Proceedings World Geothermal Congress 2000
Kyushu - Tohoku, Japan, May 28 - June 10, 2000

MT METHODOLOGY IN THE DETECTION OF DEEP, WATER-DOMINATED GEOTHERMAL SYSTEMS

Adolfo Fiordelisi[(1)], Adele Manzella[(2)], Giorgio Buonasorte[(1)], Jimmy C. Larsen[(3)], Randall L. Mackie[(4)]
[(1)] ENEL/DP/PDG, Via Andrea Pisano, 120 – 56122 Pisa, Italy
[(2)] CNR – IIRG, Piazza Solferino, 2 – 56126 Pisa, Italy
[(3)] PMEL/NOAA, Seattle, Washington U.S.A.
[(4)] GSY-USA, Inc. San Francisco, California U.S.A.

Key Words: geothermal exploration, magnetotellurics, Mt. Amiata.

ABSTRACT

A magnetotelluric (MT) survey was performed in an area south-west of the Mt. Amiata geothermal field to assess its usefulness for detecting deep, water-dominated geothermal systems. The survey comprised 28 sites spaced approximately 1 km apart along a SW-NE profile. Two unique aspects of the data collection included (1) a remote reference site located 50 km away on the island of Capraia, and (2) contiguous telluric dipoles between each of the 28 main sites for a continuous MT profile. Data from a far remote site were used in conjunction with robust processing algorithms to remove low frequency coherent electromagnetic noise, generated by electrified railways, from the local data. A continuous profile of MT data resulted in greater resolution of the subsurface electrical conductivity and prevented spatial aliasing problems.

Two dimensional (2D) models of electrical resistivity were merged with gravity, seismic, thermal and structural data. The integrated interpretation of these data resulted in an accurate reconstruction of the main geological features and the detection of deep horizons due to the presence of geothermal systems. Deep and shallow conductivity anomalies detected by the MT survey can be correlated with fractured areas of the geothermal reservoir and with the possible presence of a deep partially molten granitic body. From this reconstruction, the geothermal reservoir already under exploitation in the Mt. Amiata area seems to extend to the SW, expanding the possibility of geothermal exploration in southern Tuscany.

1. INTRODUCTION

The purpose of this study was to extend the geophysical exploration to the western side of the Mt. Amiata geothermal field where high thermal anomalies were previously detected (Baldi et al., 1998).

Mt. Amiata area is located in southern Tuscany (Fig. 1). In this region the last extensional phase of the Alpine orogeny gave rise to NNW-SSE normal faults and formed tectonic depressions where Neogenic sediments were deposited (Decandia et al., 1998; Barchi et al., 1998). Later on, the region underwent a general uplift, so that older units outcrop in some places, such as east of Roccalbegna.

Mt. Amiata is an extinct, recent volcano (0.3 Ma). Its effusive products and clayey Neogenic deposits cover most of the area and overlie shaly allochtonous Flysch units. Volcanites are characterised by a wide range of resistivity values (50-200 ohm-m), while Neogenic deposits and Flysch units are conductive (10-20 ohm-m). Mesozoic carbonate formations of the Tuscan Nappe outcrop in a few places (see Fig. 1) and are moderately resistive (about 100 ohm-m). Anhydritic formations of the same Nappe can, however, be very resistive, reaching values higher than 1000 ohm-m. Beneath the sedimentary cover there is a metamorphic sequence (phyllites and probably micascists at greater depth) with resistivity of about 100 ohm-m.

Two reservoirs characterise the water-dominated geothermal system of the Mt. Amiata: a shallow reservoir residing in the carbonate units at 0.5-1 km depth, and a deep one in the metamorphic basement at depths greater than 2 km. The entire system is maintained by fluid circulation through fractures and faults and is heated by an even deeper magmatic body. The presence of this body is mainly testified by granitic dykes and thermometamorphic aureoles. Furthermore gravimetric data indicate the presence of a light body at depth (Orlando et al., 1994) in accordance with a zone of reflection transparency evidenced by seismic data. The top of this body appears to reside at about 6-7 km below Mt. Amiata, deepening and then disappearing outside the volcano area.

Both a water-dominated geothermal system and a hot magmatic system can cause a conductive anomaly that, in the electrical framework of the study area, can be a typical good target for the MT method.

In Tuscany the presence of a high level of electromagnetic noise is a limit in the application of the method. For this reason the remote-remote-reference technique was used in order to remove both the local high frequency noise (Gamble et al., 1979) and the low frequency one generated by the so-called “train effect” (Fiordelisi et al., 1995; Larsen et al., 1996). Furthermore, a combined data recording system was used to enhance the resolution of shallow structures.

