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Regional gravity anomaly map and crustal model of the Central–Southern Apennines (Italy)

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Abstract

The deep structures of the Central–Southern Apennines are analysed on the basis of the regional component of gravity anomalies, obtained applying a stripping technique. This procedure allows the accurate removal of the gravimetric effect of the three-dimensional shallow (within the first 10 km) geological bodies from the observed Bouguer anomaly. The resulting anomaly map differs quite significantly from the Bouguer anomaly map, providing new constraints on the nature of the deeper part of the crust and on the upper mantle. The stripping reveals that the regional gravity lows are shifted westward in comparison with Bouguer anomaly lows. Moreover, the gravimetric pattern indicates a lack of cylindrism for the deep structures of the Apennine Chain, which in the study area can be roughly divided into three main segments. The observed differences between the gravity anomalies pattern of the Central Apennines and that of the Southern Apennines are marked.

The integration of gravimetric results with other geophysical data suggests that: (i) a ramp-dominated style for the buried Apulia (Adria) units and part of the underlying basement is compatible with gravimetric data and (ii) most of the regional gravity anomalies in the Central Apennines seem to originate within the lower crust.

Keywords: Bouguer anomalies; "Stripping" technique; Rock density; Deep crust; Southern Italy

1. Introduction

This work aims at:

- analysing regional gravity data not affected by any kind of distortion in phase or in amplitude as constraints for deep structural modelling (lower crust and upper mantle);

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- discussing and refining the existing models of the Apennine Chain (Italian peninsula and central Mediterranean), by specifically constraining the deep structural setting of this area with gravity data.

1.1. Tectonic background

The central Mediterranean geodynamic setting has its origins in the relative motion of the African and European plates, motion that has been taking place since the Late Cretaceous (80 Ma) in response to the opening of the Atlantic Ocean (Dewey et al., 1973, 1989; Channell and Horvàth, 1976 and references therein; Giese et al., 1980).

In this area, three main geographic regions can be identified: the Adriatic Sea, the Tyrrhenian Sea and the Italian peninsula (Fig. 1). The Adriatic Sea is characterised by geological and geophysical features typically ascribed to an old, almost undeformed crust, which constitutes the foreland of the Apennine Chain (Channell and Horvàth, 1976; Tapponier, 1977 and references therein; Calcagnile and Panza, 1980; Anderson, 1987; Moretti and Royden, 1988; Nicolich, 1989; Scarascia et al., 1994; Muttoni et al., 2001). On the other hand, the Tyrrhenian Sea is an extensional basin characterised by a thin young crust, partly oceanic in the southern part, and by high values of heat flow (Finetti and Morelli, 1973; Giese and Morelli, 1975; Calcagnile and Panza, 1980; Della Vedova et al., 1984, 2001 and references therein; Finetti and Del Ben, 1986; Yastrebov et al., 1988; Nicolich, 1989; Scarascia et al., 1994; Cataldi et al., 1995).

The Italian peninsula is characterised by a 25–50 km thick crust (Scarascia et al., 1994; Nicolich, 1989), while the lithospheric thickness ranges from 70 to 100 km (Calcagnile and Panza, 1980). Seismic tomography indicates the presence of an almost continuous high-velocity zone beneath the full length of the Apennines, at depth exceeding 200 km (Spakman, 1990; Amato et al., 1993; Piromallo and Morelli, 1997; Wortel and Spakman, 2000; Lucente et al., 1999; Cimini and De Gori, 2001; Lucente and Speranza, 2001). At shallower depth (40–200 km), the evidence

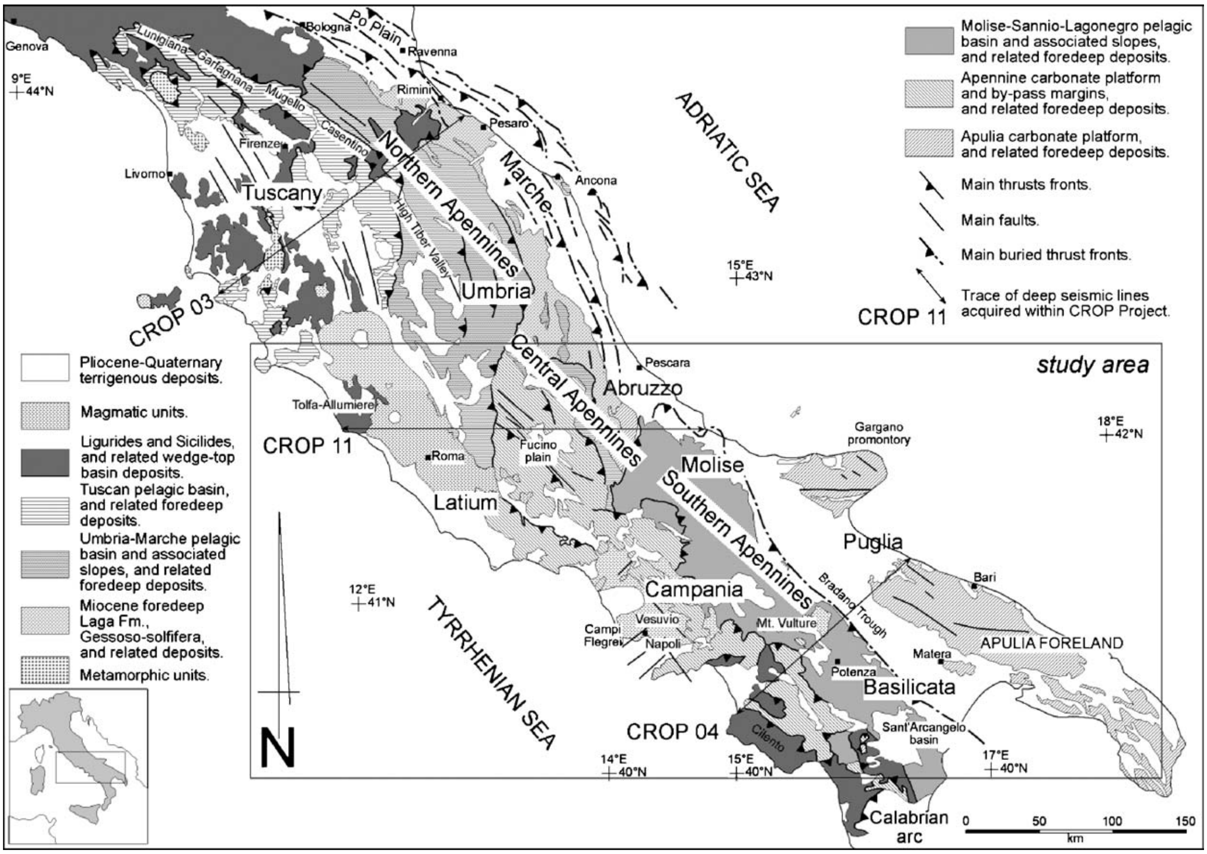

Fig. 1. Geological sketch map of peninsular Italy from the Po Plain to the north of the Calabrian arc (after Butler et al., 2004, modified).

becomes more controversial and the interpretation of the velocity anomaly pattern is still matter of debate (Spakman, 1990; Lucente et al., 1999; Wortel and Spakman, 2000; Cimini and De Gori, 2001; Lucente and Speranza, 2001).

In the Central Apennines, anomalous P wave velocity values at depth < 40 km are interpreted as suggesting a lower crust close to the melting temperature (Chiarabba and Amato, 1996). In the same area, Mele et al. (1996, 1997) identify asthenospheric material in the uppermost part of the mantle, just below the Moho discontinuity. This anomaly in the mantle extends westward to include the Tyrrhenian area, where the Moho is found at shallower depth.

The deep structural setting of the Apennine fold-and-thrust belt is interpreted by different geodynamic models (among the others, see Scandone, 1979; Boccaletti et al., 1986; Locardi, 1988 and references therein; Lavecchia, 1988; Locardi and Nicolich, 1988; Luongo et al., 1991; Doglioni et al., 1994; Elter et al., 2003; Lavecchia et al., 2003 and references therein). Some of these propose an upwelling of the asthenosphere below the Tyrrhenian Sea and a contemporary westward passive subduction of a slab of Adriatic lithosphere, with a progressive eastward migration of the subduction hinge and possible slab detachment. By contrast, alternative models contend that there is no conclusive evidence of subduction, and consider the present features as related to a process of rifting.

