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Gravity study of the Norcia intermountain basin (central Italy)

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ABSTRACT We present the results of a gravity investigation conducted in the Norcia Intermountain Basin (central Italy) in order to obtain a subsurface picture of its structural setting and to estimate the thickness of the Quaternary infill sediments. Our survey resulted in 210 measurements, placed evenly in the whole Norcia Plain. We produced gravity anomaly maps that show the Quaternary thickness spatial distribution within the basin and identify buried faults affecting the bedrock in the northern basin sector. 2.5D models along close spaced profiles were used to construct a 3D density model and a map of the bedrock top surface elevation. Our results suggest that the northern sector of the Norcia Intermountain Basin has been affected by a strong tectonic activity with respect to the southern sector where the top of the bedrock is eroded and buried by a thin layer of alluvial gravels.

Key words: gravity survey, bedrock detection, intermountain basin, Quaternary infill, potential field research, Norcia, central Italy.

1. Introduction

Gravity prospecting involves the measure of the Earth vertical gravitational field variations with the aim of locating local masses of higher or lower density through the study of the observed gravity anomalies. The gravity method can be very effective in investigating the geo-structural setting of intermountain basins (Ciccolella *et al*., 1995; Di Filippo and Miccadei, 1997; Blumetti *et al*., 2002; Cesi *et al*., 2010; Di Filippo and Di Nezza, 2010a, 2010b, 2010c; Di Nezza *et al*. 2010; Chiarini *et al*., 2014; Skrame *et al*., 2014a, 2014b) where a significant density contrast usually exists between the basin sediments filling and the bedrock. In central Apennines, this type of indirect investigation can contribute to clarify the relationship between outcropping normal faults and the morphostructural evolution of the intermountain basins during the Pliocene and Quaternary. In this work we present the results of a detailed gravity survey that was performed in the Norcia Intermountain Basin (hereinafter NIB) with the aim of investigating its deep geometry and to evaluate the thickness of the infilling deposits. This is an area of high and frequent historical seismicity and has been affected by the 2016 seismic sequence [M_W 6.6: Chiaraluce *et al*. (2017)]. Our findings of gravity discontinuities, caused by abrupt lateral density change, are particularly important as they could reveal the existence of buried faults that may have played a significant role in the structural evolution of the basin.

2. Geological setting

The Apennine chain has developed since the Miocene as the result of interactions between the African and European plates and the Adria Microplate. Since the Pliocene, and during the entire Quaternary, the chain was affected by extensional tectonics, contemporary to its significant uplift (e.g. Cavinato *et al.*, 1992; Doglioni, 1995; Meletti *et al.*, 1995; D'Agostino *et al.*, 2001a, 2001b; Galadini *et al.*, 2003). This extensional deformation occurred along NW-SE trending normal faults, and along structures that re-used fault planes inherited from the previous compressive phase (Cavinato *et al.*, 1994). Some studies on the recent tectonics of the central Apennines have indicated that the active normal faults are distributed along two parallel sets that are roughly trending NW-SE and along a NNE-SSW to N-S trend (e.g. Barchi *et al.*, 1998, 2000; Galadini and Galli, 2000). In the central Apennines this extensional tectonics has resulted in the formation of several intermountain basins (e.g. Fucino, Sulmona, L'Aquila, Middle Aterno, Cascina, Colfiorito, Rieti, Leonessa, Montereale, and Norcia basins) that have been filled by continental deposits of Plio-Quaternary age (e.g. Bosi and Bertini, 1970; Giraudi, 1988; Cavinato and De Celles, 1999; Bosi *et al.*, 2003; Centamore *et al.*, 2003; Giaccio *et al.*, 2012, 2017). The NIB, geographically named "Piana di Santa Scolastica", has a rectangular shape (10 km in length and 3.5 km in width) and is located in the axial zone of the Apennine chain. The eastern edge of the basin consists in a high relief mountain range (mounts Patino, Vetica, and Ventosola), separating the NIB from the Piano Grande di Castelluccio di Norcia basin, which feed an extended system of interdigitated alluvial fans. The western edge of the basin is bounded by lower elevation mounts and hills (Colle Croce, Colle dell'Acera, Mount Cotica) that separate the NIB from the Cascia Plain. The Norcia basin is partially separated in two sectors by the Poggio Valaccone hill. Minor rivers are present: the Sordo in the northernmost area and La Pescia in the central-southern area.

The NIB is infilled by Quaternary fluvial and lacustrine deposits covered by coarse deposits belonging to interdigitated alluvial fans of the bordering mountains (Blumetti *et al.*, 1990), whereas the geological bedrock units are represented by pelagic limestones and marls of Jurassic to Miocene age (Coltorti and Farabollini, 1995; Pierantoni *et al.*, 2013; Regione Umbria, 2018). Lacustrine and marsh deposits of Early-Late Pleistocene outcrop in the Norcia outskirts and are also found in a few shallow boreholes (Blumetti and Dramis, 1992; Galli *et al.*, 2018; Regione Umbria, 2018); no borehole reached the base of these deposits or the underlying carbonate bedrock. Since at least the Early Pleistocene, the Norcia normal fault system controlled the evolution of the NIB along the eastern border. It is a 31 km long segmented system extending from Preci to the north to Cittareale to the south, striking NNW-SSE and dipping WSW. Synthetic and antithetic splays of the Norcia fault system, outcropping east of the town, have displaced the distal part of the Quaternary Patino alluvial fan (Blumetti and Dramis, 1992; Rasse, 1995; Borre *et al.*, 2003; Fubelli, 2004), testifying also the post last glacial maximum and the historical activity of the fault (Galli *et al.,* 2015, 2018). The northern and western margins of NIB are also reported to be limited respectively by E-W and NNW-SSE normal faults (e.g. Blumetti and Dramis, 1992; Cello *et al.,* 1998; Borre *et al.*, 2003; Fubelli, 2004).

