# GEOTHERMAL ANOMALIES AND STRUCTURAL FEATURES OF SOUTHERN TUSCANY (ITALY)

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## ABSTRACT

The reconstruction of the geothermal situation in southern Tuscany is updated from a series of integrative geophysical investigations carried out over the past few years and from the analysis of almost 500 thermal measurement points (shallow gradient and deep boreholes). All of Tuscany is characterized by thermal gradient (G > 50°C/km) and heat flow density (HF) (q > 100 mW/m$^2$) positive anomalies that decrease eastwards along the Elsa-Siena grabens. Three thermal anomalies of minor extent and intensity have been found outside the well-known geothermal areas and could represent the continuation of the two main anomalies of Larderello-Travale and Mt. Amiata, circumscribed by the isoflow line of 200 mW/m$^2$. Two of these anomalies are situated south of Larderello-Travale, while the most extensive is west of Mt. Amiata. The deep HF has also been defined, within the limits of the geothermal fields under exploitation, in order to evaluate any difference with respect to raised surface values caused by shallow convective circulation. The HF anomalies of Larderello-Travale and Mt. Amiata correspond to structural and geophysical anomalies, which corroborate the hypothesis that extensive deep intrusive bodies produce the thermal anomalies.

## 1. INTRODUCTION

The updated reconstruction of the geothermal framework in southern Tuscany, described in this paper, covers an area of about 10,000 km$^2$ (Figure1); it includes the oldest and most important Italian geothermal fields (Larderello, Travale and Mt. Amiata).

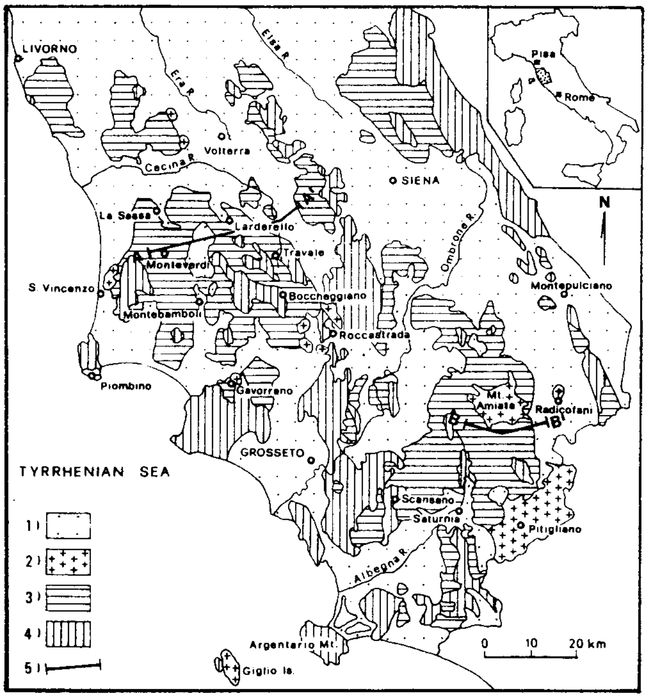


*Figure 1.* GEOLOGICAL MAP: 1) neoautochthonous sediments (U.Miocene-Quaternary); 2) igneous rocks (Plioc.-Quaternary); 3) allochthonous flysch facies units (Cretaceous-Eocene); 4) Tuscan nappe (U.Triassic-Oligocene); tectonic wedges complex (U.Paleozoic-Mesozoic); 5) geological cross section

This study is based on data collected by ENEL S.p.A. (National Italian Electricity Board), in collaboration with the CNR-IIRG, during geological and geophysical studies carried out over the last few years. Specific attention was paid to HF and gradient measurements.
Together with the geostructural reconstruction which was conducted as part of the Italian National Research Council (CNR) studies on the deep crust - CROP project - these data led to the discovery of some unknown or poorly defined geothermal anomalies and to a more accurate definition of the cause-effect relationship between the major HF anomalies in Tuscany and their deep source.
The deep thermal data within the geothermal fields were also analyzed to evaluate the deep conductive HF and the effects of convective circulation on the shallow HF values.
The correlation between the deep and shallow HF values could prove a useful tool in preliminary evaluations of unexplored areas in Tuscany.

