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Interpretation of Tuscan gravity data

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ABSTRACT

This work deals with the gravity data interpretation of the Tuscan geothermal area. Given the high degree of complexity of the area, and the difficulty in separating the gravitational effects of the sedimentary basins from those of strictly geothermal origin, a 3D stripping-off of the gravity effects of known surficial formations from the Bouguer anomaly was applied before the 2 3/4D modelling. The stripping-off technique, based on the computation of gravity effects of formations with known density and geometry and subtraction from the Bouguer anomaly, was applied to volcanic (density 2.1 g/cm^3) and Plio-Quaternary deposits (density 2.1-2.3 g/cm^3). The stripped gravity data were used to carry out 2 3/4D modelling along the profile crossing the main gravity minima located in the Larderello-Travale and Mt. Amiata areas. The modelling was based on a trial and error technique. The underground models have been constrained by means of direct (geological evidence, boreholes, etc.) and indirect data (seismic reflection, DSS, etc.).

The inversion of gravity data shows that the wide negative gravity anomalies of the geothermal fields (Larderello-Travale and M. Amiata) can be ascribed to the deep geothermal structures, and local anomalies can be ascribed to the upper and lower geothermal reservoirs. The modelling suggests that the deep sources of the Larderello and Travale geothermal fields could be different.

KEY WORDS: *gravity, 2 3/4D modelling, stripping, geothermy.*

RIASSUNTO

Interpretazione dei dati gravimetrici della Toscana.

L'interpretazione gravimetrica si inserisce nell'ambito della interpretazione della linea sismica CROP 18, che ha interessato l'area geotermica toscana. Essa è stata effettuata con l'obiettivo di ottenere informazioni sull'assetto profondo dei campi geotermici di Larderello-Travale e del Monte Amiata, dove la sismica non è di elevata qualità e per estrapolare lateralmente eventuali lineamenti riconosciuti lungo il profilo sismico. Data la complessità dell'area, si è in primo luogo effettuata una separazione delle anomalie superficiali ascrivibili ai sedimenti di riempimento dei bacini sedimentari, dalle anomalie di origine sconosciuta. La separazione è stata effettuata attraverso la tecnica dello *stripping*, che si basa sull'eliminazione dall'anomalia di BOUGUER (fig. 1) dell'effetto gravimetrico delle formazioni più superficiali a densità e geometrie note. Un esempio dei profili utilizzati per modellare i bacini di Livorno, Pisa, Volterra, Empoli e Val di Cecina è riportato nella fig. 2.

Dall'A. sono stati eliminati gli effetti dei sedimenti Plio-quaternari e delle vulcaniti (fig. 3). Le formazioni superficiali considerate nello *stripping* sono state modellate considerando dati di bibliografia. I dati ottenuti dallo stripping sono in buon accordo con l'anomalia di flusso di calore (fig. 5) (BALDI *et alii*, 1994).

A partire da questi dati è stata effettuata una inversione 2 3/4D, utilizzando il metodo del *trial and error,* lungo un allineamento che ha interessato i minimi gravimetrici dei campi geotermici di Larderello-Travale e Mt. Amiata (fig. 3). L'inversione è stata vincolata con dati di sismica a riflessione e dati DSS. Il profilo gravimetrico, oltre ad evidenziare, le due grosse anomalie legate ai campi geotermici, permette di individuare minimi gravimetrici a più corta lunghezza d'onda (λ) indicati con i numeri 1-4 nelle figg. 3, 4, 6 e 7. I vincoli utilizzati nella modellazione sono stati sostanzialmente la profondità della Moho (20-25 km) e la geometria dell'orizzonte K compreso tra 3.5 e 8 km. Si propongono tre modelli interpretativi 2 3/4D: nel primo sono state modellate le anomalie a grande λ ipotizzando un confinamento del deficit di massa tra l'orizzonte K e la Moho (fig. 4), nel secondo lasciando sostanzialmente inalterata la parte profonda, sono stati modellati i minimi a basso λ (fig. 6) e nel terzo si è avanzata una ipotesi di presenza di materiali semifluidi al di sotto dell'orizzonte K con l'introduzione di corpi a bassa densità (fig. 7).

Dai risultati ottenuti è possibile trarre alcune conclusioni: i minimi gravimetrici a più alto numero d'onda (λ) presenti in corrispondenza dei campi geotermici di Larderello-Travale e del Monte Amiata possono giustificare la presenza in profondità di camere magmatiche. In corrispondenza di Larderello-Travale l'anomalia viene meglio modellata se si considerano due corpi separati. I minimi gravimetrici a basso λ possono essere ascritti ai reservoir geotermici. L'estrapolazione laterale di tali minimi sulla carta corretta per lo *stripping*, permette di definire la probabile estensione planimetrica dei campi geotermici.

TERMINI CHIAVE: *gravimetria, modellazione 2 3/4D, stripping, geotermia.*

INTRODUCTION

The sequence of Tuscan units, ranging in age from the Paleozoic to Quaternary, is the result of the complex geological history of the Tyrrhenian-Apennines setting. The complexity of geology and the spatial distribution of formations in the area produce nested anomalies in the gravity data, mainly characterized by minimum values. In the past, gravity data were used to reconstruct the geological setting of the Tuscany area (ORLANDO, 2001; GIANELLI *et alii*, 1988; MARSON *et alii*, 1996; BERNABINI *et alii*, 1994, 1995a; ORLANDO *et alii*, 1991, 1994). For a long time it was recognised that such minima were due to the low-density formations cropping out in the area, such as the light sediments filling basins, volcanic formations and the geothermal fields. The geothermal origin of the gravity minimum in the Mt. Amiata area is particularly clear, because part of the gravity minimum is located on the outcropping limestone.

