Gravity and magnetic modeling of Central Italy: insights into the depth extent of the seismogenic layer

P. Mancinelli[1], M. Porreca[1], C. Pauselli[1], G. Minelli[1], M. R. Barchi[1], F. Speranza[2]

[1]Dipartimento di Fisica e Geologia, Università degli Studi di Perugia, Via A. Pascoli, Perugia, Italy – Member of CRUST (Centro inteRUniversitario per l'analisi SismoTettonica tridimensionale con applicazioni territoriali).

[2]Istituto Nazionale di Geofisica e Vulcanologia, Rome, Italy

Corresponding author: Paolo Mancinelli (paolo.mancinelli@unipg.it)

ORCID: 0000-0003-4524-3199

Highlights:

- Combined gravity and magnetic anomalies models are produced for the active seismic sector of Central Italy.
- Models are constrained with surface geology and recent geological models.
- The models provide information regarding the depth distribution of the basement and highlight its role in controlling the seismicity cutoff.

Index terms

0545 Modeling

1219 Gravity anomalies and Earth structure

1517 Magnetic anomalies: modeling and interpretation

8015 Local crustal structure

8031 Rheology: crust and lithosphere

Keywords

Gravity anomalies and Earth structure, Magnetic anomalies: modeling and interpretation, Magnetic properties, Basement, Seismogenic layer, 2016-2017 seismic sequence in Italy

Abstract

The recent 2016-2017 seismic sequence in Central Italy has prompted the investigation of several geological and geophysical data in order to derive more accurate subsurface geological models. We present the results of combined gravity and magnetic modeling performed along three sections crossing the area of the seismic sequence in order to evaluate the geological parameters controlling or affecting the thickness of the seismogenic layer of this part of the Apennines. The models are constructed using all the available geological and petrophysical constraints derived from previous studies. Resulting models are consistent with the top of the basement located at 8-12 km depth and contribute to the geological and geophysical understanding of the area investigating the role of the basement in the seismic events. The basement, involved in Miocene thrusting, formed the base of seismicity for the recent seismic sequence in the area. Moreover, the models provide information about the nature and composition of the basement and lower crust. Finally, these findings contribute in the investigation of the mechanisms controlling the thickness of the seismogenic layer in extensional post-orogenic scenarios.

Plain Language Summary

In geologically-complex regions such as the Apennines (Italy), surface observations and deeper information should be combined in a multidisciplinary approach to advance understanding of the factors that influence the distribution of earthquakes. The geologic and the geophysical models are combined here to investigate the thickness of the crustal bodies capable of generating seismic events such those observed during the 2016-2017 seismic sequence. Results, coherently show that seismic events are mostly located in the sedimentary units and this will help in the general understanding of how the Apennines and similar chains evolve.

1 Introduction

In complex geodynamic areas characterized by active tectonics, combined gravity and magnetic models can help validate subsurface geological models (e.g. Garland, 1951; Telford et al., 1990; Düzgit et al., 2006; Rybakov et al., 2011), defining the geometries and the thickness of the geological structures related to seismicity. Moreover, when the modeling is constrained by well documented geological observations both at the surface and at depth (borehole and seismic reflection profiles), its interpretation is certainly less ambiguous. In these cases, relationships between the mechanical properties of the crust and the observed distribution of the seismicity can also be addressed.

This study focuses on the South-Eastern part of the Umbria-Marche Apennines and on the adjacent Laga domain (Figure 1), in the Outer Northern Apennines (e.g. Barchi et al., 2001). This typical fold and thrust belt mainly formed during the Late Miocene-Early Pliocene and was subsequently dissected by still active extensional tectonics, as demonstrated by the 2016-2017 seismic sequence (e.g. Tinti et al., 2016; Chiaraluce et al., 2017). The sequence counted of more than 25,000 events with 0.1<Mw<6.5 between August 2016 and November 2016 with other events with M ≤ 5.5 in the Campotosto area on 18 January 2017 (Chiaraluce et al., 2017). Without any particular sequence anticipating the 24 August Mw 6.0 event, the majority of the events concentrated after this event and after the 30 October Mw 6.5 mainshock. The events were located between the towns of Montereale and Visso, at depths ranging between 0 and ~15 km (Chiaraluce et al., 2017). Seismicity clearly lineated along planes both in the E-W (e.g. in the area between the Monte Vettore and Norcia) and the N-S directions where a significant cutoff was observed at 10 km depth by Chiaraluce et al. (2017), see for example the Figure 3, sections 2c and 6 of his work.