1.2. Gravimetric background

Most of the regional work dealing with the deep setting of the Apennine Chain along the Italian peninsula has taken into account gravity data, especially Bouguer anomalies (e.g., Bally et al., 1986; Mostardini and Merlini, 1986; Royden et al., 1987; Fedi and Rapolla, 1988; Barchi et al., 1998; Scarascia et al., 1998; Ebbing et al., 2001). Actually, gravity anomalies are commonly accepted powerful constraints for investigating the deepest portions of the crust (e.g., the deep structural style of a mountain belt) and the Moho topography (Rey et al., 1990; Chakraborty and Agarwal, 1992; Marson et al., 1994; Chamot-Rooke et al., 1997; Lefort et al., 1999; Seren et al., 2000; Lefort and Agarwal, 2002; Rivero et al., 2002, among the others), especially where constrained by other geophysical data.

For instance, the principal works of gravity modelling in the Central–Southern Apennines generally correlate each Bouguer anomaly low with a deepening of the Moho discontinuity, suggesting deep sources for these gravity lows (Fedi and Rapolla, 1988; Scarascia et al., 1998). In the studies by Corrado and Rapolla (1981) and Fedi and Rapolla (1988), the crustal model is only constrained by gravity data, these being processed by means of a filtering technique in order to single out the Moho wavelength. Instead, Scarascia et al. (1998) take into account unprocessed Bouguer anomaly data and further constrain the model with deep seismic soundings (DSS) data.

On the other hand, the density and the complex geometry of the above-mentioned units of the Apennine Chain significantly condition the Bouguer anomalies spatial distribution preventing their interpretation as a direct expression of the deep structures of the chain. Gravity data inversion, in fact, has a non-unique solution as gravity anomalies result from the sum of all the gravity effects in the subsurface (e.g., Skeels, 1947; Chakraborty and Agarwal, 1992 and references therein; see also Strykowski, 1998). Hence, removing the effects of the uppermost units can help when gravity anomalies are used in crustal and Moho analysis (e.g., Lefort et al., 1999). Moreover, the considerable thickness and extension of some of these units, especially sedimentary basins, such as foredeeps and thrust-top basins, are hardly compatible with filtering techniques because the anomalies originated from these units could fall in the same frequency range of the deep sources. Therefore, filtering may cause distortion in phase and amplitude (see Orlando and Bernabini, 2003 and references therein). In this case, the most suitable technique appears that defined as “stripping off” by Hammer (1963). The stripping technique consists in computing and subtracting the gravity effect of all the surficial lithological bodies whose geometry and density are reasonably known. This procedure was originally applied for hydrocarbon exploration, and then extended to both local and regional studies (see, among the others, Orlando et al., 1991, 1994; Bernabini et al., 1996a, 2002; Scheck et al., 1999; Strykowski, 2000; Ebbing et al., 2001). It differs from the filtering techniques because it does not cause any distortion that could affect the regional pattern of anomalies.

The stripping procedure is based on gravity data consisting of Bouguer anomalies, and on geological data, consisting of all the constraints (geological maps, cross sections, wells, etc.) able to describe the three-dimensional geometry and lithology, i.e., density of the bodies whose gravity contribution has to be removed. The calculation of the gravimetric effect for each body also includes the portion between sea level and topography, so the stripping requires Bouguer anomaly data obtained by means of a plate reduction with constant density (for further details on the methodology, see Hammer, 1963; Bernabini et al., 1994). If properly constrained, the stripping allows to correctly single out the regional gravity anomalies, and consequently, to directly view the gravity features caused by the deep crust and upper mantle

(Bernabini et al., 1994). The prerequisite for the stripping technique is a good knowledge of the geological features of the studied area, with a degree of detail suitable for the scale of the work (see e.g., Bernabini et al., 1994; Scheck et al., 1999).

The Central–Southern Apennines satisfy this prerequisite, and therefore were chosen as study area for this work.

2. Central–Southern Apennines: geological setting and constraints

2.1. Geological setting

The Apennine chain (Fig. 1) is a fold-and-thrust belt with associated foredeep/thrust-top basin sedimentation (e.g., Patacca et al., 1990; Cipollari and Cosentino, 1995 and references therein). It developed through the deformation of two major paleogeographic domains: the *internal* domain, i.e., Late Jurassic to Oligocene tectono-sedimentary sequences of the Ligurian-Piedmont Ocean (which was originally linked to the Tethys Ocean), and the *external* domain, i.e., Triassic to Early Miocene sedimentary sequences derived from the deformation of the continental Adriatic-African passive margin (see Elter et al., 2003, for a review). The tectonic units overthrust toward Adria (the African promontory, according to Channell et al., 1979) since Oligocene times.

In particular, the Central–Southern Apennines (Figs. 1 and 2) mainly consists of the superposition of tectonic units derived from pelagic basins (Ligurides, Sicilides, Tuscan, Umbria-Marche, Molise, Sannio, Lagonegro) and carbonate platforms (Apennine or Western Platform and Apulia Platform). These units thrust toward a foreland represented by part of the Apulia Platform, a large carbonate domain only partially involved in the last orogenic phases of the Apennine Chain (Mostardini and Merlini, 1986; Casero et al., 1991; Monaco et al., 1998; Menardi Noguera and Rea, 2000; Butler et al., 2004).

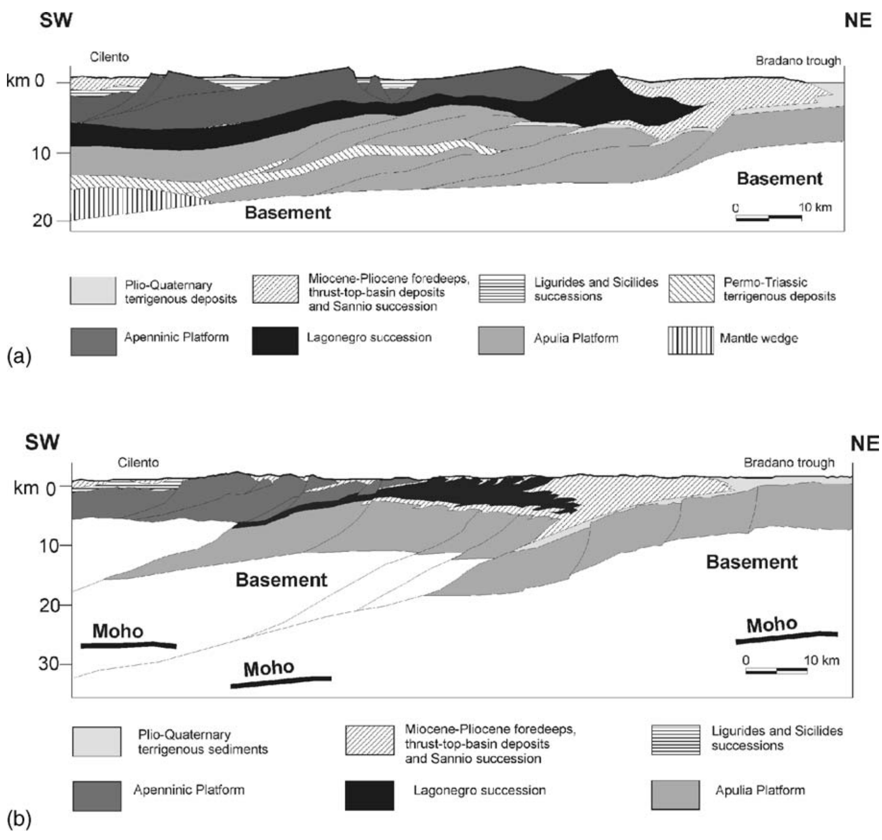

Fig. 2. Regional sections across the Southern Apennines, showing two different interpretations of the structural style of the chain: (a) after Patacca and Scandone (2003) and (b) after Menardi Noguera and Rea (2000). Both redrawn and modified.