2. METHODOLOGY

Standard wide-band MT data (0.001-125 Hz) were collected along a profile (Fig. 1) at 26 sites spaced 1 km apart. Additional dipoles were set up between these main sites to record only electric field data, which, when combined with the magnetic data at the central main sites, provided a continuous profile of MT data.

On these telluric-magnetotelluric (TMT) sites only high frequency data were recorded (0.1-125 Hz). All dipoles were 200 m long and were aligned parallel and perpendicular to the profile direction (Fig. 2). Two MT systems 1 km apart recorded high frequency data simultaneously on two main (MT) sites and on the 8 adjacent TMT sites. A total of about 3 hours of data was acquired for local remote-referencing of the TMT data in late afternoon and early morning, aiming to take advantage of relatively short but quiet periods between noisy data segments.

Low frequency data were acquired simultaneously on two main sites 1 km apart (not the TMT sites) and on Capraia island during the night, when test soundings indicated that noise tended to be at minimum. Two main sites (27 and 28) were later added to the survey, in an area where anomalous heat flow had been defined by previous studies (Baldi et al., 1998).

The use of remote-reference technique allowed to face the problem of high electromagnetic noise in the area. Local remote-reference standard technique (Gamble et al., 1979) could effectively remove the uncorrelated local noise due to power and telephone lines, cathodic protection circuits and other sources of noise which affected high frequency data. However, good quality data were recorded on most of the sites and local remote-referencing did not improve them.
Indeed, a tremendous contribution was given by the remote reference to the Capraia island on the low frequency data. At these frequencies the high-amplitude coherent electromagnetic fields generated by the d.c. powered electric train systems make it very difficult to obtain accurate estimates of the earth's MT impedance. Interpretations based on contaminated data would be incorrect since the calculated impedances are a combination of the MT and non-MT impedances. The contamination is manifested as a linear increase in the log of apparent resistivity versus log of period with a slope of one or even higher and a corresponding E/H phase shift near zero degrees (see Fig. 3). To deal with this problem it was necessary to record data on a remote site where correlated train signals were absent and the island of Capraia, 50 km away to the west of the coast, was chosen.
Since static shifts are a common problem in magnetotellurics, the data were checked against electric d.c. data close to the MT sites. This problem arises from local resistivity perturbations that mainly affect the electric fields, causing a shift of the apparent resistivity curves whereas phase data are not affected. Schlumberger electric data, which provide more accurate estimates of the near-surface resistivity structure, were used to correct the main MT sites for static shift.

3. DATA ANALYSIS

Due to the particular kind of noise affecting the study area, standard robust processing techniques fail in dealing with our data. Hence, time series at all sites were processed using a robust method for extracting MT transfer functions from time series highly contaminated by correlated noise signals (Larsen *et al.* 1996).
The data from each site were processed for both local least-squares and remote-reference transfer functions in order to assess general data quality. The high frequency data were of good quality and there was not much difference between least squares and local remote reference processing in this band. For the low band, the use of data from the far remote (Capraia Island) was effective for extracting MT transfer functions from the highly contaminated time series.
Sites at the edges of the profile were more affected by correlated noise signals since they were closer to electrified railways. For example, Fig. 3 shows processing results for site 3, which is about 7 km from the railroad. Local least squares processing produces very small error estimates, but the low frequency response is primarily made of correlated noise signals.
Notice that the remote reference results show a much flatter and more realistic curve at low frequencies, but because of the high levels of correlated noise signals, the remote reference error estimates are higher than those computed for local least squares.
The definition of major electric field direction during processing and standard decomposition showed a regional NW-SE strike direction. Apparent resistivity and phase composite data were then computed in the direction of this regional strike.

4. INTERPRETATION

All the main geophysical data (MT, gravity, seismic profile) available in the study area were interpreted separately, but matching the results in order to obtain a coherent integrated interpretation.