Since the geothermal bodies are located a few kilometres below the topographic surface and the light surficial formations have a sheet-like shape, both sedimentary formation and geothermal sources produce negative anomalies with similar wavelengths. This poses difficulties in the inversion of the Bouguer Anomaly (B.A.). To reduce the complexity of B.As without distorting the data in amplitude and phase, a non-linear technique of data separation was introduced by HAMMER (1963), also known as stripping. This technique is based on the computation of the effects of a formation of known density and geometry and the subtraction of such effects from the BA, so as to obtain the simplified gravity data related only to the unknown formations.

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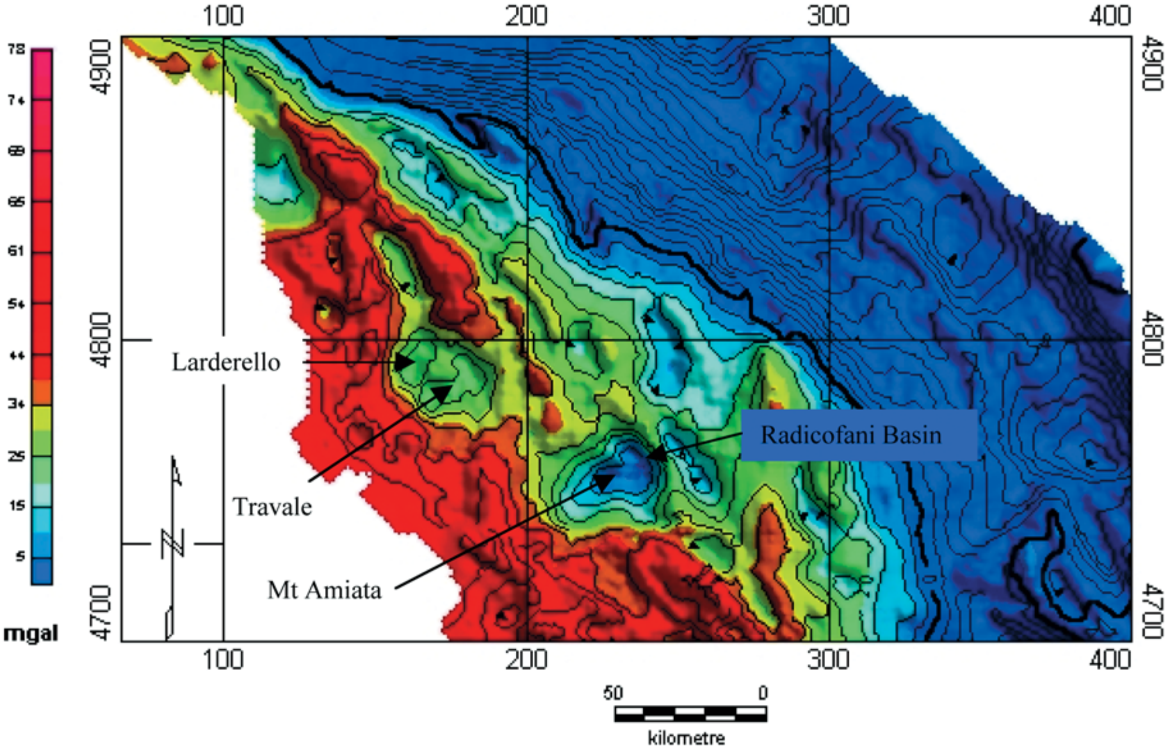

Fig. 1 - Bouguer anomaly computed with a constant density of 2.67 g/cm^3.
– *Anomalia di Bouguer calcolata con una densità costante pari a 2.67 g/cm^3.*

Lately, this technique was also successfully used in the Mt. Amiata area (ORLANDO, 2001; BERNABINI *et alii*, 1994, 1995a; ORLANDO *et alii*, 1991, 1994) and in central-southern Italy (BERNABINI *et alii*, 1995b, 1997, 2000, 2001).

In the Mt. Amiata area, we used the stripping technique to eliminate from the B.A. the gravity effects of the main light formations filling the basins. Then the stripped data were used for a 3D inversion. This rigorous approach supposes that the Mt. Amiata geothermal field produces two types of gravity anomaly with different wavelengths: high wave number anomalies (λ) (15-20 milligal in amplitude) due to the deep geothermal sources, and low λ anomalies (4-5 milligal in amplitude), located in Piancastagnaio and Vallerona, due to the geothermal reservoirs.

On the basis of these results, to reduce the complexity of the B.A., the stripping-off technique was also applied in this paper. In detail, the gravity modelling along the main gravity anomalies was carried out starting with gravity data from which the effects of volcanic sediments and Plio-Quaternary formations filling the basins were eliminated. Careful 3D modelling of their geometries by using direct (geology, boreholes, etc.) and indirect (seismic, geothermal, etc.) data was used to calculate the gravity effects of these bodies.