As a consequence of the eastward migration of the deformation, siliciclastic foredeep and thrust-top-basin sediments were deposited from the Burdigalian to the Early Pleistocene, and these sediments generally overlap (or are sometimes interfingered with) the aforementioned tectonic units (among others Cello et al., 1990; Patacca et al., 1990, 1992a,b; Cipollari and Cosentino, 1995; Menardi Noguera and Rea, 2000). The most recent foredeep consists of Plio-Pleistocene deposits outcropping in the Bradano Trough and in the northeastern part of the Abruzzo–Molise region, at the front of the Apennine Chain. These siliciclastic sediments also lie between the buried Apulia Platform and the Apennine thrust sheets (Mostardini and Merlini, 1986; Casnedi, 1988a,b and references therein; Patacca et al., 1990; Casnedi, 1991 and references therein).

Along the Tyrrhenian side, several basins filled with Plio-Pleistocene sands and clays developed as a consequence of the Tyrrhenian opening, which started in the Late Tortonian (Scandone, 1979; Malinverno and Ryan, 1986; Mostardini and Merlini, 1986; Patacca et al., 1990; Cinque et al., 1993). Extensional tectonics progressively affected the inner margin of the chain, coexisting with the compressional tectonics at the chain front; over time, both phenomena migrated eastward (Meletti et al., 1995 and references therein). At the core of the Central–Southern Apennines (Fig. 1), extensional basins filled with fluvial-lacustrine deposits developed during Quaternary times (Cavinato and De Celles, 1999; D'Agostino et al., 2001). Moreover, since Pliocene times (e.g., Tolfa-Allumiere), and still today (e.g., Vesuvio, Campi Flegrei; Bigi et al., 1992) the Tyrrhenian side of Central–Southern Italy has been affected by important volcanic phenomena. Within the chain, the only volcanic deposits with regional gravimetric significance correspond to Mt. Vulture (Fig. 1).

2.2. Geological constraints

An accurate data collection and analysis was carried out in order to constrain the 3D geometry of each geological body expected to have a gravity contrast compared with the reduction density previously used in the Bouguer correction (2670 kg/m^3; see next paragraph).

The geological data (i.e., geometric constraints and density values) for the study area derive from almost 300 logs of hydrocarbon wells (Fig. 3), from seismic profiles and from the literature (among others Balduzzi et al., 1982a,b; Casnedi et al., 1981, 1982; Accordi et al., 1986; Bally et al., 1986; Mostardini and Merlini, 1986; Bonardi et al., 1988; Casero et al., 1988; Luongo et al., 1988; Bigi et al., 1992; Berrino et al., 1998; Menardi Noguera and Rea, 2000; Butler et al., 2004). In particular, density data mainly come from the work of Mostardini and Merlini (1986): each value results from a mean of well data and laboratory determinations on samples from all over the Southern Apennines. These were integrated with density data after Carrozzo and Nicolich (1977), Luongo et al. (1988), Cassinis et al. (1991), Gualteri et al. (1992), Berrino et al. (1998) and Gualteri and Zappone (1998). Where seismic wave velocity data were available,

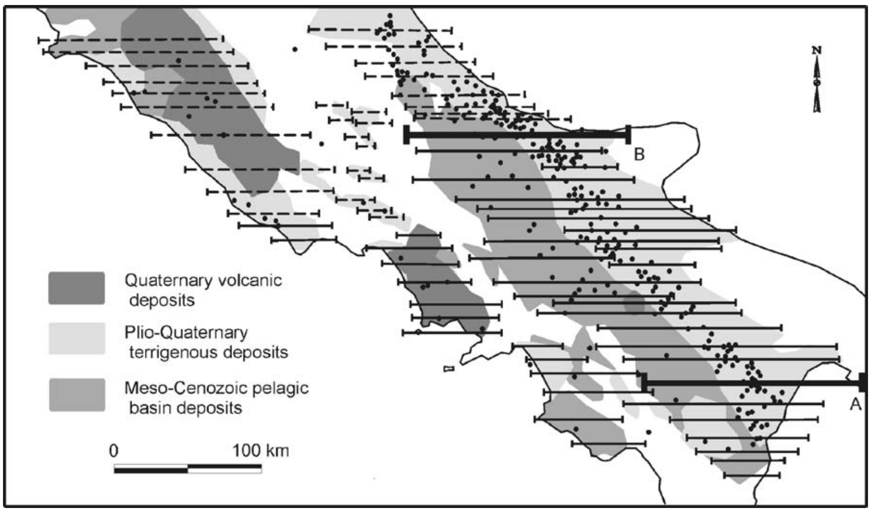

Fig. 3. Location map of the lithological cross sections realised for the 3D reconstruction of geological bodies modelled for the stripping. The thicker lines correspond to the cross sections of Fig. 5. Dashed lines: sections from a previous data set (Bernabini et al., 1996a); dots: deep wells.

Table 1
Density values of the geological units processed in the stripping procedure

Unit	Description	Density (kg/m^3)	References
Quaternary volcanic deposits	Deposits of the volcanic complexes of Latium, Campania and Mt. Vulture	2250–2350	Berrino et al. (1998), Luongo et al. (1988), Mostardini and Merlini (1986)
Plio-Quaternary terrigenous deposits	Pliocene, Pleistocene and Holocene sediments filling the Bradanic Trough and its north-western continuation, the intramontane valleys and the extensional basins along the Tyrrhenian side	2300	Carrozzo and Nicolich (1977), Gualteri et al. (1992), Mostardini and Merlini (1986)
Meso-Cenozoic pelagic basin deposits	Ligurides, Sicilides and Tuscan successions, part of the Molise–Sannio–Lagonegro successions, Miocene-Pliocene foredeeps and thrust-top-basin siliciclastic deposits involved in the chain	2400–2550	Carrozzo and Nicolich (1977), Cassinis et al. (1991), Gualteri et al. (1992), Gualteri and Zappone (1998), Mostardini and Merlini (1986)
Carbonate rocks	Apulia and Apennine carbonate platforms' limestones and dolostones present all over the Apennines (part of the Lagonegro succession with comparable density was also included in this group)	2670	Gualteri et al. (1992), Mostardini and Merlini (1986)

a further check was made in order to test the consistency between density values from literature and density values coming from known relationships with the velocity (see e.g., Nafe and Drake, 1961; for a discussion, see Barton, 1986; Federico et al., 1995).

All the geological bodies expected to be relevant from a gravimetric point of view for their geometry and density have been grouped as in Table 1 (see Fig. 1 for location; for geological details, refer to Bernabini et al., 2002).

2.3. Gravity data

Gravity data consist of more than 14,000 Bouguer anomaly values coming from the database of the Italian National Geological Survey (see e.g., Carrozzo et al., 1981). They cover an area about 350 km long and 600 km wide, which lays between 4380 and 4760 latitude North and between 160 and 800 longitude East (in km; coordinates in UTM projection, ED50, zone 33).

The Bouguer anomaly values derive from a 3 km-spaced sampling of the database of all the Italian gravimetric stations onshore (1 station/km^2), and they are the result of the Faye reduction referred to the ellipsoid, of the indefinite plate reduction with a constant reduction density of 2670 kg/m^3 and of the topographic reduction. The gravity survey accuracy is estimated to be about 1 mGal.

In the study area, the Bouguer anomaly map (Fig. 4a) shows two areas of significant gravity high, corresponding to the Tyrrhenian Sea and to the southern Adriatic coast. In the Southern Apennines, a relative gravity low lies between these two highs, running the full length of the chain, while in the Central Apennines, this low shifts toward the Adriatic Sea (Figs. 1 and 4a).

The close connection between the Bouguer anomaly main trends and the surficial geological features is evident where comparing Fig. 1 with Fig. 4a. In particular, the most relevant gravity low corresponds to the Marche and Abruzzo coast area, where foredeep deposits reach the maximum thickness (more than 5000 m; see e.g., Bally et al., 1986). Other gravity lows are located along the core of the Central and Southern Apennines, in particular nearby the Sant'Arcangelo and Fucino Basins. Finally, small gravity lows are located along the Campania coast, where extensional basins are filled by Plio-Pleistocene sands and clays up to 5000 m thick (Mostardini and Merlini, 1986).