4.1 2D MT modelling

2-D MT inversions were carried out using the 2-D Mackie code, which finds smooth resistivity models that best fit the observed data using the method of Tikhonov regularisation (Rodi and Mackie, 1998, submitted to Geophysics).
A uniform resistivity of 10 ohm-m was used in the apriori model and all parameters were allowed to change except those corresponding to seawater, which were fixed at 0.25 ohm-m.
Fig. 4 shows the resistivity model obtained from the inversion of the entire TM and TE mode data set. The TMT data are sensitive primarily to structure down to about 2 km depth, because they are limited to higher frequencies.
The main MT sites, with their lower frequency range, were sensitive to structure to depths of approximately 6 km. Sensitivity to deeper structure is precluded due to high error estimates for the longer period data.
The model in Fig. 4 shows a shallow conductive unit above a more resistive unit at a depth of about 0.5 km. The latter is interrupted by dipping conductive bodies on the west of Roccalbegna and by broader conductive structure near Mt. Amiata, where the water-dominated geothermal system is located. Below Mt. Amiata, the conductive anomaly extends to about 6 km depth, and cuts across the resistive units on the west, connecting directly with the conductive structure to the west of Roccalbegna. The shallower conductive units correspond to flysch and Neogene units, which cover the deeper carbonate units. East of Roccalbegna there is an uplifted unit belonging to the carbonate units of the Tuscan Nappe but intercalated with clays and therefore still electrically conductive.
The resistive bodies at 0.5-2 km depth b.s.l. are probably linked to anhydritic and metamorphic units. Where these units are fractured and filled with hot saline water, as in the eastern portion of the profile, their resistivity does not exceed 30 ohm-m, but it can exceed 1000 ohm-m when they are still massive, as in the central and western portion.
Below 2 km, comparison of the MT model with well stratigraphy and seismic data suggests that the conductive anomaly below the Amiata area is due to various factors. The outcropping resistive volcanites and adjacent conductive flysch unit in this area are located above anhydritic and metamorphic units, where the water dominated geothermal system resides. This would reduce the resistivity of metamorphic units to the values shown in Fig. 4. The conductive anomaly of this water dominated geothermal system overlies the regional crustal conductive anomaly due to the high temperature gradient of southern Tuscany. Inside this anomaly an even stronger anomaly can be recognised, with resistivity of few ohm-m. This is probably due to a deep magmatic body which creates the best condition for current flow (fractured and fluid filled rocks above it, molten condition inside). The body seems to be connected through very steep and conductive interfaces to the shallower structures, cutting across the resistive anhydritic and metamorphic units. Where the interface is wider, below sites 7-10, heat flow data assume higher values, suggesting buried geothermal system in this area.

Sites 27 and 28 are located on each side of the main profile, close to sites 9-10. The resistivity models show that, west of Roccalbegna, the conductivity increases from site 28, in the SE, through site 9 and to site 27 in the NW. This indicates a more interesting area, from a geothermal point of view, a little to the north of the main profile, which probably does not cross the most conductive body.

4.2 2D Gravity modelling

The Bouguer anomaly map shows a wide gravimetric minimum that extends from Mt. Amiata area towards SW reaching the village of Murci. Part of this minimum is justified in correspondence of the Amiata volcano by the low density of the volcanic products (2.3 g/cm^3) and the nearby Neogene light sediments of the Radicofani graben, whereas in the Murci area many outcrops of dense carbonate formations (2.68 g/cm^3) should cause a positive gravimetric anomaly. In order to investigate the possibility of deep density anomalies a 2D gravity model was composed. The model section (Fig. 5) is coincident with the MT profile and extends to Mt. Amiata where the presence of many wells gives reliable constrains for the shallow structures. The most interesting result of this modelling was the definition of a wide light body (2.55 g/cm^3) located at a depth of 5-6 km below the Amiata area and extending towards Murci where its top reaches a depth of about 8 km. This body can be interpreted as a partially molten granitic batholite. At greater depth, a decrease of density to 2.45 g/cm^3 is necessary to fit the observed anomaly. This means that the batholite should be totally molten at a depth greater than 10 km.

4.3 Seismic Profile

A seismic reflection profile is available along the MT line and perpendicular to the main geological structures. It was possible to identify many reflectors on this seismic profile (Fig. 6), such as the top of the Anhydritic formations, the top of the Metamorphic sequence and the “K” marker. The latter plays an important role, from geothermal point of view, through the hypothesis that it represents a transition zone between a ductile and brittle behaviour of the rocks at temperatures higher than 400-450 °C (Cameli et al., 1993). The “K” marker shows a sub horizontal trend along the entire profile. It is located at a depth of about 4 km (1.9-2 sec twt) below the Amiata area and becomes deeper towards SW, reaching a depth of 7 km (3 sec twt). Immediately SW of Roccalbegna, the seismic profile shows an important discontinuity with an apparent slope of 40° and the depth to all the main seismic reflectors increases. Beneath the “K” marker, a transparency zone is observed (a zone of no reflection), extending from the Amiata area to Murci. This seismic signature is typical of homogeneous body such as granitic batholites. The location and shape of the transparency zone show a similarity with the deep light body of the gravity anomaly.