The 3D stripped gravity data were input to the 2D gravity reconstruction of the Larderello-Travale and Mt. Amiata geothermal fields.

PROCESSING AND ANALYSIS OF DATA

The gravity database consists of data on a 3 km regular grid. The data were extracted from the database of the National Geological Service with a mean sampling density of 1 station every 1 km^2. The Bouguer and topographic corrections were calculated using a constant density of 2.67 g/cm^3.

In detail the processing steps applied to the data were:

1) Computation of the Bouguer anomaly using a constant density;

2) 3D geometric modelling of Plio-Quaternary and volcanic formations;

3) 3D computation of their gravity effects on the topographic surface;

4) Stripping of their gravity effects from the Bouguer anomaly;

5) Extraction of 2D data crossing the main gravity minima from 3D stripped data;

6) 2 3/4D gravity data inversion using the trial and error method.

For more details about the stripping-off method and its efficiency, see HAMMER (1963), BERNABINI *et alii* (1990, 1994) and ORLANDO (2001). The 3D effects of the stripped formations were computed using the Götze and Lamayer algorithm (1988).

To reduce the lateral effects of the non-cylindrical bodies, the inversion was carried out considering the length of 3D bodies in the *y*-direction to be approximately similar to the *x*-direction.

The Bouguer anomaly of the study area is plotted in fig. 1, which shows a regional trend dipping towards the chain and anomalies with gravity values greater then 15-20 mgal. The main minima are located in the Larderello-Travale and Mt. Amiata areas. The latter anomaly is clearly formed by the sum of two minima, one located at the Radicofani Basin and the other in the Mt. Amiata area.

The lithotypes cropping out in Tuscany can be grouped into four main units according to their densities: the Tuscan Nappe with a mean density of about 2.67 g/cm^3, the Ligurid complex with density 2.55 g/cm^3, the Neogene complex with densities varying from 2.1 to 2.4 g/cm^3, and the volcanic complex with a density of 2.35 g/cm^3 (CARROZZO & NICOLICH, 1977; MOSTADINI & MERLINI, 1986; BERNABINI *et alii*, 1995a). Therefore the main surficial effects on the Bouguer anomaly are due to the last two units: the Neogene complex and the volcanic formations.

In the stripping process, because of limited knowledge of the 3D geometries of older formations, only the Plio-Quaternary complex and the volcanic formations have been taken into account.

The effects of each body were calculated starting from the topographic surface. In detail, a density of 2.3 g/cm^3 was assigned to the Eastern basins of Siena, Radicofani and Val di Chiana, a density of 2.2 g/cm^3 to the Western basins of Elsa, Era, Fine, basso Valdarno, Cecina and Livorno-Viareggio, and a density of 2.1 g/cm^3 for Firenze and alto Valdarno and volcanic deposits. The 3D modelling of each body was carried out by taking carefully into account its geometry according to published data (LAZZAROTTO, 1967; LAZZAROTTO & MAZZANTI, 1976; DAMIANI *et alii*, 1980; DECANDIA *et alii*, 1981; COSTANTINI *et alii*, 1982, BATINI *et alii*, 1983; BOCCALETTI *et alii* 1995; BOSSIO *et alii*, 1993, 1994; LIOTTA & SALVATORINI, 1994). The geometry of each body was reconstructed by 2D parallel profiles, the distance between each profile was chosen depending on the complexity of the geometry. An example of the profiles used for the modelling of Livorno, Pisa, Volterra, Empoli and Val di Cecina basins is shown in fig. 2.

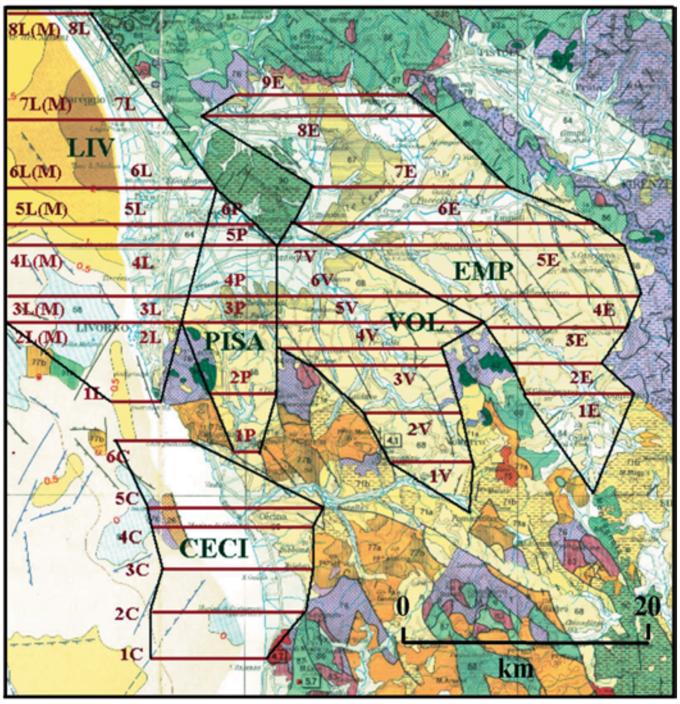

Fig. 2 - 3D gravity modelling of the Livorno, Pisa, Volterra, Empoli and Val di Cecina basins.
– *Modellazione 3D dei bacini di Livorno, Pisa, Volterra, Empoli and Val di Cecina.*