The subsurface geology of this part of the Northern Apennines has been widely studied in the last three decades (e.g. Bally et al., 1986; Lavecchia et al., 1994; Barchi & Mirabella, 2009; Barchi, 2010; Bigi et al., 2011 and references therein). These authors propose contrasting structural styles, characterized by either thin-skinned deformation which involves the sedimentary cover of Triassic evaporites and younger sedimentary cover (e.g. REF), or thick-skinned deformation involving the deeper basement (e.g. Calamita et al., 2014). These authors estimate a depth of the basement varying between 6 and 13 km. Recently, Porreca et al. (2018) proposed a geological and structural model, based on previously unpublished seismic reflection profiles and borehole data, and characterized by a combination of thick- and thin-skinned styles (e.g. Barchi et al., 1998) where both the sedimentary cover and the basement are involved. According to this interpretation, the distribution of the seismicity responsible for the 2016-2017 sequence seems to be lithologically controlled and the cutoff of the seismicity is marked by an important seismic reflector interpreted as the top of the basement, located between 8 and 11 km of depth. This observation confirms the results of previous, similar studies, focused on northernmost structures of the seismically active extensional belt (Barchi, 2002; Mirabella et al., 2008; Latorre et al., 2016).

The composition and rock types that form the basement and its magnetic properties are also uncertain and still a matter of debate (e.g. Bally et al., 1986; Arisi Rota & Fichera, 1987; Speranza & Chiappini, 2002) even if most of the authors agree with a basement characterized by high magnetic susceptibility (k) values with respect to the sedimentary cover (e.g. Mattei et al., 1997; Speranza & Chiappini, 2002; Mancinelli et al., 2015; Minelli et al., 2018). Recent models (Minelli et al., 2018) in the L'Aquila and Sulmona basins, located respectively ~50 km and 80 km SE of the study area, proposed a deep origin for the magnetic anomaly in the area, without other significant contributions from basement or upper crust.

In a regional transect across the whole Northern Apennines, Ponziani et al. (1995) used seismic refraction data to identify two different, partially superposed Moho discontinuities: the Tuscan-Latial-Perityrrhenian (TLP) overlying a mantle with a Vp of 7.7 km s^{-1} and the Adriatic Moho (AD) overlying a mantle with a Vp of 8 km s^{-1} toward east. Along the same transect, Scarascia et al. (1998) modeled gravity anomalies in order to determine the 3D spatial relationships between the AD and the TLP Moho across the Central and the Northern Apennines. Other gravity models were focused along profiles of the CROsta Profonda (CROP) project that only marginally intersected the study area (inset in Figure 1) with the profile CROP 03 (e.g. Barchi et al., 1998; Marson et al., 1998; Larocchi et al., 1998) to the north, and profile CROP 11 (Tiberti et al., 2005; Di Luzio et al., 2009) to the south. More recently, Luiso et al. (2018) used multi-scale gravity analyses to evaluate the geometry of the active master faults in the area. The study area has not been the primary subject of magnetic modeling but was partially investigated by studies focused on the Adriatic foreland (Mancinelli et al., 2015) and Northern and Southern Apennines (Arisi Rota & Fichera, 1987; Cassano et al., 2001; Speranza & Chiappini, 2002).

In this paper, we report the results obtained by the combined gravity and magnetic modeling of the region affected by the 2016-2017 seismic sequence, at the boundary between the Northern and the Central Apennines (Figure 1). The models are constructed from a new Bouguer anomaly map and magnetic anomaly map by Caratori Tontini et al. (2004). The geometries of the main crustal bodies are based on the geological model of Porreca et al. (2018) and the petrophysical parameters were retrieved from previous works investigating the area or its surroundings through modeling (Arisi Rota & Fichera, 1987; Cassinis et al., 1991; Mattei et al., 1997; Scarascia et al., 1998; Speranza & Chiappini, 2002; Pauselli & Federico, 2003; Di Luzio et al., 2009; Mancinelli et al., 2015; Pauselli & Ranalli, 2017; Minelli et al., 2018) or logging petrophysical properties of the investigated units from borehole data (Montone & Mariucci, 2015). Results contribute to locating the depth of the basement in the study area and provide insights into the mechanisms controlling the depth of the seismogenic layer in extensional post-orogenic settings.

2. Geological setting

The evolution of the Central Apennines is the result of the contemporaneous opening of the Tyrrhenian sea, the eastward migration of a compressive front and the flexural retreat of the Adriatic lithospheric plate (Boccaletti et al., 1982; Malinverno and Ryan, 1986; Royden et al., 1987; Patacca et al., 1990; Carminati & Doglioni, 2012). The structural evolution of this region is characterized by Late Miocene-Early Pliocene compressional phase, followed by Late Pliocene-Quaternary extension (e.g., Pauselli et al., 2006; Cosentino et al., 2017).

