GRAVITY MODELLING ALONG CROP04 SEISMIC PROFILE

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MODELLAZIONE GRAVIMETRICA LUNGO IL PROFILO SISMICO CROP04

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ABSTRACT

The processing and interpretation of seismic lines, together with the analysis of surficial geological data and hydrocarbon wells data, are powerful tools for the investigation of crust structures. Nevertheless, for depths exceeding that portion of crust usually investigated for commercial purposes, only geophysical data are generally available (among the others: NVR seismic from CROP project, DSS data, magnetic data, gravity data).

In this context, the possibility of comparing two independent geophysical data sets, such as data from seismic exploration (CROP Project) and gravimetric analysis (Bouguer anomalies), is of particular interest for investigations into the deeper crust portion. In the present work gravity data modelling was used to study deep crust, constraints being provided by WARR data and by reflection seismic data obtained along the CROP04 profile that crosses the Southern Apennines (Italy) from Agropoli (SW) to Barletta (NE).

A preliminary interpretation has been made of the regional gravity anomaly trend in deep crust in Southern Italy; the role of this anomaly trend as an independent constraint for the geological interpretation of the CROP04 seismic line is discussed.

RIASSUNTO

Il *processing* e l'interpretazione di linee sismiche, unitamente all'analisi geologica di superficie e ai dati provenienti dai sondaggi per idrocarburi, sono utili strumenti d'indagine a livello crostale, specie in un loro utilizzo integrato. Tuttavia, a profondità crostali maggiori di quelle normalmente indagate per scopi commerciali,

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sono disponibili solo alcuni tipi di dati geofisici (tra gli altri: sismica NVR del progetto CROP, dati DSS, dati magnetici, dati gravimetrici).

La finalità principale di questo lavoro di modellazione gravimetrica lungo la traccia del profilo sismico CROP04 è proprio quella di fornire informazioni gravimetriche relative alla porzione più profonda (10-50 km) della sezione in questione, per integrare le conoscenze geofisiche finora esistenti.

I dati gravimetrici utilizzati sono stati estratti da un *database* relativo a tutto il territorio dell'Italia centro-meridionale. Tali dati si riferiscono ai valori di anomalie gravimetriche regionali ottenuti dalla separazione delle componenti dell'anomalia di origine superficiale da quelle di origine più profonda mediante una metodologia denominata *stripping* (HAMMER, 1963; BERNABINI *et alii*, 1996a; 1996b; 1996c;ORLANDO *et alii*, 1999; BERNABINI *et alii*, 2002a; 2002b).

Lungo la traccia del profilo CROP04 sono stati estratti i valori di anomalia gravimetrica al termine dello *stripping*. Su queste basi sono stati elaborati e vengono qui presentati alcuni modelli gravimetrici di distribuzione delle densità in profondità. Nell'interpretazione sono stati presi in considerazione i principali vincoli, di natura essenzialmente sismica, disponibili in letteratura e riguardanti sia l'andamento del contatto piattaforma apula-basamento, sia l'andamento della Moho (PATACCA *et alii*, 2000; PATACCA & SCANDONE, 2001; ANELLI *et alii*, 2000; CIPPITELLI, 2001 e 2002; MAZZOLI *et alii*, 2000; MENARDI NOGUERA & REA, 2000; SCARASCIA *et alii*, 1994). I due tipi di modelli analizzati prevedono, lungo il lato tirrenico della sezione considerata, rispettivamente: un forte ispessimento della porzione sedimentaria della catena, un basamento indeformato e la presenza di materiale mantellico a profondità relativamente modeste, o, in alternativa, un basamento coinvolto nella struttura della catena appenninica e un raddoppio della Moho. La modellazione gravimetrica ha consentito di mettere a fuoco alcuni punti fondamentali di cui è necessario tenere conto nella costruzione di modelli geologici basati su dati anche geofisici. Essi contribuiscono a evidenziare alcuni tra i principali vincoli all'interpretazione della porzione più profonda della linea sismica CROP04.

INTRODUCTION

The principal purpose of the work was to obtain, by means of gravity modelling, gravity information on the deepest portion (10-50 km) of the CROP04 seismic line, information pertinent to achieving a reliable geodynamic model of Southern Italy. The CROP04 profile crosses the Southern Apennines from Agropoli (SA), on the Tyrrhenian side, to Barletta (BA), on the Adriatic. The CROP04 seismic information available for the above-mentioned depth range is inadequate to define the structural setting of the principal crust and mantle elements therein, hence the need to integrate the available geophysical constraints (WARR: SCARASCIA *et alii*, 1994; CASSINIS & SCARASCIA, 2001; 2002) with other constraints, such as gravity data.

The basis for the present work is a Bouguer anomaly study carried out throughout Central-Southern Italy, a study that began some years ago (BERNABINI *et alii*, 1996a; 1996b; 1996c) and is now coming to a conclusion (ORLANDO *et alii*, 1999; BERNABINI *et alii*, 2002a; 2002b). The work methodology consists in separating deep gravity anomalies from superficial ones by a stripping procedure, and then performing 2D gravity modelling along the CROP04 profile.

DATA PROCESSING

The National Geological Survey supplied Bouguer anomaly values that had been obtained by a 3 km sampling of the database of all the Italian gravimetric stations (one station *per* km^2). In this data set, the reduction density for Bouguer anomaly correction is 2.67 g/cm^3, a value comparable with that of the average density of carbonate rock. The Bouguer anomaly values (fig. 1) show two important gravity highs, corresponding to the Tyrrhenian and the Adriatic coasts (see also CARROZZO *et alii*, 1991), where anomaly reaches about 100 mGal. Between these two highs, and running the full length of the Apennine chain, is a gravity low, the anomaly reaching values of –50 mGal near the Abruzzo coastline and further south close to the Sant'Arcangelo basin and Sibari plain.