3. Methodology

As previously stated, the stripping technique was employed to separate the deep (i.e., regional) components of the Bouguer anomaly from the surficial ones. In the computation, only those bodies whose density differs from the reduction density were taken into account; the topography as well was included in the 3D model.

The bulk of the Apennines backbone (especially the Central Apennines; see Fig. 1) consists of carbonate rocks or other lithologies (i.e., Triassic-Jurassic formations of the Lagonegro succession) characterised by density values

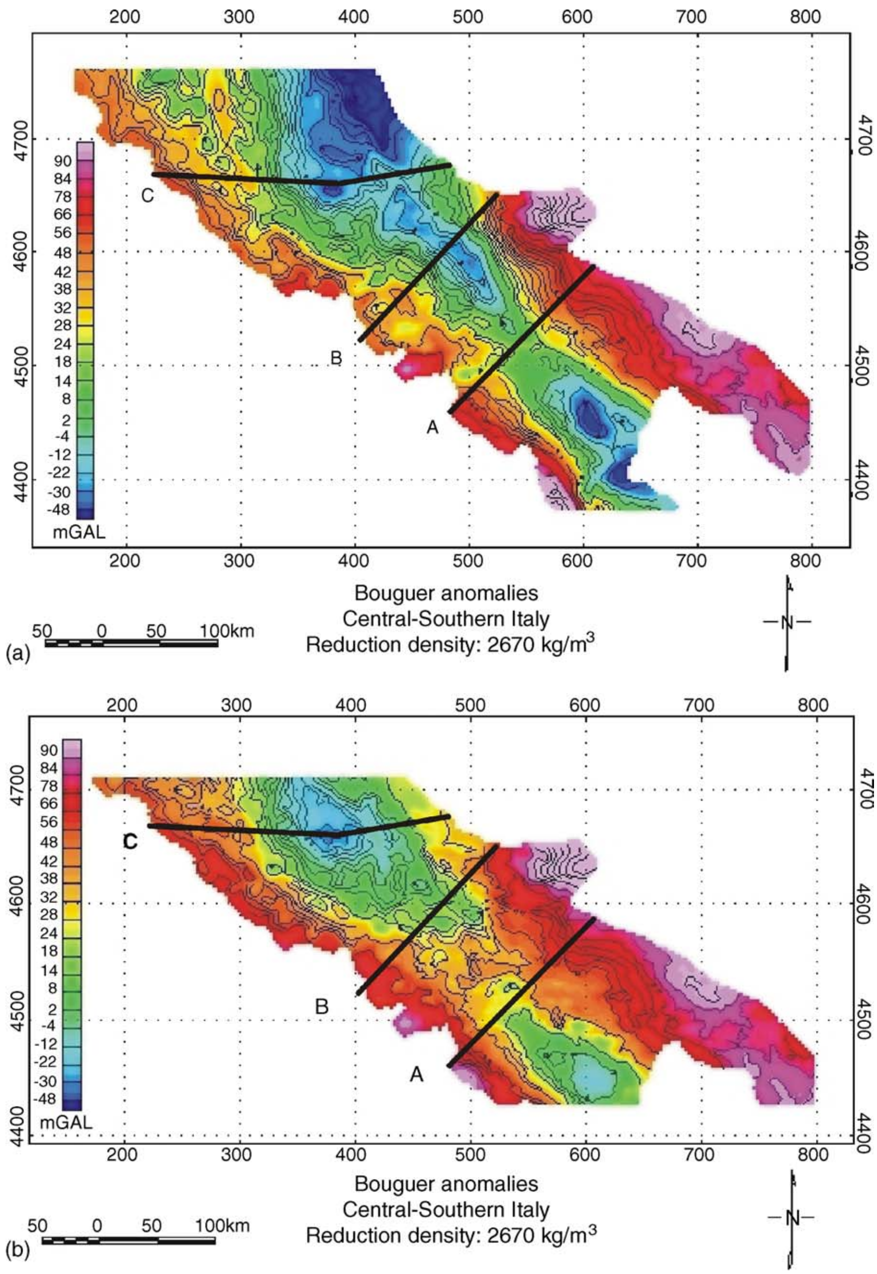

Fig. 4. (a) Bouguer anomaly map of the Central–Southern Apennines (from the gravity data of the National Geological Survey). The main gravity highs correspond to the Tyrrhenian Sea and to the Southern Adriatic coast. The gravity lows lie between these two highs in the Southern Apennines and along the Adriatic coast in the Central Apennines. (b) Regional gravity anomaly map of the Central–Southern Apennines, obtained from the map above by applying the stripping method. The gravity lows sourced in the deep crust are limited to the core of the Central Apennines and nearby the Sant'Arcangelo basin: they are small and shifted westwards compared to the Bouguer gravity lows. In black, location of the three gravity cross sections of Fig. 7.

equivalent to the reduction density; units formed by these deposits were not included in the 3D model. The deepest limit of the stripped units is the top of the Apulia Platform (which outcrops in the Apulia region, while it is buried under the chain elsewhere; Figs. 1 and 2). Units formed by the Apulia Platform succession have not been modelled, as a density of 2670 kg/m^3 can be assigned to the related carbonate rocks. The bottom of the Apulia units (i.e., the top of the underlying crust) is instead object of analysis in the present study.

The geological bodies located above the top of the Apulia units and belonging to the first three groups listed in Table 1 have been considered for the stripping because of their different density with respect to 2670 kg/m^3.

Each geological body was given a mean density on the basis of the available data (see Section 2 and Table 1). The geometrical limits of these bodies do not necessarily coincide with stratigraphic or structural limits; they simply encompass a volume of rocks of homogeneous density. Obviously, none of the bodies is expected to really have a homogenous density, because of both the presence of lithologic alternations and the natural increasing of density with depth. Nevertheless, the bias between the mean density assigned to the bodies and the average of the real densities they are supposed to have in each of their parts is considered negligible. Each body was processed separately in order to further reduce this bias.

For some bodies the density datum provided by the literature was slightly modified a posteriori, in accordance with what suggested by the results of the first computation of the gravity effect. It was possible to do this only in case of bodies' geometry strictly constrained by the geological data.

A geometrical/lithological model of each body known in the uppermost portion of the sedimentary cover was built up based on density contrasts. The 3D modelling of all the previously described bodies was carried out using more than 70E–W oriented cross sections (Fig. 3), which define the main geological features of the Southern Italian peninsula.

The scale adopted was 1:250,000 with a maximum spacing of about 10 km between sections. The spacing was chosen on the basis of the complexity of the geometries and of the spatial distribution of the constraints. Fig. 5 shows two examples of these sections.

Based on all these sections, an input file was built up for each body (or part thereof), and then subject to the computing procedure for the stripping. Each body was individually processed so as to achieve a more accurate control of the results at each step of the stripping. The calculation of the gravity contribution of each modelled body was, in part, accomplished automatically by software based on Götze and Lahmeyer (1988) algorithm.

In summary, the complete procedure consists of:

- defining density and geometry (by means of parallel cross sections) of each body on the basis of the available constraints;
- building up an input file to be processed for each body;
- computing the gravity effect;
- checking the reliability of the density assigned by comparing the gravity effect of each body with the Bouguer anomalies;
- subtracting the gravity effect of each body processed from the Bouguer anomaly values.

At the end of the computation, the gravity contribution of all the bodies considered in the stripping procedure was subtracted from the Bouguer anomaly values. The result is a map of the gravity anomalies produced by all the unknown (or not modelled) bodies. For the sake of simplicity, in what follows this map will be called "regional gravity anomaly map".

4. Regional gravity anomaly map of the Central–Southern Apennines

Figs. 4b, 6 and 7 summarise the results of the stripping procedure. Fig. 4b represents the regional gravity anomaly map of the Central–Southern Apennines. Significant differences can be seen between this map and the Bouguer anomaly map (before stripping; Fig. 4a). This is not surprising considering the marked size of the surficial effects removed from the Bouguer anomaly and shown in Fig. 6, which represent the sum of the effects originated from all the units considered in the stripping procedure.

The gravity contribution of the "Quaternary volcanic deposits" is limited to small areas in northern Latium and Campania, and does not exceed −20 mGal. The removal of this contribution produces a slight smoothing of the anomaly isolines along the Tyrrhenian side.

