EARTHQUAKE TOMOGRAPHY IN THE LARDERELLO GEOTHERMAL AREA

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ABSTRACT

A **3D** velocity structure model of the Larderello geothermal area has been constructed by analyzing seismic data recorded by the Enel network of Larderello and using two different techniques:

- the analysis of teleseismic travel time residuals of more than 100 teleseismic events, chosen for their high quality;
- a joint hypocenter-velocity inversion of local earthquake arrival time data of approximately 270 local events.

The inversion of these data showed a sharp low velocity zone in the center of the geothermal area, characterized by a 15-20% diminuition of P wave velocity.

The velocity model obtained from the 3D inversion of teleseismic and local earthquakes is supported by further geophysical data. Peaks of the seismic reflector known as the "K horizon" are in agreement with P wave velocity anomalies at depth of 4-8 km. Furthermore, the 2D gravimetric model shows a deep low density body (d = 2.55 g/cm^3), while the 2D resistivity model shows an analogous conductive body (resistivity < 100 ohm.m)

The convergence of these elements supports the hypothesis that the velocity anomaly is related to an intrusive, still partially molten body, that might be the heat source of the Larderello geothermal area.

1. INTRODUCTION

Geothermal energy has been exploited in the Larderello geothermal field for many decades. Geothermal fluid, in the form of steam, has been produced mainly from fractured anhydrites and dolomites which constitute the main reservoir. This is located in the upper one kilometer of the earth, below a cap rock represented by post-orogenic sediments and clayey, arenaceous flysches.

Since the early 1970's, production from the above mentioned shallow reservoir has declined and exploration is now aimed at fractured zones in the metamorphic basement, between depths of roughly two and four kilometers (Barelli *et al.*,1995).

In order to understand the regional processes and the origin of the geothermal phenomena which control this important economic resource, the deep structures of the Larderello geothermal field were also investigated by inversion of teleseismic travel time residuals. More than 100 teleseismic events were analyzed to determine the size, extent, and magnitude of a low velocity zone (LVZ) within the geothermal region (Foley *et al.*,1990).

In order to enhance the exploration program, a joint hypocenter-velocity inversion of the local earthquake arrival time data was carried out with the aim of imaging the velocity structure of the upper 10 kilometers and relating the results to geologic features In particular, a P wave velocity model was determined from the inversion of amval time data from 269 local earthquakes (Block *et al.*,1994).

2. EARTHQUAKE DATA

The earthquake data sets utilized for both analysis procedures come from seismic data recorded by the ENEL seismic network installed in the Larderello area since 1977. The network covers an area of approximately 800 km2 with an average station spacing of 6.5 km and it has 26 uniform and calibrated stations with 1Hz vertical geophones (Figure 1) which are radio linked to a real time data acquisition and processing system (Batini *et al.*,1985).

More than 3000 seismic events were recorded during the 1977-1993 period. Epicentral distribution (Figure 2) shows an intense seismic activity in entire the area covered by the network, with a high concentration of earthquakes west of Larderello, and Monterotondo, south of Travale.

More than 90% of the events have magnitude < 2, while the maximum magnitude recorded has been 3.3 for one event only. Earthquakes generally occur at a depth between 1 and 8 km; just a few events have a hypocentral depth of 10-15 km.

For the inversion of teleseismic travel time residuals, 101 teleseismic earthquakes and nuclear explosions were chosen from a data set of 200 events recorded in the period 1985-1988; on the basis of high quality of time histories (good definition of first onset) and by the requirement that recordings from at least **15** stations shall be available for each quake. Gaps in coverage are quite large from SW (74 degrees); however, there is sufficient azimutal variation in the data to obtain a varied cross-fire of rays throughout the model.