In order to separate the deep Bouguer anomaly component from the surficial one a technique called stripping was employed. This methodology consists in determining the geometry of all the known surficial bodies of density differing from the reduction density, computing the gravity effect of such bodies and then subtracting it from the Bouguer anomaly values at each station. The iteration of this procedure for each body leads to the elimination of the superficial components of the Bouguer anomaly, allowing the isolation and, consequently, easier analysis of the regional components reflecting the layout of the deep crust and upper mantle (for further information on the methodology the reader is referred to HAMMER, 1963; BERNABINI *et alii*, 1994).

The first stages employing the stripping procedure concerned Central Italy (BERNABINI *et alii*, 1996a; 1996b; 1996c; ORLANDO *et alii*, 1999) while Southern Italy was dealt with at a later stage (see BERNABINI *et alii*, 2002 aand b and references therein for the geological data used in the stripping). The results of this second stage were used in the present work. The bodies considered in this latter stage can be grouped into three main units (see figure 2 for the location; for geological details refer to *Bernabini et al.*, 2002b).

Quaternary volcanic deposits: deposits of the volcanic complexes of Latium and Campania, as well as Mt. Vulture;

Plio-Quaternary terrigenous sediments: Pliocene, Pleistocene and Holocene sediments filling the intramontane valleys and coastal plains of the Marche, Latium, Abruzzo, Molise, Campania, Puglia and Basilicata regions;

Meso-Cenozoic pelagic basin deposits: Ligurides, Sicilides and Tuscan successions, Molise-Sannio-Lagonegro successions, Miocene foredeeps and Pliocene thrust-top-basin siliciclastic deposits.

The 3D modelling of the previously described bodies was carried out using more than 70 E-W oriented cross-sections (Figure 5), these all being parallel as required by the software (IGAS3D, GÖTZE AND LAHMEYER, 1988). As the study was a regional one the scale adopted was 1:250,000.

Each unit was assigned an approximate mean density, slightly modified in each case in accordance with the individual body being modelled. The gravity effect was calculated by applying values of contrast in relation to a density of 2.67 g/cm^3, the value used in correcting Bouguer anomaly. Table 1 shows the density contrast values applied.

The results of the stripping procedure (BERNABINI *et alii*, 2002a and b) i.e.the gravity anomalies originating at depths beyond the top of the Apulian Platform, are shown in fig. 3. Note the very different gravity imprint of the Southern Apennines with respect to the Central. In the Southern Apennines, after the elimination of the superficial gravity effects, the disappearance of the gravity lows could be observed in correspondence with the chain core, while in the central region the situation was quite different. In the Southern Apennines the only significant gravity low detected (about 20 mGal) corresponds to the area of the Sant'Arcangelo basin. The CROP04 profile (fig. 3) lies right along the northern edge of this gravity low, in a zone of transition towards higher values of the gravity anomaly, although these values constitutes a relative low in relation to the Tyrrhenian and Adriatic coasts.

GRAVITY DATA ALONG THE CROP04 PROFILE

Gravity anomaly values before and after stripping were extracted along the CROP04 profile (fig. 4b). Fig. 4a shows a CROP04 profile cross-section where bodies modelled during the stripping procedure are highlighted. The Mesozoic portion of the Lagonegro succession was not considered in the stripping as its density values are very similar to the values used in the corrections.

It is important to note that the gravity effect of this bodies was computed and subtracted by 3D modelling, thus not only the gravity effect of the bodies within the cross-section plane, but also the lateral effect of their extension in an orthogonal direction was eliminated.

As shown in fig. 4b, the stripping procedure resulted in a slight increase in the gravity anomaly values at the Tyrrhenian coast and the disappearance of an important series of gravity lows in the central-eastern part of the profile. In effect, there is the delineation of a regional trend in the gravity anomaly, this trend following a path different from that that of preliminary Bouguer anomaly observations. In fact, the main feature of this new anomaly trend is a gravity low located about 40 km from the Tyrrhenian coastline, not at 80 km. The low at 80 km was evidently due to the presence of allocthon thrust sheets that form the core of the Southern Apennine chain.

The undulations observed in the central-eastern part of the anomaly curve after the stripping (fig. 4b) are artificial effects generated by the triangulation performed by the software, because of the extreme complexity of the Southern Apennine geometry. This problem would be properly solved increasing the number of cross-sections used in modelling each body, but this was not relevant given the regional scale of the work. As a matter of fact, the undulations do not mask the regional trend, which is easily identified, and were not taken into consideration in the following 2D gravity modelling of the deepest part of the profile.

Hence the anomaly trend in fig. 4b reflects the density distribution in this specific case beneath the Apulian Platform, given that carbonate rock has an average density of 2.67 g/cm^3, which corresponds to the reduction density, and the gravity contribution of the other bodies in fig. 4a has been eliminated by means of the stripping procedure. A 2D gravity modelling was carried out in order to interpret this anomaly trend; thus it was necessary to single out and consider all the available constraints, both of a geological and a geophysical nature, that could lead to the detection of lithospheric features giving rise to the anomaly trend above. To this end, reference was made to the main existing geological models, especially models from reflection seismic data, both commercial and CROP, and wide-angle seismic data.

GRAVITY MODELS

PRINCIPAL EXISTING GEOLOGICAL AND GEOPHYSICAL CONSTRAINTS

As far as it concerns the geometry of the top of the crystalline basement, the literature deals, essentially, with two model types related to the structural and geometrical setting of the Southern Apennines.

One model (PATACCA *et alii*, 2000; PATACCA & SCANDONE, 2001) derives from a direct interpretation of the CROP04 seismic line, and considers an undeformed crystalline basement (already adopted in the ‘80s by MOSTARDINI & MERLINI; 1986). In this model the top of the basement plunges gently towards the Tyrrhenian side, starting from a depth of more than 6 km on the Adriatic side and reaching one of more than 20 km on the Tyrrhenian.

A second series of models, also derived from an interpretation of the same seismic profile (ANELLI *et alii*, 2000; CIPPITELLI, 2001 e 2002) or from commercial seismic lines available in the surrounding area (MAZZOLI *et alii*, 2000; MENARDI NOGUERA & REA, 2000), consider, instead, a basement involved in the deformations of the Apennine chain. In such models we find not the doubling of the Apulian Platform, but basement thrust sheets that rise to depths of less than 10 km beneath the Tyrrhenian coast.