In particular, the surface geology of the investigated area is characterized by the prevalence of Mesozoic-Cenozoic carbonate and marly rocks of the Umbria-Marche sequence to the west and Upper Miocene–Pliocene syn-orogenic siliciclastic deposits to the east (Flysch della Laga Fm.; Centamore et al., 1992). The lithology and thickness of the sequences are well known in literature, since this region has been extensively mapped and subjected to hydrocarbon exploration investigations in the past. The Umbria-Marche carbonate and pelagic domain is composed of upper Triassic anhydrites and dolomites, up to 2000 m thick (Anidriti di Burano Fm. and Raethavicula

Contorta beds; Martinis and Pieri, 1964), that are not exposed in external sector of the chain but have been penetrated in exploration wells (Varoni1; Antrodoco1; Villa Degna1). The sequence continues upward with shallow water carbonates (Calcare Massiccio Fm.; Late Triassic-Early Jurassic) through pelagic domain, characterized by condensed and complete successions with variable lithology and thickness (Centamore et al. 1992; Santantonio 1994; Bigi et al. 2011; Pierantoni et al., 2013 and references therein). This articulated stratigraphic setting was involved in the Late Miocene-Early Pliocene compressional phase, producing the formation of the Umbria-Marche fold and thrust belt and the Laga foredeep basin. The Laga basin is infilled by a thick (up to about 3000 m) succession of siliciclastic turbidites (Milli et al., 2007), overlying the Umbria-Marche succession and generally subdivided in two units (Units 1 and 2), characterized by an overall fining upward trend until the occurrence of a gypsum–arenite horizon (Milli et al., 2007; Bigi et al., 2011), which marks the occurrence of the Messinian Mediterranean salinity crisis (e.g. REF. Ryan, Cita, etc..).

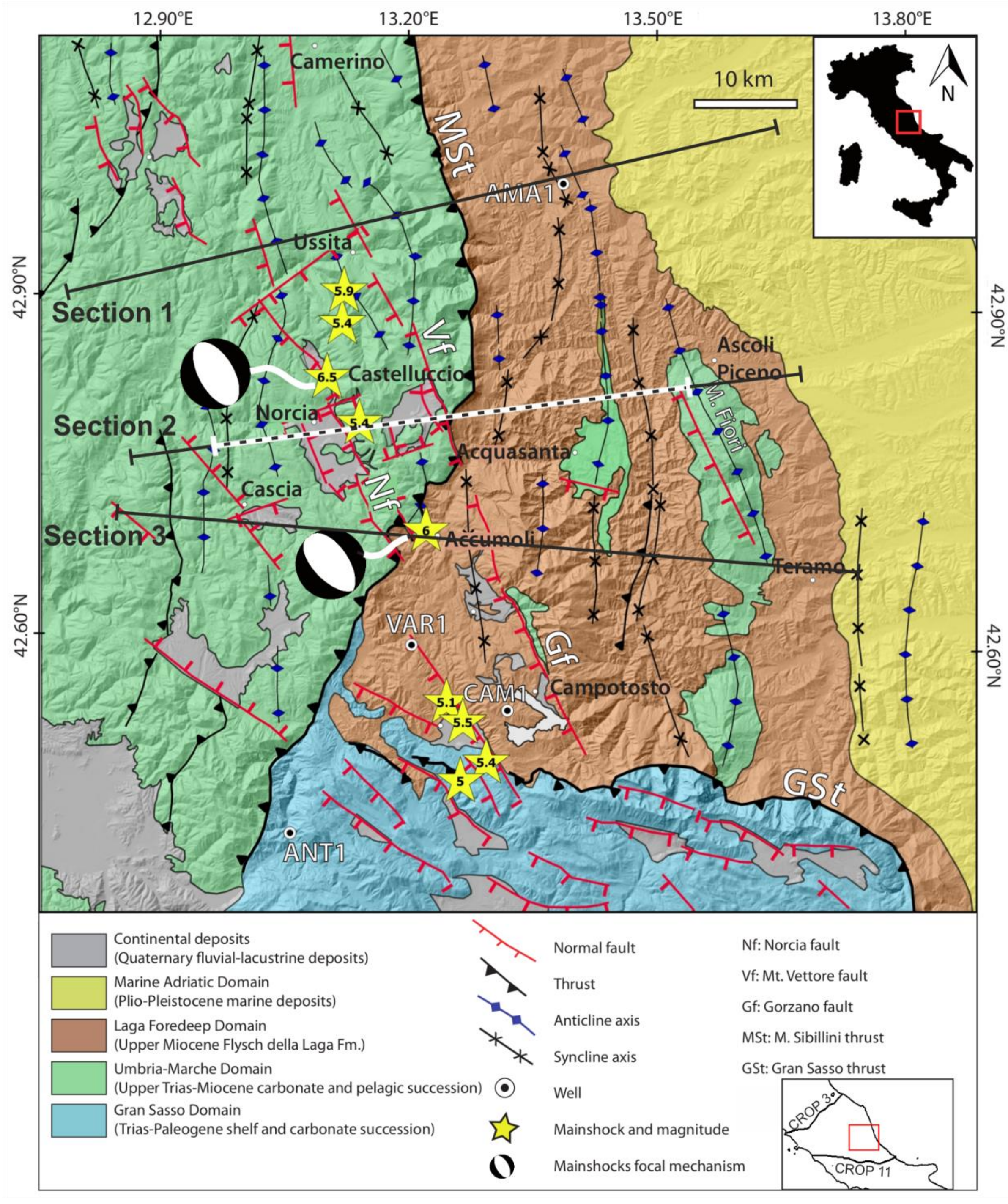
The compressional tectonics produced a "typical" thrust belt structures whose geometries are widely exposed and well known. In the study area, the Umbria-Marche fold-and-thrust belt overthrusts the Laga Domain, through a major arc-shaped thrust, namely the M. Sibillini thrust (Koopman, 1983; Lavecchia, 1985), with eastward convexity. The tectonic style is characterized by important amount of shortening along the main thrust (see Porreca et al., 2018 for a detailed review) with a progressive nucleation of the compressional structures toward the foreland (i.e. toward ENE). The main detachment is localized at the base of or within the Triassic Evaporites sequence and involves the whole sedimentary sequence deformed in a NE verging anticlines. Other minor detachments are located in the upper part of the sedimentary sequence, mainly concentrated within weak mechanical lithologies, such as the Cretaceous Marne a Fucoidi Fm. and at the base of the Laga Fm. (Barchi et al., 1998).