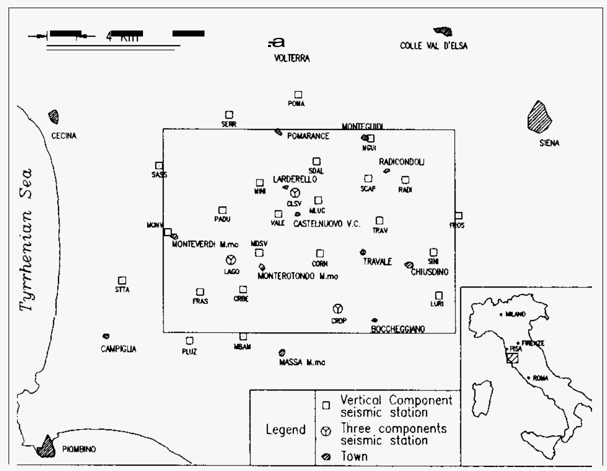

Figure *1* - Configuration of the Larderello seismic network (rectangle box corresponds to the area plotted in Fig.2).

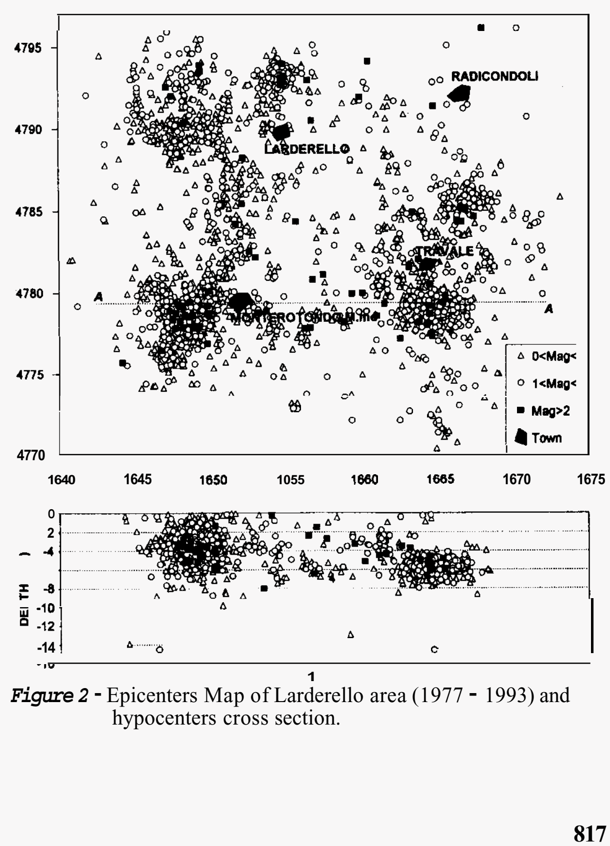

Figure 2 - Epicenters Map of Larderello area (1977 - 1993) and hypocenters cross section.

For the joint hypocenter-velocity inversion. 269 local events were selected from a data set of 2340 earthquakes recorded between March 1977 and December 1985, and from Jannuary 1988 to May 1990 Earthquakes were selected on the basis of well-constrained hypocenters, the azimutal ray coverage, the number of arrival times, the distance from the epicenter to the nearest recording station, and the variance of the hypocenter parameters. Most of these earthquakes occur at less than 8 km depth, with only 6 earthquakes occuring at depths below 13 km.

3. INVERSION OF TELESEISMIC TRAVEL TIMES

Teleseismic waveforms recorded by the ENEL seismic net have been processed in order to obtain a crustal velocity model from the travel time inversion.

In order to automate the travel time residual calculation, a waveform correlation procedure has been realized following the simulated annealing technique (Foley, 1990). This technique searches for each quake a set of trace shifts that maximize the energy of a time history obtained by stacking the shifted waveforms. Simulated annealing is an iterative Monte Carlo procedure, where time shifts are randomly generated In early iterations, traces are allowed to shift with few constraints, later the rate of possible **shifts is** reduced, in a way similar to the growth of crystals (annealing), where the temperature is reduced during the process.

After having determined a set of relative travel times, the Hemn Earth model has been used to obtain relative travel time residuals Further reductions of residuals include the station elevation as well as the near surface velocity structure (down to a depth of 6 km) determined from seismic reflection surveys carried out in the region (Batini and Nicholich, 1984) In this way the travel times were reduced to a depth of 6 km, and the research focused on the crust at greater depth.