For the Moho location we considered the WARR (wide-angle reflection-refraction) data interpreted by SCARASCIA *et alii*, 1994 (see also CASSINIS & SCARASCIA, 2000; 2002), these being the only available deep seismic data in the area of the CROP04 profile. The data suggest the presence of two distinct crust-mantle discontinuities: one defined as the Moho of the Peri-Tyrrhenian thinned crust, the other interpreted as the Moho of the Afro-Adriatic plate. For the sake of simplicity we will respectively refer to them as “Tyrrhenian” and “Adriatic”. The “Tyrrhenian” Moho, on the western side of the studied area, is located at a depth of 27 km and dips gently to the east, while the “Adriatic” one, on the eastern side of the studied area, is located at a depth of about 30 km and dips in a SW direction beneath the Tyrrhenian Moho to a depth of 50 km.

GRAVITY MODELS RELATED TO THE CURRENT GEOLOGICAL MODELS

We considered two geological models, hypothesizing both an undeformed basement and a basement involved in the deformation of the chain. In both cases, WARR data constraints were used to complete the deepest portion of the profile. The gravity effect for both models was computed.

Fig. 5a shows the gravity effect of the model with the basement involved in the chain deformation. The gravity anomaly observed after the stripping, and hence related to the deep portion of the model, passes from 70 mGal on the Tyrrhenian side to 20 mGal in the central gravity low, then rises to nearly 90 mGal on the Adriatic side. The gravity effect computed for the model, excluding the effects of carbonates that, in this reference system, generate no anomaly, and everything else eliminated by the stripping, is from 20 mGal to 150 mGal, with a low reaching about 0 mGal. Hence, this model results in an excess of density along the Adriatic side, while appearing to be too "light" on the Tyrrhenian one.

Fig. 5b shows the gravity effect of the model with an undeformed basement; the Moho location deduced from WARR data implies very marked thinning of the Tyrrhenian lower crust, almost to the point of its disappearance. In this case, the difference between the calculated curve and that computed at the end of the stripping procedure is slightly more evident than in the other case (fig. 5a) on the Tyrrhenian side. Nevertheless, the two models are far from the best fitting as the computed anomaly starts from –10 mGal on the Tyrrhenian coast and reaches 140 mGal on the Adriatic.

At this point we introduced further modifications, in addition to the already foreseen main constraints, to improve the fitting of the two models and achieve a realistic model from the gravimetric point of view.

2D GRAVITY MODELLING

In both the following models it was necessary to make a first, substantial modification. It consisted of a lateral density variation within the portion of the Adriatic crust under the Apulian Platform (fig. 6). In fact, for a better fitting of the gravity data, lower density values were needed for the easternmost part of the Adriatic crust. As the proposed models are only a simplified description of the reality, this variation can be a transition, sharp or gradual, from East to West, or be realized in other ways, such as by horizontal changes in the easternmost parts of the Adriatic crust. For example, according to the Puglia 1 well (courtesy of Ministero dell'Industria, Commercio e Artigianato), beneath the Apulian Platform lies a Permo-Triassic terrigenous succession more than 1000 m thick, whose density could be ca.2.6 g/cm^3. The presence of this unit could reduce the density of the upper portion of the crust in the above-mentioned area, thus considerably conditioning the average density of the whole Adriatic side.

According to the literature, (e.g.: MONGELLI *et alii*, 1989; DELLA VEDOVA *et alii*, 1991; DELLA VEDOVA *et alii*, 2001) the Tyrrhenian area is characterized by high heat flow values so that the Tyrrhenian mantle is expected to be less dense than the mantle in the Adriatic area. In fact, according to the 2D model along CROP11 by BERNABINI *et alii*, 1996c, the Tyrrhenian mantle is given a density of 3.26 g/cm^3, while the density of the Adriatic mantle is 3.32 g/cm^3. However, in the area crossed by the CROP04 profile, heat flow variations are not so marked between Tyrrhenian and Adriatic side, suggesting a slighter difference in density. The consequent chosen density for the Tyrrhenian mantle is 3.31 g/cm^3. Although a difference of 0.01 g/cm^3

between the Adriatic and Tyrrhenian mantle could seem negligible, it produces a difference of ca. 6 mGal when computed for a thickness of about 15 km.

In the model with the deformed basement (fig. 6a), the fitting of the two curves requires a reduction in the crust wedge (characterized by a density of 2.67 g/cm^3) interposed between the two Moho coming from the WARR data interpretation after SCARASCIA *et alii* (1994) and CASSINIS & SCARASCIA (2001 and 2002) and considered by these Authors as evidence of subduction of the Adriatic crust beneath the Tyrrhenian one. In the gravity data interpretation, this wedge is confined within a depth of ca. 55 km.

In the model with the undeformed basement (fig. 6b), the same degree of fitting can be obtained only with a further reduction of the said crust wedge. In the gravimetric interpretation, it is necessary to limit the presence of the continental crust to a depth of about 45 km. Hence, in this case the constraints are not completely fulfilled by the model. It is interesting to note that such a model necessarily implies a very marked thinning of the Tyrrhenian lower crust.

DISCUSSION

As shown in fig. 6a, the crust wedge defined in the WARR data analysis, and interpreted as evidence of Adriatic crust subduction beneath the Tyrrhenian crust (SCARASCIA *et alii*, 1994; CASSINIS & SCARASCIA, 2001; 2002), can be correlated with a small-size relative gravity low. This gravity low is completely compensated by a crust wedge that doesn’t exceed a depth of 55 km.

On the other hand, in the model with the undeformed basement (fig. 6b) the marked thickness of the doubled Apulian Platform causes the base of the carbonate unit to reach a depth of about 20 km. Thus there is a lightening of the Tyrrhenian portion of the crust, sufficiently so as to compensate a large part of the gravity low and reduce the possibility of finding continental crust in the lower part of the model. This results in part of the WARR constraints being unfulfilled.