In fig. 3 the gravity data obtained from the stripping of surficial formations from the Bouguer anomalies are shown. Comparing the stripped gravity data (fig. 3) with the Bouguer anomalies (fig. 1), it appears that the stripping has allowed better definition of the minima in the

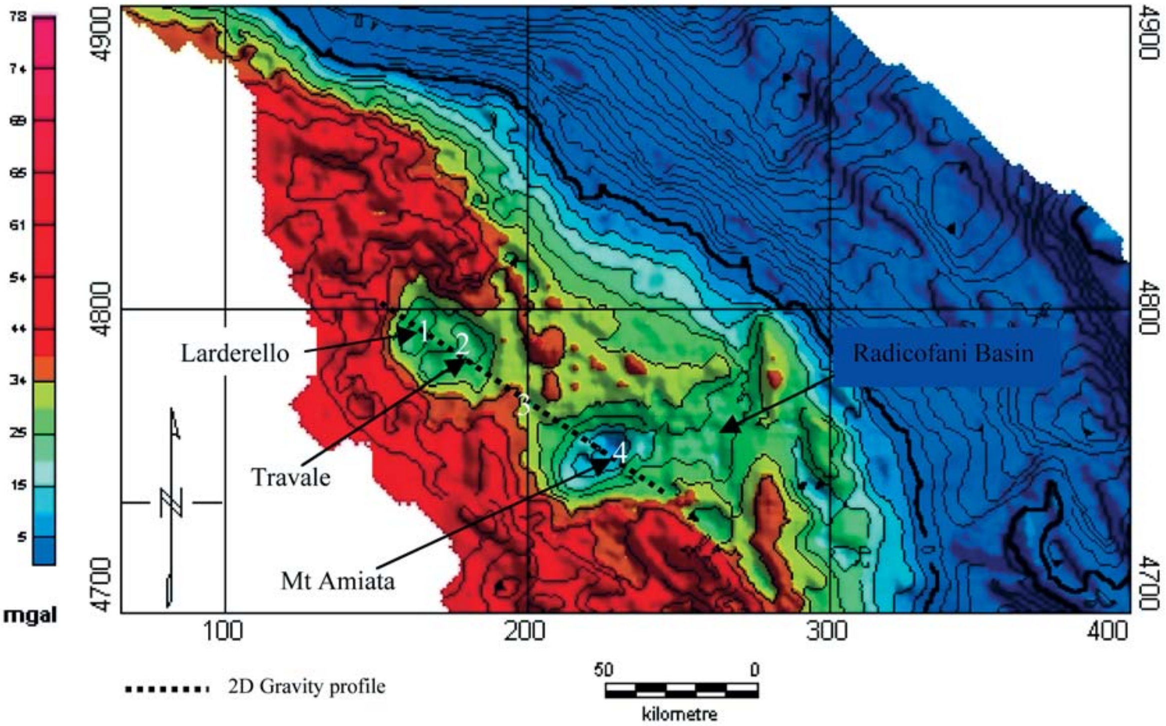

Fig. 3 - The gravity anomaly obtained from the stripping-off of effects of the volcanic and Plio-Quaternary formations from the Bouguer Anomaly.
– *Anomalia gravimetrica ottenuta dopo l'eliminazione degli effetti delle formazioni Plio-quaternarie e vulcaniche dalla anomalia di Bouguer.*

