APPLICATION OF THE MAGNETOTELLURIC METHOD USING A REMOTE - REMOTE REFERENCE SYSTEM FOR CHARACTERIZING DEEP GEOTHERMAL SYSTEM

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Abstract

In 1990, the Larderello geothermal field was tomogaphically imaged using teleseismic data. This study led to the discovery of a P-wave low velocity anomaly. located at a depth of about 7 km. The hypothesized presence of a deep magmatic body is corroborared in this paper by a magnetotelluric (MT) investigation to determine the electrical resistivity of the subsurface. This conclusion is based upon the expectation that a magmatic body will give rise to an increase in electrical conductivity. An MT survey was carried out and simultaneous recordings of the electromagnetic fields were made at sites alog two E-W profiles and also at the distant site of Capraia Island. The use of a remote island as a reference location allowed the removal of interference caused by a nearby electric train railway. A technique was developed that simultaneously solved for the frequency domain train impedance and naturally occurring MT impedance. This effectively separated the train effect from the natural MT signals. All the data were analyzed in this fashion and were used as input to two-dimensional inversion modelling. The results of inversions were consistent with the results of seismic traveltime tomography and other geophysical data

1. INTRODUCTION

Electromagnetic methods have become. in the past few years. particularly useful in depicting geothermal features. The effectiveness of magnetotelluric (MT) surveys conducted in the Tuscany geothermal fields during the last 20 years has been negatively impacted by a variety of problems including strong noise and a geologically complex environment (Celati *et al*, 1973; Hutton *et al*., 1985; Duprat *et al*., 1985). The noise is mainly cultural. created by the geothermal power plants. the highly populated environment. and the close proximity of a railroad which produces a highly coherent electromagnetic source which competes with the natural MT source.

In 1992. a new attempt at the application of this method was promoted by ENEL (Italian Electricity Board). The aims were: 1) to define and remove the train noise by improving current data processing techniques; and 2) to verify what features of the geothermal system could be detected using MT data by comparing the results of the MT survey with results from previous geophysical surveys in the same area. A previous seismic travel time tomography survey had delineated a velocity anomaly at the Larderello Geothermal Field. Verifying whether the MT method would indicate the presence of a resistivity anomaly at the same location was of primary interest.

The data set to be used in the processing and modelling was collected at the end of 1992. along two east- west trending survey lines (Figure 1).