As already mentioned, the CROP04 profile is located at the northern edge of a gravity low area (fig. 3). Hence, part of the gravity low observed about 45 km from the Tyrrhenian coast (fig. 4b) could simply be a lateral effect due to deep structures, and not derive directly from the real setting of the structures within the plane of the considered cross-section. In fact, although the superficial bodies underwent 3D modelling and their gravity lateral effects were eliminated during the stripping procedure, this was not applied to deep structures, as *a priori* knowledge would have been necessary. Thus, deep modelling is exclusively two-dimensional, and can therefore be affected by the gravity effects of deep, non-cylindrical, bodies located to the north and south of the section. This is a typical limit of 2D modelling, especially where complex geometry prevents bodies from being considered cylindrical. For this reason, the computed anomaly trend of the proposed models (figs. 6 a and b) is an attempt to mediate the observed anomaly trend, and not to fully compensate the central gravity low. Furthermore, the characteristic wavelengths of the said low are shorter than those produced with Moho position variation in that particular cross-section.

CONCLUSIONS

The gravity modelling shown in the present work has allowed the highlighting of some essential points to be taken into account when realizing geological models based also on geophysical data.

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Above all, the achievement of an optimal fitting of the gravity data requires lateral variations in density within the Adriatic crust that is, on the average, lighter in the easterly direction and denser towards the Tyrrhenian side. Also the mantle seem to show a differentiated density, being slightly less dense on the Tyrrhenian side than on the Adriatic one.

In the case of the model with an undeformed basement, a careful check must be made of the overall thickness assigned to the piled units of the Apulian Platform.

As a final comment we would like to state that, as the gravity low between the Tyrrhenian and Adriatic gravity highs is quite small, the only models that could be developed were ones where the continental crust reaches, at most, a depth of 55 km. Such a depth relates only to continental crust with the same features as the overlying crust, being the question of whether a slab lies under the considered area beyond the purpose of this work.

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FIGURE CAPTIONS

Fig. 1 – Bouguer anomaly map of Central-Southern Italy (from National Geological Survey's data set).

Carta delle anomalie di Bouguer in Italia centro-meridionale (data set del Servizio Geologico Nazionale).

Fig. 2 – Geological sketch map of peninsular Italy from the Po Plain to north of the Calabrian Arc (after DI BUCCI & MAZZOLI, 2002, modified).

Schema geologico dell'Italia peninsulare dalla Piana del Po fino all'estremo settentrionale dell'Arco Calabro (tratta da: DI BUCCI & MAZZOLI, 2002, modificata).

Fig. 3 – Deep gravity anomaly map obtained by means of a stripping procedure (from BERNABINI *et alii*, 2002b; modified) . In black, the CROP04 profile.

Carta delle anomalie di origine profonda ottenuta mediante stripping *(tratta da: BERNABINI et alii, 2002b; modificata). In nero, la traccia del profilo sismico CROP04.*

Fig. 4 –a) Bodies (in grey) characterized by density values lesser than 2.67 g/cm^3 and corresponding to the first three units in table 1; their gravity effect was computed and subtracted during the stripping. The white portion of the figure comprises both the fourth unit in table 1 and all the other unknown bodies beneath it. Vertical scale has been doubled. b) Gravity anomaly trend curves along CROP04 profile before (dashed line) and after (continuous line) the stripping.

a) Corpi (in grigio) caratterizzati da densità minori di 2,67 g/cm^3 e corrispondenti alle prime tre unità della tabella 1; il loro effetto gravimetrico è *stato calcolato e sottratto durante lo* stripping. *Nella parte bianca della figura è compresa sia la quarta unità della tabella 1, sia tutti i corpi sconosciuti sottostanti*. *La scala verticale è raddoppiata*.

b) Andamento dei valori di anomalia gravimetrica in corrispondenza della traccia del CROP04 prima (linea tratteggiata) e dopo (linea continua) lo stripping.

Fig. 5 – Gravity anomaly trend after the stripping (continuous line) compared with the gravity effect produced by each model (dashed line). The latter was computed giving carbonate units, and whatever was eliminated in the stripping, a density contrast value of zero (density of 2.67 g/cm^3); this was done to allow proper comparison of the two curves.

Numbers within the bodies indicate the density values, in g/cm^3.

a) Model with the basement involved in the deformation of the Apennine chain.

b) Model with an undeformed basement.

Andamento dell'anomalia gravimetrica ottenuta dopo lo stripping *(linea continua) a confronto con la curva dell'anomalia prodotta dai modelli considerati (linea tratteggiata). Quest'ultima è stata calcolata attribuendo un contrasto di densità pari a zero ai carbonati, che in questo sistema di riferimento non danno anomalia (densità: 2,67 g/cm^3), e a tutto ciò che è già stato eliminato nel corso dello* stripping*, proprio per consentire un corretto confronto tra le due curve.*

I numeri all'interno dei corpi nel modello indicano i valori di densità in g/cm^3.

a) Modello che prevede il basamento coinvolto nelle deformazioni della catena.

b) Modello che prevede il basamento indeformato.

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Fig. 6 – a) Hypothesis for gravity corrected model based on a geological model with a deformed basement. In bold black, the main constraints provided by WARR data.

Ipotesi di modello gravimetricamente accettabile, a partire da un modello geologico che prevede un basamento deformato. In grassetto nero sono evidenziati i principali vincoli forniti dai dati WARR.