The basement never crops out, is penetrated only by a few deep wells, all located far away from the study area, and shows an accentuated lithological variability. Beneath the evaporites, two wells (S. Donato 1 and Perugia 2 wells; Minelli and Menichetti, 1990; Anelli et al., 1994), have intercepted the upper part of the basement, finding Late Paleozoic phyllites. Other wells (e.g., Alessandra1 and Puglia1; Bally et al., 1986; Patacca & Scandone, 2001), have penetrated Permian to Early Triassic slightly metamorphosed sandstones and pelites lying beneath the Middle Triassic

Tuscan Verrucano Group (e.g. Lazzarotto et al., 2003). For a compelling review of the literature about the basement and locations of main outcrops across Italy the reader should refer to Vai (2001) and references therein.

The compressional structures of the study area were subsequently disrupted by extensional tectonics, generating both WSW and ENE dipping normal faults, starting from the Late Pliocene-Early Pleistocene (Cosentino et al., 2017), which control the deposition of important continental basins such as the Norcia and Castelluccio di Norcia Basins (Figure 1). These basins represent the topographic expression of the active faults that generated the 2016-2017 seismic sequence.

Figure 1 should be inserted here in colors.



Caption for figure 1: Geologic map of the study area with the location of the three model sections. White dashed line across section 2 corresponds to the geologic cross-section described by Porreca et al. (2018). Events locations, magnitude and focal mechanisms are from Chiaraluce et al. (2017). Basemap topography is from Tarquini et al. (2007; 2012).

3 Data and Methods

The study area consists of the area affected by the 2016-2017 seismic sequence. Here the Umbria-Marche fold and thrust belt places a Triassic to Miocene carbonate sequence over the siliciclastic turbidites of the upper Miocene Laga Formation. These two sedimentary sequences are separated by the M. Sibillini thrust (MSt in figure 1).

The magnetic data used in this work (Figure 2a) are derived from the aeromagnetic map obtained by integrating previous datasets (Caratori Tontini et al., 2004 and references therein). Across the study area, the intensity of the anomaly ranges between -15 and 50 nT, with a general eastward increasing trend.

The Bouguer anomaly map (Figure 2b) was calculated from ~50,000 original data points provided by the Italian oil company (eni) across Central Italy (see Figure S1), using a reduction density of 2670 kg m^{-3}. The Bouguer gravity anomaly shows an eastward decreasing trend, from maximum values of ~10 mGal (10^{-5} m sec^{-2}) to minimum values of -70 mGal toward the eastern sector of the study area.