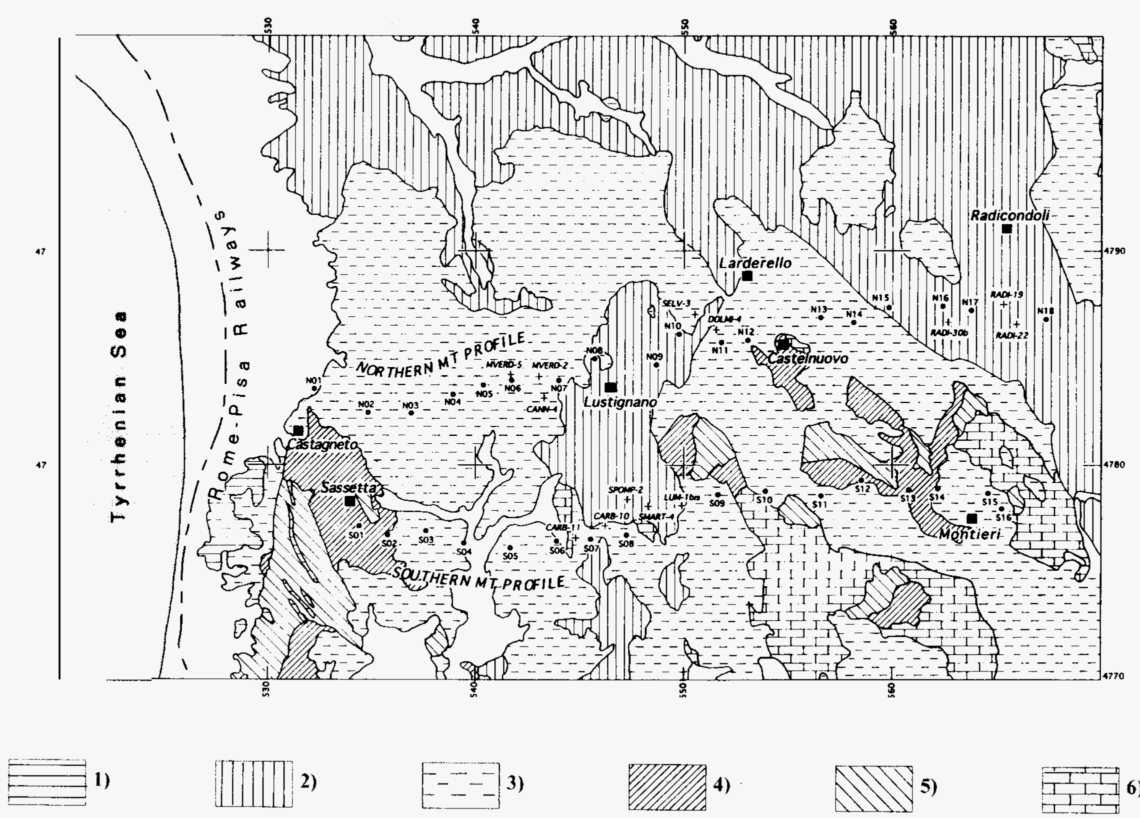

Figure 1: Location map and main geological features of Larderello geothermal area. **Legend:** 1) volcanics; 2) Neogenic units; *3)* Tertiary Flysch units: **4)** Ologocene-Cretaceous Tuscan nappes: 5) Giurassic-Cretaceous limestones; *6)* Triassic dolostomes.

These profiles were located so that they transect the Larderello Geothermal Field and are bordered on the west by the main railroad of the area, which runs along the coast. The two MT lines comprise 34 stations; 18 along the northern line and 16 along the southern line. The station separation is 2-3 km. Data were collected simultaneously from pairs of stations located in Tuscany main land and the island of Capraia - about 40 km off the coast- which was to be used as a very remote reference site.
This paper presents the results of this remote-remote reference MT investigation. Included are: a description of the processing techniques used to address the noise problems, and the results of the 2D modelling.

2. DATA PROCESSING

MT data are processed using power spectra analysis. This techique converts the electric and magnetic time series data from a particular site to the corresponding frequency spectra by application of the Fourier Transform. From these, the iinpedences and apparent resistivity and phase values can then be computed. Simple single site processing can be improved with the introduction of a remote-reference site. allowing the minimization of the noise contribution to the impedence calculation (Gamble *el al.*, 1979 a,b). The critical assumption is that any noise in the data from the remote site is uncorrelated with the noise in the data from the local site.
The noise sources in the Larderello area were mainly of two kinds. The first kind is due to the presence of power plant equipment. power lines, and other local cultural disturbances.