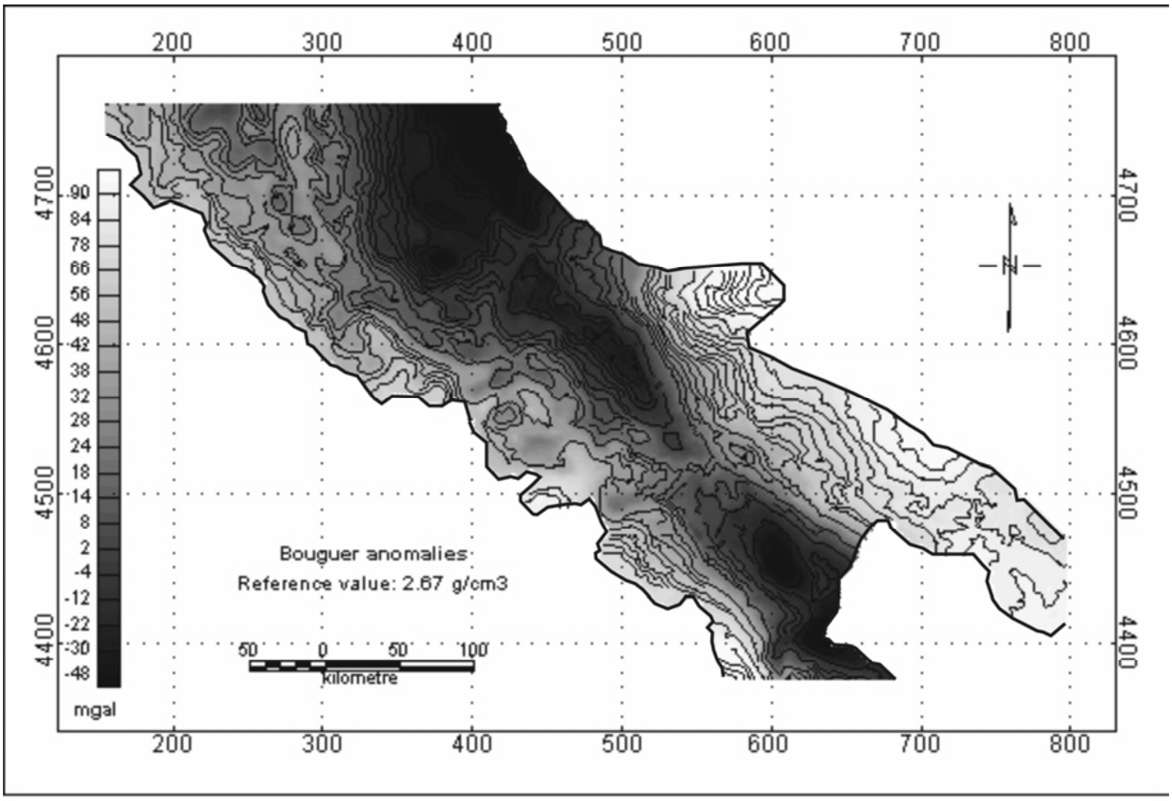
b) Hypothesis for gravity corrected model based on a geological model with an undeformed basement. In bold black, the main constraints provided by WARR data.

Ipotesi di modello gravimetricamente accettabile, a partire da un modello geologico che prevede un basamento indeformato. In grassetto nero sono evidenziati i principali vincoli forniti dai dati WARR.

Lithologic units	Density (g/cm^3)	Density contrast to 2.67 g/cm^3
Quaternary volcanic deposits	2.20÷2.40	-0.47÷ -0.27
Plio-Quaternary terrigenous sediments	2.30	-0.37
Meso-Cenozoic pelagic basin deposits	2.40÷2.55	-0.27÷ -0.12
Carbonate units and other units with similar density	2.67	0

Table 1 - Units modelled in the stripping.

Unità considerate nel corso della modellazione gravimetrica.



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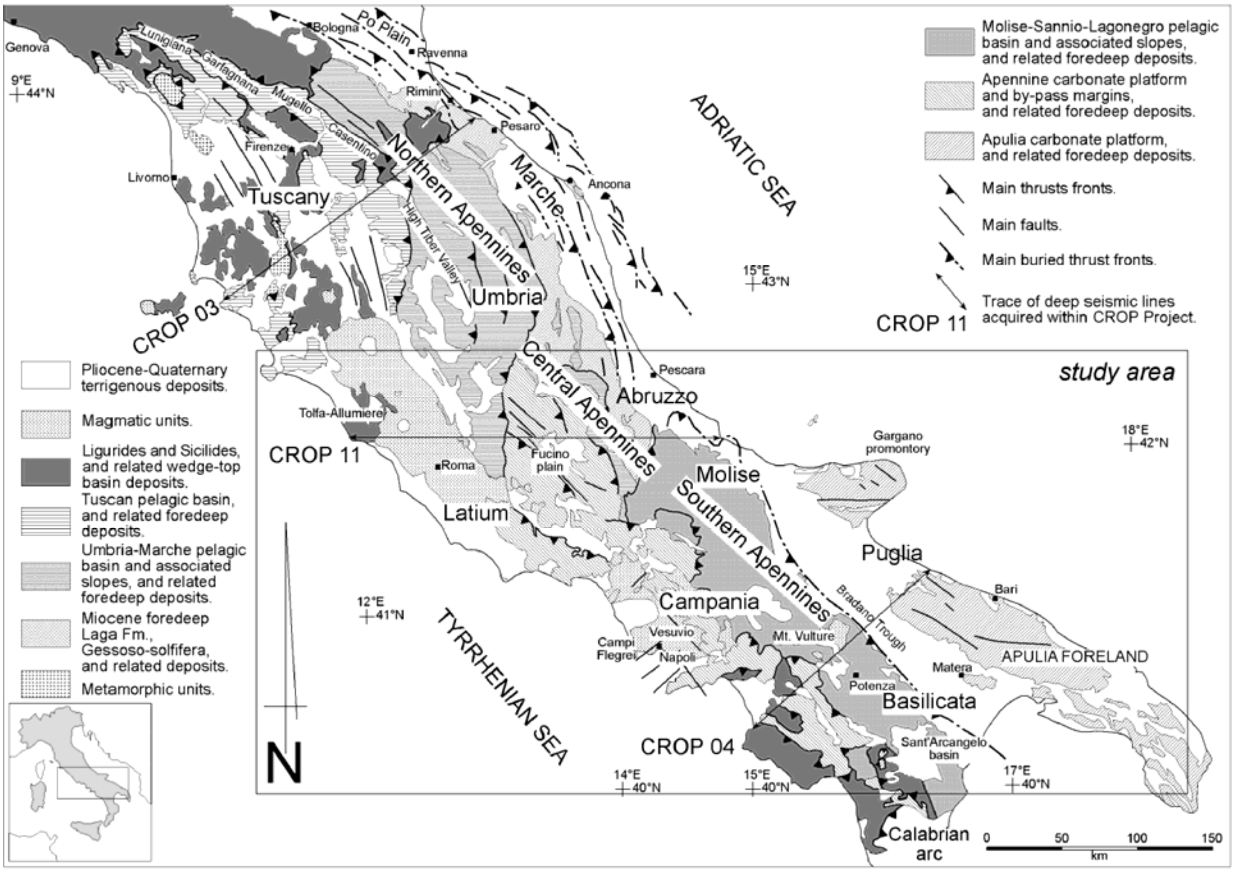