The huge amounts of "Plio-Quaternary terrigenous deposits", especially in the southern part of the study area, contribute with values up to −35 mGal to the gravity anomaly. Removing this effect leads to an enlargement of the gravity high corresponding to the Apulia region (Southern Adriatic coast), and a consequent reduction of the gravity low width along the Southern Apennines.

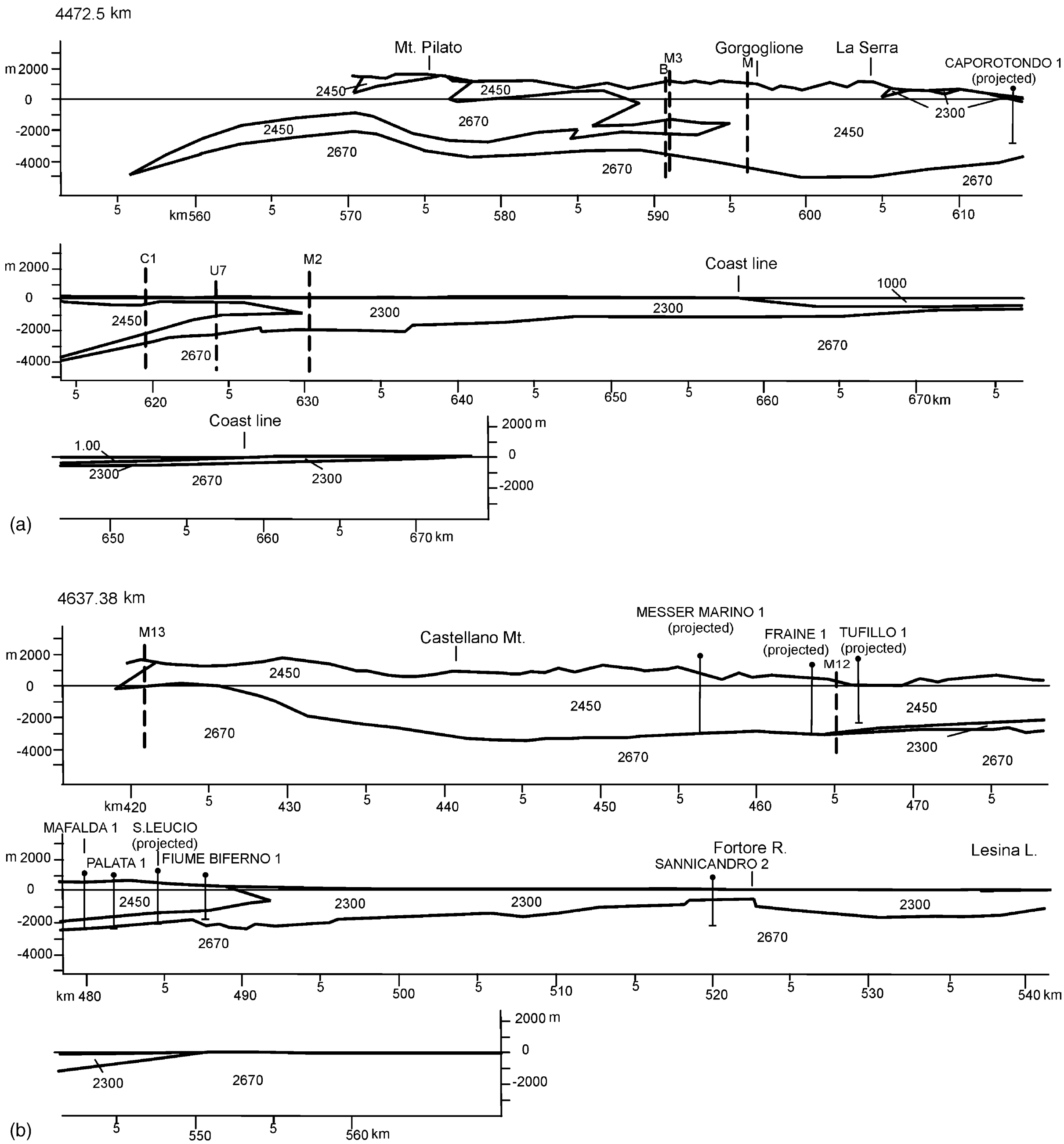

Fig. 5. Examples of cross sections realised for the 3D modelling of the lithological bodies. Numbers inside lithological bodies indicate density values (in kg/m^3). Below the profile, longitude kilometric values are indicated; at top-left, the latitude of the entire cross section is reported in km (coordinates referred to zone 33, U.T.M. projection). Dashed lines correspond to the location of the main constraints; wells location is also reported. (a) U7: intersection with the second cross section of Balduzzi et al. (1982a); M2 and M3: intersections with cross sections 2 and 3, respectively, of Mostardini and Merlini (1986); C1: intersection with the cross section F of Casero et al. (1988); M: intersection with the southernmost cross section of Butler et al. (2004); B: intersection with cross section B in Menardi Noguera and Rea (2000). (b) M12 and M13: intersections with cross sections 12 and 13, respectively, of Mostardini and Merlini (1986).

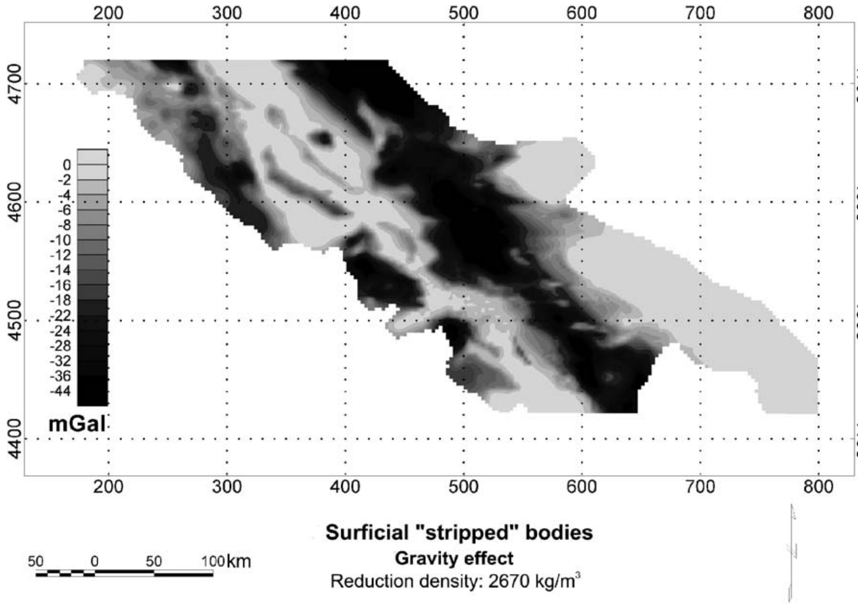

Fig. 6. Gravity contribution of all the bodies considered in the stripping.

Finally, the “Meso-Cenozoic pelagic basin deposits” generate the most relevant contribution to the gravity anomaly. In fact, in spite of the relatively small density contrast, the extension and thickness of these bodies produce gravity anomalies exceeding −40 mGal over large areas, e.g., along the chain at a latitude of about 4550 km (Fig. 6).

It is worthwhile noting the extension of the areas affected by surficial gravity effects: the removal of all the related gravity contributions (Fig. 6) leads to substantial modifications with respect to the Bouguer anomaly trend.

The stripping procedure reveals that the gravity low, which characterises the Apennine Chain in the Bouguer anomaly map, is mainly due to surficial bodies. In particular, the gravity low at the core of the Southern Apennines is due to the Apennine thrust sheets, while the low along the Marche–Abruzzo coastal area originates from the thick cover (more than 5000 m) of Plio-Quaternary deposits that fill the Adriatic foredeep. Hence, the source of most of the gravity lows in the Bouguer anomalies of the study area is located in the upper portion of the crust, at a depth not exceeding 6–8000 m. After the stripping, the remaining gravity low is not continuous, but strongly fragmented. Significant regional lows are present only at the core of the Central Apennines, nearby the Fucino plain, and in the Southern Apennines, nearby the Sant’Arcangelo basin.