5. CONCLUSIONS

The combination of the various geophysical methods shows that the whole survey area is anomalous. The shallower structure defined by the MT model in Fig. 4 fits well the stratigraphic information extracted from wells and seismic data in the first 2 km (Fig. 7). At greater depths a general conductive condition is shown, which is probably linked to two factors. The anhydritic and metamorphic units are host the water dominated geothermal reservoir, which causes the shallow (0-2 km b.s.l.) conductive anomaly on the eastern part of the profile. Moreover, a possible magmatic body is present below Mt. Amiata , dipping towards the west and disappearing west of Roccalbegna. This body is inferred from gravimetric low in the Bouguer values and from the lack of reflections and a transparency in reflection seismic data. (Figures 5 and 6). From the MT models, we see that this body causes a decrease in the resistivity above it, showing a broad correspondence in depth to the “K” seismic marker. Why the resistivity of the body increases below Mt. Amiata is still not clear and will be investigated in the future with new MT soundings. Between Murci and Roccalbegna, the deep conductive body seems to be connected through very steep interfaces to the shallower structures, cutting across the resistive anhydritic and metamorphic units. In the area where the interface is wider, below MT sites 7-10, the uplift of isotherms suggests a buried geothermal system.

A potentially interesting and unexplored area is therefore located just to the north of our profile, near MT sites 7-10. Seismic data are unable to corroborate the existence of these conductive interfaces. On the basis of MT results, the series of faults defined in the seismic reflection profile could be interpreted as being responsible for the up-flow of hot fluids heating the area. Conductive anomalies identified by MT are consistent with the locations of gravity anomalies and the structural reconstruction from seismic profiling.

ACKNOWLEDGEMENTS

The authors are indebted to Geosystem s.r.l. for the collection, preliminary processing and modelling of the data.

REFERENCES

Baldi, P., Bellani, S., Buonasorte, G., Fiordelisi, A., and Manzella, A., (1998). Geothermal exploration in Tuscany (Italy) for high temperature resources. *World Renewable Energy Congress V*, (Florence, Italy) Part IV, pp.2733-2736.

Barchi, M., De Feyer, A., Magnani, M.B., Minelli, G., Pialli, G. and Sotera, M., (1991). Extensional tectonics in the Northern Apennines (Italy): evidences from the CROP03 deep seismic reflection line. *Mem. Soc. Geol. It., Proc. of “Results of the CROP03 deep seismic reflection profile” Congress,* Vol. 52, pp. 527-537.

Cameli, G.M., Dini, I. and Liotta, D., (1993). Upper crustal structure of the Larderello geothermal field as a feature of post-collisional extensional tectonics (Southern Tuscany, Italy). *Tectonophysics*, Vol. 224, pp. 413-424.

Decandia, F.A., Lazzarotto, A., Liotta, D., Cernobori, L. and Nicholich, R., (1998). The CROP03 transverse: insight on post-collisional evolution of Northern Apennines. *Mem. Soc. Geol. It., Proc. of “Results of the CROP03 deep seismic reflection profile” Congress,* Vol. 52, pp. 427-439.

Fiordelisi, A., Mackie, R., Madden, T., Manzella, A. and Rieven, S., (1995). Application of magnetotelluric method using a remote-remote-reference system for characterising deep geothermal system. *Proc. of World Geothermal Congress*, Vol. 2, pp. 893-898.

Gamble, T.D., Goubau, W.M., and Clarke, J., (1979). Magnetotellurics with a remote magnetic reference. *Geophysics,* Vol. 44, pp. 53-68.

Larsen, J.C., Mackie, R., Manzella, A., Fiordelisi, A., and Rieven, S., (1996). Robust smooth magnetotelluric transfer functions. *Geophys. J. Int*., Vol. 124, pp. 801-819.

Orlando, L., Bernabini, M., Bertini, G., Cameli, G.M., and Dini, I., (1994). Interpretazione preliminare del minimo gravimetrico del Monte Amiata. *Studi Geol. Camerti*, Vol. 1, pp. 175-181.