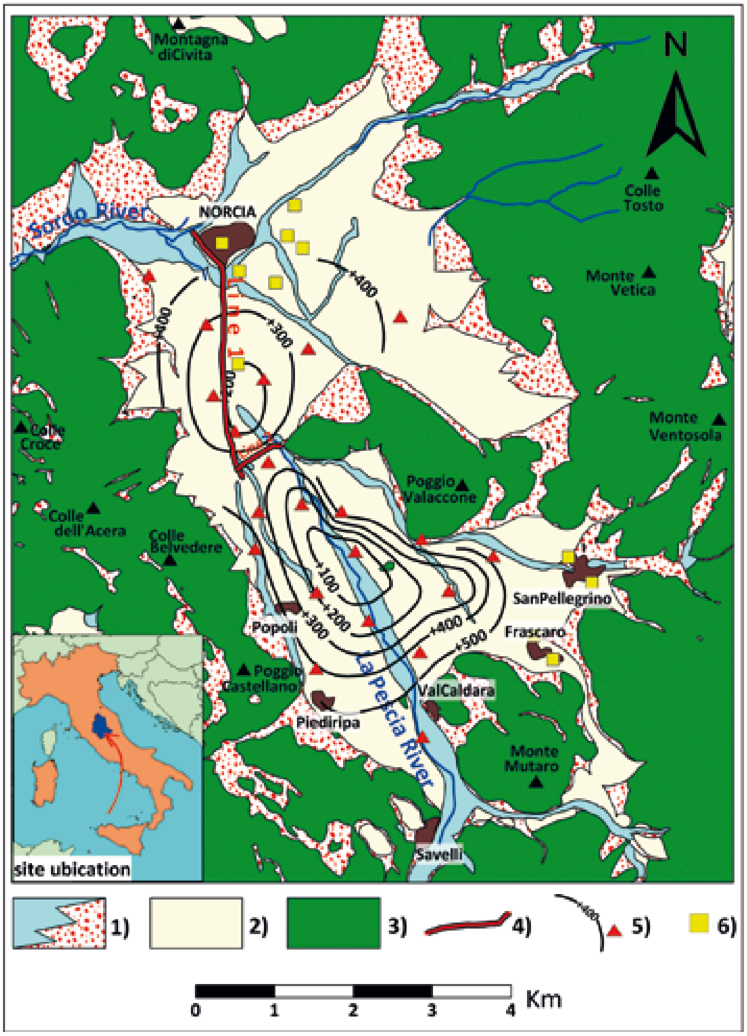

Fig. 1 - Geological map of the NIB (modified from: Motti *et al*., 2014) and previous geophysical surveys: 1) fluvio-lacustrine, slope deposits (Holocene); 2) fluvio-lacustrine deposits (Pleistocene-Holocene); 3) calcareous-siliceous-marly deposits (Meso-Cenozoic); 4) seismic lines by Böhm *et al*. (2011); 5) VES and bedrock elevation in metres a.s.l., by Biella *et al*. (1981); 6) HVSR and arrays by Regione Umbria (2018).

3. Previous geophysical surveys

Previous geophysical studies (Fig. 1) have investigated the NIB using different methods, such as vertical electrical soundings (VESs) (Biella *et al*., 1981), and gravimetry (Fig. 2) (Aringoli *et al*., 2012, 2014; Ruano *et al*., 2012). However, these works were not conclusive for the definition of the bedrock geometry of the entire basin, mainly due to the small number of VESs and the non-uniformity of the gravity stations distribution, that were positioned only along the main roads. In the northern part of the basin, Böhm *et al*. (2011) performed two reflection seismic profiles. Moreover, near surface geophysics was applied to survey limited areas chosen for seismic microzonation (SM), the results of which are summarised in the DPC-ReLUIS projects 2016 and 2018 (ReLUIS-INGV Workgroup, 2016). Electrical resistivity tomography profiles (Galli *et al*., 2018) and a high-resolution seismic reflection profile (Borre *et al*., 2003) were carried out across the faults affecting the Patino fan. Lastly, ambient noise measurements [Horizontal to Vertical Spectral Ratio (HVSR) and 2D arrays] were collected in the study area (Ercoli *et al*., 2018) resulting in a new frequency-amplitude map of the NIB.