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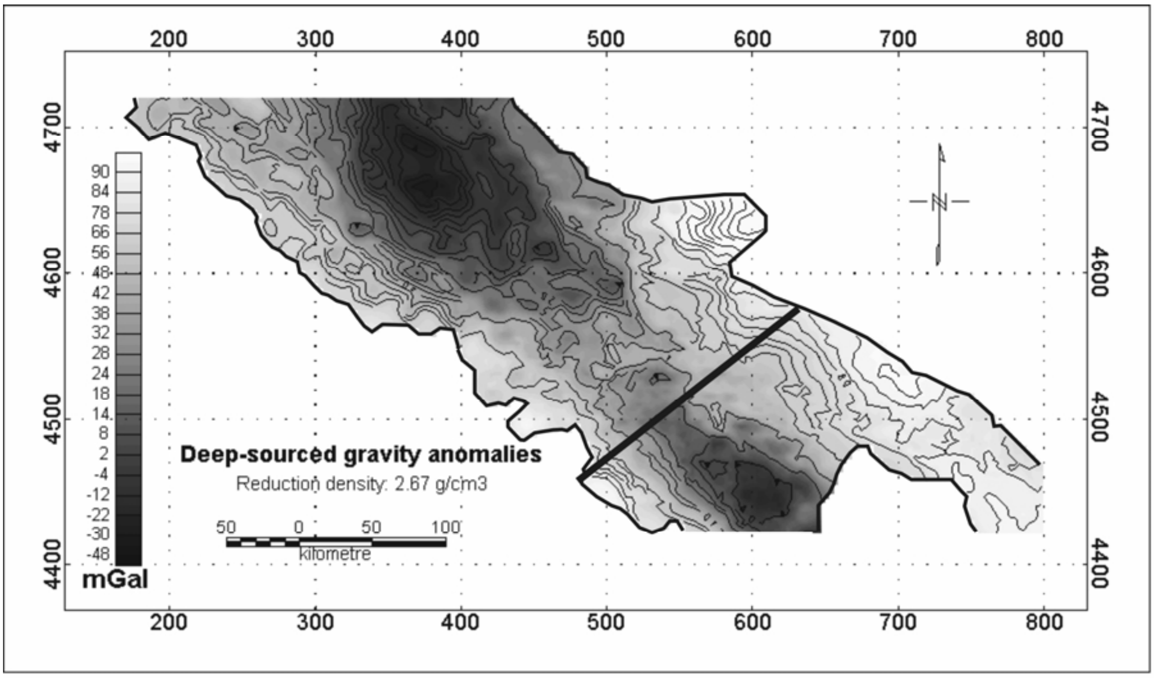

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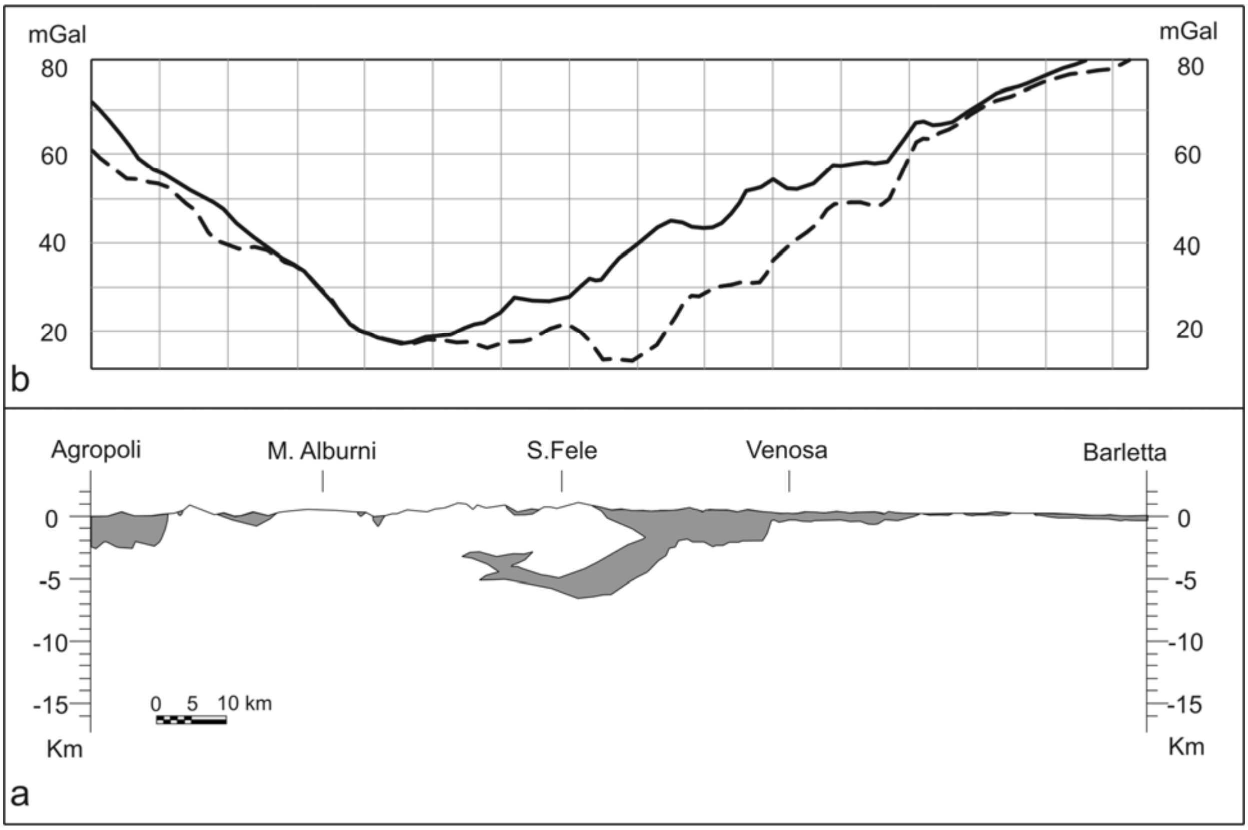