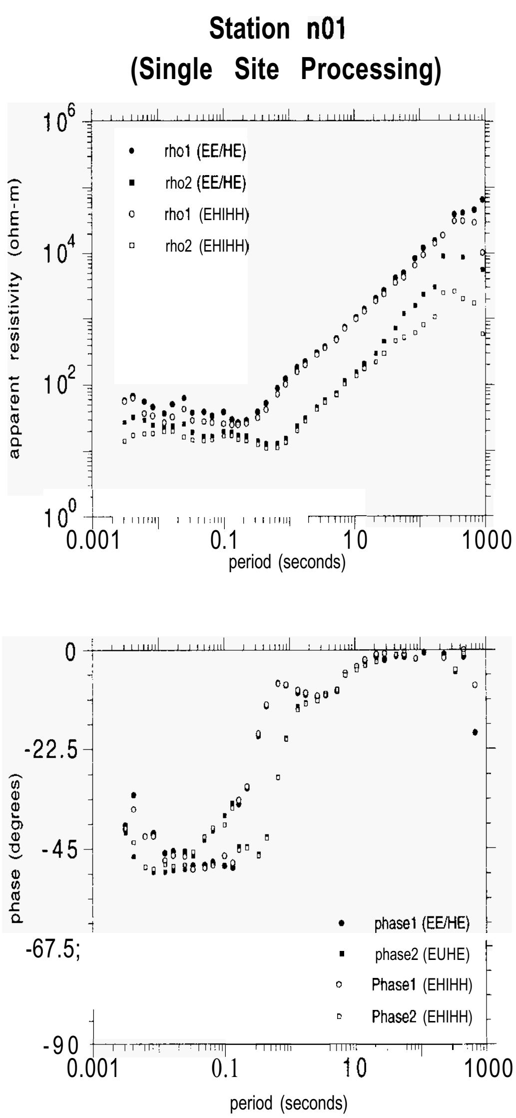

Figure 2 Apparent resistivity and phase data from station n01 showing the characteristic effects of train noise This response is typified by a slope of one in the log (apparent resistivity) vs log (period)

All these very local disturbances produce an incoherent noise mainly affecting higher frequencies - usually above 1 Hz - which could be removed with a remote-reference only a site few kilometers away.
For this reason the 34 stations were collected as 17 couples, i.e., adjacent sites were collected simultaneously, in addition to the recording at the Capraia island (Geosystem, 1993). This technique of local remote-referencing had been previously used in Tuscany and had given fairly good results at higher frequencies (Geosystem. 1990).
The second kind of noise is due to the presence of direct current electric trains, which generate coherent electromagnetic signals that can render the analysis of MT data incorrect at frequencies lower than about 1 Hz. Although the MT data may appear very coherent. the apparent resistivity and phase derived from these data look very much like the response due to a local dipole source instead of the plane wave MT source. This response is typified by a slope of one in the log (apparent resistivity) vs. log (period) and phase near zero degrees (Figure 2). The main railway line in this area is the Roma-Genova line which runs north-southalong the coast (Figure 1). with trains running approximately every 30 minutes. The train signal in the Larderello area can be quite large. and too strong on any site in the main land to allow the use of those as a "noise free" remote-reference site. The Capraia island was then considered a possible site uncontaminated by the train signal due to its remote location and the effect of the surrounding conducting sea water. Comparison of the magnetic field recorded in Capraia and locally in Larderello (Figure 3) showed that Capraia data was free of train signal and was therefore suitable as a very remote reference

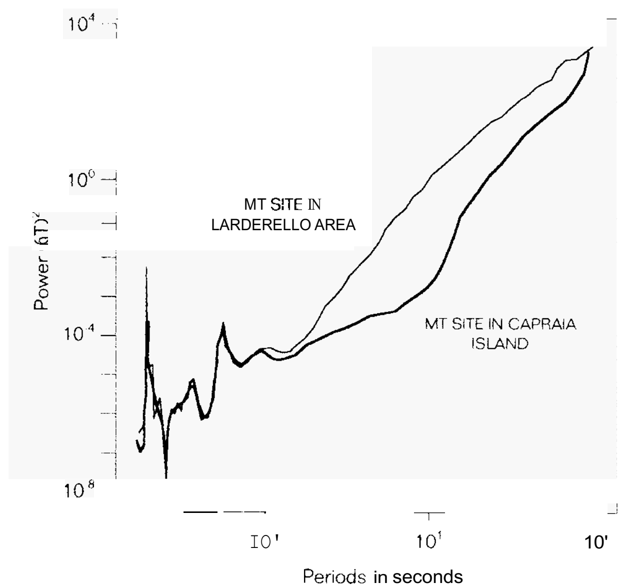

Figure 3: Comparison of Hx field recorded simultaneously at two MT sites, one in Larderello and one on Capraia Island.