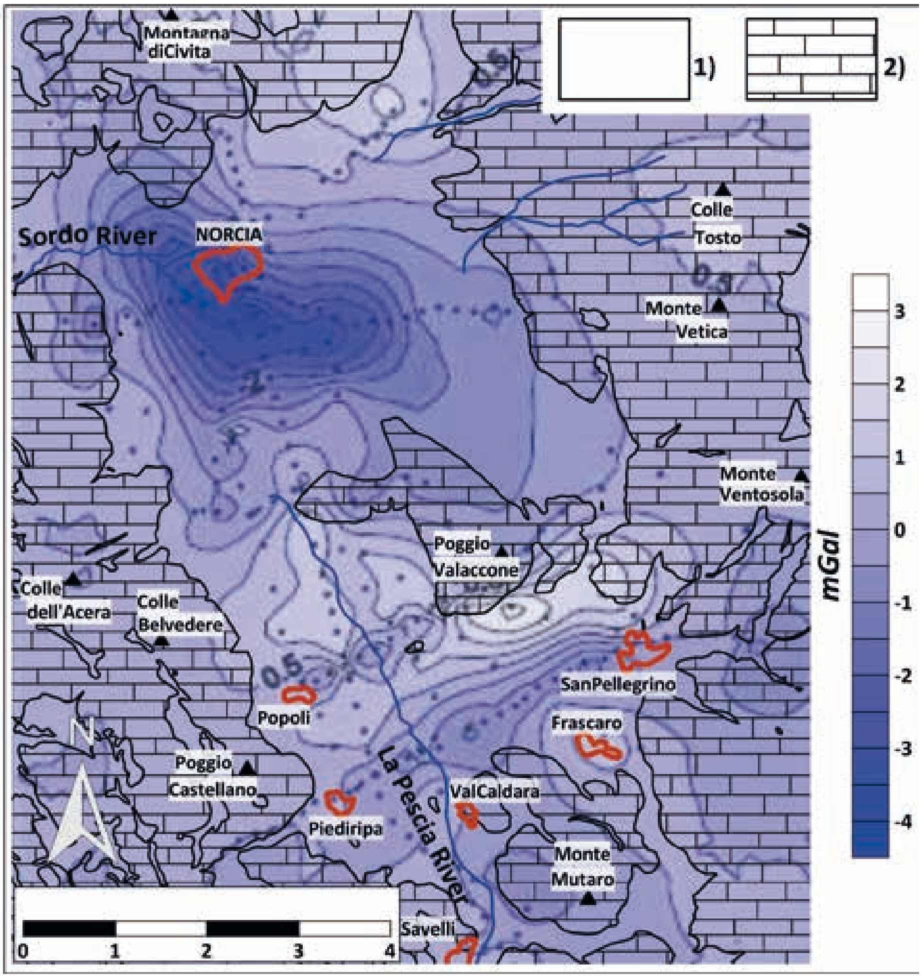

Fig. 2 - Previous residual gravity map of the NIB, modified from Ruano *et al*. (2012): 1) fluvio-lacustrine deposits (Pleistocene-Holocene); 2) calcareous-siliceous-marly deposits (Meso-Cenozoic).

4. Data acquisition and processing

The gravity survey was performed in 2018 with the measurement of 210 stations that were spaced at 300-m intervals on the whole plain, extending to the surrounding limestone outcrops (Fig. 3), with a resulting mean station density of 7.7 stations/km^2. Moreover, some additional gravity stations were positioned on the mountain slopes (blue dots, Fig. 3). The measurements were taken with two LaCoste & Romberg gravimeters (G 523 and D 60). The Sant'Angelo Romano absolute gravity station (Berrino *et al*., 2006; Di Nezza, 2007; D'Agostino *et al*., 2008), located on Meso-Cenozoic carbonate rocks of the Mounts Cornicolani (Rome), was used to refer all the measures to IGSN71 (Morelli *et al.,* 1974). Moreover, a local 2-station base was established to check the calibration of the 2 instruments. The elevation and position of the gravity stations were measured by rapid static differential GPS surveys (Ashtech Z-Xtreme, Trimble 5007). The field data processing consisted of removing tidal effects and instrumental drift. For removing the short-term drift, the base stations measurements were scheduled every hour. The Somigliana