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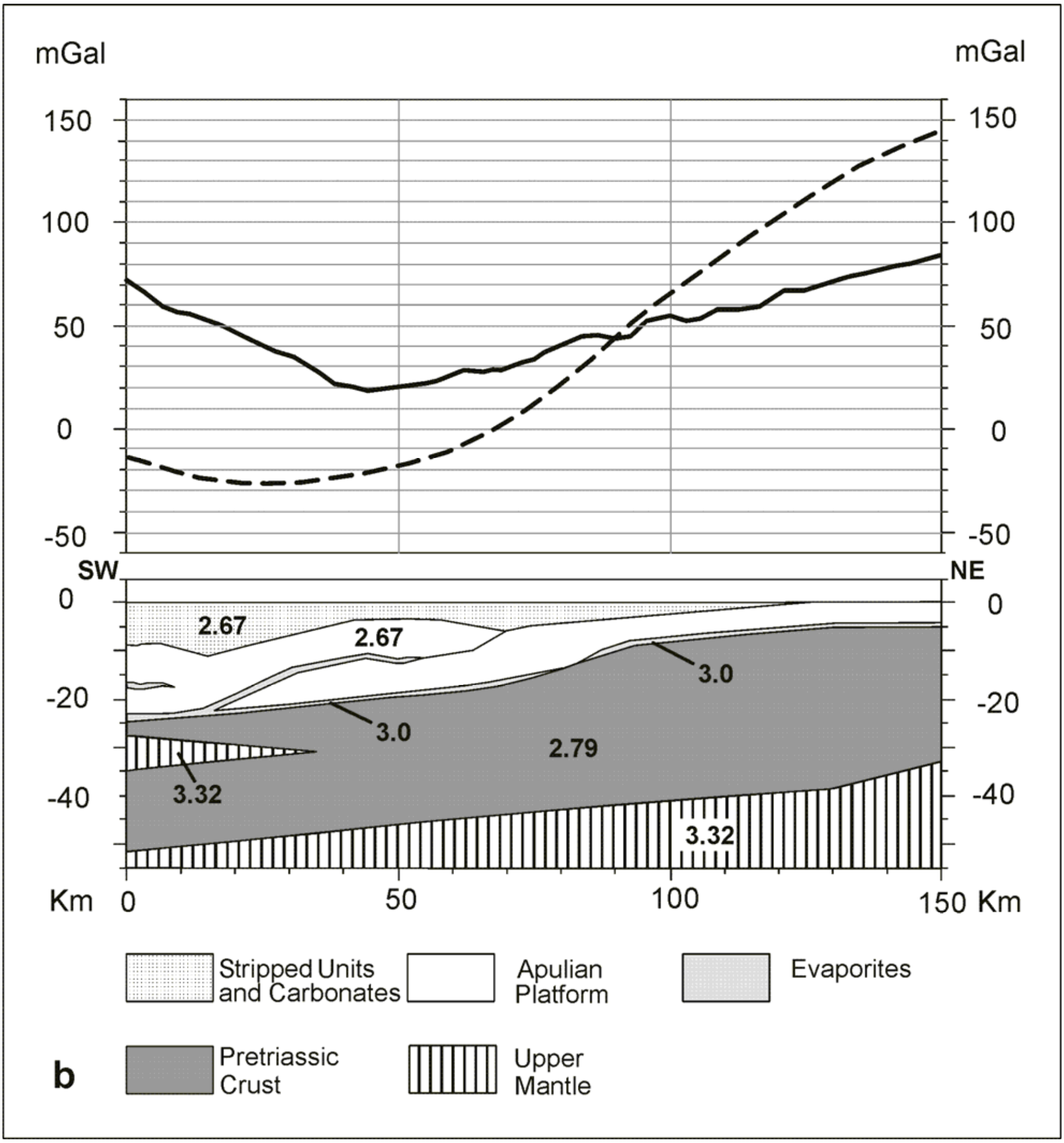