The regional gravity anomaly values along the Apennines range from −30 mGal in the Central Apennines to +30 mGal in the Southern Apennines. The gravity pattern of the Southern Apennines is very different from that of the Central Apennines. In the last one, the regional gravity low is quite evident, suggesting the presence of crustal sources below the bodies considered in the stripping. In the Southern Apennines, instead, no regional gravity lows persist along the core of the chain after the removal of the surficial gravity effects, except for the Sant’Arcangelo basin small area.

The regional map also shows some high frequency residual anomalies left, with very small wavelength (a few km), even after the stripping. This kind of anomalies is due to the regional scale chosen for the geological model, which in turn is conditioned by the spatial distribution of the constraints. As these residual anomalies do not affect the regional anomaly trend, and the consequent interpretation, their removal is not necessary for the present work purposes.

Regional gravity anomaly values were picked up along three regional cross sections (Fig. 7; see Fig. 4 for the location). A comparison between the anomaly trends before and after the stripping along these sections highlights some relevant differences.

In the southernmost cross section (Fig. 7A), the removal of surficial effects causes a slight increase of the positive gravity anomaly values on the Tyrrhenian side as well as the disappearance of the lows in the central-eastern part of the profile. The obtained regional trend markedly differs from the Bouguer anomaly trend, because the main gravity low is located on-shore at about 40 km from the Tyrrhenian coastline, instead of 80 km. This implies that the Bouguer gravity low is strictly related with the shallow thrust sheets at the core of the Southern Apennines.

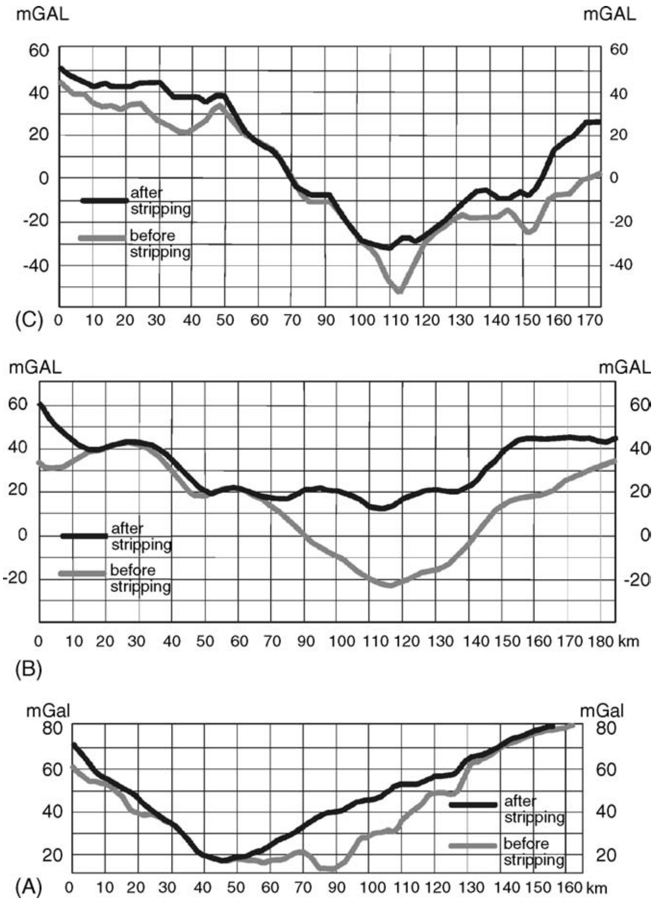

Fig. 7. Sections across the gravity maps of Fig. 4. Regional gravity anomaly values were picked up along these three regional profiles in order to highlight the differences between the Bouguer and the regional anomaly trends (before and after the stripping). (A) Southern Apennines: the main gravity low of the regional anomaly is located at about 40 km from the Bouguer main low; (B) Central–Southern Apennines: no gravity lows persist after the stripping, suggesting that most of the Bouguer anomaly lows originate in the shallowest portion of the crust; (C) Central Apennines: the gravity anomaly values along the Tyrrhenian and Adriatic coast areas increase after the stripping while the gravity low in the Fucino area is reduced.

In the central cross section (Fig. 7B), no gravity lows persist after the stripping, and the regional gravity anomaly trend of this area appears quite flat. This means that in this region most of the Bouguer anomaly lows originate in the shallowest portion of the crust.

In the northernmost cross section (Fig. 7C), the first kilometres of the chain are mainly made up of carbonate rocks; therefore, only slight differences mark the regional gravity trend if compared with the Bouguer anomaly trend: among these, the increase of gravity anomaly values along the Tyrrhenian and Adriatic coast areas and the reduction of the gravity low in the Fucino area.

Summing up, the stripping reveals that the bulk of largest gravity lows observed on the Bouguer anomaly map in Fig. 4a originate in the shallowest portion of the crust and that the gravity lows sourced in the deep crust are small and shifted westwards compared to the Bouguer gravity lows.

5. 2D gravity model of the Southern Apennines deep crust

Two main hypotheses exist for the tectonic setting of the Southern Apennines upper crust (Fig. 2; also see Section 2).

In the first hypothesis (Patacca and Scandone, 2003; Fig. 2a), which is an interpretation of the CROP04 deep seismic line, the Apulia Platform is strongly shortened in a thinned-skin style, and its bottom plunges towards the Tyrrhenian side starting from a depth of about 6 km below the Adriatic side. On the Tyrrhenian side, a mantle wedge is present within the crust in a depth range between 16 and 20 km, immediately below the buried Apulia units.

The second hypothesis (Fig. 2b) derives from the interpretation of commercial seismic lines (Menardi Noguera and Rea, 2000; Butler et al., 2004) but it is also adopted in alternative interpretations of the CROP04 seismic profile (Anelli et al., 2000; Cippitelli, 2001). This hypothesis encompasses a ramp-dominated structural style for the buried Apulia units (Butler et al., 2004) and part of the underlying basement. This last rises to depths of less than 10 km below the Tyrrhenian coast.

The only deep seismic data available for this area (except for the CROP04 profile) are the deep seismic soundings data interpreted by Cassinis et al. (2003); see also Scarascia et al. (1994). These data suggest the presence of two distinct crust-mantle discontinuities: the Moho of the Peri-Tyrrhenian thinned crust, and the Moho of the Afro-Adriatic plate. For the sake of simplicity, we will, respectively, refer to them as “Tyrrhenian” and “Adriatic” Moho. On the western side of the studied area, the “Tyrrhenian” Moho is located at a depth of about 27 km and gently dips to the East, while on the eastern side of the studied area, the “Adriatic” Moho is located at a depth of about 30 km and dips towards SW beneath the Tyrrhenian Moho, up to a depth of 50 km.

On the basis of the abovementioned hypotheses and of the DSS data (Fig. 8), we carried out two different 2D gravimetric models along the CROP04 profile (Fig. 9, Models 1 and 2, respectively). The aim was to check the reliability of the two hypotheses with respect to the new regional gravity anomalies. The use of these stripped data simplifies and reduce the uncertainties while modelling the part of crust under investigation (i.e., below the Apulia Platform), as it allows the gravity effect to be computed excluding the previously considered shallowest part of the crust. As the stripping was carried out in 3D, data used for the modelling are free from lateral effects caused by the removed units. In both cases, DSS data were used to constrain the deepest portion of the profiles.

Gravity modelling was carried out by means of a software based on the algorithm of Won and Bevis (1987) and on the method of Talwani et al. (1959). Density values for the lower crust and upper mantle come from literature (e.g., Pasquale et al., 1997; Gualteri and Zappone, 1998).

Below the shallowest portion of the models, fixed by the aforementioned hypotheses, the density distribution shown in Fig. 9 was progressively changed by means of a trial-and-error procedure. The shown best fitting between the two curves (observed and calculated gravity) was obtained while fulfilling the seismic constraints as much as possible with the most conservative solution; in fact, as previously discussed in Section 1.2, gravity inversion has non-unique solution.