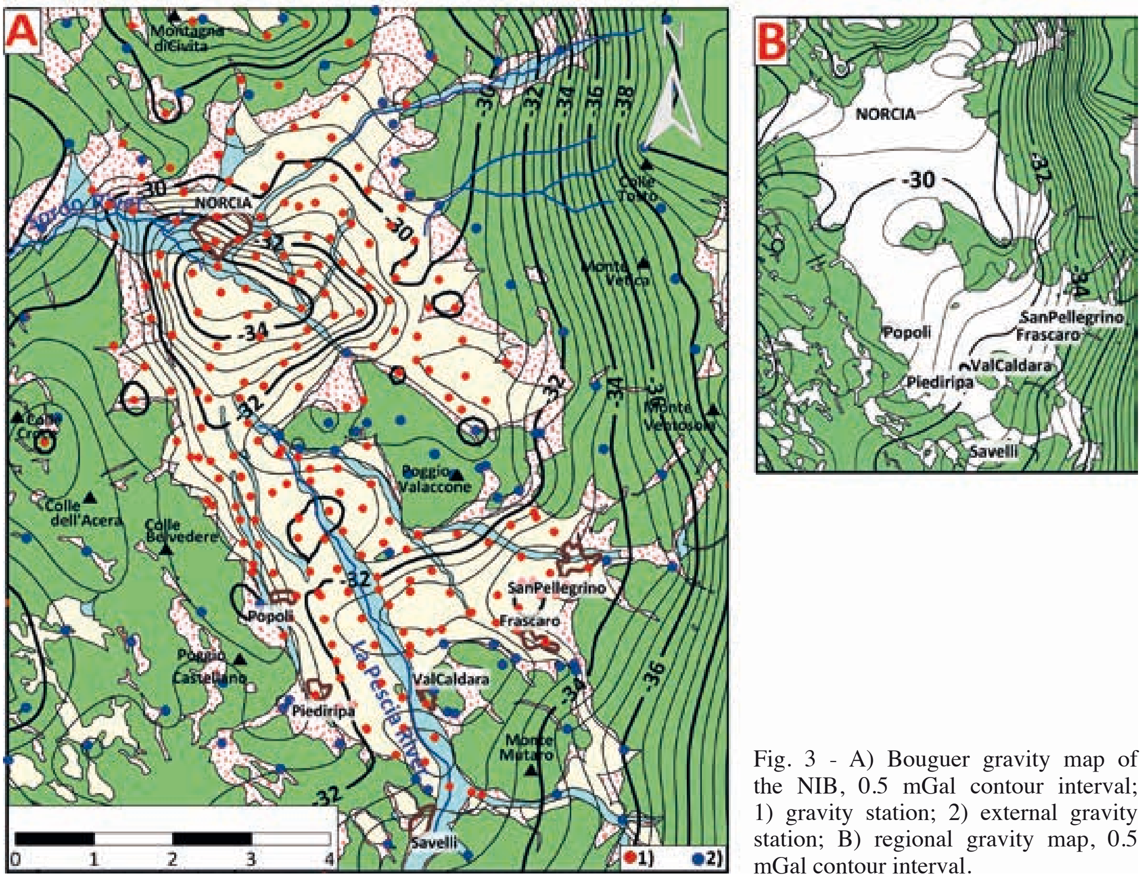

Fig. 3 - A) Bouguer gravity map of the NIB, 0.5 mGal contour interval; 1) gravity station; 2) external gravity station; B) regional gravity map, 0.5 mGal contour interval.

(1930) closed-form formula was used for computation of the theoretical gravity on the GRS80 ellipsoid (Moritz, 1980). A second-order approximation formula (Heiskanen and Moritz, 1969) was used for correcting the theoretical gravity for a height relative to the ellipsoid. Moreover, an atmospheric correction was applied to all stations (Hinze *et al.*, 2005). The gravity effect of a spherical cap with radius of 166.7 km (LaFehr, 1991) was computed for the Bouguer correction using a density of 2600 kg/m^3. For all stations the terrain correction was computed with an in house software in 2 steps using the Messerschmidt formula (Hammer, 1939) and a density of 2600 kg/m^3: for the inner zone, up to 28 km from the station, a 10-m-cell-sized digital terrain model (DTM) was used (Tarquini *et al.*, 2007, 2012) and for the outer zone correction, from 28.0 to 166.7 km, a 250-m-cell-sized DTM of Italy. For gravity stations positioned in rugged topography (mountains bordering the plain), an additional terrain correction was computed applying a conic prism formula (Olivier and Simard, 1981) dividing a circular inner zone of 10 m radius in 4 quadrants where height differences were computed by field estimation.

5. Bouguer and residual maps

The Bouguer map (Fig. 3A), using also some available ENI gravity stations, was produced with a standard Kriging interpolator and a grid cell spacing of 100 m. It shows a marked gravity signature difference between the northern and southern sectors of the basin which are partially separated by the relative gravity high of Poggio Valaccone. The Bouguer anomaly values range from -27 to -35 mGal and fit well with those of ISPRA, ENI and OGS (2009) for this sector of central Italy. In the northern sector of the NIB, a strong gravity minimum exists (up to -35 mGal) with significant horizontal gradients, while in the southern sector the anomalies are smooth and less intense. Finally, at the NIB western border, the Bouguer anomalies show again a horizontal gradient oriented NNW-SSE. Considering the regional geological setting and the distribution of the Meso-Cenozoic outcrops, a residual map was produced to better define the local anomaly trends and provide the input data to the modelling. The regional component of the Bouguer map (Fig. 3B) was computed considering only the gravity stations (blue dots in Fig. 3A) placed on the bedrock (Mickus *et al.*, 1991) for an extension of about 5 km from the plain. The resulting residual map (Fig. 4A) shows that the northern sector of the NIB is characterised by a closed negative residual anomaly reaching -5.0 mGal, approximately south of the Norcia town. This anomaly is roughly triangular shaped and it is bounded by clear gravity gradients suggesting the presence of normal faults. In the southern sector, smaller negative anomalies are present (-1.5 mGal).

6. Gravity modelling

The gravity residual anomalies of the whole Norcia basin have been interpreted using a forward 2.5D modelling method, computing model fields along 34 profiles oriented ENE-WSW (azimuth