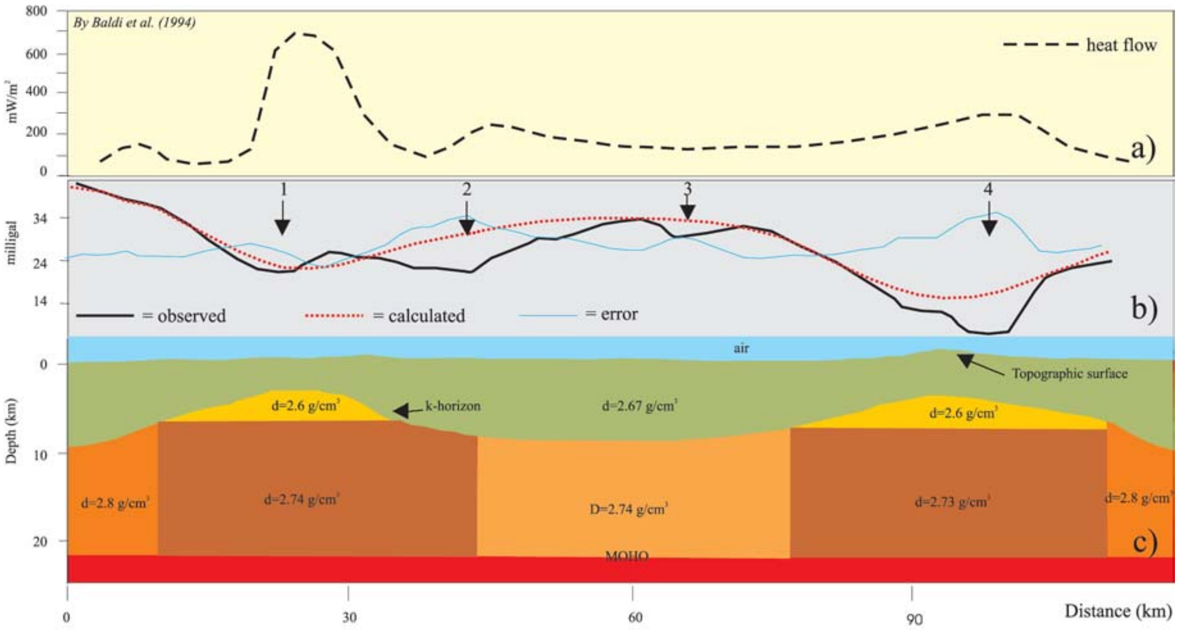

Fig. 4 - 2-3/4 D gravity inversion along a profile crossing the gravity minima of Lardello-Travale and Mt. Amiata (for location see fig. 3) of the deficit of mass below the K-horizon. (*a*) Heat flow (BALDI *et alii*, 1994) obtained from fig. 5a; (*b*) observed and theoretical gravity data; (*c*) density model. Densities are in g/cm^3. The numbers label the low wave number minima.
– *Inversione gravimetrica 2-3/4D lungo i minimi gravimetrici di Larderello-Travale e Monte Amiata (la localizzazione del profilo è rappresentata in fig. 2) delle masse al di sotto dell'orizzonte K.* a) *Flusso di calore estratto dalla fig. 5a (*BALDI *et alii, 1994);* b) *Gravità osservata e teorica;* c) *il modello di densità. Le densità sono espresse in g/cm^3. I numeri indicano le anomalie a piccola lunghezza d'onda.*

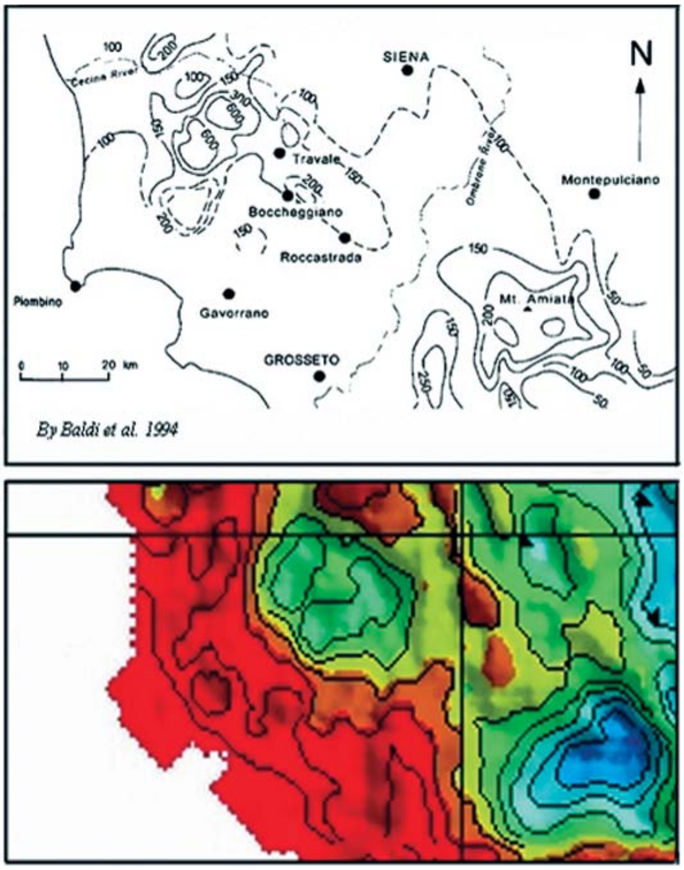

Fig. 5 - Comparison of heat flow by BALDI *et alii* (1994) (top) and stripped gravity data (bottom) in Tuscany.
– *In alto è riportata la carta del flusso di calore (*BALDI *et alii, 1994) ed in basso i dati gravimetrici ripuliti degli effetti delle formazioni superficiali.*

Larderello-Travale and Amiata zones. The Larderello-Travale minimum has a circular shape, while the Mt. Amiata minimum has an elliptical shape with the main axis along the anti-Apennine direction. On the Larderello-Travale gravity minimum, two lower λ minima (1 and 2 in fig. 3) located in the Larderello and Travale areas are superimposed; these minima are longer in the anti-Apennine direction.

Along the profile are bodies with limited lateral extension; to take into account their non-cylindrical structures, these bodies were modelled considering a lateral width similar to the length along the profile. The gravity inversions based on the TALWANI (1959) method were carried out along the profile crossing the Larderello-Travale and Mt. Amiata gravity minima. The 2D gravity data from Casaglia to Centeno (see fig. 3), with a NW-SE direction, 112 km long and crossing the Larderello-Travale and Mt. Amiata minima, was modelled. The profile (fig. 4b) shows a regional dipping towards the chain, two minima located in the Larderello-Travale and Mt. Amiata areas and four lower λ minima indicated with numbers on fig. 4. On the basis of the analysis of gravity anomalies, we can suppose that the regional trend could be due to the deep structures, i.e. Moho geometry, the two high λ minima to the deep sources of geothermal fields, and the low wavelength anomalies (indicated by numbers on figs 3, 4, 6 and 7) to surficial deficit of mass.