The modeling was performed along three ~65 km long sections oriented from WSW-ENE (sections 1 and 2) to WNW-ESE (section 3) in order to include the main 2016-2017 seismic sequences and to avoid data gap in the gravity anomaly in the internal areas of the mountains (see Figure S1). The sections cover the Umbria-Marche Apennines on the west, dominated by Mesozoic-Cenozoic carbonates, and the eastern Laga Domain, dominated at the surface by siliciclastic turbidites.

Below we describe in more detail the procedure used to create the models: Step 1 – Geological model. The geological constraints are provided by (i) surface geology (Pierantoni et al., 2013; Carta Geologica Regionale 1:10000 – Regione Marche, 2014; Carta Geologica Regionale 1:10000 – Regione Umbria, 2016); (ii) the geologic model recently proposed by Porreca et al. (2018) for the upper crust (0-12 km), constrained to surface data, boreholes and seismic reflection profiles (hereafter called the “reference geological model”); (iii) seismic refraction data to constrain middle and lower crust geometries (e.g. Ponziani et al., 1995) and densities (e.g. Gualtieri & Zappone, 1998); and (iv) Moho maps (e.g. Pontevivo & Panza, 2002; Piana Agostinetti & Amato, 2009; Di

Stefano et al., 2011). In this work we define the basement as the central part of the crust, between the Triassic evaporites and the lower crust, with a positive k, capable of producing detectable magnetic anomalies (i.e. magnetic basement, sensu Speranza & Chiappini, 2002). The section 2 of this work was traced on the same section of the Reference Geological Model and extended both toward east and west (figure 1). The geological models along sections 1 and 3 were produced integrating the reference geological model with a preliminary interpretation of the seismic reflection profiles of the dataset provided by eni (see Figure S2). This task was accomplished using the MOVE © software.

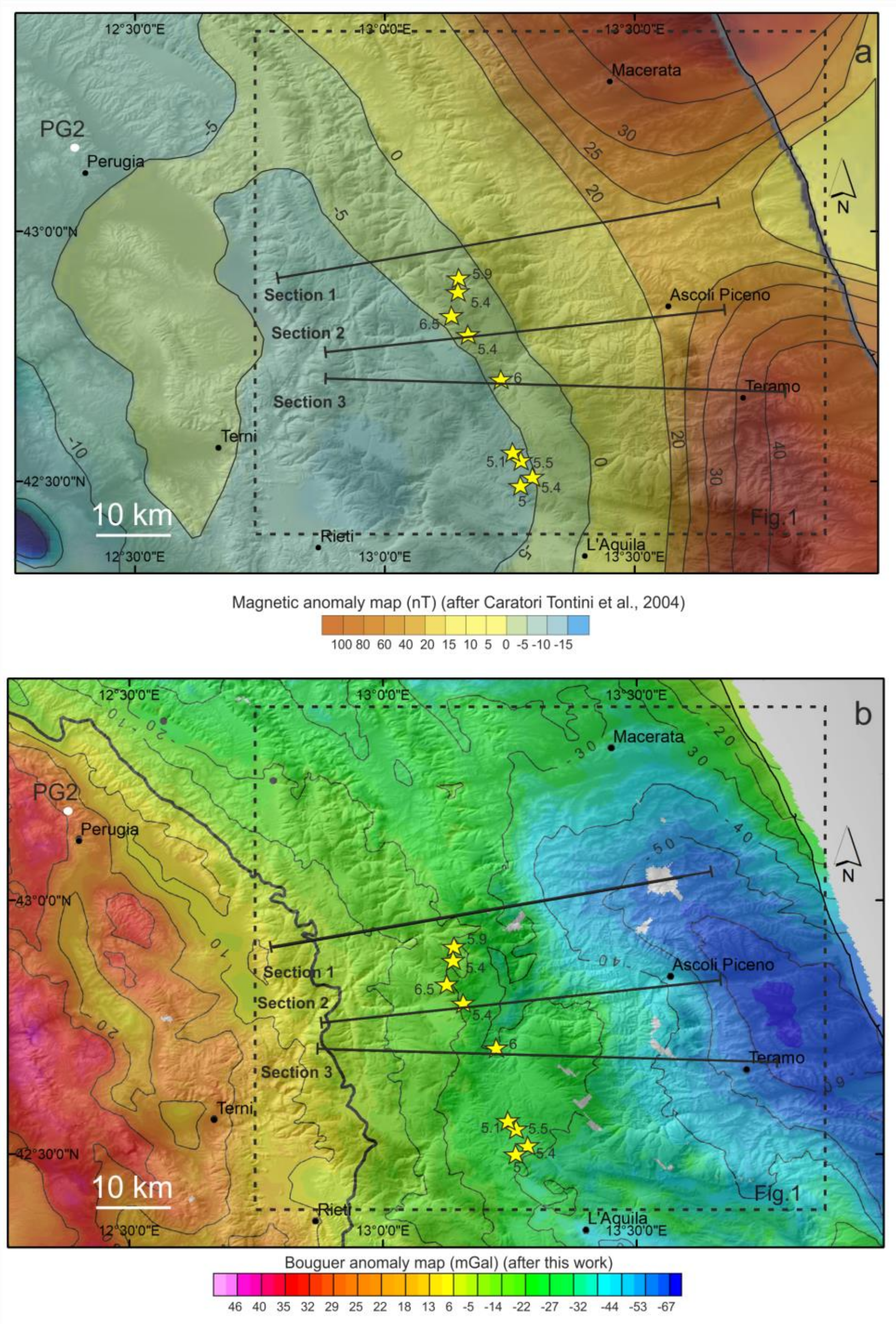
Step 2 – Geophysical data. The magnetic anomaly map (Figure 2a), the Bouguer anomaly map (Figure 2b), the heat flow map (Figure 7.2 from Della Vedova et al., 2001) and locations of the events of the 2016-2017 sequence (Chiaraluce et al., 2017) were georeferenced and included in the dataset. This step, along with the Bouguer map creation (see supporting material) was achieved using the Oasis Montaj © GEOSOFT software suite.