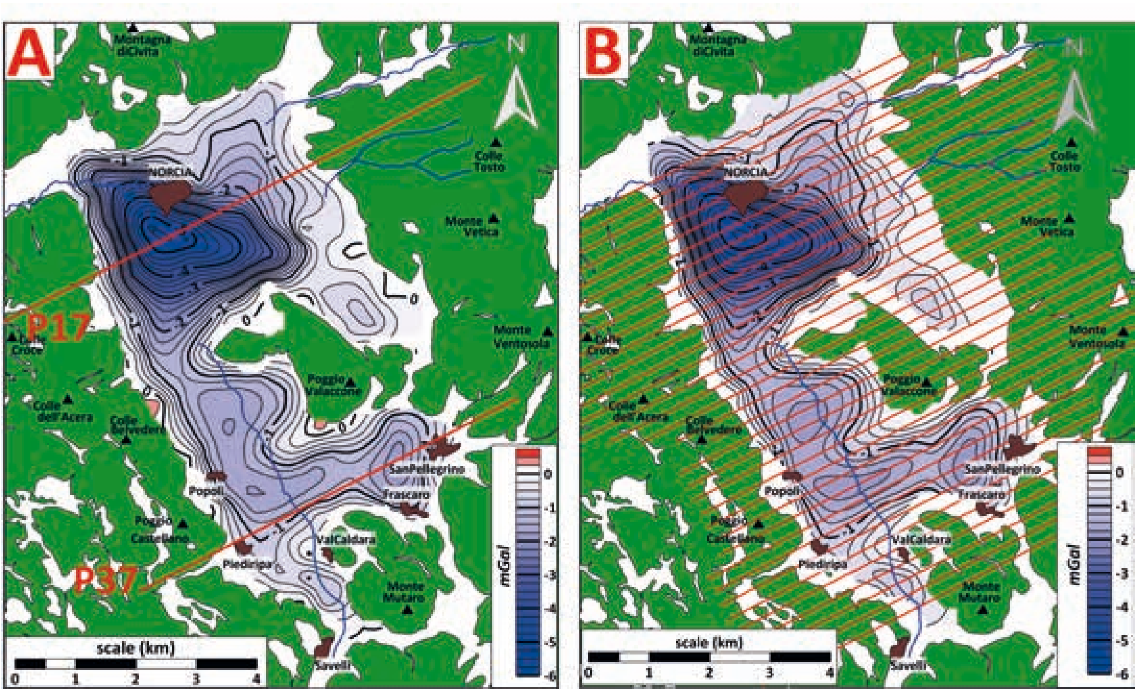

Fig. 4 - A) Residual gravity map of the NIB, 0.25 mGal contour interval; B) computed gravity map, 0.25 mGal contour interval and profiles traces.

63°) with 250 m line spacing and 100 m data sampling (Fig. 4B). This profile orientation has been chosen in order to cross at right angles the higher gradient isoanomalies. The final model is made of 85 polygon bodies (each with 250-m strike length) and their outcropping limits, where existing, were positioned according to the 1:10,000 geological map (Motti *et al.*, 2014). A high resolution digital elevation model (Tarquini *et al.*, 2007, 2012) was used for the profiles topography. The densities of the polygonal bodies have been chosen according to literature data and technical reports available for the area (DPC - RELUIS, 2018) in which the unconsolidated Quaternary deposits densities were determined on core samples. Moreover, as a test, we applied Gardner's formula (Gardner *et al.*, 1974) to the velocity model data of a reflection seismic profile (Böhm *et al.*, 2011) and we obtained, for the whole Quaternary deposits, densities in the range 1900-2100 kg/m^3. The whole gravity model, with a background density of 2600 kg/m^3, consists of 2 main bodies: coarse cemented deposits of density in the 2100-2200 kg/m^3 range and fluvial, lacustrine, and marsh alluvial deposits with a density of 2000 kg/m^3. The latter outcrops only in a limited area SW of Norcia. Additional polygonal bodies of limited extent account for the weathered part of the limestone outcrops and slope debris on the mountains flanks (density = 2200 kg/m^3).

Where available, well data was used to constrain the depth of the outcropping Quaternary coarse cemented deposits. Two examples of the profile modelling are presented in Fig. 5: the profile P17 crossing the gravity minimum south of Norcia town and the profile P37 crossing the gravity minimum at the south of Poggio Valaccone hill. They are representative of the subsurface setting of the northern and southern sectors of the NIB. The model depth values of all profiles have been used to construct an elevation map of the top surface of the carbonate bedrock (Fig. 6). The resulting synthetic anomalies (Fig. 4B) calculated for the whole model are consistent in shape, intensity and wavelength with the residual gravity anomalies (Fig. 4A), with a grid difference rms error of 0.16 mGal. The closed low bedrock topography of the Norcia basin northern sector (Fig. 6) is interpreted as filled with low density (2000 kg/m^3), mainly lacustrine, sediments and reaches a bedrock maximum modelled depth of 350 m. This gravity minimum is affected along its north-eastern flank by a normal fault system highlighted by NW-SE gravimetric discontinuities (profile P17 in Fig. 5 and D1 and D2 in Fig. 6). The low amplitude minimum gravity anomalies of the southern NIB sector are caused by the presence of buried valleys filled with a small thickness of coarse sediments, with an assigned density of 2100 kg/m^3 (profile P37 in Figs. 5 and 6). The western side of the 3D model (Fig. 6) shows a gentler decrease (profiles P17 and 37 in Figs. 5 and 6) that follows the bordering mountains slopes mainly due to erosion processes.