To characterize the origins of those minima, an analysis of heat flow of the area (CATALDI *et alii*, 1995; BALDI *et alii*, 1994; MONGELLI *et alii*, 1989; CALAMAI *et alii*, 1970) was made. The heat flow shown by BALDI *et alii* (1994) (fig. 5a) shows anomalous values that are greater then 600 mW/m^2 in the Larderello area and greater then 200 mW/m^2 in the Mt. Amiata area. The comparison of heat

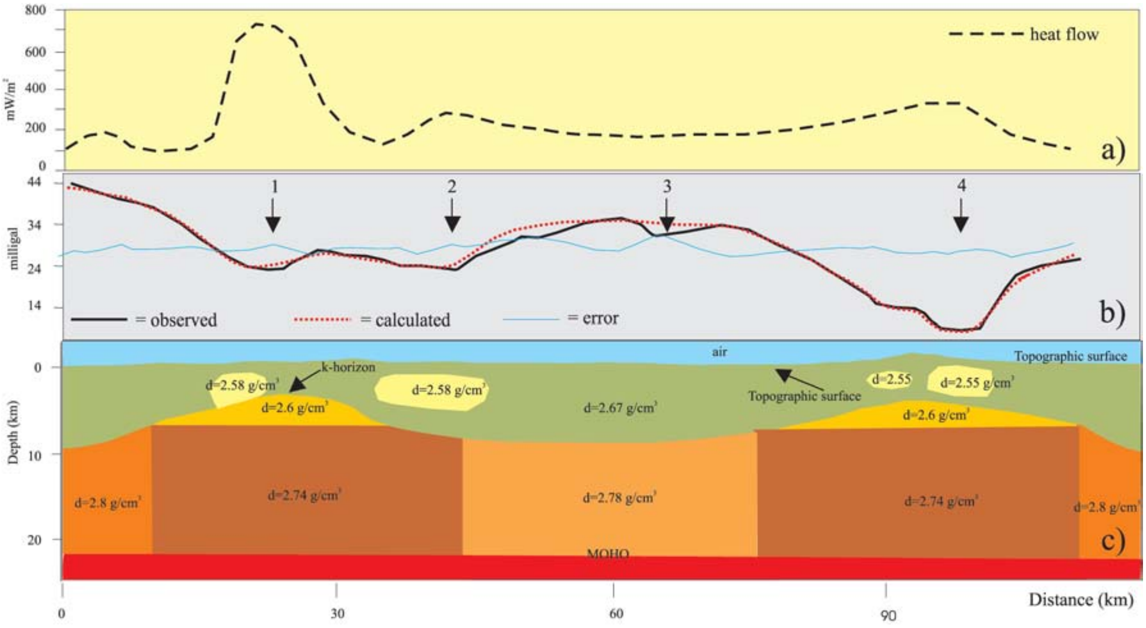

Fig. 6 - 2-3/4 D Gravity inversion along a profile crossing the gravity minima of Lardello-Travale and Mt. Amiata (for location see fig. 3). The low λ anomalies 1, 2 and 4 are modelled with bodies located above the K-horizon. The modelling of mass below the K-horizon was as in fig. 4. (*a*) Heat flow (by BALDI *et alii*, 1994) carried out from fig. 4a; (*b*) observed and theoretical gravity data; (*c*) gravity model. Densities are in g/cm^3. The numbers label the low λ minima.

– Inversione gravimetrica 2-3/4 D lungo un profilo che attraversa i minimi gravimetrici ad alta lunghezza d'onda di Larderello-Travale e del Monte Amiata (per la localizzazione vedere la fig. 3). Le anomalie 1, 2 e 4 a basso λ sono state modellate con corpi posti al di sopra dell'orizzonte K. La modellazione delle masse al di sotto dell'orizzonte K è riportata nella fig. 4. a) *Flusso di calore (*BALDI *et alii, 1994, estratta dalla fig. 4a);* b) *dati gravimetrici osservati e teorici e modello di densità* (c). *Le densità sono espresse in g/cm^3. I numeri indicano i minimi a basso λ.*

flow data with the gravity data (fig. 5b) shows an excellent correspondence of the maximum heat flow values located in the Larderello-Travele and Mt. Amiata areas with the gravity minima located in the same area.

In fig. 4a the heat flow extracted along the gravity profile from the data of fig. 5a is shown. Comparing fig. 4a and 4b we observe that the maximum heat flow values are located in the same position of gravity low λ minima 1, 2 and 4, and therefore we can suppose the low λ minima could be produced by geothermal reservoirs as hypothesized by BERNABINI *et alli* (1995a) in the Mt. Amiata area.

The theoretical modelling of the subsurface was computed on the topographic surface (BERNABINI *et alii*, 1990; BERNABINI *et alii*, 1994) and was carried out using all the constraints provided by direct and indirect methods. The main constraints were the Moho depth located at 20-25 km and the seismic K-horizon (ACCAINO *et alii*, 2004; BELLANI *et alii*, 2004; CECCARELLI & RANALLI, 2004). The latter (characterized by high reflectivity in the geothermal area of Mt. Amiata and Larderello-Travale) is located between 4 and 9 km depth (BATINI *et alii*, 1983, 1985; BATINI & NICOLICH, 1984; CAMELI *et alii*, 1993). The interpretation of CROP18 seismic profiles (BROGI *et alii*, this volume) shows, above the K-horizon, a sequence of gneiss, mica-schists, Triassic phyllites, Tuscan Nappe, Ligurids, Miocene and Pliocene formations. According to ORLANDO *et alii* (1994) and GUALTERI & ZAPPONE (1998), densities of 2.67 g/cm^3 can be assigned to the upper crust, 2.8 g/cm^3 to the lower crust and 3.2-3.4 g/cm^3 to the mantle. Considering the anomalous heat flow of the area, these densities can be slightly reduced.

