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Evidence of Apulian crustal structures related to low energy seismicity (Murge - Southern Italy)

Vincenzo Del Gaudio (1), **Vincenzo Festa** (2), **Rosa Rita Ripa** (1), **Vincenzo Iurilli** (1), **Pierpaolo Pierri** (3),
Gildo Calcagnile (1)(3), **Massimo Moretti** (1), **Piero Pieri** (1) **and Marcello Tropeano** (4)
(1) *Dipartimento di Geologia e Geofisica, Università di Bari, Italy*
(2) *Dipartimento Geomineralogico, Università di Bari, Italy*
(3) *Osservatorio Sismologico, Università di Bari, Italy*
(4) *Dipartimento di Scienze Geologiche, Università della Basilicata, Potenza, Italy*

Abstract
The discovery of recent co-seismic sedimentary structures and the detection of low energy seismic activity in the Murgian plateau (Apulia - Southern Italy) motivated a more detailed examination of the tectonics in this part of the Apulian plate commonly believed to be aseismic. In particular, we examined the north-western zone where a seismic sequence with maximum magnitude 3.2 and tensional focal mechanism occurred in 1991. The analysis of the existing gravimetric data, integrated by three new profiles carried out across the epicentral area, disclosed an anomaly possibly due to an old tensional tectonic structure located within the upper crust. Even though the depth and the age hypothesised for the anomaly source would exclude a direct causal connection with the observed seismicity, this structure could be a shallower expression of a tectonic structure extending down to the crystalline basement: it could represent a zone of relative «weakness» where the regional stress, due to the interactions between Apennines and Apulian plate, encounters conditions facilitating the release of seismic energy.

Key words *Bouguer anomalies – Murgian plateau – low energy seismicity – tensional structures*

1. Introduction

Seismotectonic studies of Southern Italy pointed out that Apulia is a relatively stable and scarcely deformed area which corresponds to the exposed foreland (represented by Gargano, Murge and Salento areas) of the Southern Apennine chain (De Vivo *et al.*, 1979; Ciaranfi *et al.*, 1981, 1983). Apulia belongs to the so-called Adriatic plate (Channel *et al.*, 1979; Anderson and Jackson, 1987), a rigid block which plays the role of foreland for the peri-Adriatic orogenic belts (Apennines, Alps, Dinarides, Albanides, Hellenides) and is characterised by a minor seismic activity in comparison with the more deformable surrounding regions. This does not implies that Apulia is free from seismic hazard. Indeed, its northern part was historically hit by well documented strong earthquakes, but their frequency is much lower than in the Apennine chain; furthermore the areas located south of the Ofanto river (Murgian plateau and Salento peninsula) have been generally considered almost aseismic and a moderate hazard was recognised for them only in relation to the seismogenic structures of neighbouring regions (Apennines, Gargano, Albania, Greece).

However, some recent observations suggested that the seismotectonic characterisation of

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Mailing address: Dr. Vincenzo Del Gaudio, Dipartimento di Geologia e Geofisica, Università di Bari, Via E. Orabona 4, 70125 Bari, Italy; e-mail: delga@geo.uniba.it this area should be re-examined. In particular, some sedimentological structures found in recent (Tyrrhenian) deposits of the area around the town of Bari were recognised as produced by seismically induced liquefaction phenomena (Moretti *et al.*, 1995; Moretti and Tropeano, 1996): these structures imply that in geologically recent times events of magnitude ≥ 5 occurred within few tens of kilometres from Bari. Furthermore, a local seismic network recorded a recurrent low energy seismicity whose sources are located in the North-Western Murgian plateau. In particular, on 22 February 1991 a seismic sequence of about 50 shocks of magnitude 1.8 ÷ 3.2 started in the area of Castel del Monte, lasting until the beginning of May. Even though the seismic network coverage leaves some uncertainty margin in the definition of source characteristics, reliable indications on depth and focal mechanism of the events were obtained thanks to the availability of seismic stations very close to the epicentral zone: the depth was about 15-20 km and the focal mechanism was characterised by a T axis having trend 255° and plunge 15° and a P axis having trend 75° and plunge 75°. This implies a purely dip-slip tensional mechanism with a strike parallel to the main tectonic structures of the Apennine chain (Del Gaudio *et al.*, 1996; Pieri *et al.*, 1997).

These observations suggested investigating the structural characteristics of this area examining the existing geological and geophysical data and then integrating them by means of new gravimetric profiles, to clarify the tectonic framework which determines the observed seismicity.

2. Geological setting of the Murge area

The Apulian foreland represents the Plio-Pleistocene foreland of the Apenninic (westward) and the Dinaric-Hellenic (eastward) orogens corresponding to the Mesozoic Apulian Carbonate Platform (D'Argenio *et al.*, 1973; Ricchetti *et al.*, 1988). The Adriatic offshore of Apulia region represents the Upper Miocene - Quaternary foredeep of Dinaric orogen (Royden *et al.*, 1987; Argnani *et al.*, 1993); Bradanic trough and Taranto Gulf represent the Pliocene - Quaternary foredeep of Apenninic orogen (Crescenti, 1975; Casnedi, 1988; Pieri *et al.*, 1996) (fig. 1a). During the Neogene and Pleistocene the Apulian Carbonate Platform was progressively involved in the foredeeps of Apenninic and Dinaric-Hellenic orogens and, at the same time, took up the role of foreland (Ricchetti *et al.*, 1988). It constitutes the southwestern margin of the Adriatic plate in the Central Mediterranean area (Anderson and Jackson, 1987; Ricchetti *et al.*, 1988) and corresponds to a wide WNW-ESE trending antiform (Ricchetti and Mongelli, 1980; Auroux *et al.*, 1985; Royden *et al.*, 1987; Ricchetti *et al.*, 1988; Doglioni *et al.*, 1994), interpreted as the Neogenic-Quaternary effect both of the Apenninic orogeny (Ricchetti and Mongelli, 1980; Argnani *et al.*, 1993; Doglioni *et al.*, 1994) and the Apenninic-Dinaric-Hellenid orogenesis (Royden *et al.*, 1987). It shows a uniform crustal structure with a Variscan crystalline basement and an approximately 7 km thick Mesozoic sedimentary cover mainly characterised by limestones and dolomites (Ricchetti *et al.*, 1988) of the Apulian Carbonate Platform (D'Argenio *et al.*, 1973); this succession is overlain by relatively thin discontinuous Tertiary and Quaternary deposits (Ricchetti *et al.*, 1988).

The cropping Apulian foreland, which practically corresponds to the Apulia region (South-Eastern Italy), is characterised by three main relatively elevated areas; from NW to SE and from the higher to the lower: Gargano, Murge and Salento (fig. 1a). These zones are separated from each other by morpho-structural depressions (Ricchetti *et al.*, 1988; Funiciello *et al.*, 1991; Gambini and Tozzi, 1996). A 3 km thick sedimentary Cretaceous succession of the Apulian Carbonate Platform crops out in the Murge area (Ciaranfi *et al.*, 1988) (fig. 1b). Such succession is characterised by monotonous well-bedded dolomites and carbonates mainly back-reef facies (Ciaranfi *et al.*, 1988; Ricchetti *et al.*, 1988; Luperto Sinni, 1996) and, locally, by facies of carbonate platform margin (Luperto Sinni and Borgomano, 1989; Pieri and Laviano, 1989; Laviano *et al.*, 1998). Two main Cretaceous formations have been distinguished in Murge area (fig. 1b): «Calcare di Bari» Fm. (Lower Cretaceous), below and «Calcare di