According to the Puglia 1 well log (Butler et al., 2004) and to Patacca and Scandone (2003), a unit of Permo-Triassic terrigenous deposits was located below the Apulia Platform on the eastern side of both models. In Model 1 (Fig. 9A), the presence of a mantle wedge at shallow depth (16 km) significantly affects the gravity values on the Tyrrhenian side, and most of all, the gravity gradient of the entire model. The continental crust below the mantle wedge, provided by the first hypothesis, can compensate only in part the increase of gravity values produced by the mantle wedge. Therefore, in order to fulfil the gravity constraint, we have to assign the mantle wedge a density value (3260 kg/m^3) lower than the remaining portion of the mantle (3320 kg/m^3). This could be partly supported by the high values of heat flow in the Tyrrhenian area, although they mainly characterise the northern Tyrrhenian Sea (Cataldi et al., 1995; Della Vedova et al., 2001 and references therein).

This geometry of the mantle wedge and underlying crust completely disregards the constraints provided by DSS data; in particular, the location of the flexure of the underlying crust is shifted westwards. This is also in contrast with gravity data, as this geometry produces a gravity low significantly less conspicuous and 20 km closer to the Tyrrhenian coastline than the regional gravity low. What’s more, this gravity trend is obtained by assigning the lower crust a homogenous density of 2850 kg/m^3 up to 50 km depth: in the probable case of a lower crust characterised by increasing density, these discrepancies would be even larger.

Model 2 presents geometries more consistent with respect to DSS constraints and gravity data. The regional gravity low can be compensated with the deepening of the Moho, as suggested by DSS data, provided that a progressively increasing density is assigned to the crust that dips into the mantle. This is in accordance with the density distribution figured out in the thermal models of Goffé et al. (2003; see the model named “upper crust”).

The modelled crust wedge completely falls within that identified by DSS data. At a depth greater than 50 km, no density contrast with respect to the mantle is expected, based on the fit of the curves (notice that, at depth of 100–150 km, our data only allow to rule out density contrasts higher than 100 kg/m^3, which is the minimum value necessary to modify the gravity trend).

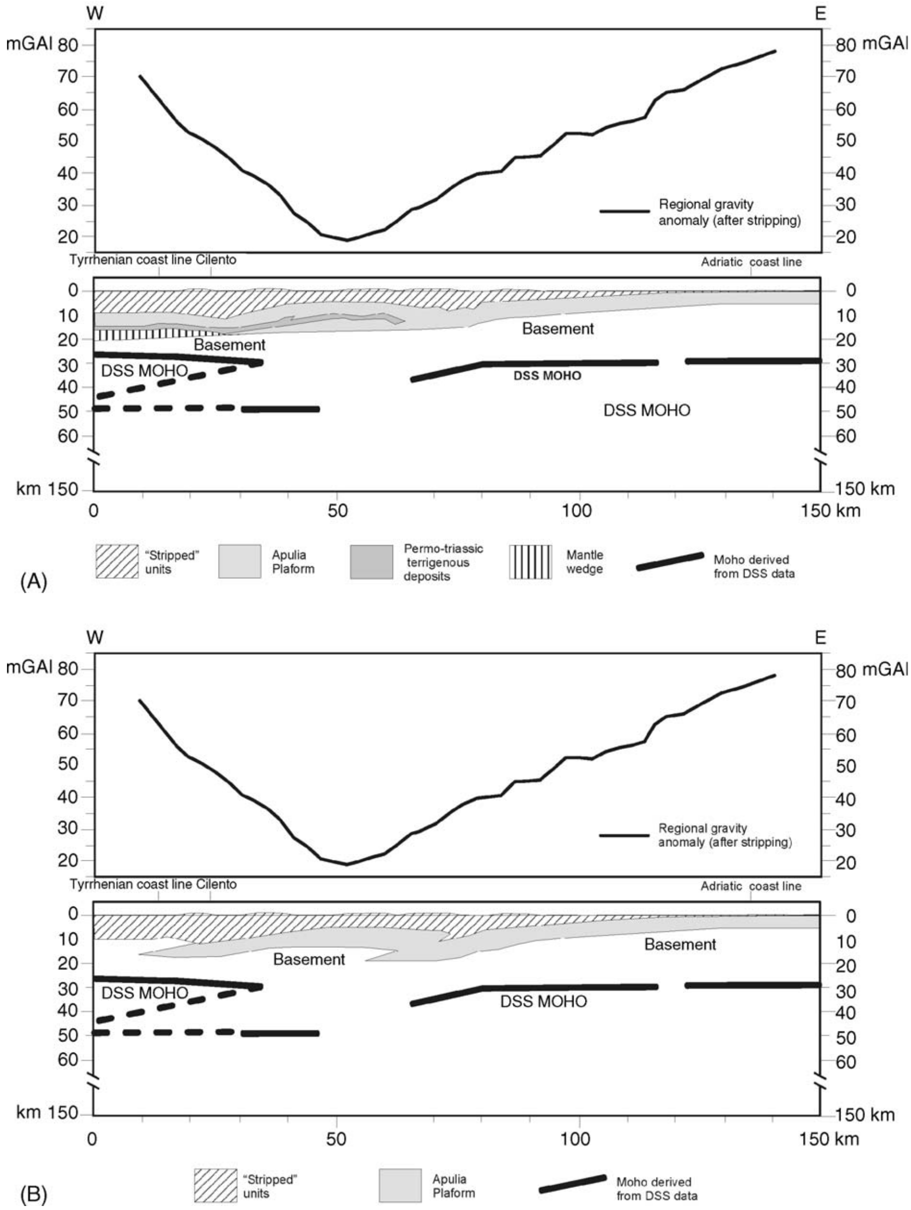

Fig. 8. Geological and gravity constraints for the 2D gravity models along the CROP04 seismic profile. (A) Thinned-skin style, according to Patacca and Scandone (2003) and (B) ramp-dominated style, involving the Paleozoic basement, in accordance with Menardi Noguera and Rea (2000) and Butler et al. (2004). Constraints for the geometry of the deepest portion of the profiles come from DSS data after Cassinis et al. (2003).

6. Discussion

The Bouguer anomaly trend along the Italian peninsula (Fig. 4a) is interpreted as due to a thinner and less dense crust, associated with a less dense mantle on the Tyrrhenian side with respect to the Adriatic one (Corrado and Rapolla, 1981; Fedi and Rapolla, 1988; Cassinis et al., 1991; Anelli et al., 1994; Marson et al., 1998; Scarascia et al., 1998). The gravity low between the two areas of gravity high is generally attributed to the overlap of "Tyrrhenian" and "Adriatic" Moho (e.g., Corrado and Rapolla, 1981; Anelli et al., 1994; Scarascia et al., 1998); this overlap would be somehow related to a subduction process (Royden et al., 1987).

More in detail, Corrado and Rapolla (1981) and Fedi and Rapolla (1988), interpret the regional gravity lows obtained by applying a filtering method as depressions of the Moho. However, the present work showed that these