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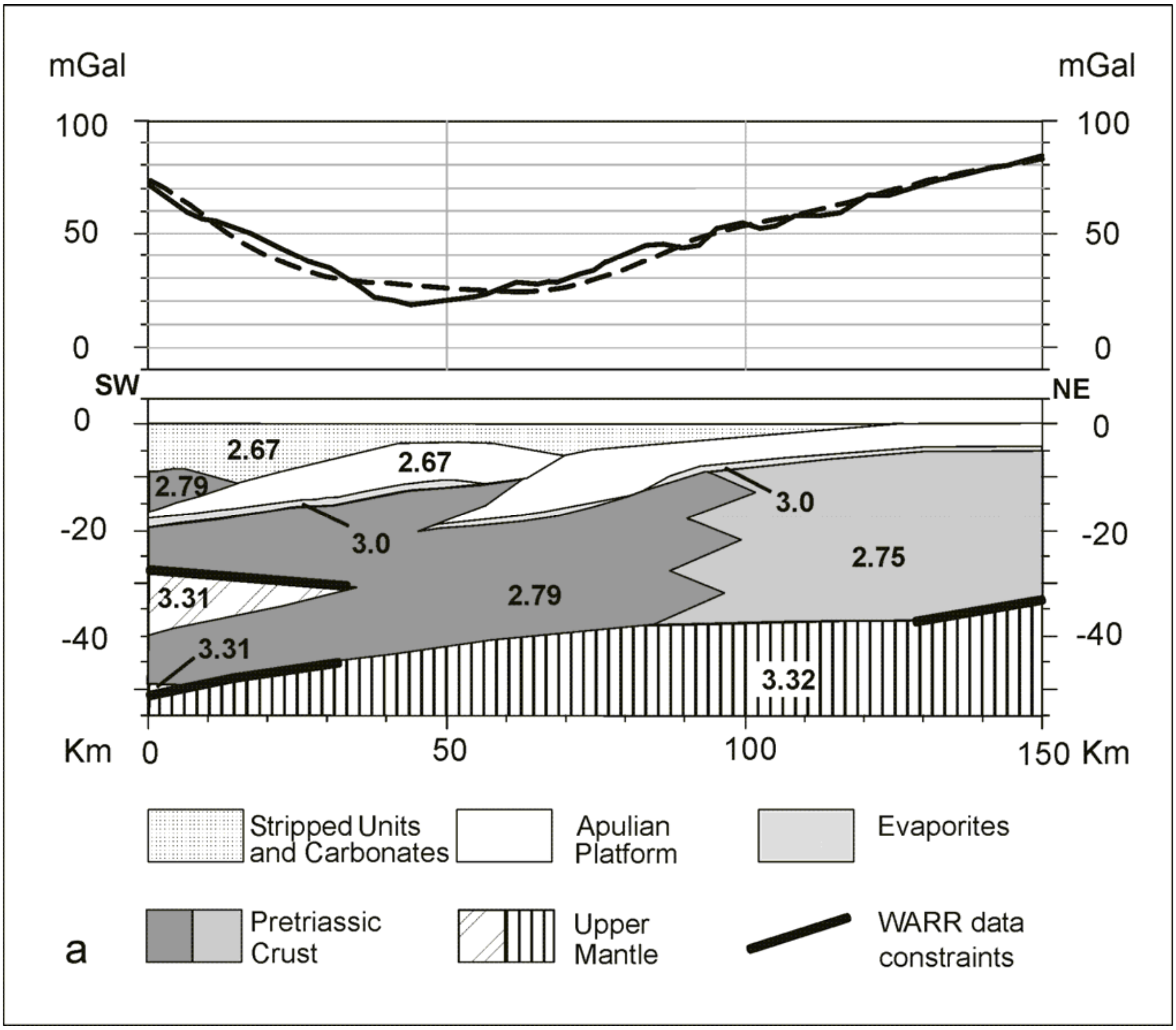

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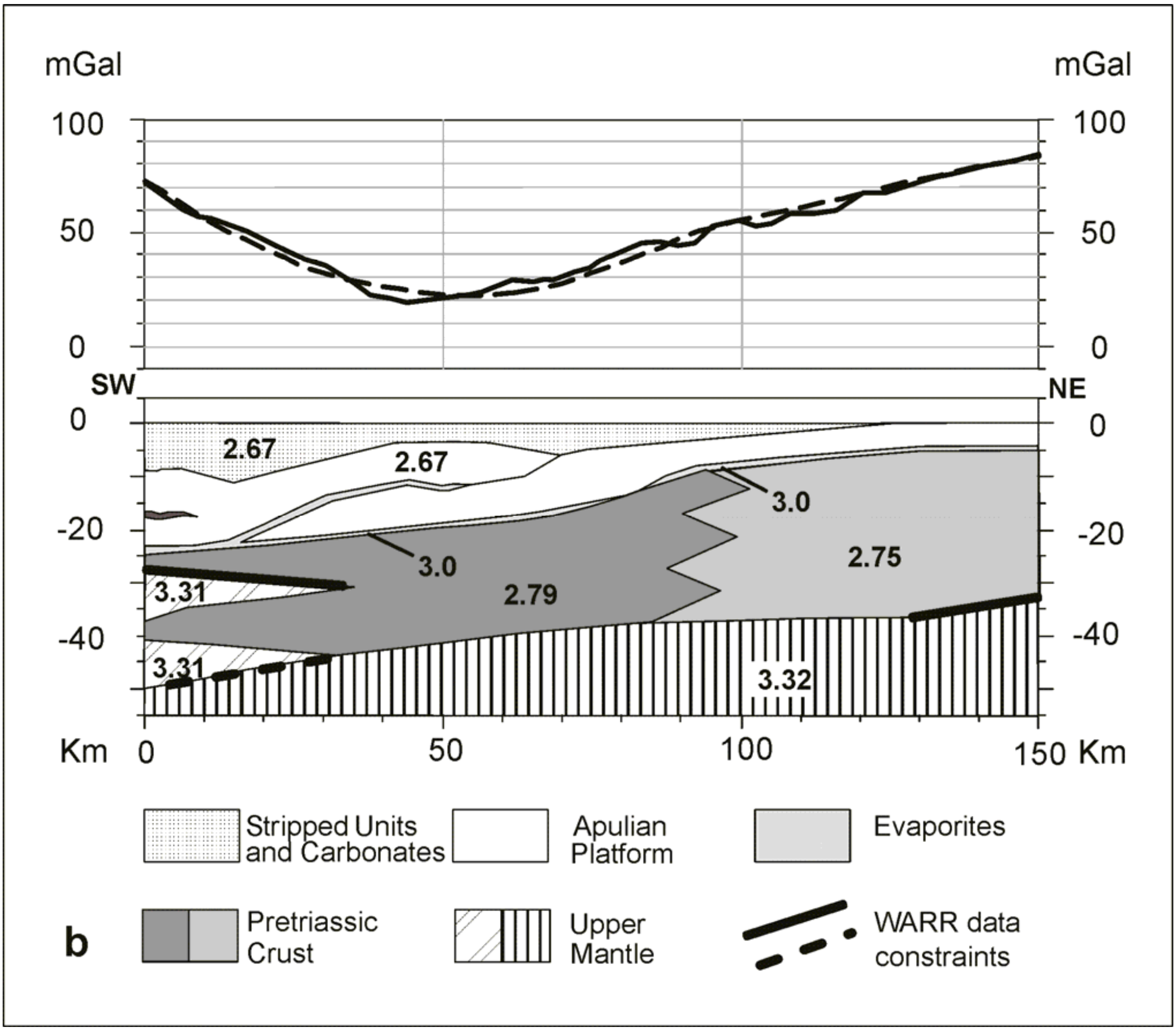

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