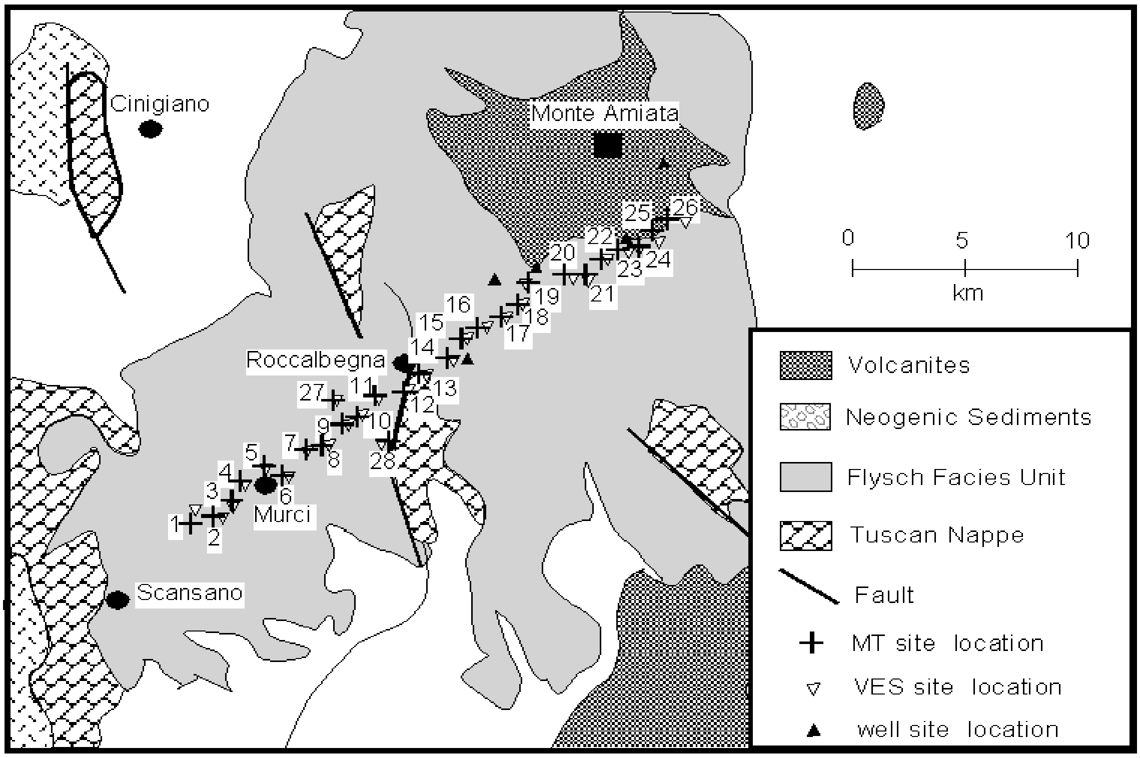

Figure 1. Map of magnetotelluric site locations, Schlumberger site locations, geothermal wells, and a schematic geological map showing the known surface evidences of the main faults.

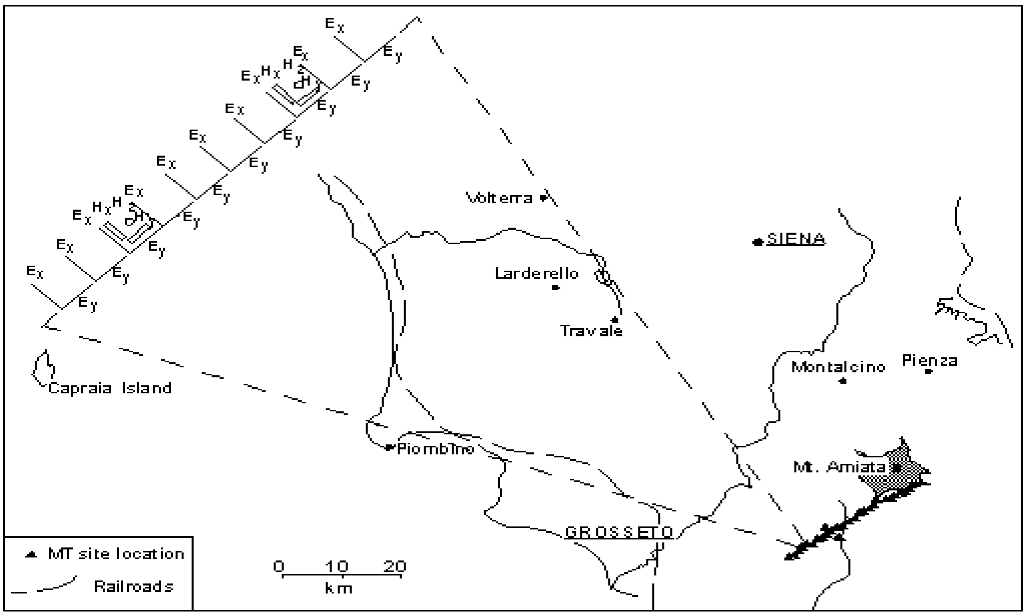

Figure 2. Layout of magnetic and telluric sensors for synchronous recording.
Two complete MT sites (2 telluric and 3 magnetic components) were recorded together with 8 other telluric dipoles, 200 m long. Southern Tuscany, Capraia Island and major railways are also shown.