Step 3 – Petrophysical constraints. In this step we compiled and organized the physical properties of the geological units involved in the modeling to constrain the modeled blocks. Considering the lack (see Figure S1 in the supporting material) of sonic logs from borehole data in the area crossed by the sections (the Amandola1 well reports no sonic log), values of density (ρ) and magnetic susceptibility (k) of the investigated units, were derived from previous studies that used forward modeling on gravity and/or magnetic anomalies (e.g. Arisi Rota & Fichera, 1987; Cassinis et al., 1991; Scarascia et al., 1998; Speranza & Chiappini, 2002; Di Luzio et al., 2009; Mancinelli et al., 2015). Additional information were derived from studies using seismic velocities to retrieve densities used in Finite Elements Models (FEM) (e.g. Pauselli & Federico, 2003), from sonic velocity from borehole drilling the same units investigated here but in the Northern Apennines and Po plain (e.g. Montone & Mariucci, 2015 and references therein) or direct measurements on samples of Neogene and Quaternary basins (Mattei et al., 1997) or in the L'Aquila and Sulmona basins (Minelli et al., 2018). After a careful review of the available data (see Table T1), several values have been tested during the initial modeling of section 2 in order to provide reference starting values of the Mesozoic-Cenozoic units where the Reference Geological Model provided geometric and lithological constraints. The resulting values – i.e. ρ of 2670 kg m^{-3} and null k for the evaporites, ρ of 2580 kg m^{-3} and null k for the carbonates and ρ of 2300 kg m^{-3} and 0.0001 SI units of k for the turbidites, have been taken as starting values for these units. ρ of 2900 kg m^{-3} and k of 0.001 SI units for the lower crust and ρ values for the AD mantle of 3200 kg m^{-3} and for the TLP mantle of 3170 kg m^{-3} have been taken from previous models (e.g. Arisi Rota & Fichera, 1987; Scarascia et al., 1998; Speranza & Chiappini, 2002). The Curie depth was also estimated to provide the maximum depth of magnetic sources used in the models. Considering surface heat flow values between 40 and 50 mW m^{-2} (Della Vedova et al., 2001) and an average thermal conductivity of the crust between 2.5 and 2.0 W m^{-1} K^{-1} (Pauselli et al., 2006; Pauselli & Ranalli, 2017), the thermal gradient within the area ranges between 16 and 25 K km^{-1} (Fourier, 1822). Thus, assuming a magnetite Curie temperature of ~600 °C (e.g. Frost & Shive, 1986; Shive et al., 1992), the calculated Curie depth ranges between 24 and 37.5 km.

Step 4 – Model calculation. Finally, considering the aforementioned constraints, through forward modeling we fit the observed gravity and magnetic anomaly values by matching the calculated anomaly produced by model blocks according to their geometries, ρ and k. Once the modeling on section 2 was completed, we adopted similar geometries on sections 1 and 3. This step was constrained by using the same ρ and k used in section 2. Modeling was carried out assuming the bottom of the models as Pratt's depths of compensation where a constant isostatic load is achieved. Declination (-0,1°), inclination (+58°) and intensity (45613 nT) of the magnetic field used for modeling, are in agreement with the data reduction epoch of the aeromagnetic map – i.e. 1979 (Caratori Tontini et al., 2004). Moreover, to reduce edge effects, models were extended in both ends for the length of the modeled section (i.e. ~70 km), maintaining the contacts between bodies at the level modeled at the ending points of the sections. Considering the length of the sections, we neglected the effect of the roundness of Earth's surface along all models.