7. Discussion

Here we compare our results with the previous geophysical surveys, providing some hints concerning the subsurface interpretation:

- VES map: there is a striking difference between the bedrock contour map (Fig. 1) of Biella *et al.* (1981) and our map (Fig. 6). Biella *et al.* (1981) identify the maximum bedrock depth in the southern sector, besides a secondary depocentre in the northern sector. This discrepancy is not easily explained and it would require a re-interpretation of the resistivity curves. However, the map confirms the presence of a bedrock saddle separating the 2 basin sectors and shows contours lines congruent to our bedrock map in the southern basin area;

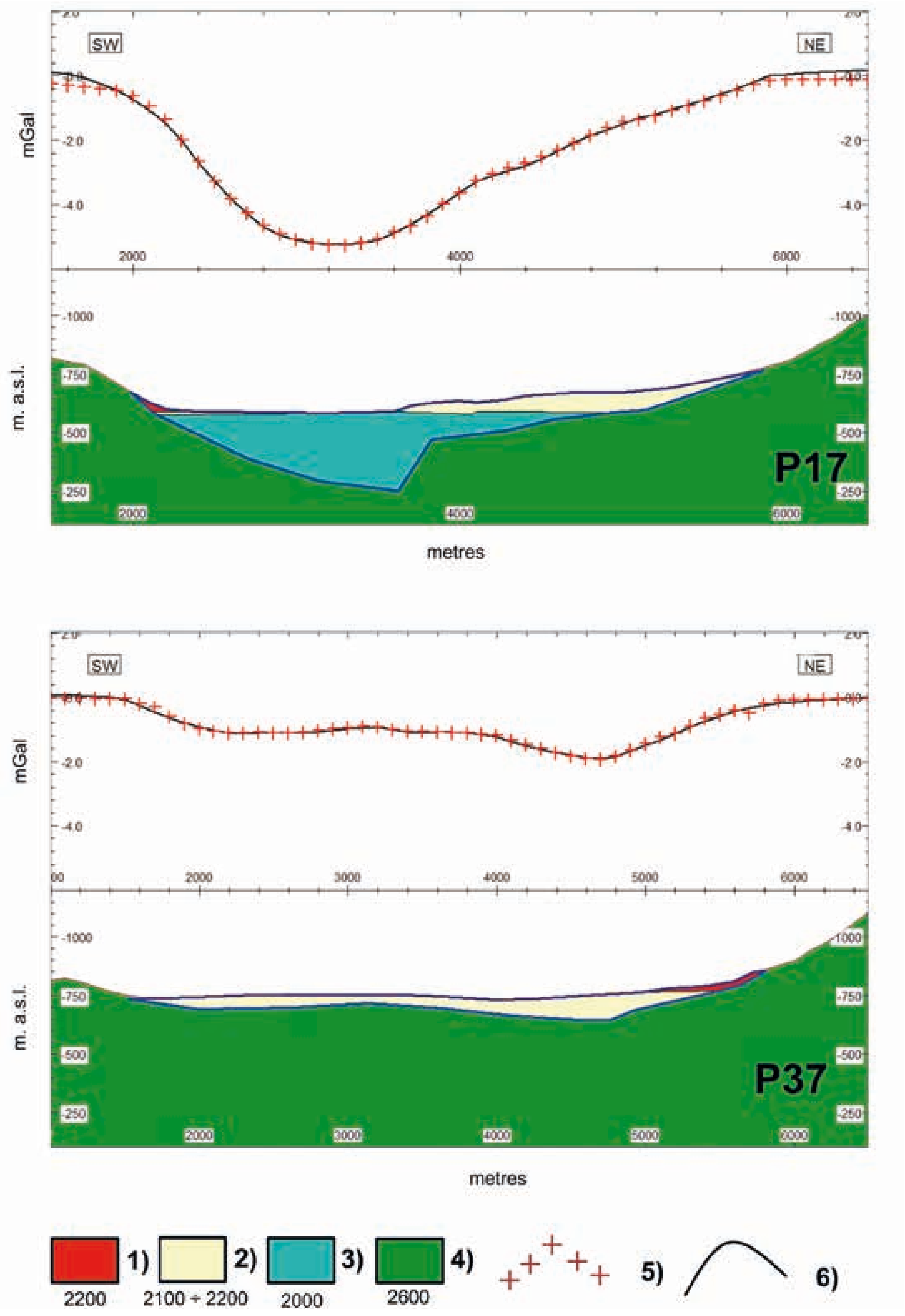

Fig. 5 - Interpretative sections along the P17 (crossing gravity minimum south of Norcia town) and the P37 (crossing gravity minimum at southern side of Poggio Valaccone hill) profiles. Density values are kg/m^3 in: 1) slope deposits; 2) coarse fan deposits; 3) fluvio-lacustrine deposits; 4) Meso-Cenozoic carbonate bedrock; 5) residual anomaly; 6) computed anomaly.