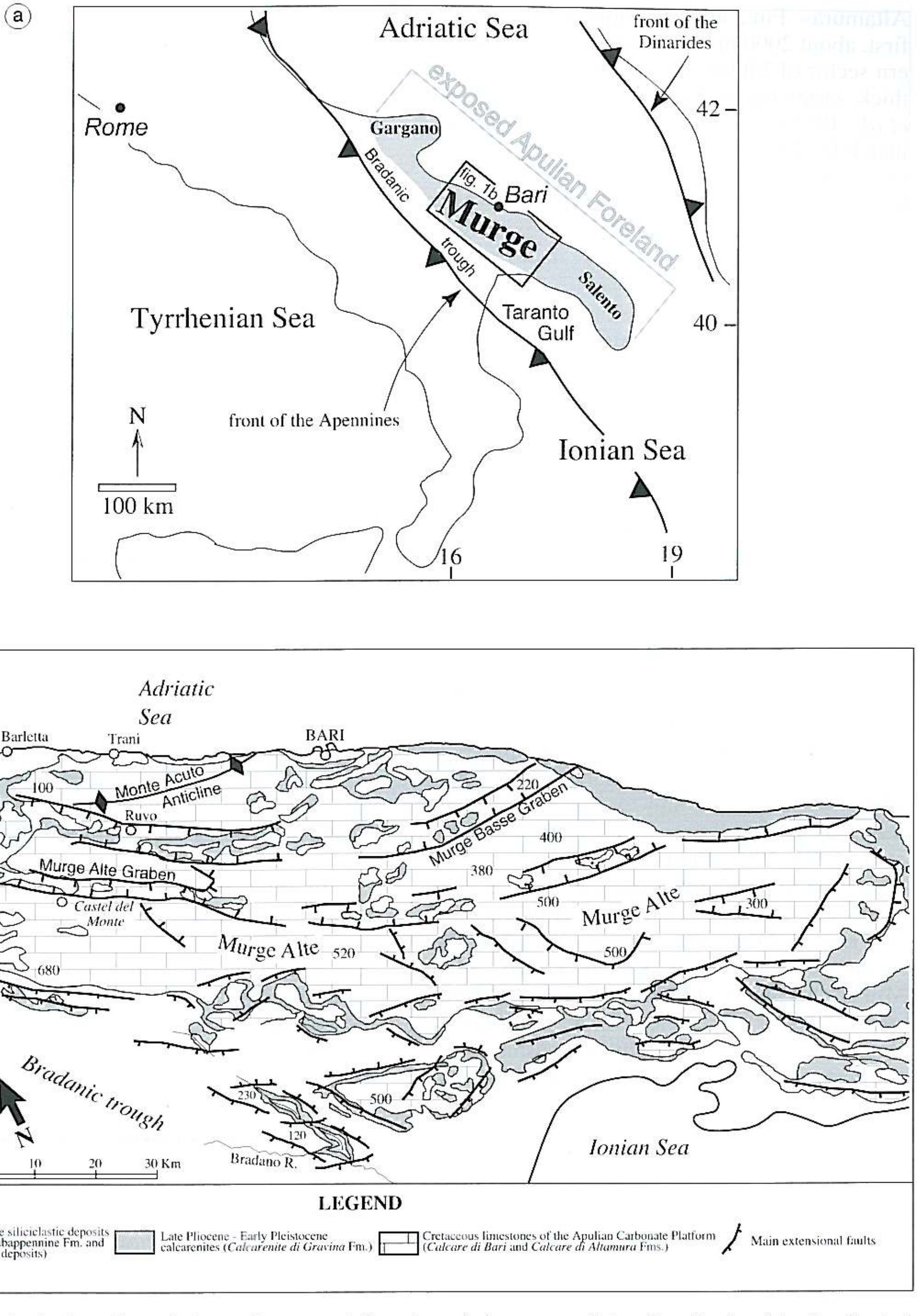

Fig. 1. Geological outline of the study area: a) location of the emerged Apulian foreland in the Central Mediterranean area; b) geological sketch of the Murge area (after Tropeano *et al.*, 1997, modified).

Altamura» Fm., above (Valduga, 1965). The first, about 2000 m thick, crops out in the northern sector of Murge, the second, about 1000 m thick, crops out in the southern area (Ciaranfi *et al.*, 1988). They are bounded by a Cenomanian P.P. - Turonian P.P. unconformity (Ciaranfi *et al.*, 1988; Luperto Sinni and Reina, 1996) locally marked by bauxites, green clays and/or marly sands (Crescenti and Vighi, 1969). Discontinuous and thin Middle and Late Pliocene - Quaternary terrigenous deposits overlie the aforesaid Cretaceous succession in narrow zones and on the limbs of the Murge high (Ciaranfi *et al.*, 1988). These deposits are represented, from bottom to top, by transgressive and deepening-upward deposits («Calcarenite di Gravina» Fm., below and «Argille subappennine» Fm., above) (Iannone and Pieri, 1982) and by shoaling-upward regressive deposits (Ciaranfi *et al.*, 1988; Pieri *et al.*, 1996) (fig. 1b).

Structurally, the Murge area is characterised by brittle tectonic deformations, without particular upsettings. Deformational macrostructures recognised in the Murge area consist of WNW-ESE and WSW-ENE oriented gentle folds (Martinis, 1961; Valduga, 1965; Ciaranfi *et al.*, 1983, 1988; Ricchetti *et al.*, 1988) and N-S, NW-SE, WNW-ESE, NE-SW and E-W oriented extensional faults (Martinis, 1961; Valduga, 1965; Iannone and Pieri, 1982; Ciaranfi *et al.*, 1983; 1988; Ricchetti *et al.*, 1988; Tropeano *et al.*, 1994, 1997; Pieri *et al.*, 1997) (fig. 1b).

Gentle folds are interpreted as the effects of: 1) intraplate deformations related to Turonian and Eocene-Oligocene compressive phases of Alpine orogenic events (Ricchetti *et al.*, 1988; Mindszenty *et al.*, 1995); 2) foreland deformations related to Late Cenozoic compressive tectonic regime of the Apennines pushing forces (Festa, 1999). An important anticline structure, called 'Monte Acuto' anticline (Martinis, 1961), arranges the Cretaceous succession in the North-Eastern Murge, where the most ancient rocks of the Murge area crop out in the core (Luperto Sinni and Masse, 1984) (fig. 1b).

Faults in the Murge area are mainly considered as Pliocene and Pleistocene deformations (Auct.), but Cretaceous (Pieri and Laviano, 1989) and Miocene activities (Iannone and Pieri, 1982; Ciaranfi *et al.*, 1983; Funiciello *et al.*, 1991; Gambini and Tozzi, 1996) are not excluded. Recently (Festa, 1999; Festa *et al.*, 1999), NW-SE and E-W striking faults of the Murge area are considered as extensional faults active at least from the Upper Cretaceous.

The main regional fault deformation zones are represented by: the «Bradanic Valley fault» (Martinis, 1961), the «Fasano fault» (Campobasso and Olivieri, 1967), the «North-Salento Fault Zone» (Gambini and Tozzi, 1996), the «Ofanto line», the «Murge alte graben» and the «Murge basse graben» (Iannone and Pieri, 1982). The first four bound the Murge plateau from the adjacent morpho-structural depressions; the «Murge alte graben» and the «Murge basse graben» represent large-scale structures within the considered area (Auct.) (fig. 1b).

3. Pre-existing geophysical data

Despite the spatial correspondence between observed low energy seismicity and graben-like structures and despite also the tensional character that they both consistently show, it is not possible to establish a direct connection between the present seismicity and the surface tectonic structures because the former appears to have its source confined well inside the basement, whereas the latter likely affect only the sedimentary cover.

To draw further information on structural characteristics down to the depth of the earthquakes recorded, the geophysical data existing in this area have been re-examined. The geomagnetic field does not show evidence of particular structures in the Murgian area: this is not surprising considering that this area is characterised by a thick sedimentary cover. Some indications can be obtained about the basement. The magnetic basement shows a general weak descending trend from the Adriatic coast towards the west (Cassano *et al.*, 1986) which reflects the regional trend of the Apulian plate sinking under the Apennine orogenic belt. Its depth ranges from 12 to 14 km, with the minimum corresponding to a possible small structural high near the coast (fig. 2). The magnetic basement does not coincide with the geological basement,

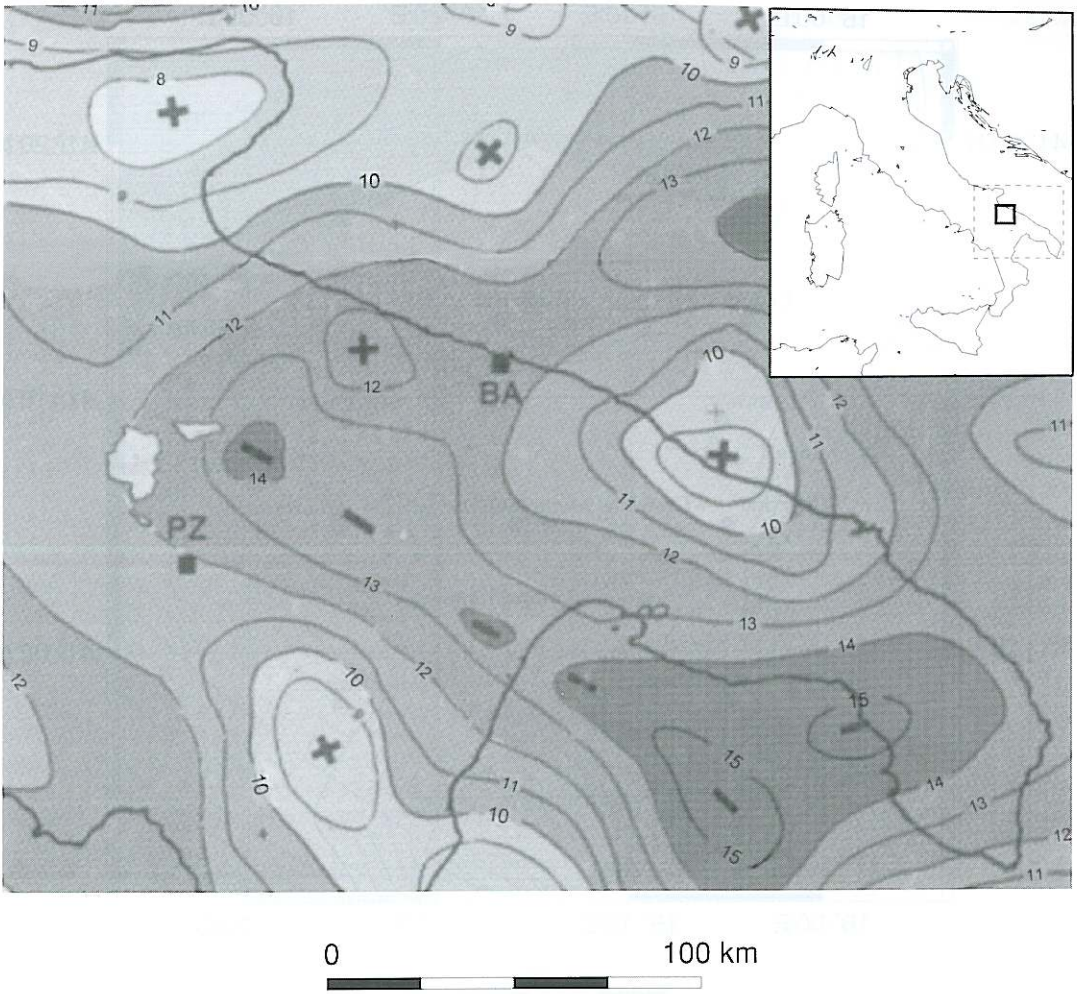

Fig. 2. Map of presumed magnetic-basement depth (contour spacing 1 km) in the area of the North-Western Murge (modified after Cassano *et al.*, 1986). In the top right corner frame, the dashed-line rectangle indicates the geographical location of the area covered by this map, whereas the thick-line square marks the area covered by the gravimetric maps of figs. 3, 4 and 5.

being a few kilometres deeper, but they probably have a similar trend (Morelli, 1997). However, the available magnetic data are not detailed enough to point out structures of size of few tens of kilometres.