Travel time residuals were then inverted using the Aki method (Aki *et al* ,1977) to obtain the crustal velocity structures below 6 km

The geometry adopted for the earth model comprises a set of layers divided into right rectangular blocks describing the structure at depths starting at 6 km down to **41** km. The input model for the travel time inversion includes five layers, the three shallowest 5 km thick with velocities of 6 5, 7.0, and 7 5 km/s, respectively The lower part of the earth model is described by two 10 Km thick layers of 8.0 km/s. Velocity values derive from the above-mentioned reflection seismic data and from a refraction model of Giese *et al.*(1981)

For each station and each quake, rays are traced throughout the model The residuals are distributed in the blocks crossed by the rays in a way proportional to the length of the ray in each block Quakes come from different distances and azimuths, so each block **is** characterized by a set of residuals. The numerical problem is defined as an over-determined linear equations system, solved by a damped least square technique.

Figure **3** shows the results of the teleseismic travel time inversion.

For each of the aforesaid five layers of the model. plots show the P velocity perturbation in percentages of the background velocity as contours of equal velocity perturbation. These layers have depths ranging between 6-11, 11-16, 16-21 and 21-31 km. The shallowest three layers (from 6 to 21 km) have a low velocity zone (LVZ) confined to the center of the network, with an elongated pattern to the NE In the deepest layer (from 21 to 31 km) LVZ migrates to the nort-east and its extension increases.

4. LOCAL EARTHQUAKE TOMOGRAPHY

The P velocity model of the Larderello geothermal area has been obtained by inverting arrival time data of local earthquakes recorded by the local ENEL seismic net.

The adopted procedure simultaneously determines a three dimensional velocity model and the hypocenters' parameters. To efficiently implement the joint hypocenters-velocity inversion, the separation of parameters technique (Pavlis and Booker, 1980; Spencer and Gubbins, 1980) has been used. In the first step the crustal model is obtained keeping the hypocenters fixed, but taking indirectly into account the effect of changes in the hypocenters' parameters. This step is followed by hypocenter relocation based on the updated velocity model This procedure allows for the processing of a large number of events, without the need for a corresponding amount of computer memory

The three-dimensional velocity structure is represented as a rectangular grid of nodes. The grid shall not be uniform, that is, the coordinates of the nodes do not have to be equi-spaced The velocity at any point is found by linear interpolation of the velocities at the eight surrounding nodes of the rectangular grid; the contribution of each velocity node **is** measured by its distance from the point along the three coordinate axes.

To compute the travel time from a Aurrent hypocenter to a station, in the current crustal model, the three-dimensional ray bending method of Um and Thurber (1987) has been used.

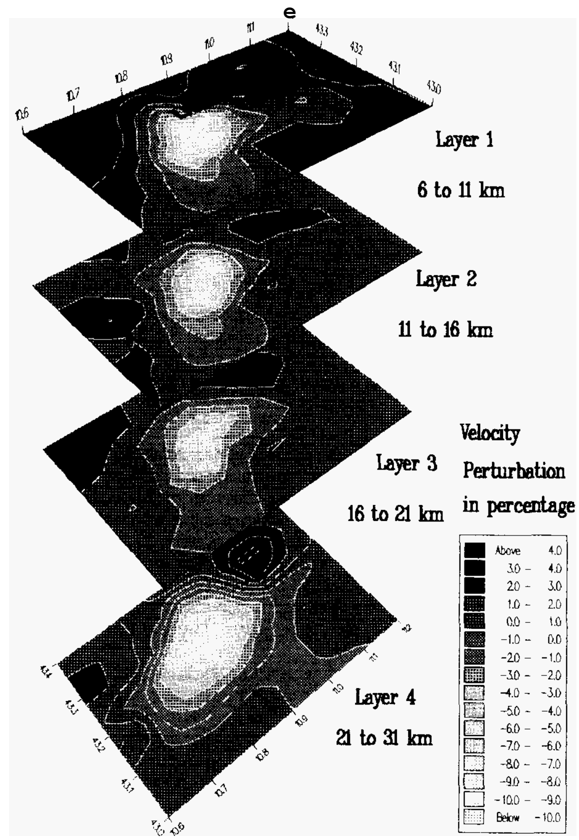

Figure 3 - 3D P Wave Velocity perturbation from teleseismic travel time inversion