Due to the availability of this suitable site, a standard remote reference processing was then applied to the data. The improvement to the processed data was greatest at the eastern most station due to the greater distance from the railroad. Near the rairoad, however, this processing technique showed more and more failures, since the increasing effect of the train noise masked the natural MT source signal. An additional check based on the coherency of signal between Capraia and Larderello sites was then applied. Only those data sections with a coherency greater than 0.8 between the local magnetic field and the remote one were used. The improvementover the standard remote-reference techniques was not enough to consider the problem solved.
To address this difficulty, we modified the standard remote reference technique to simultaneously solve for an MT impedance and a train impedance. We considered the local fields to he a sum of the MT and train signals:

$$H(\omega) = H_{MT}(\omega) + H_{tr}(\omega)$$
$$E(\omega) = E_{MT}(\omega) + E_{tr}(\omega) \qquad (1)$$

At a given frequency, the electric fields are related to the magnetic fields by an impedance matrix

$$E = E \quad + E \quad = Z \quad H \quad + Z \quad H \quad =$$

then

$$E^T = \left|H_{MT}^T \quad H_{tr}^T\right| \begin{vmatrix} Z_{MT}^T \\ Z_{tr}^T \end{vmatrix} \tag{3}$$

where ' T ' stands for transpose and ' Z_{MT} ' and ' Z_{TR} ' stand for the MT iinpedence and train impedence respectively. Assuming that the MT inagnetic field is equal to the remote magnetic field H_R on Capraia island, the train magnetic field is equal to the local field minus the reinote field. This. we feel. is a reasonable assumption given that magnetic fields are coherent over large distances (Madden *et al.*, 1964). Indeed, robust magnetic tranfer function estimates between the island and Larderello have validated this assuinption for this data (Larseii *et al.*, 1994).Then the solution for the iinpedence matrices is given by

$$\begin{vmatrix} Z_{MT}^T \\ Z_{tr}^T \end{vmatrix} = \left|H_r^T \quad H_r^T\right|^T \left|H_r^T \quad H_{tr}^T\right| \left|H_r^T \quad H_{tr}^T\right|^H E^T \tag{4}$$

where ' H ' stands for Hermitian.

In our iinpleineiiiation of equation (4).we edited the data that went into the computation **of** the impedances to exclude those data that had particularly low coherencies between the local and reiiiote magnetic data.

Then this processing technique was applied to the data at every station along both profiles for the longer period data only (greater than 0.1 secs). At the higher frequencies, standard remote referencing gave adequate results. and any higher frequency train signals yield the same impedance inforination as MT signals. In Figure 4. we show plots of the processing result.; for site 11 along the southern profile. which we feel shows the typical behavior of the analyses. At this site and for most others, there was a definite improvement iii the impedance results using standard reinote reference down to periods of 3-30 secs. In most cases, there was some improvement at the longer periods using the two-source solution. and often times. we saw soinewhat smoother results down to periods of 100 secs.

There were exceptions, however. where reinote referencing gave excellent results (usually on the eastern end of the profiles away from the trains). and also where remote referencing failed and the two-source solution gave superior results. Our coinpanion paper (Larsen *et al.*, 1995) details the characteristics of the train signals versus the MT signals. and also suggests a robust technique for separating the train signals from the MT signals.

3. MODELLING AND INVERSION

Two dimensional inodelling of the subsurface conductivity Structure was coinpleted using TM inode data showing the best overall noise reduction obtained with the techniques described above. Since the transverse electric (TE) mode data are severely distorted by 3D conductive inhomogeneities, and they are notoriously difficult to correctly interpret, only TM inode data were used for the modelling (Wannamaker. 1984). Data froiii each station were evaluated by comparing the results of the various techniques and admitting only the data sets more error free and with more geophysically realistic trends.

Development of the apriori resistivity models utilized previously available geologic and geophysical data from along the survey lines. Electric (resistivity). reflection seismic and gravity data. structural geologic maps and well stratigraphy provided a detailed model of the shallower structure (between 0 and 3 kin) of the Larderello area. Below 3 **kin,** horizontal layers were put in the apriori inodel, not including the crustal anomalous zones already defined with other methods - seismic tomography (Block, 1991) and teleseismic (Foley. 1990) - to see if the MT data independently required such zones. The only oblique interface considered in the model was the Moho. whose depth was estimated at 25 km for the eastern margin of the Tyrrhenian Sea, 30 kin beneath Corsica. and 25-35 kin below the western Adriatic part (Della Vedova *et oi.*,1984, Royden *et al.*, 1987).