More information can be derived from gravimetry. Like the magnetic field, the Bouguer anomalies (fig. 3) also show an evident descending trend from the coast towards the Bradanic Foredeep with an axial maximum along the coast and a SW-NE gradient slightly less than 1 mgal/km (Carrozzo *et al.*, 1986b). Such a trend is generally explained as an effect of the bending of the Apulian plate which causes a rise of the Mohorovic discontinuity (and of denser mantle materials) towards the Adriatic

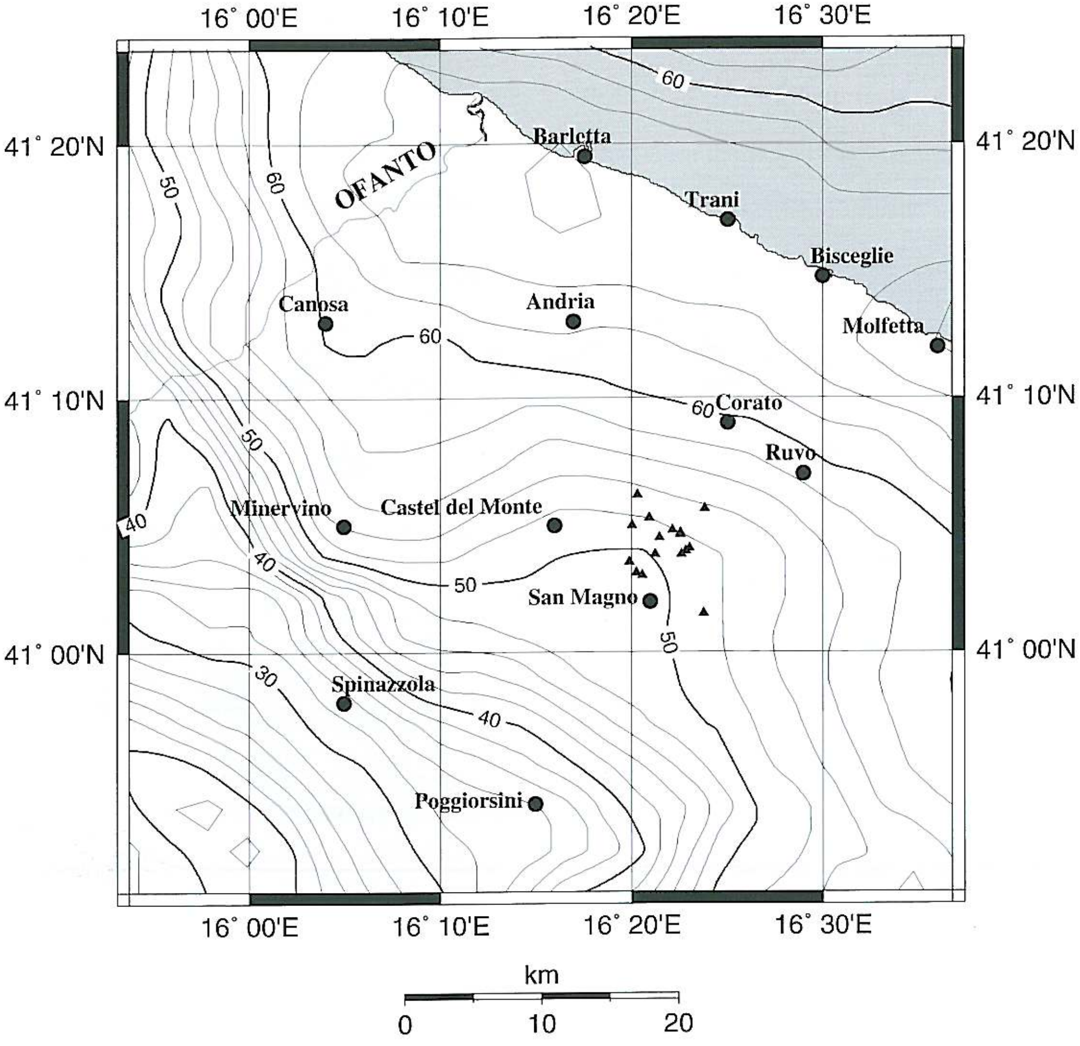

Fig. 3. Map of Bouguer anomalies in the area of North-Western Murge (data from Carrozzo *et al.*, 1986b; see fig. 2 for geographical location). Black triangles mark the location of the epicentres of the seismic sequence of February-March 1991. Contour spacing 2 mgal.

Sea (Ricchetti and Mongelli, 1980). This dominant character of the Bouguer field tends to make the presence of anomalies of minor wavelength superimposed on the regional trend less evident.

In order to disclose these anomalies, a filtering based on FFT was carried out on a gravimetric database consisting of a grid of 3 km spaced values. The cut-off wavelength of the filter was adjusted to 70 km: considering that the anomaly sources must have their top surface at a depth not less than 25-30% of wavelength size, this choice implies that the corresponding residuals are originated by bodies located down to the earthquake depth (~ 20 km). On the other hand, the regional field obtained for wavelengths

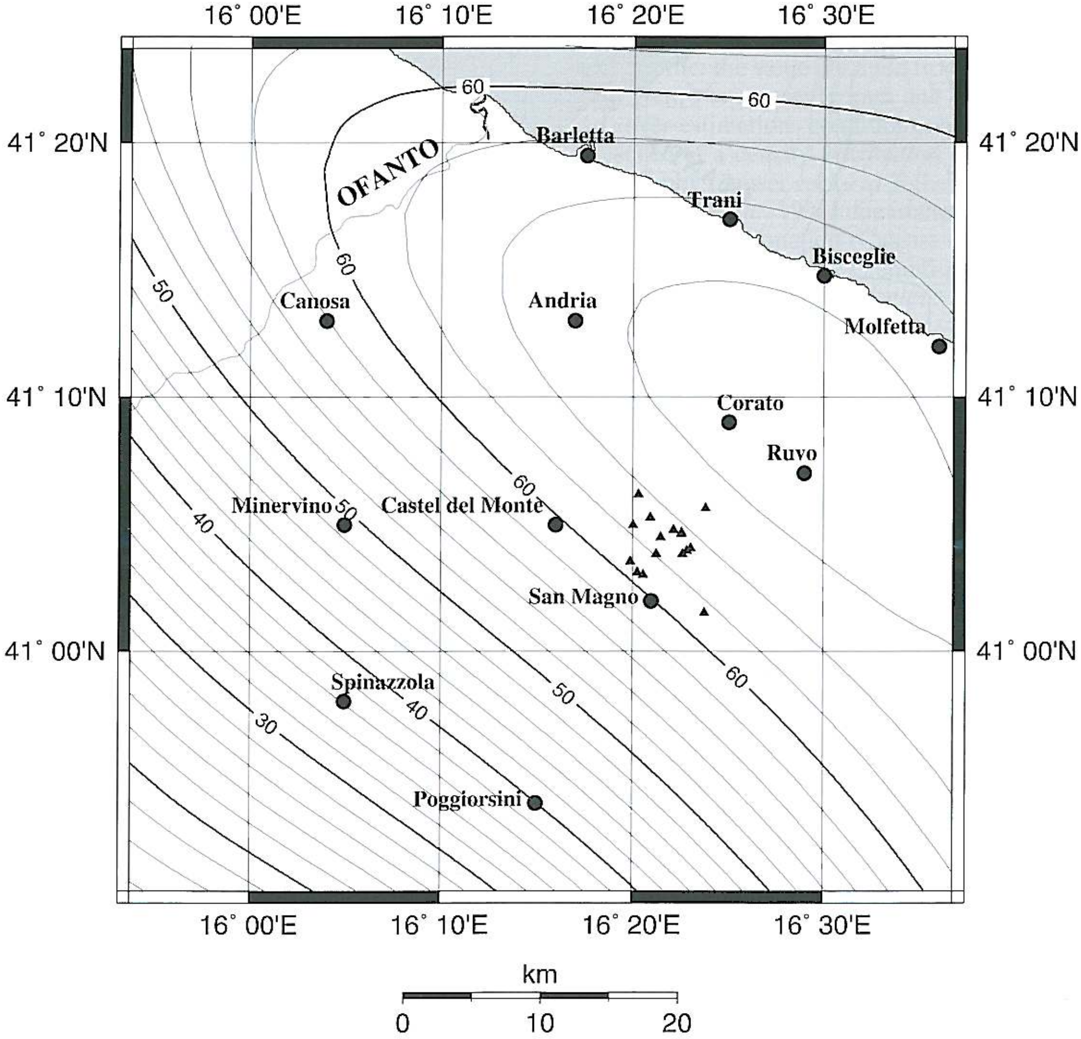

Fig. 4. Map of the regional field obtained from the Bouguer field removing wavelengths < 70 km. Black triangles mark the location of the epicentres of the seismic sequence of February-March 1991. Contour spacing 2 mgal.

$\lambda > 70$ km shows practically only the effect of the plate bending (fig. 4), with a decrease from the coast towards the Apennine chain, even though this effect is not necessarily due to the Moho deepening only, because any shallower interface between differently dense lithotypes, dipping parallel to the Moho, would contribute to determine this regional trend.