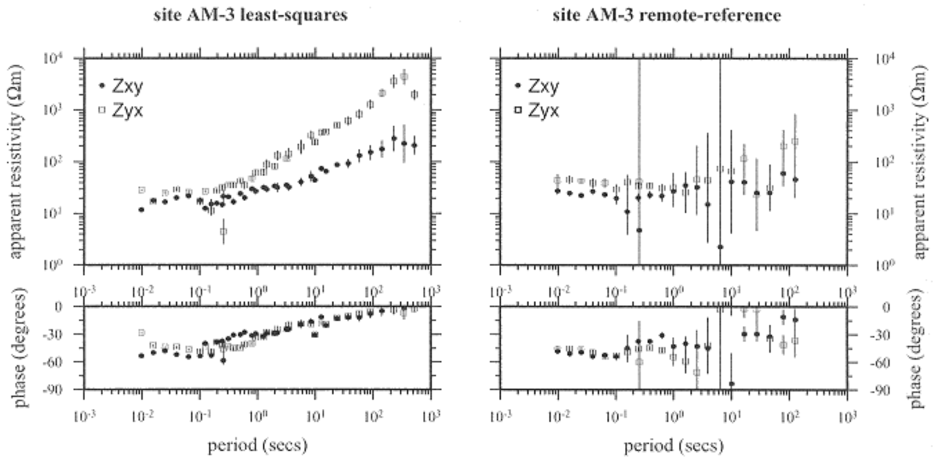

Figure 3. Apparent resistivity and phase plots obtained from processing at site 3: robust least-squares single site processing results on the left; Larsen's robust remote-reference processing results using the island of Capraia site as remote on the right.