The ability to resolve a lower crustal conductivity anomaly is related to the choice of using TM inode data in the inversion. The TM inode data is particularly sensitive to the increased amounts of current trapped in the upper crust near conductive bodies such as oceans and seas (Park *et al.*, 1991).

This current leaks off into the mantle as one progesses away from the coast in a very systematic and spatially gradual manner. If. however, there are large conductive zones in the lower crust that provide a short circuit for this current, the effect in the TM mode response is a large change in the slope of the apparent resistivity curves across the zone (Figure 5). Since this change is manifested in the phase as well. it is robust with respect to near-surface conductivity structures.

The apriori inodel extended out to the west and east of the survey area to include the Tyrrhenian sea and the Adriatic sea in order to include the effects of these bodies of water. These portions of the inodel were constructed using general geologic and gephysical data (CROP, 1991).

We performed three two-dimensional inversions for each profile using the composite data. Various inodelling parameters were tried in order to explore the model space and determine which features of the inversions were robust. The parameters used in the thee trials were as follows; case 1) only the resistivity of the sea water was fixed at 0.3 ohin-meters: case 2) the sea water resistivity and the model paraineters for the whole shallow structure (0-3km) were fixed at their apriori values:

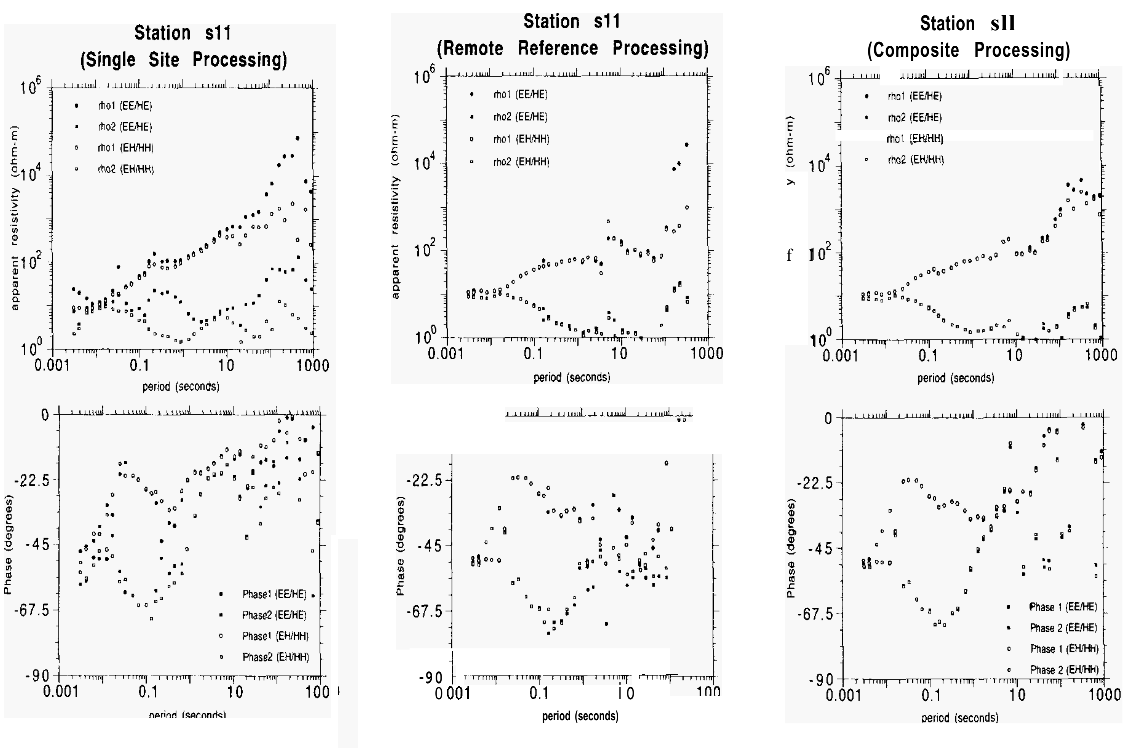

Figure 4: Processing results for station s11 using the three techniques used in this study: Single Site processing. Remote Reference processing and Composite processing.