Figure 5 shows the residuals corresponding to $\lambda < 70$ km: an evident minimum of -12 mgal, slightly elongated in NW-SE direction, is located among the localities of Castel del Monte, Corato, Ruvo and San Magno and corresponds almost exactly to the area where the epicentres of the 1991 seismic sequence are distributed. This correspondence attracted our attention and led

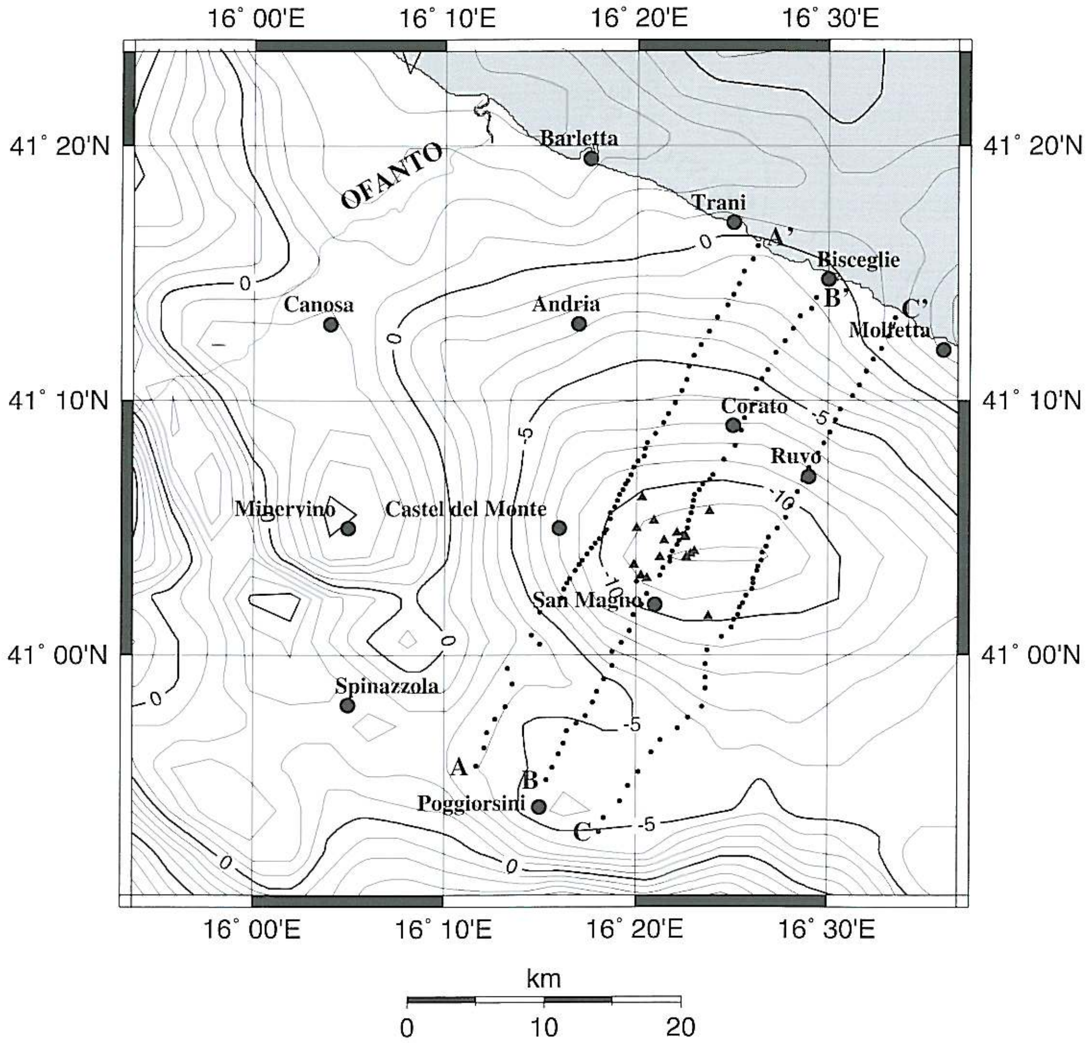

Fig. 5. Map of the residuals obtained from the Bouguer field removing the regional field of fig. 4. Black triangles mark the location of the epicentres of the seismic sequence of February-March 1991. Black dots mark the location of the new gravimetric measurements. Contour spacing 1 mgal.

us to investigate the anomaly source in more details.

A direct interpretation of the available gravimetric data can be biased by the density adopted in Bouguer and terrain correction. This value for the Gravity Map of Italy (Carrozzo *et al.*, 1986b) is 2.4 g/cm^3 and corresponds to an average value for all Italian regions. Previous studies (Canziani *et al.*, 1989; Del Gaudio *et al.*, 1998) showed that the density of the carbonate units of the Murgian plateau can be higher (2.5-2.6 g/cm^3), therefore, since it was not possible to recover the original field data of the gravity map, a new more detailed survey was carried out in the area of the observed anomalies.

4. Gravimetric survey

4.1. *Data*

The gravimetric survey consisted of 153 measurement stations distributed along three 40-45 km long parallel profiles (marked as AA′, BB′, CC′ in fig. 5) oriented in NNE-SSW direction and spaced by about 5 km. This distribution was chosen to obtain coverage of the area where 1991 seismic sequence was located, crossing the main tectonic structures of this area in an approximately normal direction. The measurements were carried out with a Lacoste & Romberg D 40 whose scale factor was calibrated on an absolute gravity base. This instrument was employed at a low level of sensitivity, considering that a measurement precision of 0.1 mgal was sufficient for the purpose of the survey. Tide effects were corrected by means of a computation code and the instrumental drift was checked by repeated measurements in two base stations at intervals of 3-4 h and its rate was 0.03 mgal/h on average. The gravity values were obtained connecting the base stations to the absolute gravity station of Foggia, which belongs to the Italian Zero Order Gravity Net (Berrino *et al.*, 1995). In data processing, the effect of earth curvature was taken into account using the LaFehr formula (LaFehr, 1991) for the «Bullard B» correction. Terrain correction was computed according to a procedure (Del Gaudio and Ruina, 1995) consisting in the generation of a numerical model of topography, assimilated to a set of rectangular prismatic elements, and in calculating their effect on measurement stations; the correction was extended up to a maximum distance of 50 km, coherently with the limit adopted for the Gravity Map of Italy (*cf.* Carrozzo *et al.*, 1986a).

Estimates of the rock average density to be employed in Bouguer and terrain correction were obtained from the gravimetric data themselves by means of modified versions of classical Nettleton and Parasnis methods described in Canziani *et al.* (1989). The values obtained with the two methods were 2.61 and 2.60 ± 0.05 g/cm^3, respectively, but from a more detailed analysis of these results, they appeared biased by the data of the CC′ profile. Indeed the values obtained considering separately the data of each profile were all around 2.5 g/cm^3, except for the CC′ profile: the value obtained from this profile (2.8 g/cm^3) is unusually high and could reflect an «over-estimation» condition connected to the presence of a density distribution correlated to topography (denser rocks at higher altitude: *cf.* Del Gaudio *et al.*, 1998) due to the outcrop of a more massive formation (Calcare di Altamura) at the top of plateau (*cf.* Ciaranfi *et al.*, 1988). For this reason the value 2.5 g/cm^3 was adopted as average value for corrections.

Figure 6 shows the curves of the Bouguer anomalies obtained along the three profiles compared with the profile of topographic elevations. The progressive distances along each profile are measured starting from an axis normal to the central profile (BB′) and passing through its westernmost station. The three profiles show a similar trend characterised by a general gradient of 0.6-0.7 mgal/km ascending towards the Adriatic sea and an undulation superimposed on it, due to the sequence of a local maximum followed by a minimum. The local maximum corresponds to the top of the plateau (the so-called «Murge Alte»), whereas the minimum extends along the mid-high part of the plateau flank descending towards the Adriatic Sea. The minimum shows an increasing width towards the most south-eastern profile and includes the area crossed by the two aforementioned narrow grabens («Murge Alte» and «Murge Basse» grabens of Iannone and Pieri, 1982). Minor details of the gravimetric curves seem to be correlated to faults recognised in the field: this correspondence is probably due to lateral density contrast associated with different intensity of rock fracturation, because these faults, cutting the thick carbonate sequence, do not cause lateral contact between different lithologies.