## 2. GEOLOGICAL BACKGROUND

Southern Tuscany (see geological sketch in Figure 1) belongs to the Tyrrhenian-Apennine orogenic system that developed in the Eocene through Quaternary. From the structural point of view it can be considered a compressional fold and thrust belt (Eocene-Late Miocene) affected, in the Late Miocene through Quaternary time, by large scale, prevalently tensional tectonics (Carmignani and Kligfield, 1990; Baldi *et al.*,1994; b).
The regional substratum consists of phyllites, micaschists and, in the deepest part, a gneiss complex in amphibolite facies belonging to the Paleozoic-Precambrian. The latter was discovered during deep geothermal drilling in the Larderello area.
The following outcropping tectonic units overlie the regional metamorphic substratum:
- tectonic wedges complex, made up of overthrusted phyllites, quartzites, anhydrites and dolomitic limestones;
- Tuscan nappe, consisting of mainly carbonate and anhydritic formations at the base, and terrigenous formations at the top (Upper Trias - Oligocene);
- allochthonous flysch facies units ("ligurids"), composed of mainly argillitic and subordinately calcareous and arenaceous formations.

From the Late Miocene on, the predominantly extensive tectonics led to the formation of lacustrine, lagoonal and marine sedimentary basins; most of these basins are elongated in a NW-SE direction, and are filled by neoautochthonous sediments (clay and, subordinately, conglomerates and sands) (Upper Miocene-Quaternary).
During the same period strong magmatic phenomena affected the Tyrrhenian belt of central Italy. Intrusive and effusive igneous rocks outcrop discontinuously in southern Tuscany; these are mainly of the acidic type, oversaturated in silica, and form the so-called "Tuscan magmatic province", within which the magmatic activity migrated in space and in time along a NW-SE direction.
In the post-Pliocene period, the region underwent a general uplift, whose peaks correspond to the major geothermal areas.
The Tuscan geothermal fields are included in this general geological framework. Their hydrogeological setting, from top to bottom, is:
- the **cover rocks** are made up of mainly clayey facies of Neogenic deposits and the underlying flysch facies units.
- the **potential reservoir** is made up of mainly carbonate and anhydritic Mesozoic formations of the Tuscan nappe and of underlying metamorphic formations belonging to the tectonic wedges complex and to the "regional basement" (Figure 2).