Figure 4 shows five horizontal cross section at different depths of the obtained P wave velocity model

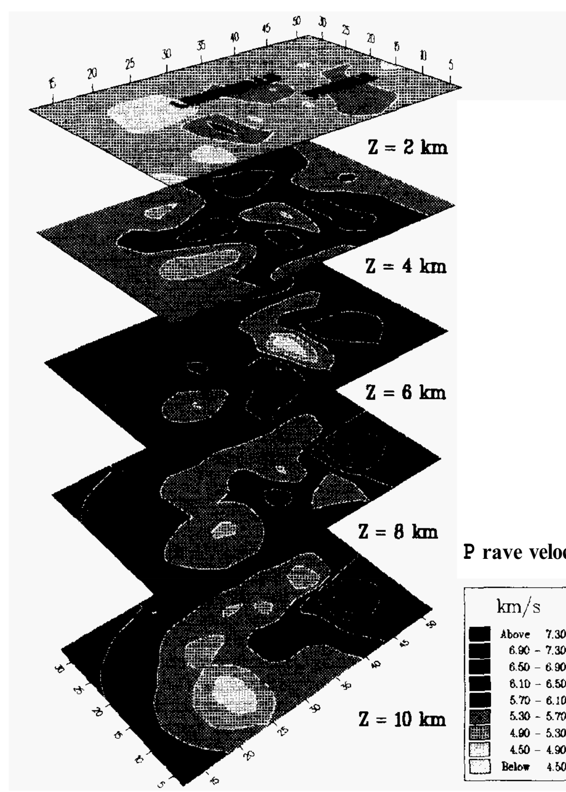

Figure 4 - 3D P Wave velocity structures from local earthquakes inversion

The joint hypocenter-velocity inversion is a non-linear process solved by iterating the linearized problem

The goal is to change model and hypocenters' parameters in such a way as to minimize (in the least square sense) the differences between calculated and observed travel times

Unfortunately, this problem is characterized by the fact that many combinations of hypocenters parameters and velocities may occur and yeld approximately the same root-mean square arrival time residual For this reason it is appropriate to apply additional constraints to the inversion scheme

To prevent fluctuations in the velocity structures at poorly resolved nodes, P velocity is constrained within specified bounds. defining a penalty for velocities that fall outside of the desired range, and minimizing the penalties during the subsequent iteration

For the same reason a smoothness constraint **is** added in such a way as to minimize the spatial first velocity derivatives in the x,y,z directions

Vertical seismic profiling and seismic reflection surveys were used to constrain the P wave velocity model in the shallowest nodes of the grid The procedure minimizes the misfit between calculated velocities and those coming from surveys

The constrained least squares solution is found by minimizing a linear combination of the sums of the squares of the following quantities· arrival time residuals, spatial velocity derivatives. penalties. velocity misfits, and the sum of P wave station corrections

Three low velocity anomalies are present in the above mentioned Figure **4**

Two of these are small and come out in the horizontal section at a depth of *6* km They are located near Lago (10 km **SW** of Larderello) and Travale respectively The third low velocity anomaly (P velocity less than 5.0 km/s) becomes very wide on the horizontal section at a depth of 10 km It has a crescent shape across the western and northern parts of the region and seems to be the down going extension of the Lago shallowest anomaly

5. DISCUSSION OF RESULTS AND COMPARISONS TO OTHER GEOPHYSICAL DATA

Comparison of the velocity models from the local and teleseismic inversions shows that for the greater part of the investigated area the results are generally in agreement This is particularly true if we consider the 8-10 km horizontal cross sections of the local earthquakes inversion and the first horizontal layer of the teleseismic inversion

Both inversions yield a low velocity anomaly (velocity perturbation in the case of the teleseismic inversion) whose locations in the two models do not coincide completely (Figure 5), but this **is** not surprising considering the different resolution properties of each method

In any case, we can affirm that the hypothesis that the same deep anomaly is defined at its deepest by teleseismic inversion and at its shallowest, by the inversion of local earthquakes

This anomaly covers a large zone of the Larderello geothermal field and extends roughly to depths between 7 and 20 km.