The local maximum does not necessarily imply the presence of a local «mass excess» but could be just due to a zone of «normal» density (*i.e.* 2.5 g/cm^3) included between two negative anomalies: the first, at the south-western end of the profiles, could be generated by the effect of the lateral contact between the border of the Apulian plate and the thick sequence of incoherent sediments filling the Bradanic trough; the second anomaly, located well inside the

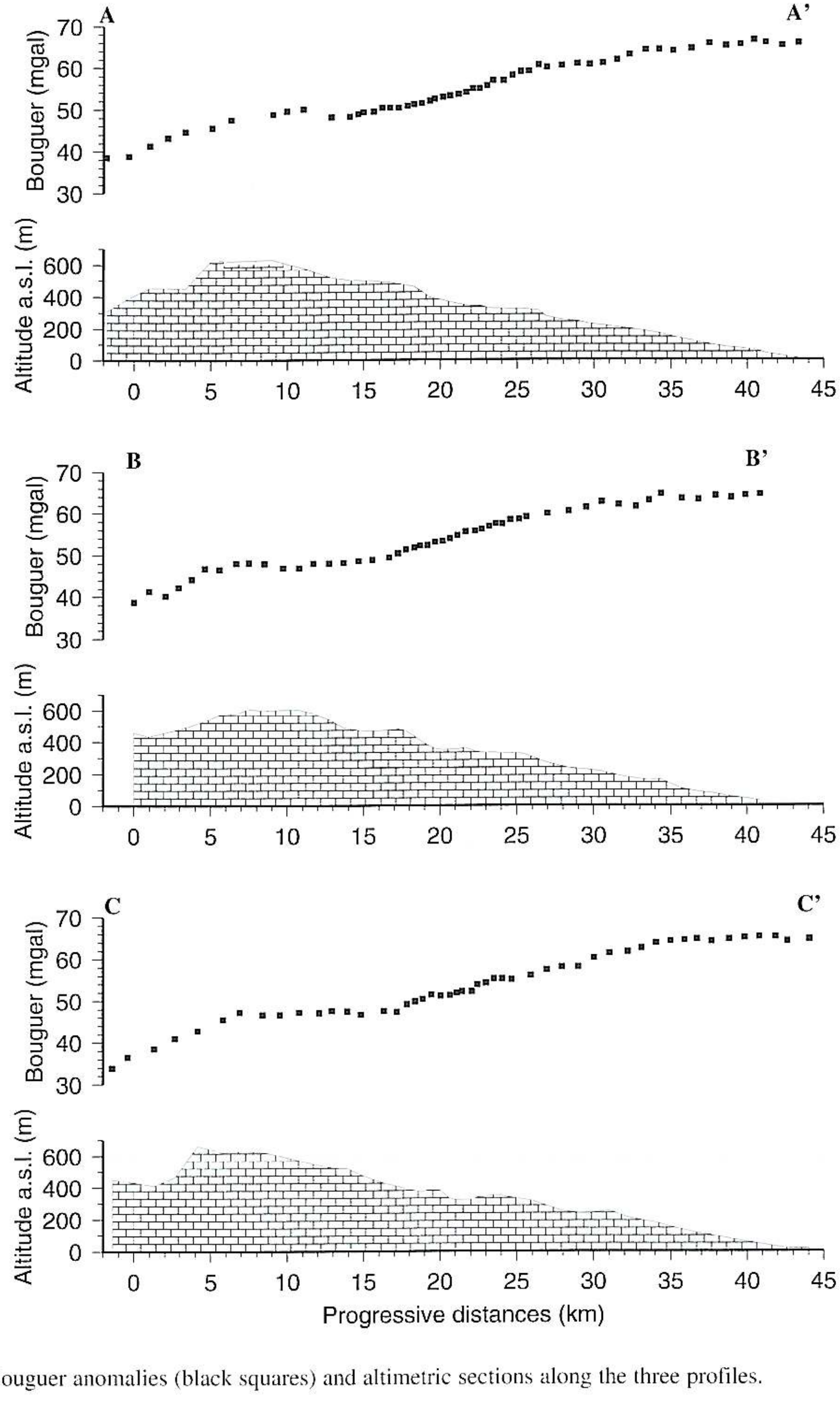

Fig. 6. Bouguer anomalies (black squares) and altimetric sections along the three profiles.

Apulian plateau, has an uncertain origin because no tectonic structure recognised from surface geology has a size compatible with the wavelength of the gravimetric minimum. On the basis of the previous considerations, defining the limit of the negative anomaly in correspondence of the relative maximum, a total extension of up to 20-30 km results for the anomalous zone.

4.2. *Interpretation: preliminary hypotheses*

The local negative anomaly is characterised by a wavelength that implies a location of its source between the top of the basement (probably at a depth of 7-8 km) and the surface. On the basis of previous works (Iannone and Pieri, 1982; Pieri *et al.*, 1997; Tropeano *et al.*, 1997; Festa, 1999; Festa *et al.*, 1999), different hypotheses were examined about the structure that may generate it:

a) A surface mass deficit due to a wide intensely karstified area.

b) A lateral heterogeneity involving the evaporitic formation.

c) An inflexion of the crystalline basement.

The first hypothesis is justified considering that, in the inner part of the Murgian plateau, the karstic process may involve a larger thickness of the carbonate formations on account of the combination of higher elevations and a lower karstic base level (which deepens from the coast towards the inland); this phenomenon can have been further enhanced during the Pleistocene by the eustatic variations of the sea level (which during the glacial periods lowered down to over 100 m with respect to the present). However this hypothesis would imply a certain correlation between Bouguer anomaly and topography, that is not observed: indeed the gravimetric minimum does not correspond to the plateau top where, on the contrary, a relative maximum is present. It could be observed that a differentiation in the development of karstification could be due to a tectonic control (presence of a denser net of faults and fractures), but a previous study (Del Gaudio *et al.*, 1998) showed that in the area of Castel del Monte, which is well inside the negative anomaly zone, the measurement of the bulk density of the calcareous formations resulted in a value of 2.6 g/cm^3, *i.e.* higher than the mean density obtained for the whole profile AA′ passing across the same zone. This implies that, at least near the surface, the formations in the area of the gravimetric minimum do not appear more fractured or karstified. Furthermore, the results of electrical soundings carried out by other authors along a profile marginally crossing the same region (Loddo *et al.*, 1990) does not show a shallow resistivity significant lateral variation correlated with the gravimetric minimum, and does not support the hypothesis that this part of the Murgian plateau is characterised by a significant differentiation in fault and fracture density or in karst development.

The hypothesis of an effect of the evaporites was formulated considering that bore-holes drilled in different parts of the Apulian region (included the North-Western Murge) disclosed 1 km thick evaporitic deposits under the carbonatic series. Thus, a lateral contact between carbonatic and evaporitic rocks, as suggested by Festa (1999) and Festa *et al.* (1999), could cause a gravimetric anomaly. Some tentative models showed that, considering the local depth of the evaporites (about 5 km, according to the stratigraphy derived from the «Puglia 1» borehole: Ciaranfi *et al.*, 1988; Ricchetti *et al.*, 1988), the negative anomaly observed can be reproduced only admitting a remarkable density contrast (at least -0.5 g/cm^3), a sub-vertical lateral boundary and a remarkable vertical size of the lateral contrast (at least 1 km). These conditions imply a large vertical dislocation of the evaporitic series caused by some important tectonic structure or by diapirism. However, the evaporitic series consist of gypsum, anhydrites and dolomites, so its bulk density cannot be much lower than carbonatic rocks and not deformable enough to support diapiric phenomena. On the other hand, even though evidence exists of an important tectonic structure dislocating it vertically by one kilometre or more, this must affect also the crystalline basement (which is probably only 1-2 km below the evaporites) (Festa, 1999; Festa *et al.*, 1999): therefore there is no need to attribute to evaporites the origin of the whole gravimetric anomaly and its possible contribution can be taken into account in a model based on hypothesis (c).

4.3. *Interpretation: modelling*

The hypothesis of an inflexion of the crystalline basement, suggested by Festa (1999) and Festa *et al.* (1999), is particularly attractive. In fact, it implies the presence of some ancient tectonic structure buried under the sedimentary cover which would potentially represent a «weakness» element along which the regional stress could be occasionally released (Festa, 1999) through seismic activity like that observed in 1991 (Del Gaudio *et al.*, 1996; Tropeano *et al.*, 1997).

To verify whether the gravimetric anomaly detected can be attributed to a similar structure, a quantitative modelling of the anomaly was undertaken. This modelling was developed in 3D by generating numerical representation of the crustal lateral heterogeneities with a digitisation step of 1 km. In order to minimise the border effect in the computation of the theoretical gravimetric anomalies, the model was extended beyond the limit of the survey area by 50 km in the profile direction and by 30 km in the transversal direction. Furthermore, each crustal structure was modelled in terms of lateral density variation strictly confined between the minimum and the maximum depth reached by the separation interface. To avoid the distortion generated by filtering techniques, the modelling was applied to the whole Bouguer field without any preliminary removal of a regional field. At the scale extent of the gravimetric profiles, the regional field basically consists of the regional gradient caused by the variation of the Moho depth and, possibly, by similar trends of shallower interfaces: indeed, Corrado and Rapolla (1981), pointed out that in the Bouguer field of the Italian region anomalous wavelengths longer than 215 km are to be attributed to the Moho effect. Therefore, although an accurate modelling of the lower crust is far beyond the purposes of this work, a schematic representation of discontinuities located down to the Moho depth were introduced in the models only to reproduce the regional trend.

During the 60's and early 70's, Deep Seismic Soundings (DSS) showed that in the Apulian region the crust-mantle discontinuities is located between 30-32 km of depth (Giese and Morelli, 1975). This interpretation was also confirmed by subsequent studies (Calcagnile *et al.*, 1982; Locardi and Nicolich, 1988). A more detailed reconstruction of the Moho was based on the interpretation of the long wavelength components of the Bouguer anomalies (Morelli, 1975, Corrado and Rapolla, 1981): in these interpretations the Apulian Moho shows a depth increasing from 30 km along the coast to 35 km at the border with the Bradanic trough. However a 5 km deepening of the Moho across the Murgian plateau poses some difficulties: the analysis of the stratigraphy of the Murgian formations showed that near the coast the carbonate series was eroded by 1-2 km with respect to the top of Murgian plateau. Also considering the difference in elevation, it can be evaluated that the base of the carbonatic series deepens by not much more than 1 km from the coast to the plateau western border. Furthermore, data derived from differently located bore-holes (Ricchetti *et al.*, 1988; Ciaranfi *et al.*, 1988), indicate that the lower sedimentary formations (Triassic evaporites and Permo-Triassic terrigenous rocks) on the whole seems to have a relatively constant thickness of about 2-3 km throughout the Apulian carbonate platform, therefore a deepening of the Moho by 5 km across the Murge would imply a thickening of the lower crust of about 3 km that appears rather problematic to explain, considering that it would occur going towards the external margin of a relatively stable and poorly deformable continental crust. On the other hand, since the aforementioned studies had been carried out on quite a large scale, they had derived the estimated amount of the Moho deepening by simplified modelling attributing the whole regional gradient to the effect of the Moho. However, at a more detailed scale, it should be considered that other shallower discontinuities, like that between sedimentary cover and crystalline basement, dipping with a trend sub-parallel to the Moho, can also contribute to the regional trend so that the observed gravimetric gradient can be reproduced by models including a less steep Moho.