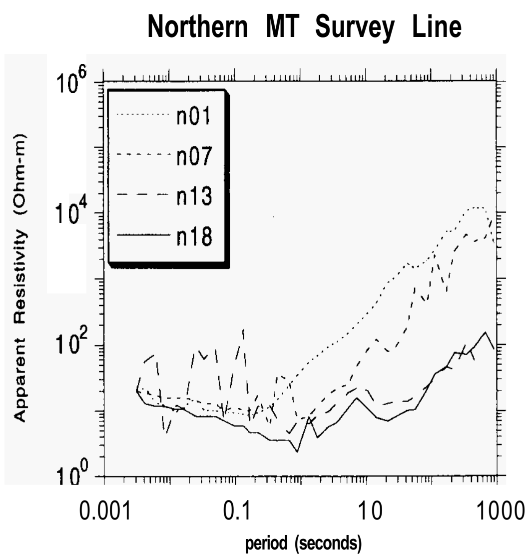

Figure 5: Coastal effects on TM data froin the northem MT line are indicated by the gradual decrease in slope on the log-log plot froin one station to the next as an observer looks progressively eastword away froin the coast.

and case 3) the sea water resistivity and the inodel parameters of the lower crust and inaiitle were fixed at their apriori values.

For inversions of case 1) and case 2) above, the results suggest the presence of a zone of decreased resistivity (≤100 ohm-m) located in the lower crust. corresponding in position with the seismic anoinaly. When the lower crust and upper inantle were fixed for case 3). an unrealistically large conductive zone in the upper crust east **of** the profile was necessary to ensure that enough current was represented in the upper crust.

A plot of the results of inversion case 2) for the two profiles is shown in Figure 6. The character of the lower crustal resistiviry anomaly is consistent for the different values of the lower crust that were used. Comparing the two profiles. the results of inversion show a inore coinplex upper crustal structure and a greater lateral extent of the conductive anoinaly underlying the southern line than for northern line.

4. CONCLUSION

I'he data processing techniques described in this paper produced good results at stations located beyond 20 **kin** from the railroad. At stations closer than 20 km. only the separation **of** train and MT iinpedences proved to be effective for a large range **of** frequencies. However, this technique also failed for stations where the train noise completely masked the natural signal.

These preliininary results arc promising, since they show an evident improvement over previous processing routines.

A clear correspondence occurs between the MT resistivity anomaly and the low velocity anomaly detected hy tomography. This latter was already correlated to a light deep body in a two dimensional gravity modelling (Figure 7).

The locations of the resistivity, seismic and gravity anomalies correlate very well with the most active geothennal zones in the Larderello area. These anomalies seem to be strongly correlated to the deep features of the geothernial system. and may possiby be associated with magmatic bodies residing in the middle-lower crust.

