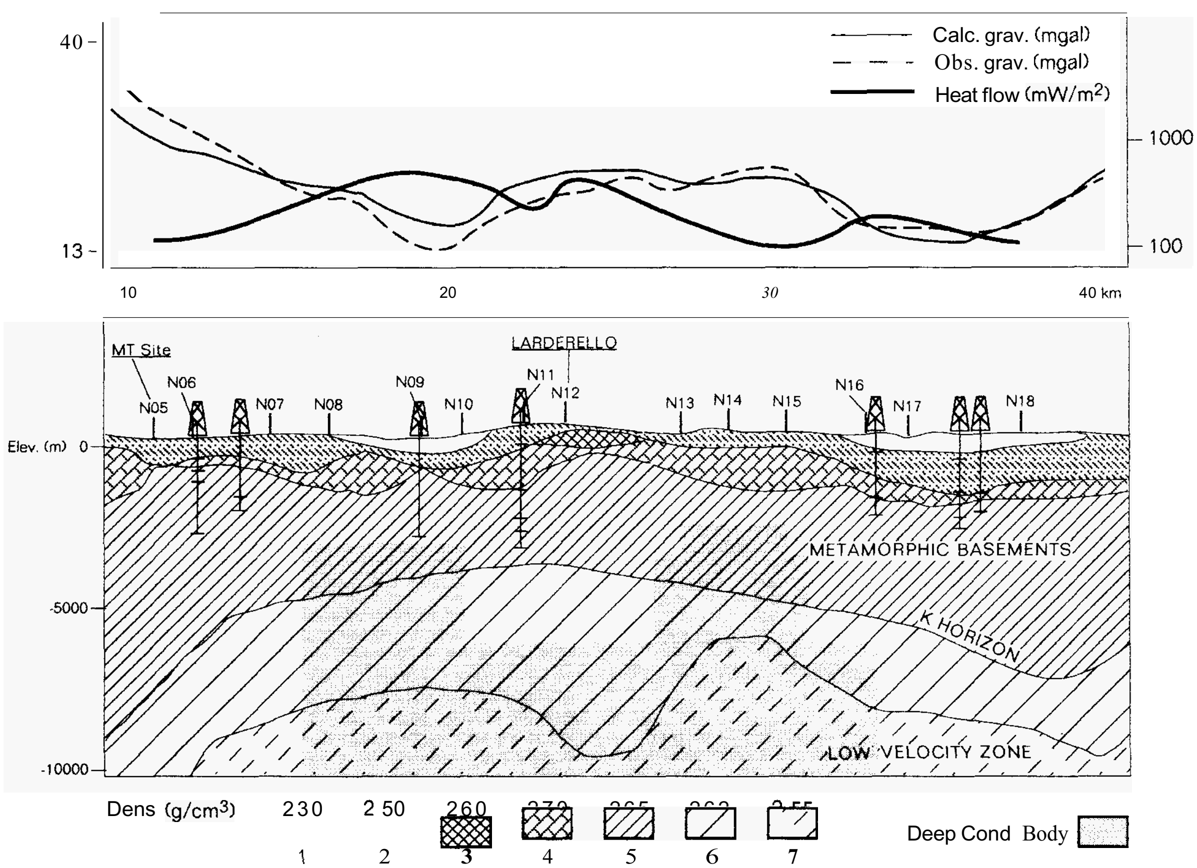


**Figure 2:** Geophysical data and model along a cross section of the Larderello geothermal system. Upper part of the figure: Heat flow data, observed gravity data (Bouguer anomaly) and computed gravity value for the model below. Lower part: Gravimetric model together with magnetotelluric, seismic reflection (K horizon) and seismic tomography results. The shallowest 3 km of the gravimetric model were derived from well stratigraphy extrapolated by seismic reflection data. Legend: 1) Neogenic units; 2) Tertiary Flysch units: 3) Tertiary to Triassic limestones; 4) Triassic dolostomes; **5)** Triassic - Paleozoic metamorphic units; *6)* Tennometamorphic and granitic rocks; 7) Igneous intrusion.

## 4. DISCUSSION

We can consider four possible models to explain the geophysical data. The following discussion takes into consideration the available geological data at the Larderello geothermal field.

According to Cameli ***et al.*** (1993) the K horizon represents the rheological boundary separating the brittle and the ductile crust. These authors support a very shallow transition of the upper/lower crust, minimize the occurrence of granites and hypothesize the presence of a gneissic core complex. The boundary is characterized by the occurrence of mylonites along a lozange-shaped band, recalling the structure of the Basin and Range Province of the western United States (e.g. Hamilton, 1987).
We agree that the planar structure of mylonites can explain the strong reflectivity of the bright-spot type (Fountain ***et al.***, 1984). The offsets in the K horizons can be explained by a variation in the amount of phyllosilicates and in their more or less oriented fabric (Jones and Nur, 1982). Alternating layers of oriented and non-oriented rocks can also enhance or reduce the reflectivity (Jones and Nur, 1984). Only rocks with very high amounts of phyllosilicates which are fully oriented parallel to the mylonite foliation and with low content of feldspar (<10%) could reach the anisotropy values suitable for seismic reflection. At Larderello only micaschist fulfills these requirements: the deepest part of the basement is made up of gneiss with a high modal percent of plagioclase and quartz, which strongly lower the anisotropy. Mylonitized gneiss levels are unable to produce the strong reflection observed at the K horizon. In support of their model Cameli ***et al.*** (1993) state that, at temperature in excess of 400°C, the siliceous rocks below the geothermal area should have a ductile behaviour. The occurrence of earthquakes below the K horizon implies partially brittle properties of the crust below the mylonitic layer. Other geophysical data cannot be explained by this model. The negative gravity anomaly found in the geothermal field cannot detect the occurrence of mylonites, since mylonitization does not produce a change in density (Jones and Nur, 1982). Similarly, the increase in conductivity and the decrease in wave velocity are not consistent with the presence of mylonites. in particular because these anomalies are confined to a relatively restricted area. Mylonitic rocks have been found in some wells at Larderello. They are clearly affected by the thermal metamorphism induced by the intrusion of dikes and granitic bodies; they therefore formed before approximately 4 Ma and likely during the Alpine orogeny. San Pompeo 2 well reached a branch of the K horizon. which proved to be a biotite, tourmaline-rich metasomatic hornfels belonging to the thermal metamorphic rock complex usually found in the deepest part of the explored geothermal field of Larderello.