A possible contribution to the regional gradient could also derive from a «Conrad» discontinuity separating fragile and ductile parts of the crust. A «natural» location of such discontinuity would be at an approximate depth of 20 km, considering the hypocentral depth of Murgian earthquakes and indeed some indication about the presence of a «20 km» discontinuity was reported by the first interpretations of the DSS data (*cf.* Giese and Morelli, 1975). However subsequent studies showed that such a discontinuity is not necessary to data interpretation and more recent studies did not point out any evidence of a «Conrad» discontinuity along sections crossing the Apulian foreland (Scarascia *et al.*, 1994). Therefore, even though a modelling including a Conrad discontinuity was also attempted attributing density values of 3.2 g/cm^3 to the mantle, 3.0 g/cm^3 to the lower crust and 2.8 g/cm^3 to the crystalline basement, the final reference model for the regional field was based on a Moho whose depth increases from about 30 to 31 km along a section 40 km long, with a mantle-crust density contrast of 0.5 g/cm^3 (mantle 3.3 g/cm^3). This discontinuity accounts only for 40-50% of the regional trend, the rest deriving from the contribution of shallower interfaces located between the surface and the crystalline basement and dipping subparallel to the Moho.

In the preliminary models, the reproduction of the Bouguer field was attempted considering the following further structures indicated by Ciaranfi *et al.* (1988) and Ricchetti *et al.* (1988): 1) a surface layer of variable thickness (from 0 to 1500 m) depending on the amount of surface erosion (estimated from stratigraphic correlations), corresponding to the limestones of the Cretaceous carbonate series, with a density of 2.5 g/cm^3 (the same as the density adopted in terrain correction); 2) a 4 km thick layer corresponding to the Jurassic-Cretaceous dolomitic terms of the carbonate series, with an average density of 2.7 g/cm^3: it outcrops only along the «Monte Acuto anticline», near the Adriatic coast; 3) a layer having a constant thickness of 1 km and a density of 2.5 g/cm^3, corresponding to the evaporitic formation; 4) a layer having a constant thickness of 1 km and a density of 2.7 g/cm^3, corresponding to the Permo-Triassic terrigenous formation; 5) a discontinuity located at a depth of 6-7 km separating the base of the sedimentary cover from a crystalline basement having a density of 2.8 g/cm^3. These choices were based on the density model of Corrado and Rapolla (1981), which included a sedimentary sequence of 2.6 g/cm^3, a crystalline layer of 2.9 g/cm^3 and an upper mantle of 3.3 g/cm^3. Modifications to this model were introduced to take into account more details, like the differentiation between limestone and dolomia and the presence of the evaporitic-terrigenous formations below the carbonatic series, and also to make the model compatible with the geometrical constraints assumed, *i.e.* a general average gradient of all the interfaces corresponding to the thickness reduction of Cretaceous series so that all the discontinuities have a sub-parallel trend, as can be expected in an old mature crust: this is, for instance, the reason for the reduction of the density contrast between sedimentary cover and crystalline basement (0.1 against 0.3 g/cm^3 of the Corrado and Rapolla model), because, assuming for this interface such a descending trend towards the inland, a 0.2 g/cm^3 density contrast would cause a regional gradient 20% higher than that observed.

A trial was done to reproduce the local minimum observed along the three profiles by introducing an inflexion of the basement top surface in its general south-westwards dipping trend. However, after some attempts, it was evident that no geologically plausible geometry can be found to reproduce the observed anomaly with such a structure alone. Therefore a similar inflexion was also introduced in the shallower interfaces. Figure 7 shows a section of the final model obtained and the corresponding theoretical Bouguer anomalies. In this model, the inflexion of all the discontinuities (from the terrigenous rocks-basement to limestone-dolomia interfaces) causes a local deepening by a maximum amount of 600-800 m (slightly increasing from AA′ to CC′ profile) along a 10-15 km wide band transversal to the profiles and approximately including the «Murge Alte» and «Murge Basse» grabens of Iannone and Pieri (1982). These results are consistent with those obtained by Festa (1999) from geological observations.

At the south-westernmost end of the profile a model of the Bradanic trough sediments was introduced (density 2.2 g/cm^3), but it accounts for minor gravimetric curve details only. A slight

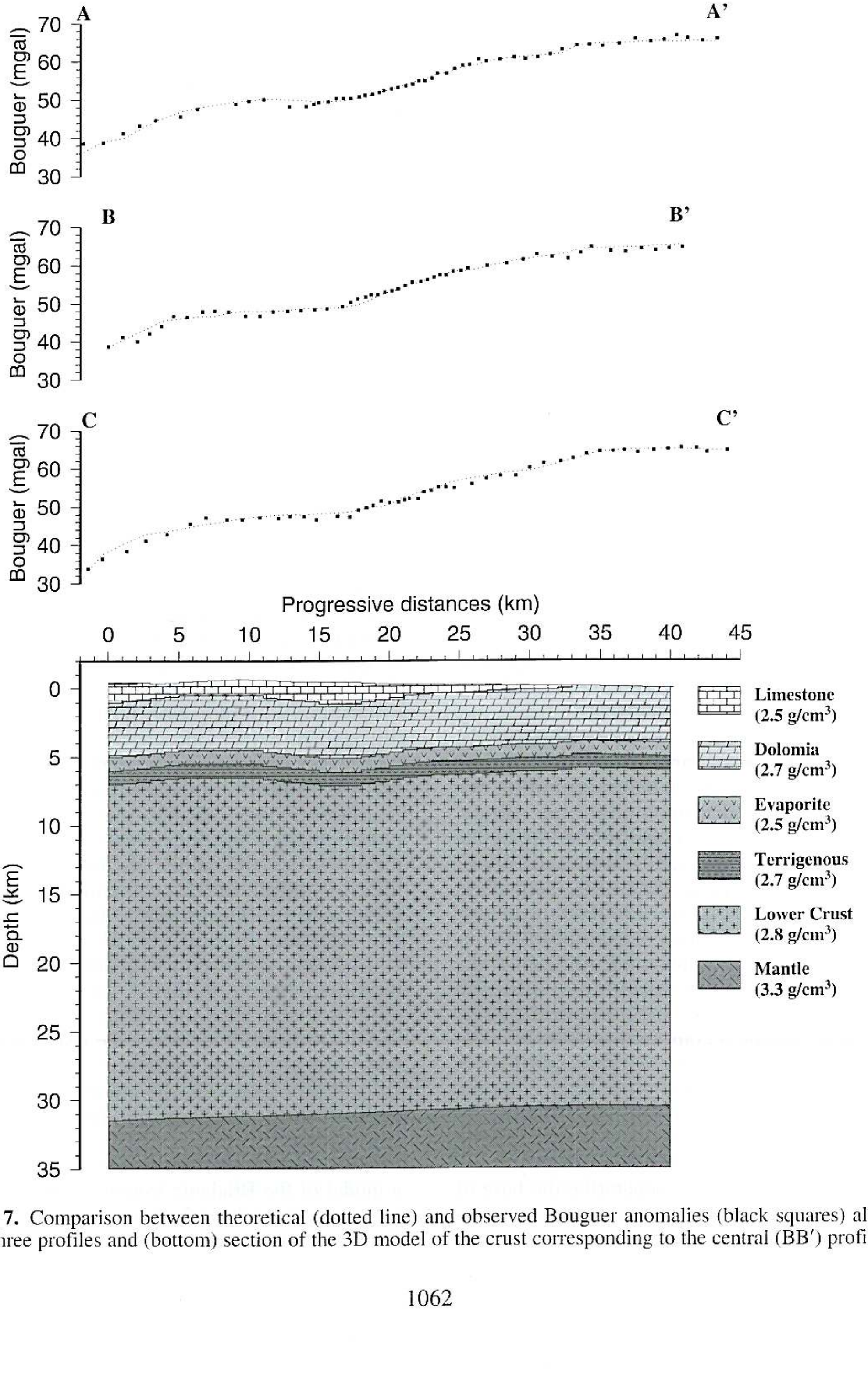

Fig. 7. Comparison between theoretical (dotted line) and observed Bouguer anomalies (black squares) along the three profiles and (bottom) section of the 3D model of the crust corresponding to the central (BB′) profile.

differentiation in dolomitic layer density was also introduced at the surface along the section BB′ (– 0.05 g/cm^3) to reproduce the slightly lower values of the Bouguer field observed at the end of the central profile with respect to the other profiles: this could correspond to a local accentuation of karstic phenomena which indeed have been observed in the area around Bisceglie.

Figure 8 shows the differences between experimental anomalies and the theoretical ones obtained for the final model. The rms is 0.8 mgal: this is indicative of a quite good agreement, considering that some larger discrepancies (up to about 2 mgal) appear to be associated with minor wavelengths corresponding to more local and surficial structures which obviously were not taken into account in modelling. Therefore an approximation of about 0.5 mgal can be assumed as representative of the accuracy level of model fitting to data: considering the sensitivity of the theoretical anomaly to model parameter variations, this implies that a variability within about 100 m can be admitted for the maximum amount of the supposed inflexion of interfaces modelled, maintaining the compatibility with the gravimetric observations.