Table T1 should be inserted here. It is attached at the end of this file.

Figure 2 should be inserted here in colors



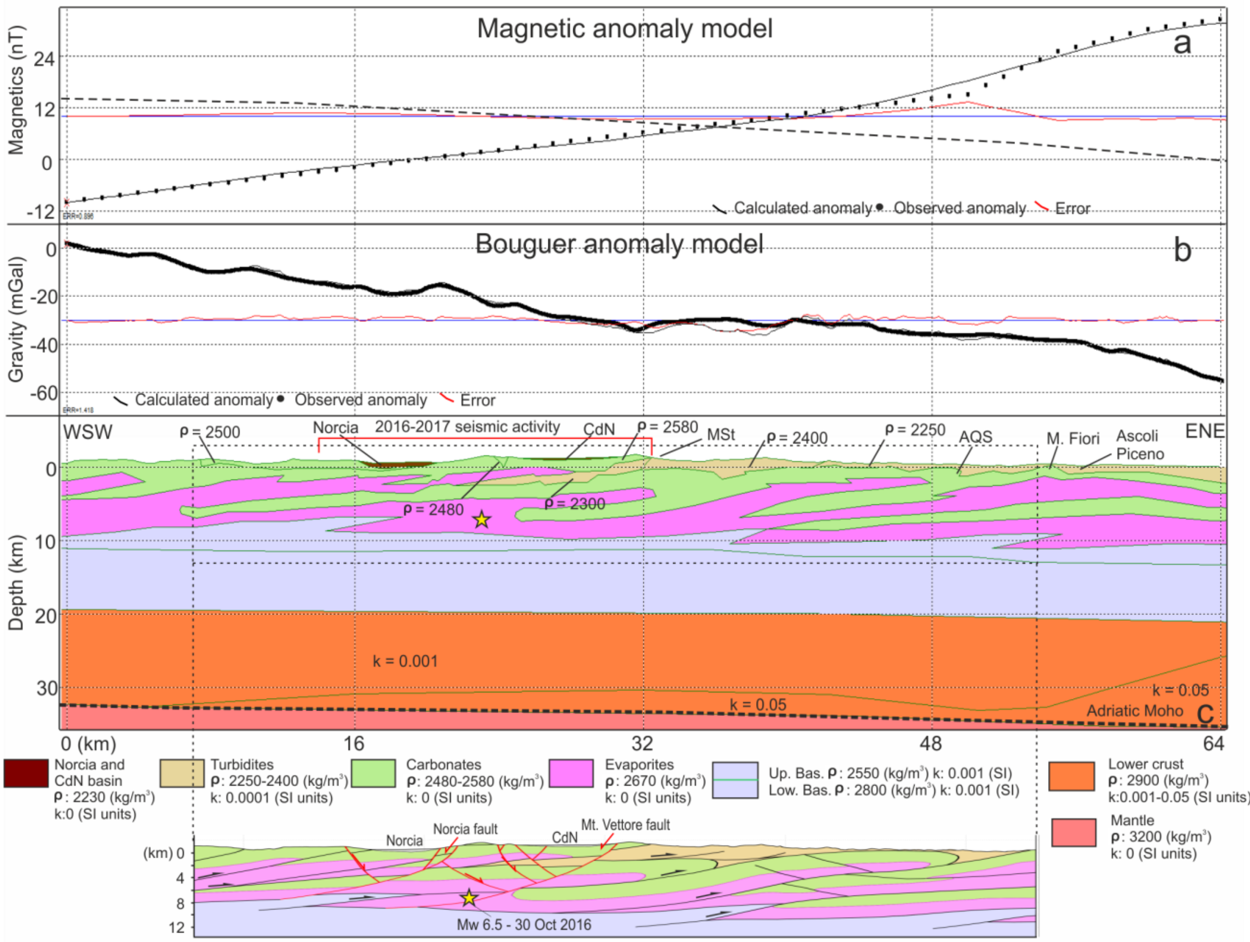
Caption for figure 2: (a) Magnetic anomaly map after Caratori Tontini et al. (2004) covering the area. (b) Bouguer gravity anomaly map from interpolation of ~50,000 data points (see Figure S1 for further details). Black bold isoline in (b) represents the zero-gravity anomaly. White dot is the Perugia 2 borehole. Events locations, magnitude and focal mechanisms are from Chiaraluce et al. (2017). Basemap topography is from Tarquini et al. (2007; 2012).