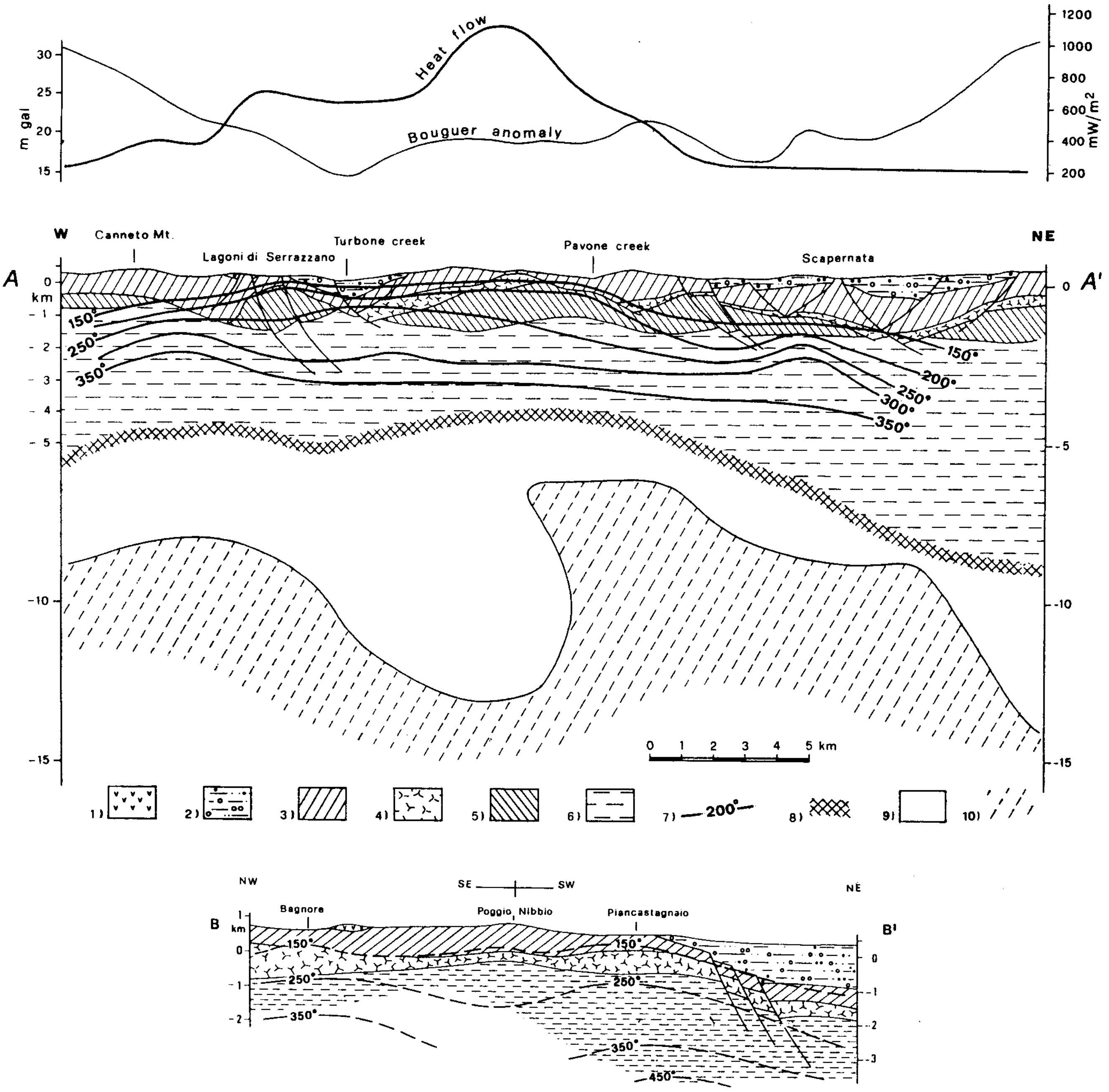


*Figure 2.* GEOLOGICAL CROSS-SECTION OF LARDERELLO AND MT. AMIATA GEOTHERMAL FIELDS (from Baldi *et al.*, 1994,a modified - Bertini *et al.*, in press): 1) Volcanic rocks (Quaternary); 2) neoautochthonous sediments (U.Miocene-Quaternary); 3) allochthonous flysch facies units (Cretaceous-Eocene); 4) tuscan nappe (U.Triassic-Oligocene); 5) tectonic wedges complex (U.Paleozoic-Mesozoic); 6) metamorphic substratum (Precambrian?-Paleozoic); 7) isotherm [°C]; 8) K-horizon; 9) thermometamorphic and granitic rocks; 10) low velocity zone (P-wave velocity < 5.4 km/s)

## 3. SURFACE TEMPERATURE GRADIENT AND HEAT FLOW DENSITY

From an analysis of all the available data we were able to update the geothermal gradient (Figure 3) and the HF map (Figure 4) of southern Tuscany. These data refer to 300 measurement points in thermal test boreholes of 30-150 m depth and some deeper wells (Baldi *et al.*, 1994, a).

In all of southern Tuscany the temperature gradient is higher than 50°C/km and HF higher than 100mW/m$^2$. Within this geothermal province there are areas with even higher gradient and HF values:

- **West of Volterra**: here the geothermal gradient is higher than 100°C/km and the HF reaches a maximum of about 200 mW/m$^2$. This anomaly was discovered during recent shallow drillings and has not yet been explored at depth;

- **Larderello-Travale-Boccheggiano**: this area is characterized by a wide, intense anomaly (isoflow >150 mW/m$^2$) that extends continuously towards the SW and discontinuously towards the SE (Travale). The maximum HF values exceed 1000 mW/m$^2$ in correspondence to the known and exploited geothermal fields.

The surface surveys carried out during the last few years have identified two other areas with HF anomalies of minor intensity, with values > 250 mW/m$^2$. These areas trend NW-SE (from Travale towards Boccheggiano) and NE-SW (from Larderello towards Montebamboli), and could be considered offshoots of the above-mentioned anomaly. Deep drilling has still to be carried out here.

- **Mt. Amiata**: the main anomaly in this area (isoflow >150 mW/m$^2$) is very wide; the maximum HF and temperature gradient occurs on the southern border of the Mt. Amiata volcano, in correspondence to the geothermal fields that have been exploited since the 1960s for electric power production.