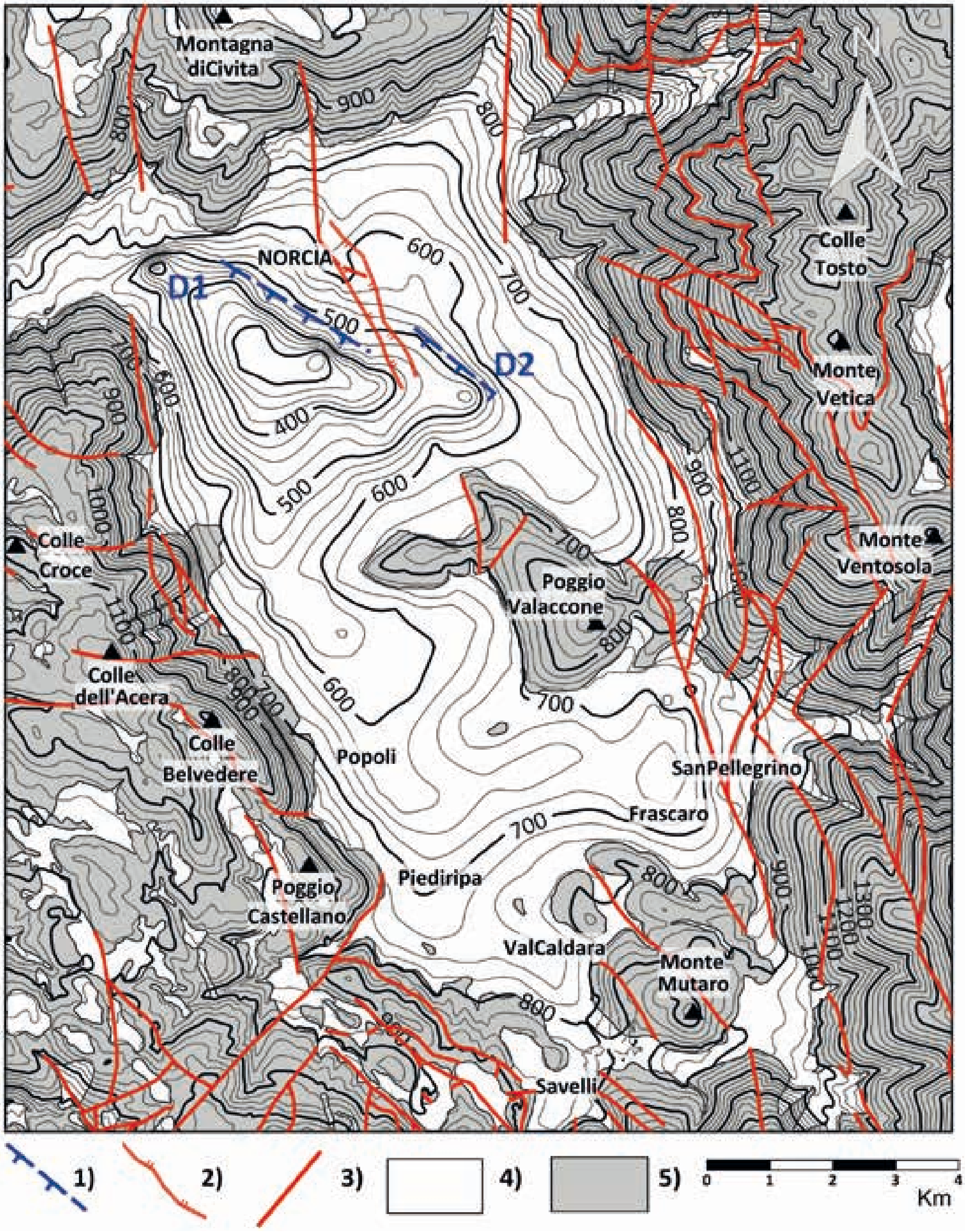

Fig. 6 - Map of Meso-Cenozoic bedrock: elevation contours in metres a.s.l., 1) gravity discontinuities; 2) Norcia fault splays; 3) surface faults; 4) top of Meso-Cenozoic buried bedrock; 5) Meso-Cenozoic outcrop.

- gravity map: the main feature in the residual gravity map of Ruano *et al*. (2012) is a closed low anomaly in the northern sector (Fig. 2), which is similar to what shown in our map (Fig. 4A). In accordance with our interpretation, Aringoli *et al*. (2012, 2014) and Ruano *et al*. (2012) interpret the northern basin structure as of tectonic origin (asymmetrical graben) with a west facing master fault located at SW of Norcia town. However, the map of Ruano *et al.* (2012) is biased by the great anisotropy of the station distribution and by possible inaccuracies in the station height values, causing deformation of the anomalies and false features, especially in areas lacking of measurement points. In the southern basin sector, obvious anomalies shape, intensities and sign discrepancies are present. Moreover, the associated modelling, using only one density contrast, was calculated with a simple 2D approach and shows questionable bedrock geometries and depth values on some profiles;

- seismic reflection profiles: the seismic tomographic inversion results (Böhm *et al.*, 2011) show a well-marked horizon at depths ranging between 150 and 200 m from the topographic surface, that these authors interpret as the top of the bedrock. The depth image of their seismic Line 1 (3.4 km long and N-S oriented, Fig. 1), shows a layered bedrock structure with a maximum depth shifted ~300 m to the south in respect to our gravity model map minimum. The top of the bedrock lower elevation reached by the seismic interpretation is ~420 m while the corresponding gravity model elevation is ~ 80 m deeper. The results of the 0.7-km long seismic Line 2 (Fig. 1) show a bedrock elevation of 520-540 m that implies the presence of a normal fault disconnecting it from the limestone outcrop of Poggio Valaccone. The corresponding gravity model bedrock elevations are in the 550-640 m range, with gradients consistent with a possible minor fault. Both seismic lines were reported by the authors to be affected by data degradation due to local noise;
- SM HVSR / ESAC: the SM studies of the Norcia district included also many geophysical surveys. The HVSR and ESAC measurements (Bindi *et al.*, 2011; DPC - RELUIS, 2018; Regione Umbria, 2018) are of some interest for our study as they can provide estimates on the depth of deep velocity layers using joint inversion methods. Particularly, in the northern sector of the Norcia basin, both methods show a general increase of the bedrock depth in the area of the negative gravity anomaly. We selected seven joint inversion results from the data set of 10 HVSR / ESAC stations (Fig. 1) available from the Norcia SM (Regione Umbria, 2018), choosing only those positioned far from the main gravity model discontinuities, in order to assure that the 1D layer condition for the HVSR / ESAC inversion was respected. It is interesting to note that for a bedrock depth range of 39-162 m, the HVSR / ESAC bedrock depths differ from the corresponding gravity model depths of a mean value of 24 m. Excluding a possible outlier, the mean difference reduces to 16 m;
- HVSR-array map: the frequency-amplitude map based on HVSR analysis (Ercoli *et al.*, 2018) shows a significant cluster of low frequencies and high amplitude values in the northern sector of NIB in very good spatial correlation with the gravity model bedrock elevation minimum. Moreover, this map generally confirms the minor depths of the unconsolidated Quaternary cover in the central saddle and southern sector.