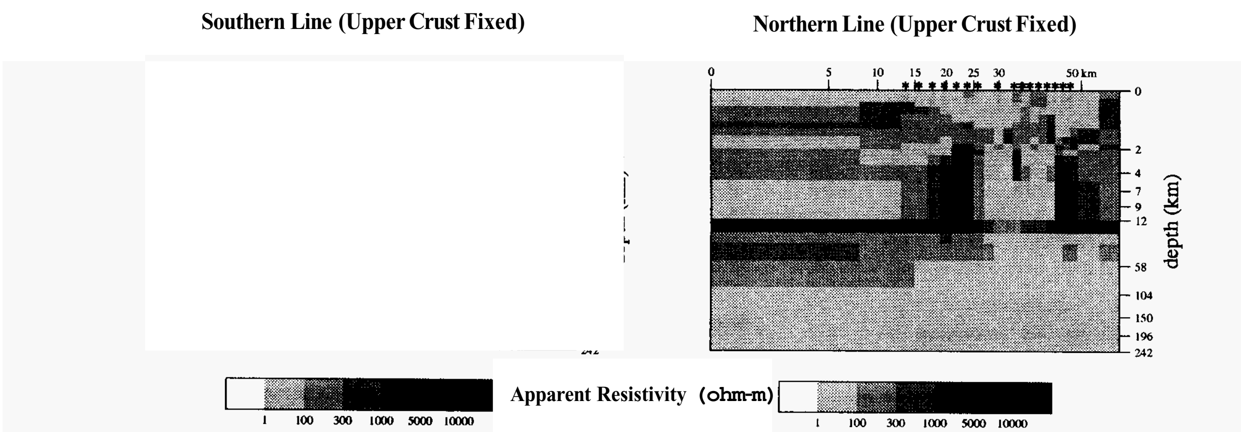

Figure 6: 2D inversion for the two profiles with fixed shallow structure. The conductive anomalous body can be detected. Asterisks correspond to the site locations.

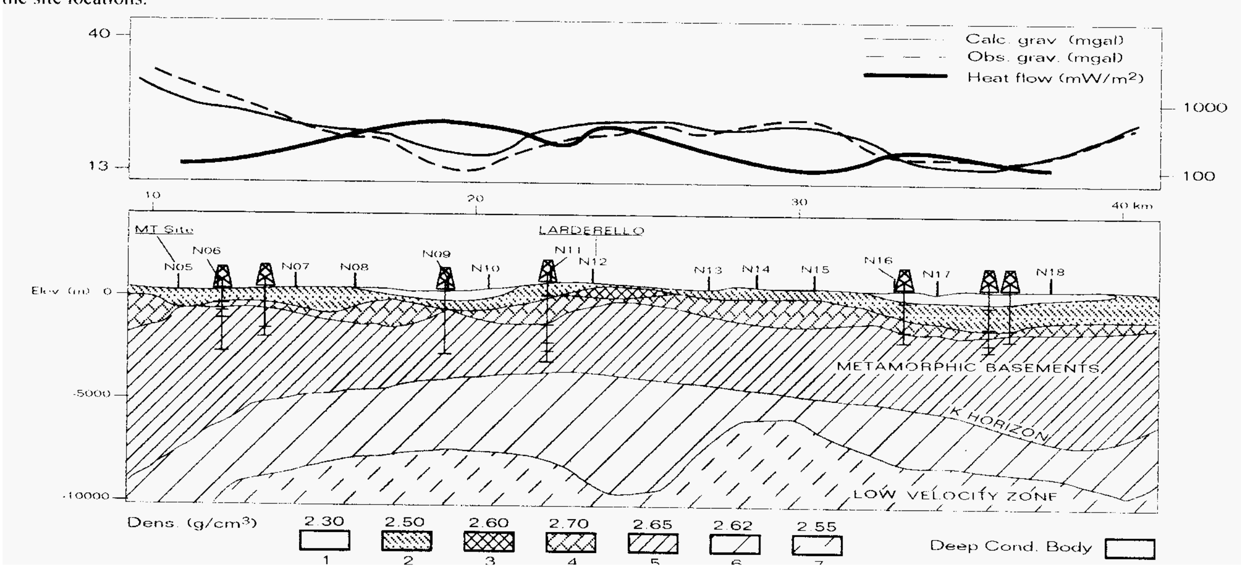

Figure 7: Coinprchensive picture of gravimetric. seismic and magnetotelluric results along the northern line. Legend: 1) Neogenic sediments: 2) Tertiary Flysch units: 3) carbonatic units: 4) anydrites; 5) metaniorpliic units: 6) fractured and hot metamorphic units: 7) igneous intrusion.

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