Recent surface surveys have detected another thermal anomaly towards the west, north of Scansano, where the HF is higher than 250 mW/m$^2$. The latter has still to be investigated by deep drilling.

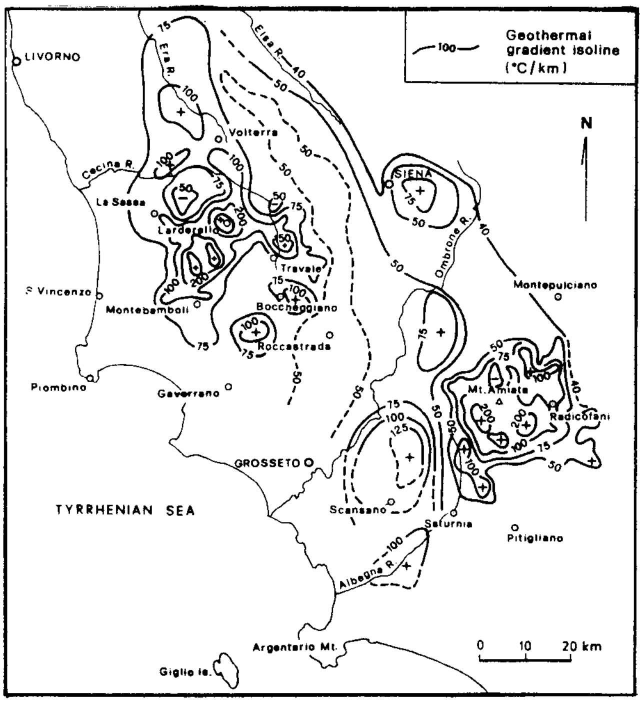


*Figure 3.* GEOTHERMAL GRADIENT MAP

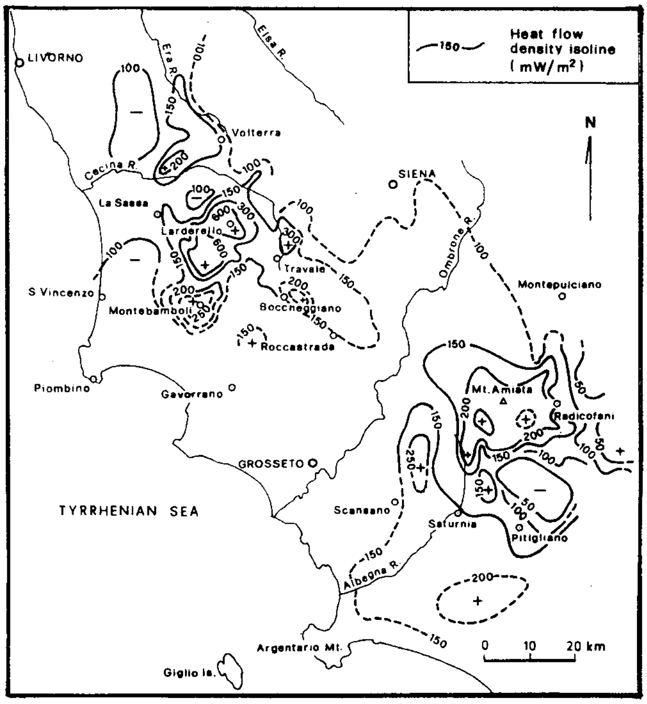


*Figure 4.* HEAT FLOW DENSITY MAP

## 4. THERMAL ANOMALIES AND DEEP TEMPERATURES

A total of 257 temperature surveys carried out in 121 deep geothermal wells of Larderello, Monteverdi, Travale and Mt. Amiata fields were analyzed in order to determine their temperature range of existence and to compare the surface thermal anomalies and the deep temperature trends (Figure 5). The picture that emerges from this data analysis seems rather scattered, as the temperature trends are affected by many factors of varying influence in different fields, or in areas within the same field. The different permeability conditions within the geothermal systems and the physical state of the fluids determine various heat transfer regimes: convection, conduction, or a combination of both.