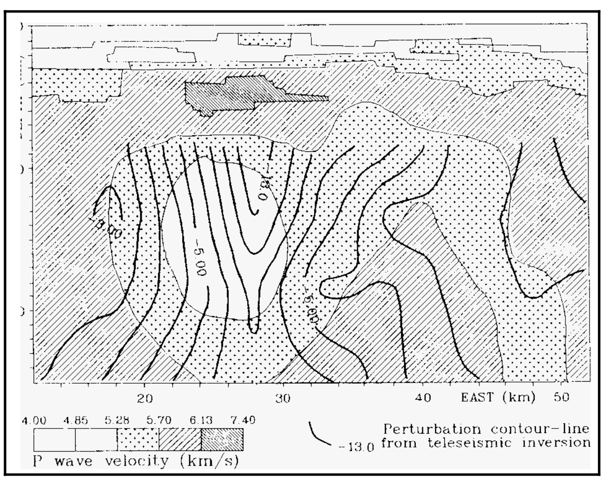

Figure 5 - Comparison between local earthquakes and teleseismic inversion results along a **W-E** cross section

Low velocity anomalies evidenced at depths of **4** km by local inversion seem to be correlated with a deep seismic reflector known as the "K horizon" (Batini *et* ~1,1978,1983,1985, Cameli *et al* ,1993) Its structure is dominated by a large anticline trending NE-SW, and Figure *6* shows a good agreement between the peak of the "K horizon" and the low P wave velocities.

The Rouguer gravity anomaly in the Larderello region is characterized by a wide circular anomaly of relatively low gravity value in spite of the presence of many outcroppings of dense carbonatic formations in the area

Therefore, a deeper cause is required to justify this anomaly

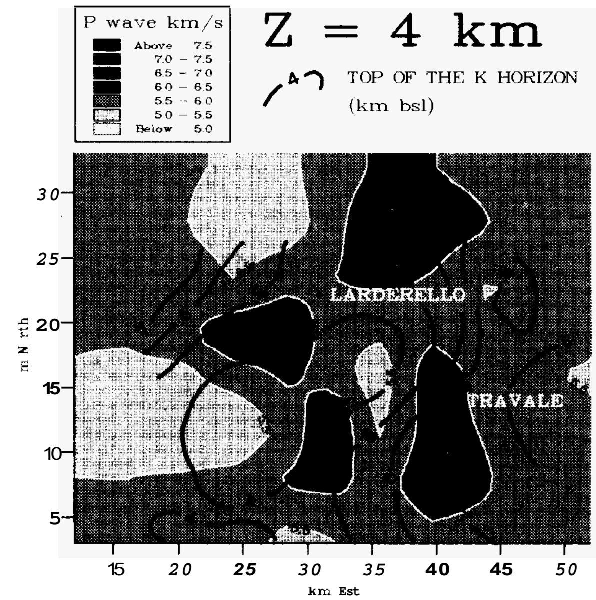

Figure 6 - Comparison between P wave velocity anomalies at a depth of **4** km and the top of the k horizon

In Figure 7 a simplified Bouguer gravity map is compared to the P wave velocity model at a depth of 10 km This figure shows that the large scale shape of the low velocity anomaly correlates well with the gravity data