Because of the ambiguity in gravity interpretation (NETTLETTON, 1954; SKEELS, 1947), which consists of the impossibility of finding one unique anomalous mass distribution for each B.A. when constraints are not available, three gravity models were developed.

The first 2 3/4D inversion was carried out modelling only the deep structures below the K-horizon. Because we have no constraints on the structures at this depth, in the first model, the minima of Larderello-Travale and Mt. Amiata are modelled using a simple distribution of deficit of mass from the K-horizon to the Moho discontinuity. Manifestly this is an approximation that has the aim of estimating the deficit of mass in the main geothermal areas, and therefore this model almost certainly does not represent the actual setting below the K-horizon, where the distribution of mass deficiency will vary laterally and with depth.

The geometries and densities used in the model are shown in fig. 4c. The constraints were the depth of the Moho (ACCAINO *et alii*, this volume; CALCAGNILE & PANZA, 1979) and the geometry of the K-horizon. The Moho was located at a depth from 22-23 km and the K-horizon geometry was obtained from CAMELI *et alii* (1993).

Other constraints were the densities of the lower (2.8 g/cm^3) and upper crust (2.67 g/cm^3). To take into account the anomalous geothermal gradient present in the area, a density of 2.78 g/cm^3 was used for the formation between the Larderello and Mt. Amiata areas, and a density of 3.05 g/cm^3 for the mantle. The densities below the Larderello and Mt. Amiata area were changed in such a way as to model most of the mass deficit. The best fit was obtained using a density of 2.6 g/cm^3 for the upper part and 2.74 g/cm^3 for the deeper part. In fig. 4c the geometries and densities used to compute the best-fit model are shown, and in fig. 4b the theoretical anomaly obtained from that model and the actual gravity data are shown. The error curve (fig. 4b) shows that the calculated data do not fit