Considering the temperature trends found in the deepest and less permeable parts of the Tuscan geothermal fields and in the marginal areas, where permeability is also poor, there seems in general to be a conductive regime, with a gradient no lower than 70°C/km. Assuming a thermal conductivity of 3.5 W/(mK) (at room conditions), and making due corrections for increasing temperature with depth (Somerton, 1992), points to a minimum conductive HF in the order of 200 $mW/m^2$. This value is in good agreement with the values of surface isoflow lines that include the main geothermal fields. Shallow convective regimes may cause local disturbances to the HF and temperature gradient anomalies measured on the surface, and produce misleading comparisons of surface and deep measurements.

## 5. GEOPHYSICAL AND STRUCTURAL DATA

There are several important geophysical and structural features that must be carefully thought about in order to investigate the origin of the widespread geothermal anomaly that characterizes southern Tuscany:

- The Bouguer anomaly map (Figure 6) shows a clear alignment of the main gravimetric structures in a NW-SE direction, with an excellent correlation between gravimetric minima and the Neogenic grabens (Era, Siena, Radicofani, etc.). There is also a fairly good correspondence between gravimetric highs and outcrops of the denser carbonate (Tuscan nappe) and metamorphic formations. The Larderello and Mt. Amiata geothermal fields are an exception to this rule. All of the area covered by Larderello, Travale and Boccheggiano is characterized by a relative gravimetric minimum (< 20 mgal), even though there are widespread outcrops of the above-mentioned formations, which should give origin to positive