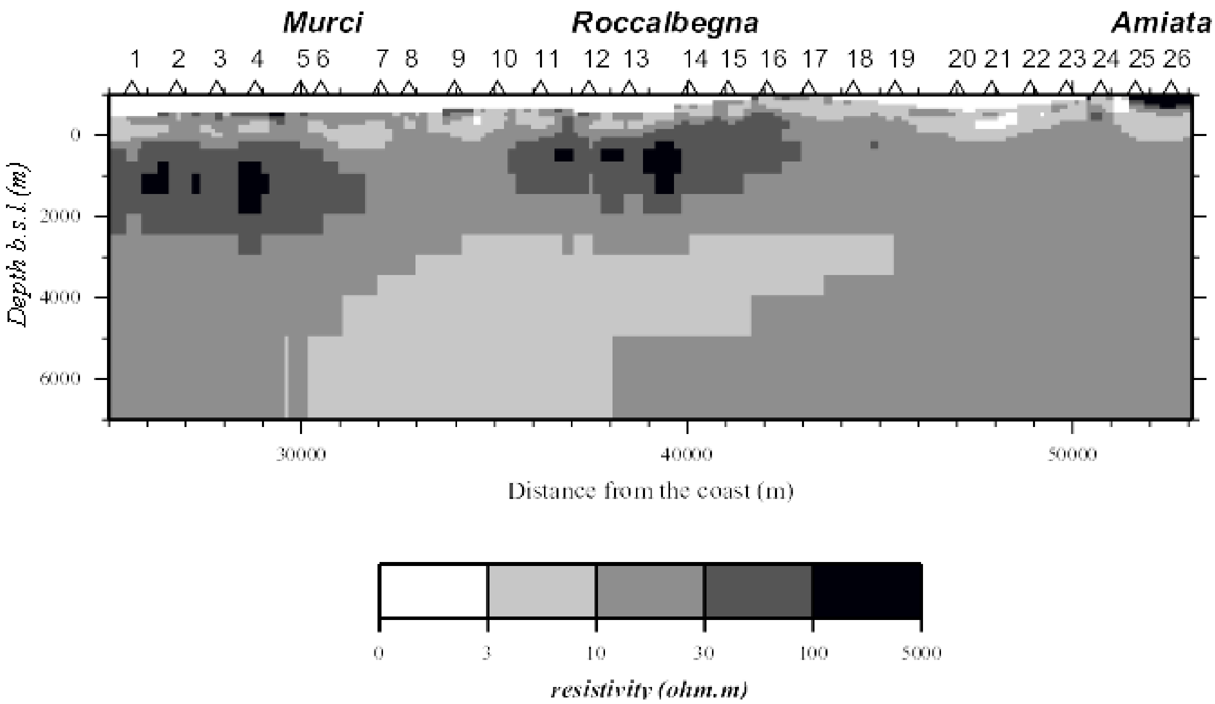

Figure 4. 2-D inversion results: TM and TE modes inversion of MT and TMT sites along the profile shown in Fig. 1.

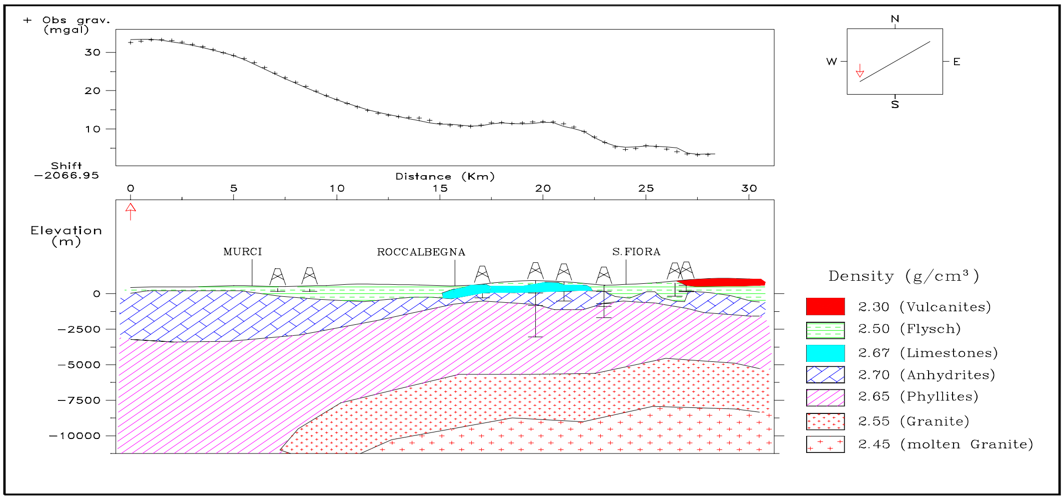

Figure 5. 2-D Gravity model.

.

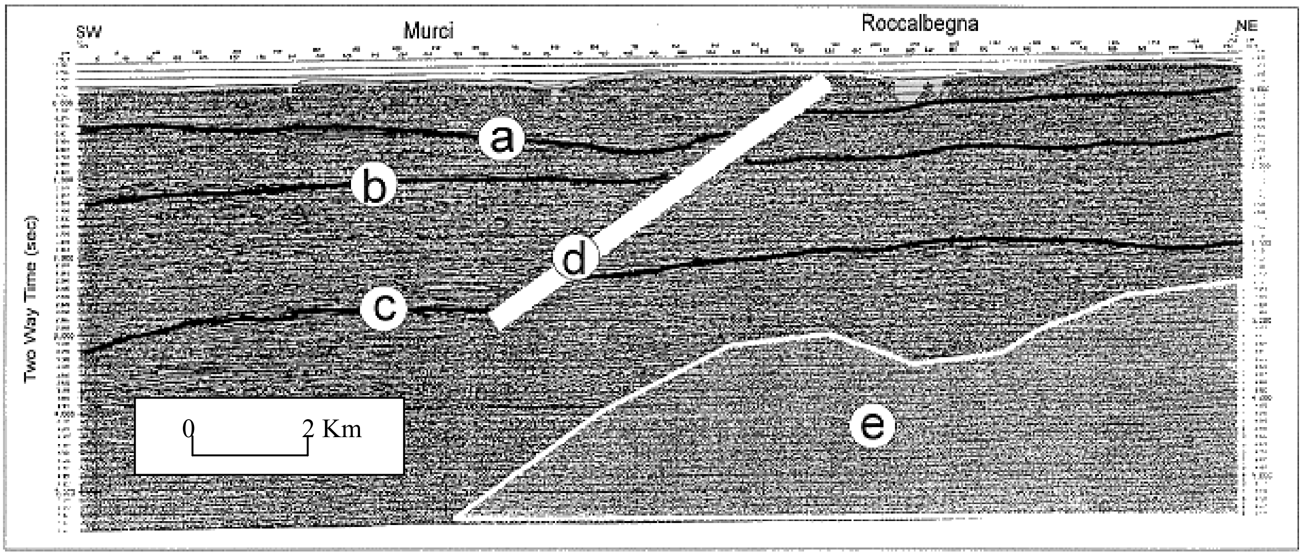

Figure 6. Main structures evidenced by reflection seismic profile: a) top of the Anhydrites , b) top of the Metamorphic sequence, c) “K” marker, d) structural discontinuity, e) zone of transparency.