5. Discussion and conclusions

Theoretically, some other models compatible with the observed data could be found. For

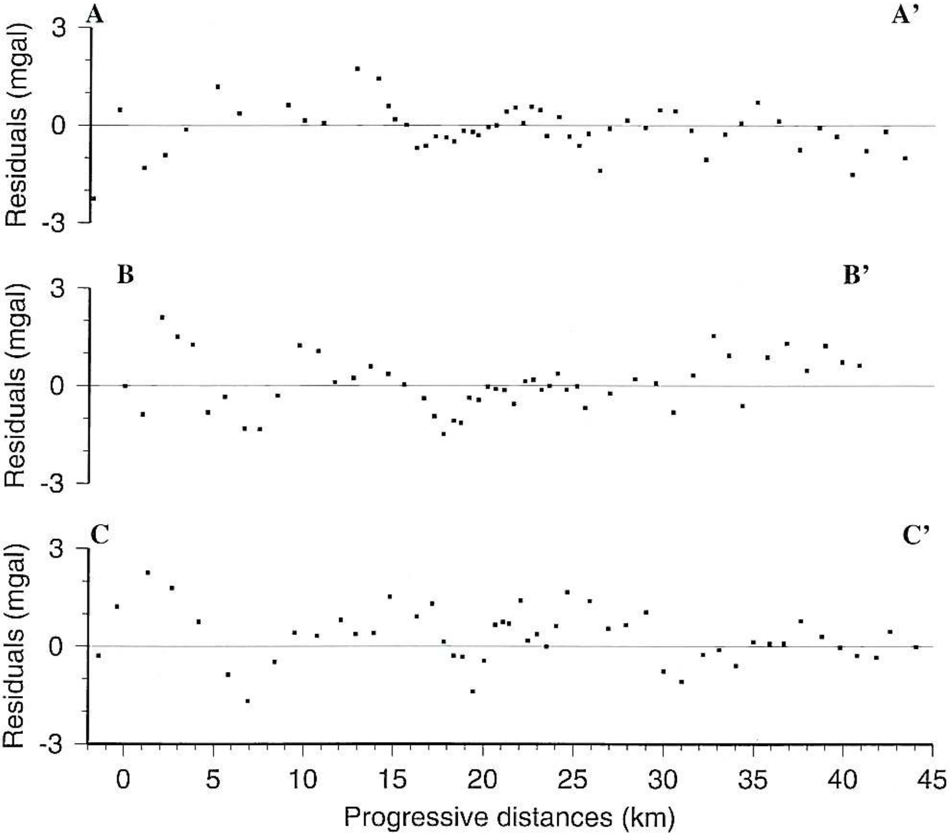

Fig. 8. Differences between theoretical and observed anomaly (in mgal) along the three profiles.

instance, it cannot be excluded that the negative anomaly is caused by a lateral density variation inside the sedimentary cover caused by some local peculiarity of the carbonate platform sedimentary process. However, in our interpretation of the gravimetric observations, preference was given to hypotheses capable of establishing some connection (possibly even only indirect) between the presence of the gravimetric anomaly, the low energy seismicity locally detected and observations on the surface tectonic structures, which are apparently consistent with the mechanism of the present seismic events. Indeed, all three hypotheses examined during the interpretative stage imply a role of tectonics in the origin of the anomalies observed, in agreement with previous geological interpretations: in hypothesis (a) tectonics may have controlled karst processes (*cf.* Iannone and Pieri, 1982); in hypothesis (b) it may have dislocated the evaporite formation which, in turn, may have possibly acted also as «tectonic lubricant» promoting the triggering of low energy events (*cf.* Pieri *et al.*, 1997; Tropeano *et al.*, 1997; Festa, 1999; Festa *et al.*, 1999); in hypothesis (c) the tectonic role is obvious (*cf.* Festa, 1999; Festa *et al.*, 1999).

As results from the gravimetric data analysis, among these three conjectures, the least questionable appeared to be the third one, even though clear conclusive evidence supporting it is not yet available. In a certain sense, this conjecture, referring to structures located between the surface and the crystalline basement, establishes a link between surface Plio-Pleistocenic tectonic structures, a possibly older and up to 7-8 km deep structure that causes the gravimetric anomalies and the present seismic activity located at a 15-20 km depth. Since geological, gravimetric and seismic features, even referred to the same location, differ for depth and time of their origin, a causative connection cannot be assumed between tectonic structures observed at the surface or inferred from gravimetry and present seismicity. However, these geological-geophysical features may reveal different elements and stages of a more general process.

A possible comprehensive explanation is that the gravimetric anomaly reflects a tensional tectonic structure generated during the sedimentation of the carbonate platform, whose existence has already been proved by Festa (1999). The quantitative modelling of the anomaly showed that a contribution from relative shallow discontinuities is necessary to reproduce it, but, on the other hand, no surficial geological evidence exists of a structure corresponding to the anomalous zone. This, would imply that this structure was generated during the Cretaceous (Festa, 1999), considering that it seems to affect the dolomitic terms of the carbonate sequence (ranging from Jurassic to lower Cretaceous), and then filled and masked by the subsequent sedimentation.

In more recent times, the buckling of the Apulian plate caused by the interaction between the Apennine orogenic belt and the Adriatic foreland is the origin of tensional stress affecting the upper crust (Ricchetti and Mongelli, 1980; Doglioni *et al.*, 1994) reflected by the long and narrow «graben-like» structures observed at the surface of the Murgian plateau (Pieri *et al.*, 1997). Tensional processes seem still in action and produce a seismicity of low energy, characterised by tensional mechanisms located in the crystalline basement (Del Gaudio *et al.*, 1996; Tropeano *et al.*, 1997; Pieri *et al.*, 1997). In this new context, the ancient tensional structure could represent a zone of relative weakness where strain is preferentially released (Festa, 1999).

At the present state, this conjectural picture still represents a working hypothesis which may be better defined through the collection of further structural data (geophysical and geological) and longer term observation of local seismicity.

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REFERENCES

Anderson, H. and J. Jackson (1987): Active tectonics of the Adriatic region, *Geophys. J. R. Astron. Soc.*, **91**, 937-983.

Argnani, A., P. Favali, F. Frugoni, M. Gasperini, M. Ligi, M. Marani, G. Mattietti and G. Mele (1993): Foreland deformational pattern in the Southern Adriatic Sea, *Ann. Geofis.*, **36** (2), 229-247.

Auroux, C., J. Mascle, R. Campredon, G. Mascle and S. Rossi (1985): Cadre géodinamique et évolution récente de la Dorsale Apulienne et de ses bourdures, *G. Geol.*, **47** (1-2), 101-127.

Berrino, G., I. Marson, L. Orlando, L. Balestri, R. Balia, A. Banni, L. Bonci, E. Bozzo, M.T. Carrozzo, G. Cerutti, C. Cesi, M. Ciminale, M. Crespi, V. d'Errico, P. De Maria, M. Di Filippo, F. Ferri, M. Loddo, G. Montrone, E. Pinna and A. Rossi (1995): Rete gravimetrica italiana di ordine zero. Stato di avanzamento, in *Atti 14° Convegno GNGTS, Roma 23-25 ottobre, 1995*, 453-460.

Calcagnile, G., F. D'Ingeo, P. Farrugia and G.F. Panza (1982): The lithosphere in the Central-Eastern Mediterranean area, *Pageoph*, **120**, 389-406.

Campobasso, V. and C. Olivieri (1967): Osservazioni preliminari sulla stratigrafia e sulla tettonica delle Murge fra Castellana Grotte (Ba) e Ceglie Messapico (Br), *Studi Geol. Morf. Reg. Pugliese*, **2**, pp. 20.

Canziani, R., V. Del Gaudio and G. Ruina (1989): Study of gravimetric data in the area of the Castellana Grottoes (Bari), *Boll. Geofis. Teor. Appl.*, **31**, 259-267.

Carrozzo, M.T., A. Chirenti, D. Luzio, C. Margiotta and T. Quarta (1986a): Carta gravimetrica d'Italia, in *Atti 5° Convegno GNGTS, Roma 17-19 novembre, 1986*, 913-918.

Carrozzo, M.T., D. Luzio, C. Margiotta and T. Quarta (1986b): Gravity map of Italy, in *Structural Model of Italy and Gravity Map*, Progetto Finalizzato Geodinamica, CNR, Publication No. 114 (3.).

Casnedi, R. (1988): La Fossa bradanica: origine, sedimentazione e migrazione, *Mem. Soc. Geol. It.*, **41**, 439-448.

Cassano, E., R. Fichera and F. Arisi Rota (1986): Rilievo aeromagnetico d'Italia. Alcuni risultati interpretativi, in *Atti 5° Convegno GNGTS, Roma 17-19 novembre, 1986*, 939-962.

Channel, J.E.T., B. D'Argenio and F. Horvath (1979): Adria, the African promontory, in *«Mesozoic Mediterranean Palaeogeography», Earth Sci. Rev.*, **15**, 213-293.

Ciaranfi, N., A. Cinque, S. Lambiase, P. Pieri, L. Rapisardi, G. Ricchetti, I. Sgrosso and L. Tortorici (1981): Proposta di zonazione sismotettonica dell'Italia meridionale, *Rend. Soc. Geol. It.*, **4**, 493-496.

Ciaranfi, N., M. Ghisetti, M. Guida, G. Iaccarino, S. Lambiase, P. Pieri, L. Rapisardi, G. Ricchetti, M. Torre, L. Tortorici and L. Vezzani (1983): *Carta Neotettonica dell'Italia Meridionale*, Progetto Finalizzato Geodinamica, CNR, Publication No. 515, pp. 62.