We have already mentioned the evidence of a widespread thermal metamorphic aureole at Larderello. The age of the granites and the associated thermal metamorphic rocks is still a matter of debate. The age of the granitic rocks implies that the granite intrusion has completely cooled and the related thermal metamorphism is not presently active. The presence of a thermometamorphic aureole surrounding solidified granite bodies would not explain the wide anomalous physical properties defined by the various geophysical soundings, another model should therefore be taken into consideration.

Batini ***et al.*** (1983 a) and Gianelli (1994) suggest the presence of a geothermal brine with pressures greater than hydrostatic, coincident with the K horizon. This idea is strongly supported by the discovery of a high temperature-high pressure fluid in San Pompeo 2 well (Batini ***et al.***, 1983 b) and by the magmatic fluids trapped in the hydrothermal minerals of many deep wells (Cathelineau ***et al.***, 1994). This high-pressure brine could lower the seismic velocity, producing a reflecting horizon such as the K marker. It could also explain the low gravity values. The thickness of the pressurized horizon is estimated to be some hundreds of metres (Gianelli and Puxeddu, 1992). This thickness is not large enough to explain the wide anomalies defined by seismic tomography and magnetotellurics. A more complex model should therefore be contemplated.

Most of the geophysical data support the presence of a partially molten granitic body below Larderello. The first clear geophysical evidence of such a melt was defined by tomography and teleseismic inversions, and subsequently corroborated by the results of magnetotelluric data inversions. Figure 2 indicates that the anomalous body defined by such different tecniques shows good agreement in location and size. The fact that the beginning of the conductivity anomaly is shallower than the velocity anomaly can be explained by assuming the existence of a swarm of vertical fractures filled with hot, probably pressurized fluids. The intense fracturing of the country rocks can be ascribed to the emplacement of the granitic body and to its retrograde boiling effects. The granite carapace and associated wall rocks are likely limited by a highly pressurized horizon that could give rise to the K reflection. This carapace and the low density body below it would produce the observed gravimetric low.
The very good correlation between the gravity minima and the maxima in the heat **flow** values also strongly supports the presence of a still molten magmatic body below Larderello.

## 5. CONCLUSIONS

In view of the previous discussion, we strongly favour the model which assumed the presence of a partially molten granite below a layer of **rocks** showing brittle to ductile behaviour (Figure 2 and 3). The features of this transition layer could be summarized as follows: 1) high pressure gradient. Pressure increases from almost hydrostatic to geostatic in a few hundred metres; **2)** hot brines are likely confined in this layer of very low permeability by the cyclic reactivation of faults due to overpressurized fluids and their sealing by mineral deposition, Details of this "fault-valve" mechanism are discussed in Sibson (1992); 3) high temperatures (>420°C) and a prograde decrease of rock permeability with depth. Similar conditions are hypothesized for The Geysers geothermal field (Nielson, 1994). At Larderello brittle rocks are present below the K horizon, allowing the occurrence of some earthquakes. In zones where ductile behaviour dominates, earthquakes are not possible.
A cyclic supply of deep fluid to the uppermost part of the geothermal field is obviously an important process in the long term evolution of the geothermal field. The supply of heat and chemicals with magmatic component could in fact come from a still active magmatic source. On the contrary, the core complex model implicitly assumes a completely impervious ductile layer about 4 km below Larderello (coincident with the K horizon) and therefore the end of the geothermal system at that depth.

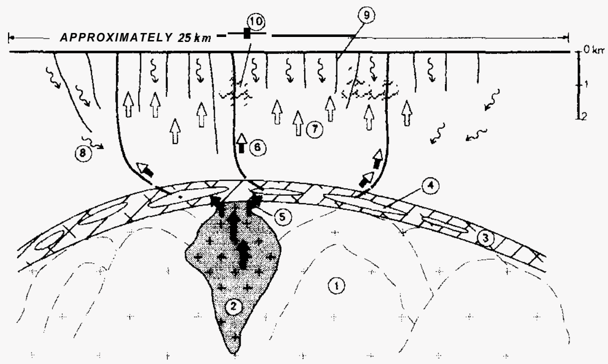


**Figure 3:** Conceptual model of the Larderello Geothermal field. Legend: 1) composite batholith; 2) partially molten granite; 3) brittle--ductile layer: 4) confined deep brine (T=450-550°C); 5) magmatic fluid (granitic subsolid temperature): 6) deep metamorphic vapour (T=350-450°C); 7) mixed vapour (meteoric+metamorphic); 8) recharge and condensed waters; 9) faults and fractures: 10) zones of hydraulic fracturing (After Gianelli, 1994).

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