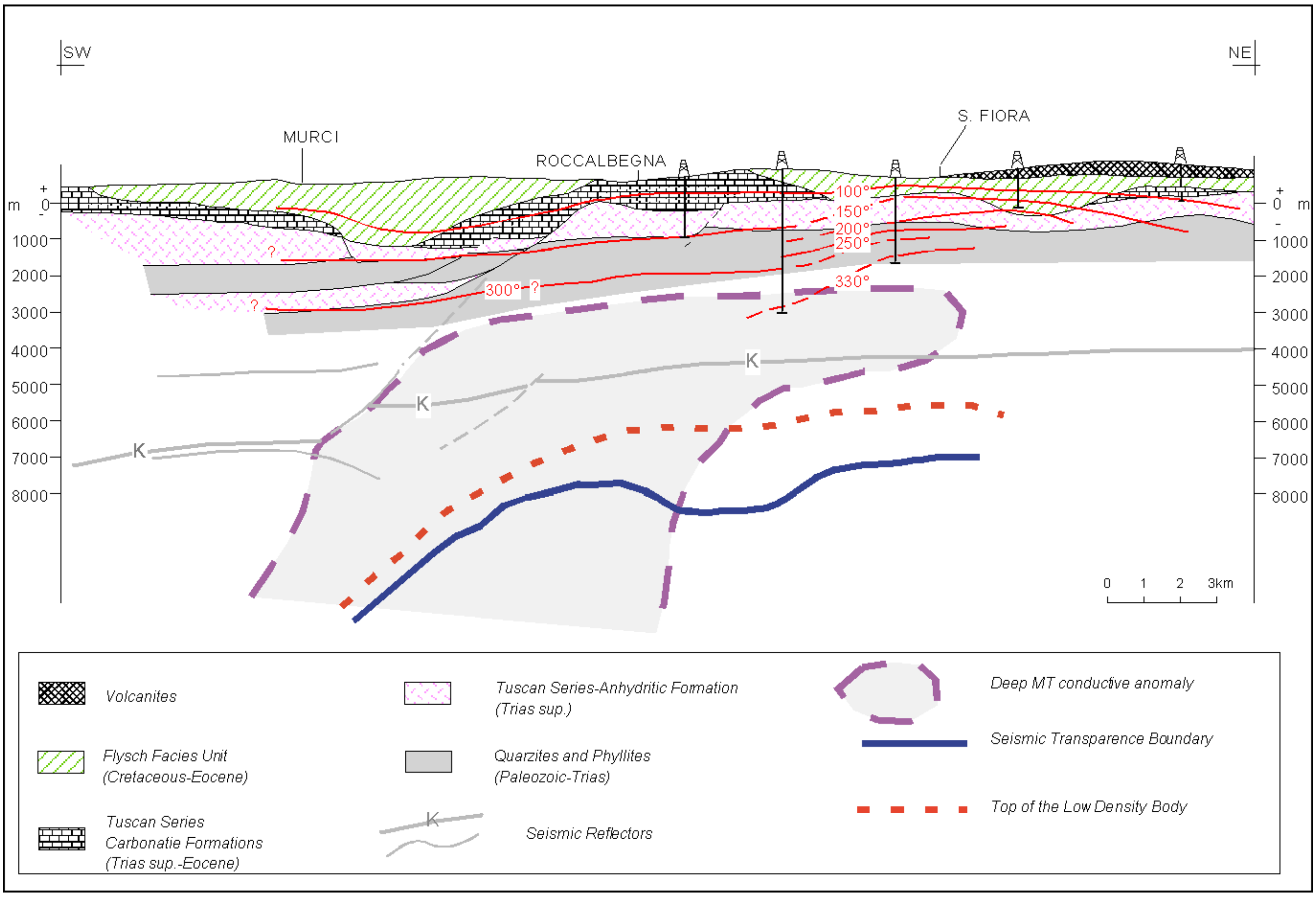

Figure 7. Geothermal and structural reconstruction from integrated interpretation.