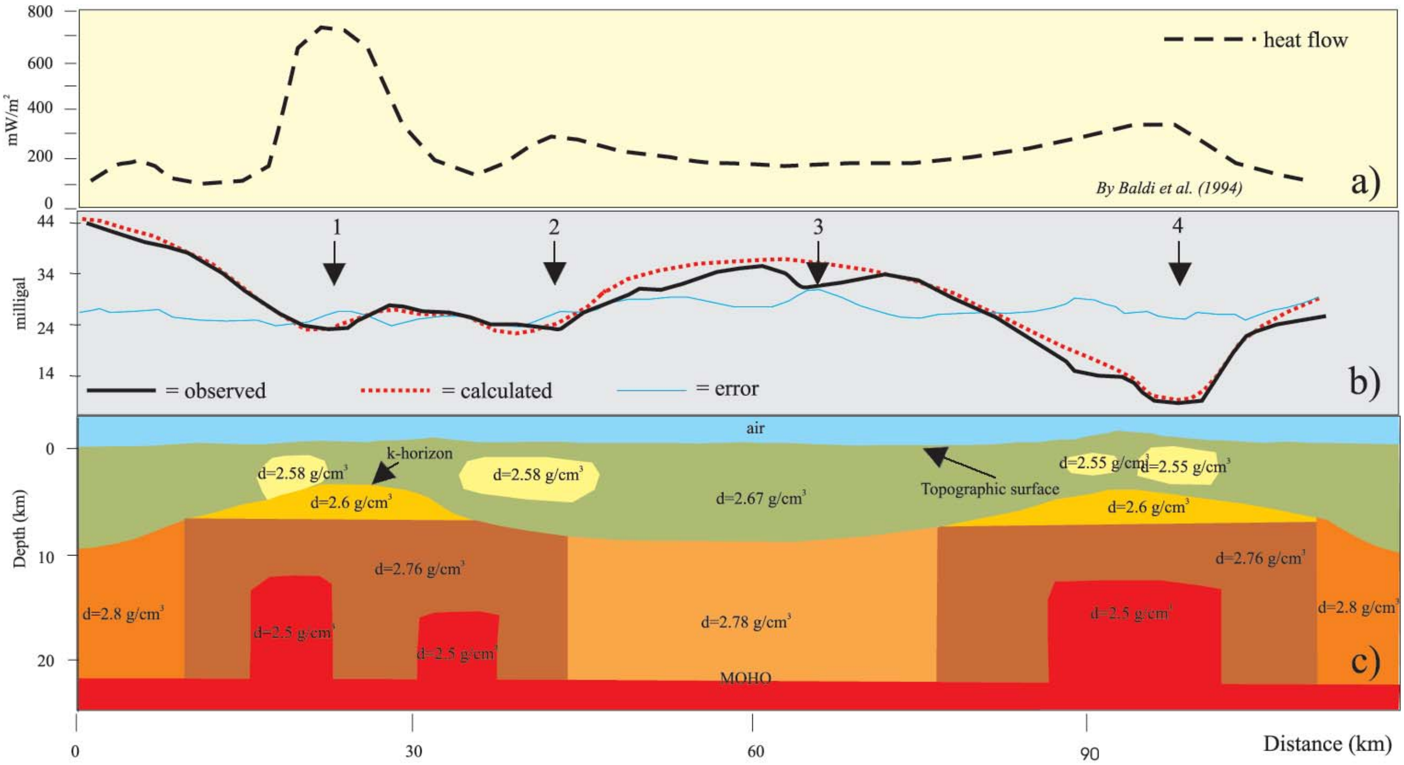

Fig. 7 - 2-3/4 D gravity inversion along a profile crossing the gravity minima of Lardello-Travale and Mt. Amiata (for location see fig. 3). The modelling of the mass above the K-horizon was as in fig. 6. Below the K-horizon, melt rocks with a density of 2.5 g/cm^3 were assumed. (*a*) Heat flow (by BALDI *et alii*, 1994) carried out from fig. 5a; (*b*) observed and theoretical gravity data; (*c*) gravity model. Densities are in g/cm3. The numbers label the low λ minima.

– *Inversione gravimetrica 2 3/4 D lungo un profilo che attraversa i minimi gravimetrici ad alta lunghezza d'onda di Larderello-Travale e del Monte Amiata (per la localizzazione vedere la fig. 3). La modellazione delle masse al di sopra dell'orizzonte K è stata la stessa utilizzata nel modello di fig. 6. Al di sotto dell'orizzonte K sono stati ipotizzati corpi semifusi con densità 2.5 g/cm^3.* a) *Flusso di calore (*BALDI *et alii, 1994) estratta dalla fig. 4a);* b) *dati gravimetrici osservati e teorici e modello di densità* (c). *Le densità sono espresse in g/cm^3. I numeri indicano i minimi a bassa lunghezza d'onda.*

the actual data very well, mainly corresponding to points 1, 2, 3 and 4. Therefore this first inversion shows the difficulty in obtaining a good fit when constraining the mass deficiencies below the K-horizon. Because of their gradients, gravity minima 1, 2, 3 and 4 can be fitted with bodies located above the K-horizon. An idea about the origin of these minima has arisen from their planimetric distribution. In the 3D gravity map (fig. 3) the low wavelength minima 1, 2 and 4 correspond to geothermal anomalies (fig. 3). Therefore they can be connected, as hypothesized by BERNABINI *et alii* (1995a) in the Mt. Amiata area, to geothermal reservoirs, i.e. due to an increase in fracturing of rocks and/or a decrease of density of pore fluids.

Therefore the 2-3/4D modelling of minima 1, 2, and 4 and the deep structures was carried out (fig. 5). Having no constraint on the geometries and densities of the bodies causing the low λ gravity minima, an evaluation of the density between 2.52 and 2.6 g/cm^3 was carried out, under the hypothesis of porosity variation between 3 and 5%, considering a density of fluid of 0.3 g/cm^3 and the density of matrix of 2.67 g/cm^3. Using these density ranges, geometries and densities of models were changed until a good fit was achieved with the actual data. In this inversion, the geometries and densities below the K-horizon were very similar to the previous model. In this second model, a good fitting was obtained using a density of 2.58 g/cm^3 for the surficial bodies in Larderello and Travale, and 2.55 g/cm^3 for the body in Mt. Amiata.

If we suppose that part of the mass deficiency below the K-horizon is due to melt rocks with a density ranging between 2.45 and 2.55 g/cm^3 (BERNABINI *et alii*, 1995a), the best-fit model shown in fig. 7 is obtained. In this third model, with respect the previous, only the bodies below the K-horizon were changed. In accordance with the magnetotelluric data (FIORDALISI *et alii*, 1995), the low λ anomaly located in the Larderello-Travale area is well modelled with two separate bodies.

Obviously, because of the fundamental properties of a gravity field, i.e. that it is a potential field, we cannot explain the anomalous mass distribution uniquely (NETTLETTON, 1940; SKEELS, 1947) if there are no constraints. Therefore the models shown in this paper must be considered as possible solutions, but they may not be unique.

CONCLUSIONS

Analyses of the Bouguer anomalies indicate that a gravity minimum zone characterizes the Tuscan area. This zone appears to be very complex, and minimum values are located in the areas of Larderello-Travale and Monte Amiata. The gravity minima are due to both recent superficial low-density deposits filling the Plio-Quaternary basins, and the geothermal framework. The use of the stripping-off technique showed that the minima in Larderello-Travale and Mt. Amiata are in effect the sum of low and high λ gravity anomalies. The high λ anomalies can be modelled with a deep body with a density of 2.5 g/cm^3 and could therefore be explained by the sources of the geothermal fields, while the low λ anomalies can be modelled with a deficit of mass located above the K-horizon. Because of geometries, densities and correlation with the anomalous geothermal heat flow, the low λ anomalies can be ascribed to the upper and lower reservoirs where fracture zones filled by steam and gas are present. The deep bodies can be interpreted as the deep source of geothermal fields. According to magnetotelluric data, the 2D modelling indicates that the high λ gravity anomaly in Larderello and Travale area can be modelled with two different deep sources. The 3D analysis of the geometries of such minima can give the limits of geothermal fields.

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