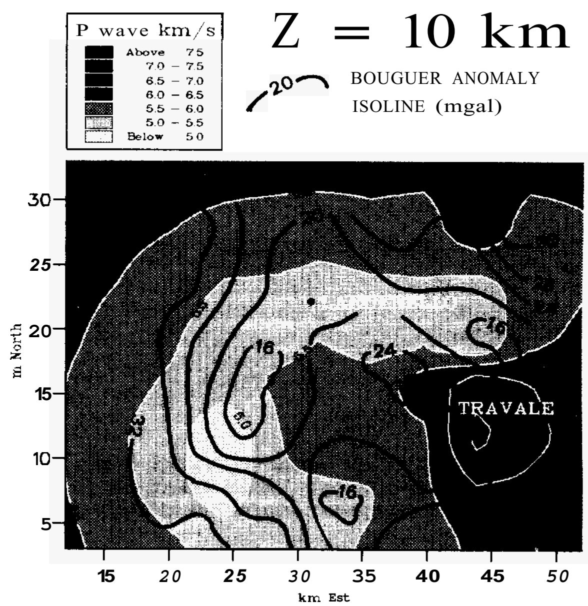

Figure 7 - Comparison between P wave velocity anomalies at a depth of 10 km and Bouguer anomaly.

2D gravity modeling has been carried out across a W-E section *3* km south of Larderello

Figure 8 shows the result of this modeling, which is constrained by well data in its shallowest layers.

A best fit has been obtained by inserting into the model two gradual density decreases correlated with the 'K horizon" and the top of the low velocity zone given by the inversion of local earthquakes This indicates specifically that a body with a density of 2 55 g/cm^3 corresponds to the deep, low velocity anomaly

Also shown in the same figure **is** the schematic shape of an electrically conductive deep body. This body has been detected by a recent magnetotelluric survey (Fiordelisi *et al*., 1995) and has a

resistivity value less than 100 ohm.m. Its location has a good correlation with the low velocity anomaly, but does not match the top in depth.
This is probably due to a different resolution of the two methods, and to the fact that a no much denser fractured system located above the low velocity zone could be interpreted more successfully as a conductive anomaly rather than a velocity anomaly.

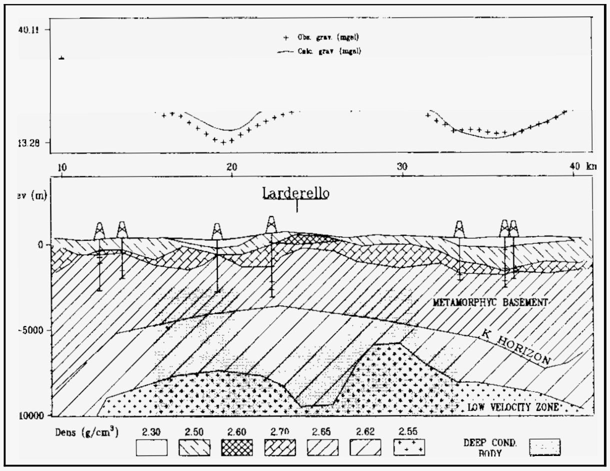

Figure 8 - 2D gravity modeling at Larderello. Constrains are given by well data, K horizon and Low Velocity Zone.

6. CONCLUSIONS

Local earthquakes and teleseismic inversions have revealed low P wave velocity anomalies within the basement of the Larderello Geothermal Field. Joint hypocenter-velocity inversion has well defined these anomalies down to a depth of 10 km, showing good correlations with the peaks of the "K horizon" seimic reflector
A deeper low velocity zone has been detected better by teleseismic inversion. This zone extends between 7 and 20 km in depth and is in agreement with the deepest anomalies seen by local earthquake inversions characterized by a P wave velocity value of less than 5 km/s
The location of the deep velocity anomaly is well correlated, both in width and in depth, with a low density body (2.55 g/cm^3) which fits the Bouguer gravity anomaly
Finally, there is a fair correlation between the aforesaid anomalies and an electrically conductive zone (resistivity less than 100 ohm.m) detected by a recent magnetotelluric survey.
The convergence of all these elements supports and reinforces the hypothesis that the deep zone characterized by velocity, gravity, and conductive anomalies, can be related to an intrusive body which is still partially molten.
This body could represent the mean heat source of the Larderello geothermal area.

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