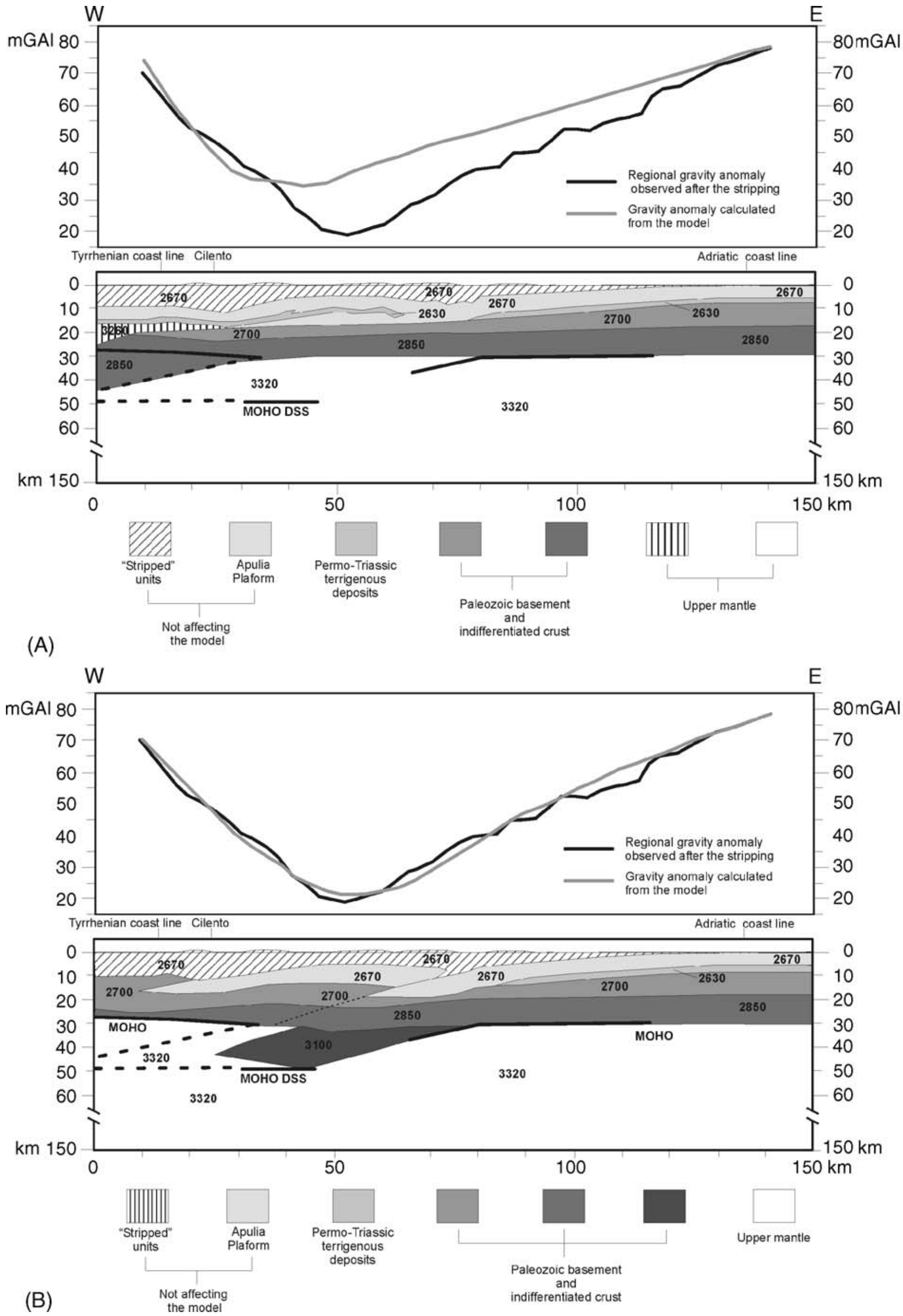

Fig. 9. 2D gravity models along CROP04 seismic line: (A) Model 1, characterised by a thinned-skin style and by the presence of a mantle wedge at shallow depth and (B) Model 2, characterised by a ramp-dominated style. Numbers within the bodies indicate the density values in kg/m^3.

residual gravity lows are in fact due to Meso-Cenozoic pelagic basin deposits along the core of the Southern Apennines as well as to Plio-Quaternary sediments of the Marche–Abruzzo coast area. On the other side, gravimetric modelling only constrained by DSS data, such as that proposed by Scarascia et al. (1998), are affected by uncertainties due to the poor resolution provided by this kind of constraints for the shallowest part of the model.

In the present work, the removal of surficial effects by means of the stripping procedure allows to focus on the deep structures. The results show that most of the gravity lows on the Bouguer anomaly map originate from surficial, relatively “light”, deposits. The gravity map here presented, free from surficial effects, differs from all the gravity maps previously published and allows some further considerations to be done.

A gravity low along a mountain belt is generally interpreted as a mass *deficit* due to an excess of crustal roots. However, the regional gravity low along the Apennine Chain appears to be small and fragmented. Minimum values are located just in two areas: in correspondence with the core of the Central Apennines and with the Sant’Arcangelo basin (Southern Apennines). Between these areas, the relative gravity low is much less evident. This reveals a lack of cylindrism in the deep structures, which appears to be a characteristic of the Apennine Chain, as it was already recognised for the shallowest structures (e.g., Casero et al., 1988; Patacca and Scandone, 1989; Cinque et al., 1993; Butler et al., 2004). However, the regional pattern of gravity anomalies suggests low correlation between deep and surficial structures.

On the basis of the Bouguer anomaly analysis, Royden et al. (1987) recognise the flexure of the Adria plate and the segmentation of the Apennine Chain, and relate these two phenomena to a hypothesised segmentation of the underlying slab. In the studied area, the regional gravity anomalies figured out after the stripping are arranged in three main segments that, respectively, correspond to the Central Apennines, most of the Southern Apennines, and the southernmost part of these, close to the Calabrian arc. So, the direct analysis of the regional gravity anomalies essentially confirms the hypothesis of segmented deep structures within the crust; however, our data do not provide conclusive evidence for a well-developed slab at greater depth. In the Southern Apennines segment, for instance, continental crust could be hypothesised to a maximum depth of 50 km on the basis of 2D gravity analysis.

As shown in the 2D Model 2 (Fig. 9B), the crust wedge defined by the DSS data analysis is correlated with a gravity low. The small-size and short wavelength of this low suggest to assign the crust wedge a relatively high density and reduced dimensions with respect to those derived by DSS data.

An open problem is the origin of the two gravity lows in the Central Apennines and along the southernmost edge of the Southern Apennines (at the boundary with the Calabrian arc). The latter gravity low, corresponding to the Sant’Arcangelo basin area, is evident but quite limited; it could represent the effect of the northern lateral edge of the slab existing beneath the Calabrian arc (see e.g., Gasparini et al., 1982; Giardini and Velonà, 1988; Selvaggi and Chiarabba, 1995).

The other gravity low is located at the core of the Apennine Chain, near the Fucino plain. Here, tomographic data reveal a low velocity zone between 40 and 200 km (Cimini and De Gori, 2001), and crustal tomographic data indicate anomalous velocity values for the propagation of P waves at depth ranging between 8 and 37 km, this last close to the Moho discontinuity (Chiarabba and Amato, 1996). Here, the lower crust should be close to the melting temperature because of the presence of asthenospheric material identified in the uppermost part of the mantle (Chiarabba and Amato, 1996; Mele et al., 1996, 1997).

A portion of crust characterised by temperatures higher than the surroundings is expected to be associated with a gravity low, as higher temperatures should result in lower densities. In the 2D gravity model along the CROP11 seismic line (Bernabini et al., 1996b), a first interpretation of the Central Apennines gravity low was attempted by hypothesising a crustal wedge that plunges into the upper mantle to a depth of about 45 km. In this way, the gravity low in the Central Apennines was interpreted as a clue of the Adriatic lithosphere subduction. However, the comparison of gravity data with more recent seismic tomography data suggests a shallower depth, within the lower crust, for the source of the bulk of the aforementioned gravity low.

Summing up, gravity data for the Central Apennines substantially support the hypothesis of a less dense portion of crust, as suggested by the seismic tomography data. In the same area, Cimini and De Gori (2001) hypothesise the presence of an asthenospheric upwelling, also highlighted in the works by Mele et al. (1996, 1997, 1998). Such upwelling, also proposed on geomorphological and stratigraphic basis by D’Agostino et al. (2001), could have modified the thermal and rheological properties of the lower crust in this area, giving rise to the gravity low and the low velocity anomaly identified.

7. Conclusions

A regional gravity anomaly map of the Central–Southern Apennines has been obtained by applying the stripping procedure to the Bouguer anomaly map of the same area. The regional gravity anomaly map is different from other published gravity maps and resulted extremely useful for analysing the deep crust and the Moho trend in the Central–Southern Apennines.

The stripping reveals that the regional gravity lows are shifted westward in comparison with Bouguer anomaly lows. Moreover, the gravimetric pattern indicates a lack of cylindrism for the deep structures of the Apennine chain that, in the studied area, can be roughly divided into three main segments. Worthy of note are the marked differences between the gravity anomalies pattern of the Central Apennines and that of the Southern Apennines.

Based on the regional gravity anomaly map, a comparison between the existing hypotheses on the deep crust structural setting of the chain was carried out. A ramp-dominated style for the buried Apulia units and part of the underlying basement resulted more compatible with gravimetric data. Finally, the integration of our results with other available geophysical data suggest that in the Central Apennines most of the regional gravity anomalies reasonably originate within the lower crust; thus, the lithospheric features below the Moho still remain a challenge for geophysical research.

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