Focusing on the interpretation of the gravimetric discontinuities D1 and D2 (profile P17 in Fig. 5 for D1 and map in Fig. 6 for D1 and D2), bordering the gravity minimum of the northern NIB sector, first of all we tend to exclude a primary karst origin. Karst landforms are known to occur in the Apennines (Coltorti and Farabollini, 1995 and references therein; Valente *et al.*, 2018), however the shape and relatively large areal extension of the gravity minimum is not consistent with a typical buried karstic feature at least for the known karst forms (Sauro, 2012). Moreover, the gravity anomaly (Fig. 4A) and related model (Figs. 5 and 6) clearly indicate a bordering linear discontinuity suggesting a tectonic main origin. Furthermore, we note that no surface evidence of karst landforms are reported for the Norcia basin area (Calamita *et al*., 1982 and references therein; Aringoli *et al*., 2012, 2014) while a large bibliography (references in the Geological setting and Previous Geophysical surveys paragraphs) supports a tectonic origin of the NIB.

The above mentioned gravity discontinuities show a NW-SE trend that is consistent with the main extensional tectonics direction of the Umbro-Marchean Apennines (Calamita *et al*., 1994, 2000; D'Agostino *et al*., 2001a; Pizzi *et al*., 2002 and references therein). Quaternary tectonic studies using kinematic analyses (Calamita *et al*., 1995) have revealed that in this Apennine area a main extensional tectonic phase N50-60° oriented has occurred followed by a secondary phase with a N10-20° direction. This complex tectonic setting is well represented in the NIB area. The trend, extension and dislocation geometry (SW-dipping) of the identified gravimetric discontinuities are consistent with the surface geological pieces of evidence (Calamita and Pizzi, 1992; Pizzi *et al*., 2002; Galli *et al*., 2005; Regione Umbria, 2015) as regards the normal faults dislocating the Meso-Cenozoic formations (Fig. 6). These faults developed in the initial phases of the extensional regime, probably from the upper Pliocene (Calamita *et al.,* 1982). In the NIB surroundings area (Fig. 6) both NW-SE (for example considering the fault systems located to the east of the NIB on the slope towards Monte Vetica and SW of the NIB between Poggio Castellano and Savelli) and more diffusely NNW-SSE fault trends are present, confirming the development of extensional regimes with different orientations. We, therefore, believe that the presence of discontinuities in the Meso-Cenozoic bedrock such as those identified by this gravimetric study are not the result of artifacts but are consistent with the tectonic setting and surface geology of this area of the Apennines. Probably these discontinuities are part of a system of normal faults that were set in the initial phases of the central Apennines extensional activity. As such, depending on the single geometries and orientations, these faults have not necessarily been all involved in the more recent extensional deformation (Fig. 6) that displaced the Quaternary sediments such as the Norcia fault splays (Galli *et al.,* 2018 and references therein).

8. Conclusion

This new gravity survey effectively improves and updates the geophysical framework of the NIB compared with what was published by previous authors (Biella *et al.,* 1981; Aringoli *et al*., 2012, 2014; Ruano *et al.,* 2012). At depth, the gravity anomalies reveal an articulated shape of the bottom of the subsurface infilling in the northern and southern sectors. In the northern sector, the residual gravity map (Fig. 4A) shows a triangular shaped minimum, that is interpreted to be a closed depression of tectonic origin (Fig. 6) whose depocentre is located just south of the historical centre of Norcia. The tectonic dislocations of the substratum have conditioned the deposition of the fluvio-lacustrine Quaternary sediments that reach a thickness of about 350 m (profile P17 of Figs. 5 and 6). The main gravity discontinuity is oriented NW-SE and is positioned at the north-eastern side of the gravity low. The carbonate relief of Poggio Valaccone is an element of separation between the two sectors and it results in continuity, from the gravimetric point of view, with the carbonate relief of Monte Ventosola. The southern sector of the basin has a completely different setting: there are no internal gravity discontinuities and the carbonate bedrock is present at shallow depths (profile P37 of Figs. 5 and 6). The bedrock elevation map (Fig. 6) supports that the northern sector of the NIB was an endorheic basin, affected by extensional tectonics (Blumetti and Dramis, 1992). The results of this work contribute to define the thickness of the whole basin Quaternary units and yield new insight into the existence of possible buried faults, detected by gravity discontinuities (profile P17 of Figs. 5 and 6). Moreover, this study can provide useful information to refine the assessment of the earthquake damage potential of this area through microzonation studies (Di Filippo *et al*., 2011). Accurate gravity measurements and appropriate processing and interpretation confirm once again to be an effective and inexpensive tool for mapping the thickness of Quaternary deposits and for detecting significant bedrock discontinuities in intermountain basins.

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