Ciaranfi, N.P. Pieri and G. Ricchetti (1988): Note alla carta geologica delle Murge e del Salento (Puglia centromeridionale), *Mem. Soc. Geol. It.*, **41**, 449-460.

Corrado, G. and A. Rapolla (1981): The gravity field of Italy: analysis of its spectral composition and delineation of a tridimensional crustal model for Central-Southern Italy, *Boll. Geofis. Teor. Appl.*, **23** (89), 17-29.

Crescenti, U. (1975): Sul substrato pre-pliocenico dell'Avanfossa appenninica dalle Marche allo Ionio, *Boll. Soc. Geol. It.*, **94**, 583-634.

Crescenti, U. and L. Vighi (1969): Caratteristiche, genesi e stratigrafia dei depositi bauxitici cretacei del Gargano e delle Murge; cenni sulle argille con pisoliti del Salento (Puglie), *Boll. Soc. Geol. It.*, **83**, 285-338.

D'Argenio, B., T. Pescatore and P. Scandone (1973): Schema geologico dell'Appennino meridionale (Campania e Lucania), *Accad. Naz. Lincei*, **182,** 49-72.

Del Gaudio, V. and G. Ruina (1995): An automatic procedure for numerical modelling of topography applied to terrain correction in gravimetry, *Boll. Geofis. Teor. Appl.*, **37** (146), 119-129.

Del Gaudio, V., V. Iurilli, P. Pierri, G. Ruina, G. Calcagnile, R. Canziani, M. Moretti, P. Pieri and M. Tropeano (1996): Sismicità di bassa energia e caratteristiche strutturali delle Murge nord-occidentali (Puglia - Italia meridionale), in *Atti 15° Convegno GNGTS, Roma 11-13 novembre, 1996*, 325-330.

Del Gaudio, V., C. Magrì, G. Ruina and R. Canziani (1998): Influence of systematic errors in density determination from gravimetric data, *Boll. Geofis. Teor. Appl.*, **39** (2), 99-111.

De Vivo, B., D. Dietrich, I. Guerra, G. Iannaccone, G. Luongo, P. Scandone, R. Scarpa and E. Turco (1979): *Carta Sismotettonica Preliminare dell'Appennino Meridionale*, Progetto Finalizzato Geodinamica, CNR, Publication No. 166, pp. 64.

Doglioni, C., F. Mongelli and P. Pieri (1994): The Puglia (SE Italy) uplift: an anomaly in the foreland of the Apenninic subduction due to buckling of a thick continental lithosphere, *Tectonics*, **13** (5), 1309-1321.

Festa, V. (1999): L'Avampaese apulo nel quadro dell'evoluzione dell'Appennino meridionale: la deformazione della Piattaforma Carbonatica Apula nel settore murgiano (Puglia, Italia meridionale), *Tesi di Dottorato*, Università degli Studi di Bari, pp. 122.

Festa, V., P. Pieri and M. Tropeano (1999): Structural heritage of a Mesozoic rifting stage in the Puglia region (Southern Italy), in *Non-Volcanic Rifting Margins: a Comparison of Evidence from Land and Sea, London, 16-17 September 1999*, Geological Society of London, abstract book, p. 18.

Funiciello, R., P. Montone, M. Parotto, F. Salvini and M. Tozzi (1991): Geodynamical evolution of an intra-orogenic foreland: the Apulia case history (Italy), *Boll. Soc. Geol. It.*, **110**, 419-425.

Gambini, R. and M. Tozzi (1996): Tertiary geodynamic evolution of Southern Adria microplate, *Terranova*, **8** (6), 593-602.

Giese, P. and C. Morelli (1975): Crustal structure in Italy, in *Structural Model of Italy, Quad. Ric. Sci.*, CNR., **90**, 453-489.

IANNONE, A. and P. PIERI (1982): Caratteri neotettonici delle Murge, *Geol. Appl. Idrogeol.*, **18** (2), 147-159.

LA FEHR, T.R. (1991): An exact solution for the gravity curvature (Bullard B) correction, *Geophysics*, **56**, 1179-1184.

LAVIANO, A., M. GALLO MARESCA and M. TROPEANO (1998): Stratigraphic organisation of rudist biogenic beds in the Upper Cenomanian successions of the Western Murge (Apulia, Southern Italy), *Geobios, Mém.*, **22**, 159-168.

LOCARDI, E. and R. NICOLICH (1988): Geodinamica del Tirreno e dell'Appennino centro-meridionale: la nuova carta della Moho, *Mem. Soc. Geol. It.*, **41**, 121-140.

LODDO, M., R. QUARTO, D. SCHIAVONE, A. ZAJA and A. GALGARO (1990): Prospezione magnetotellurica lungo un profilo delle Murge nord-occidentali, in *Atti 9° Convegno GNGTS, Roma 13-15 novembre, 1990*, vol. II, 167-174.

LUPERTO SINNI, E. (1996): Sintesi delle conoscenze biostratigrafiche del Cretaceo del Gargano e delle Murge, *Mem. Soc. Geol. It.*, **51** (2), 995-996.

LUPERTO SINNI, E. and J. BORGOMANO (1989): Le Creétacé supérieur des Murges sud-orientales (Italie méridionale): stratigraphie et évolution des paléoenvironnements, *Riv. Ital. Paleont. Stratigr.*, **95** (2), 95-136.

LUPERTO SINNI, E. and J.P. MASSE (1984): Données nouvelles sur la micropaléontologie et la stratigraphie de la partie basale du «Calcare di Bari» (Crétacé inférieur) dans la région des Murges (Italie Méridionale), *Riv. Ital. Paleont. Stratigr.*, **90** (3), 331-374.

LUPERTO SINNI, E. and A. REINA (1996): Nuovi dati stratigrafici sulla discontinuità mesocretacea delle Murge (Puglia, Italia meridionale), *Mem. Soc. Geol. It.*, **51**, 1179-1188.

MARTINIS, B. (1961): Sulla tettonica delle Murge nord-occidentali, *Rend. Cl. Sci. Fis., Mat. Nat., Accad. Naz. Lincei.*, **8/31** (5), 299-305.

MINDSZENTY, A., B. D'ARGENIO and G. AIELLO (1995): Lithospheric bulges recorded by regional unconformities. The case of Mesozoic-Tertiary Apulia, *Tectonophysics*, **252**, 137-161.

MORELLI, C. (1975): Gravity map of Italy, in *«Structural Model of Italy», Quad. Ric. Sci.*, Roma, CNR, **90**, 427-447.

MORELLI, C. (1997): Recent deeper geophysical results better accounts for the tectonics in the Italian area, *Ann. Geofis.*, **40** (5), 1345-1358.

MORETTI, M. and M. TROPEANO (1996): Strutture sedimentarie deformative (sismiti) nei depositi tirreniani di Bari, *Mem. Soc. Geol. It.*, **51**, 485-500.

MORETTI, M., P. PIERI, M. TROPEANO and M. WALSH (1995): Tyrrhenian seismites in Bari area (Murge-Apulian Foreland), in *Atti dei Convegni Lincei: Terremoti in Italia, Previsione e Prevenzione dei Danni*, **122**, 211-216.

PIERI, P. and A. LAVIANO (1989): Tettonica e sedimentazione nei depositi senoniani delle Murge sud-orientali (Ostuni), *Boll. Soc. Geol. It.*, **108**, 351-356.

PIERI, P., L. SABATO and M. TROPEANO (1996): Significato geodinamico dei caratteri deposizionali e strutturali della Fossa bradanica nel Pleistocene, *Mem. Soc. Geol. It.*, **51**, 501-515.

PIERI, P., V. FESTA, M. MORETTI and M. TROPEANO (1997): Quaternary tectonic activity of the Murge area (Apulian foreland - Southern Italy), *Ann. Geofis.*, **40** (5), 1395-1404.

RICCHETTI, G. and F. MONGELLI (1980): Flessione e campo gravimetrico della micropiastra apula, *Boll. Soc. Geol. It.*, **99**, 431-436.

RICCHETTI, G., N. CIARANFI, E. LUPERTO SINNI, F. MONGELLI and P. PIERI (1988): Geodinamica ed evoluzione sedimentaria e tettonica dell'Avampaese apulo, *Mem. Soc. Geol. It.*, **41**, 57-82.

ROYDEN, L., E. PATACCA and P. SCANDONE (1987): Segmentation and configuration of the subducted lithosphere in Italy: an important control on thrust belt and foredeep basin evolution, *Geology*, **15**, 714-717.

SCARASCIA, A., A. LOZEJ and R. CASSINIS (1994): Crustal structures of the Ligurian, Tyrrhenian and Ionian seas and adjacent onshore areas interpreted from wide-angle seismic profiles, *Boll. Geofis. Teor. Appl.*, **36** (141-144), 5-21.

TROPEANO, M., M. MARINO and P. PIERI (1994): Evidenze di tettonica distensiva plio-pleistocenica al margine orientale della Fossa bradanica: l'Horst di Zagarella, *Il Quaternario, Ital. J. Quat. Sci.*, **7** (2), 597-606.

TROPEANO, M., P. PIERI, M. MORETTI, V. FESTA, G. CALCAGNILE, V. DEL GAUDIO and P. PIERRI (1997): Tettonica quaternaria ed elementi di sismotettonica nell'area delle Murge (Avampaese apulo), *Il Quaternario, Ital. J. Quat. Sci*, **10** (2), 543-548.

VALDUGA, A. (1965): Contributo alla conoscenza delle Murge baresi, *Studi Geol. Morfol. Reg. Pugliese*, **1**, pp. 15.

WESSEL, P. and W.H.F. SMITH (1998): New, improved version of Generic Mapping Tools released, *Eos, Trans. Am. Geophys. Un.*, **79** (47), pp. 579.

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