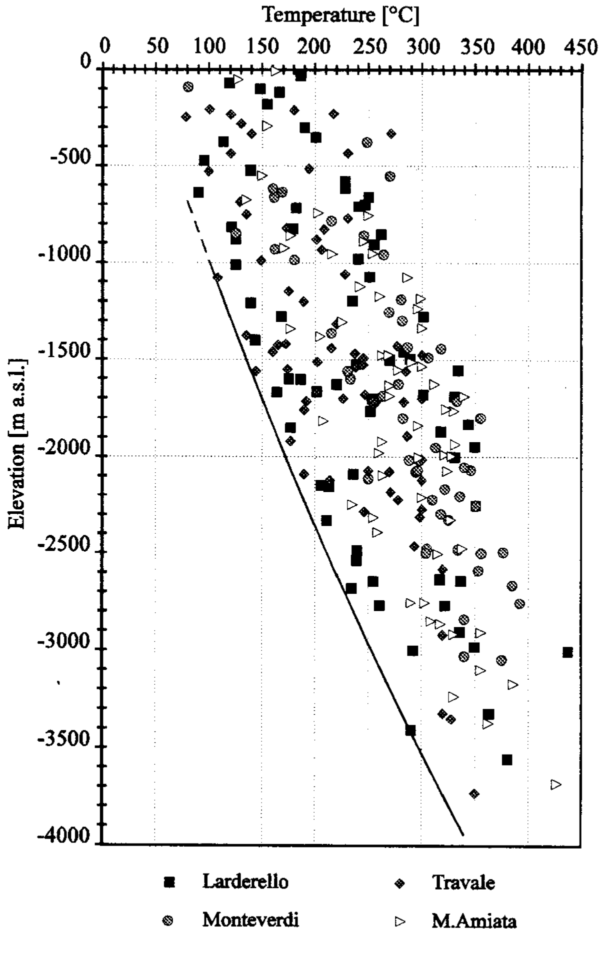


*Figure 5.* FORMATION TEMPERATURE VS ELEVATION IN GEOTHERMAL WELLS OF SOUTHERN TUSCANY

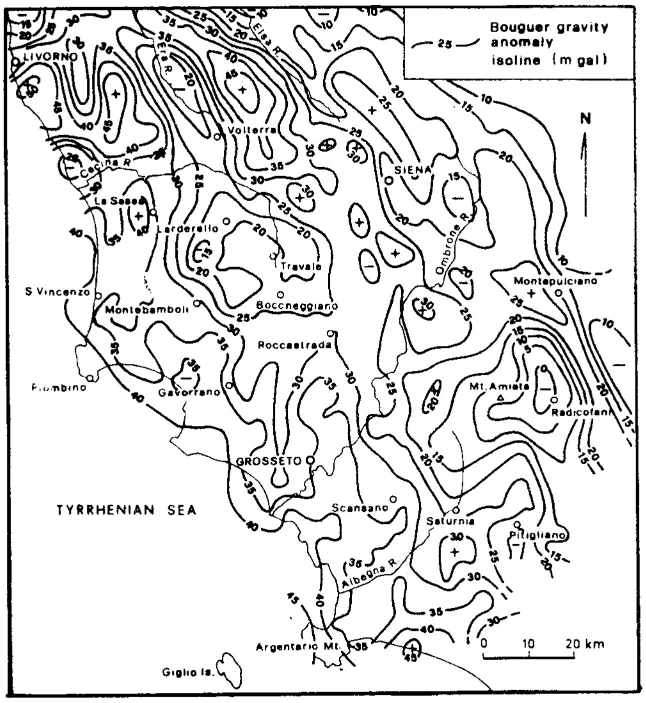


*Figure 6.* BOUGUER GRAVITY ANOMALY MAP

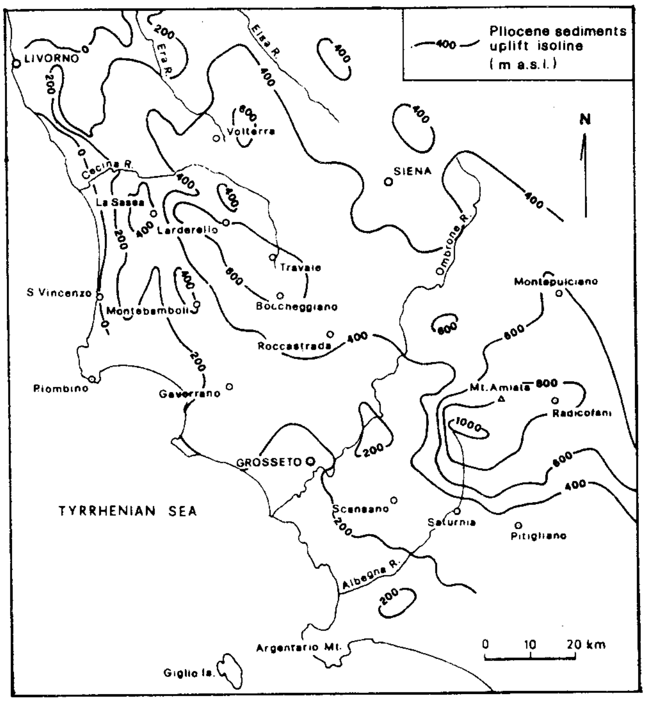


*Figure 7.* PLIOCENE SEDIMENTS UPLIFT MAP

gravimetric anomalies. The Mt. Amiata area, on the other hand, shows a gravimetric minimum, which, in the east, coincides with the Radicofani graben; this minimum extends westwards to include areas with vast carbonatic outcrops (Orlando *et al.*, 1993).

Using a two-dimensional modeling, both of these gravimetric minima can readily be interpreted as the effect of the presence of light bodies at depth (Gianelli *et al.*, 1988). The most realistic hypothesis is that of an association between these light bodies (density 2.55 g/cm$^3$) and acidic intrusions that have not entirely consolidated;

- the reconstruction of the uplift of Pliocene marine sediments (Sestini, 1931, Tongiorgi and Trevisan, 1957; Marinelli *et al.*, 1993) indicates that this phenomenon has affected the entire Tuscan Tyrrhenian belt south of the Arno river (Figure 7), and that the most uplifted areas correspond to the above mentioned gravimetric minima and to the widespread geothermal anomalies. Figure 8 shows a convergence map among Bouguer anomaly, HF and Pliocene uplift
- deep seismic survey data indicate a crustal thinning up to about 20 km (Nicolich and Pellis, 1979);
- remote (Foley *et al.*, 1990) and local seismic data (Block *et al.*, in press) monitored by the Larderello microseismic network, reveal the presence of a "Low Velocity Zone" at 6-7 km depth, beneath the area characterized by the maximum geothermal anomaly at Larderello. This LVZ, which extends to a depth of about 20 km, has been interpreted as a partially melted body, an hypothesis that is also in agreement with the abrupt reduction in seismic activity below 8 km (Batini *et al.*, 1984), which is probably caused by the passage to rocks with a ductile behaviour;
- the 2D inversion of magnetotelluric data recently obtained in the Larderello area (Fiordelisi *et al.*, in press) indicated the presence of an electrically conductive anomaly that is comparable in position and width to the velocity anomaly.
- several seismic reflection profiles, both in the Larderello- Travale and Mt. Amiata areas, have led to the detection and reconstruction of a very reflective deep horizon (Batini *et al.*, 1978, 1983, 1985), called the K horizon, whose trend (Figure 2) is correlate to the thermal and gravimetric anomalies. This reflector, which is regionally extensive, lies at 7-9 km depth outside the main thermal anomalies of Larderello and Mt. Amiata, and rises to minimum values of 3 km within the area of maximum thermal anomaly at Larderello.
- an integrative study on magnetometric, gravimetric and seismic data led to the hypothesis of a granitic intrusion at a depth of 1.3-2.5 km in an area west of Boccheggiano (Ricceri and Stea, 1992). There would appear to be no surface shallow thermal anomalies in this area, however, probably because of the widespread permeable carbonate outcrops containing cold shallow aquifers.

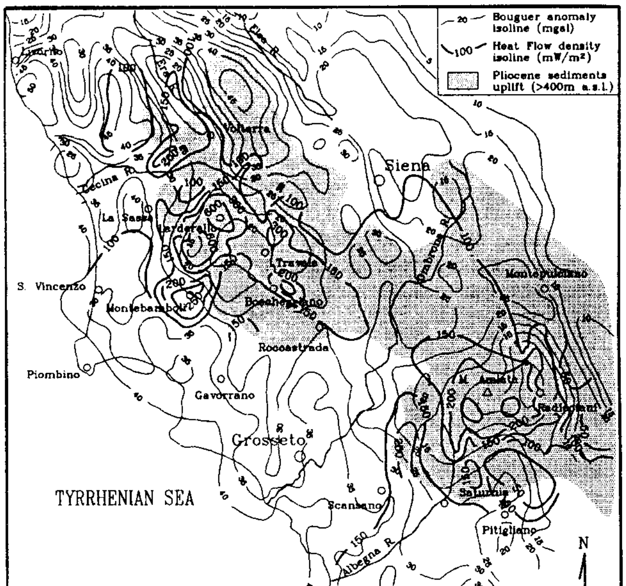


*Figure 8.* SURFACE GEOTHERMAL AND STRUCTURAL FEATURES OF SOUTHERN TUSCANY

The presence of granitic bodies beneath the Larderello area has for some time been hypothesized on the basis of geological, geophysical and geochemical data.

During the last few years this hypothesis has been corroborated by further information, both direct and indirect: aplitic and microgranitic dikes and granitic intrusions were found in geothermal wells, at depths higher than 3 km, in both the western part of the Larderello area (Monteverdi) and, further east, at Travale.

## 6. CONCLUSIONS

The regional interpretation of subsurface thermal regime, obtained both from gradient test boreholes and deep geothermal wells, allows the inference of the superposition of three levels of geothermal anomaly. The entire central Tyrrhenian belt is characterized by a wide HF anomaly within the 100 mW/m$^2$ heat flow contour which, following the Apennine trend, decreases sharply eastwards along the Elsa and Siena graben. This "regional" (or first level) anomaly could result from the crustal thinning (to a minimum thickness of 20 km) that characterizes this part of Tuscany.

Within this same belt are two wide strong geothermal anomalies, defined by heat flow contours of 200 mW/m$^2$ (second level). These are the Larderello-Travale and Mt. Amiata areas, within which are numerous and more intense local anomalies. This last group of anomalies can reach HF values of over 1000 mW/m$^2$ (third level). They are a result of fluid circulation in shallow reservoirs, and are therefore tied to the development of large convective circulations in shallow reservoirs. These systems have been the first to be explored in detail and exploited on an industrial scale. Future exploration, therefore, must be focused on the "second level" anomalies, where temperatures of 300-350°C may be present at depths of 3.5-4 km, although, at present, it is impossible to assess their permeability conditions at depth, nor, therefore, their productive capacities.

The comparative analysis of this thermal regime and the geophysical-structural elements outlined above confirms the hypothesis of magmatic bodies that have intruded a thinned crust (Marinelli, 1963,1984; Calore *et al.*, 1981; Del Moro *et al.*, 1982; Puxeddu, 1984; Villa *et al.*, 1987; Gianelli and Puxeddu, 1992; Villa and Puxeddu, in press).

These deep bodies, with their low density, P-wave velocity and resistivity values are probably partly melted, and represent the deep source of heat for the thermal anomalies described in this paper.

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