4 Results and description of the models

A good fit between the observed gravity and magnetic anomalies and those predicted by assigning reasonable density and magnetic susceptibility values to the bodies in the reference geological model, is obtained. The largest misfit (~ 5 mGal) between the observed and predicted gravity values is observed only east of the MSt, ~36 km along the section model, where the turbidites are thickest (Figure 3b). Considering the good quality of the seismic reflection data in this part of the section that encompasses the turbidites sequence (see the geological model at the bottom of Figure 3c), we maintain the geometry proposed in the starting geological model.

The observed short-wavelength gravity anomalies across section 2 (Figure 3b) are reproduced assuming slight changes in ρ values from the aforementioned reference values, for the carbonates and the turbidites. In particular, we used ρ values between 2480 and 2580 kg m^{-3} for the carbonates and values between 2250 and 2400 kg m^{-3} for the turbidites (Figure 3c). The lowest ρ values for the carbonates and the turbidites have been used beneath the Apennines ridge, while the highest values of ρ for the turbidites have been used east of the MSt (Figure 3c). These ranges are in agreement with previously published values (e.g. Montone and Mariucci, 2015) and have also been used in modeling sections 1 and 3. The best-fitting ρ and k values are provided within each model (Figure 3-5).

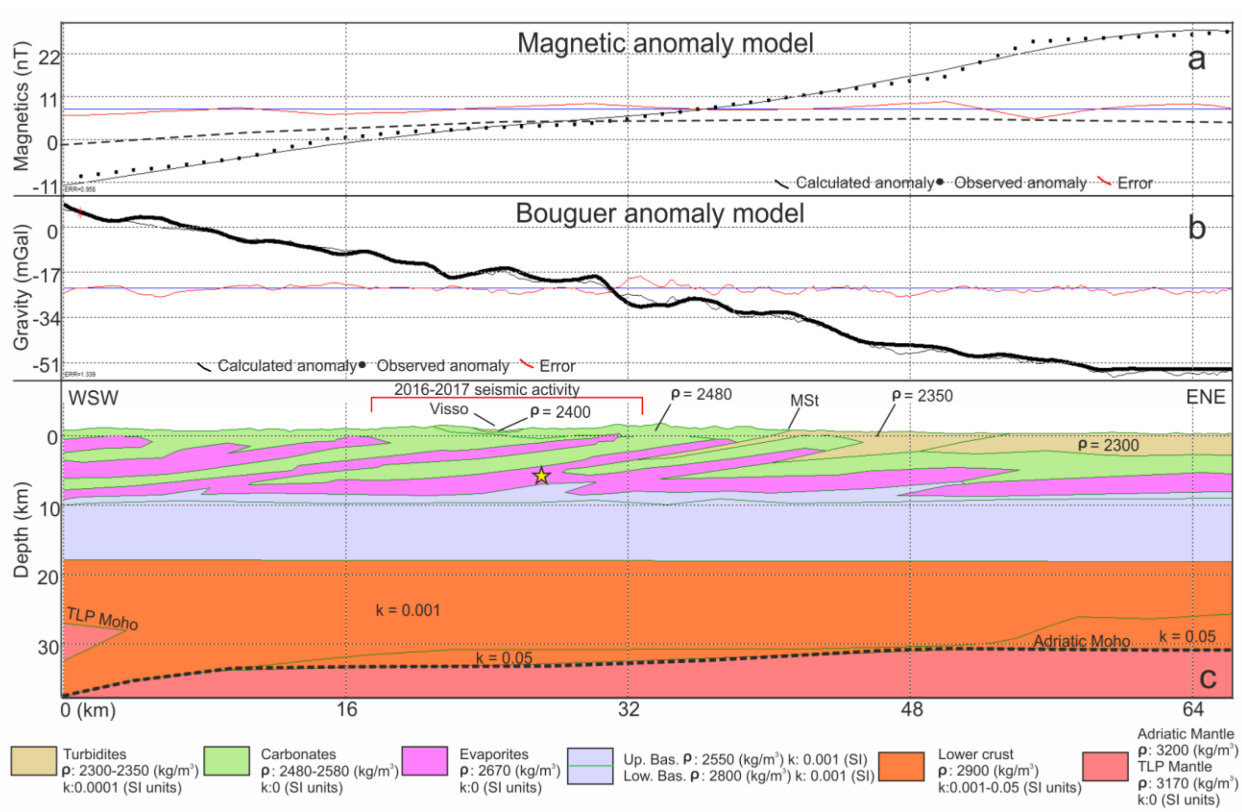
Figure 3 should be inserted here, in colors.



Caption for figure 3: Joint gravity and magnetic model of section 2. (a) Observed and modeled magnetic anomalies. (b) Observed and modeled Bouguer gravity. (c) Modelled blocks. The geological model after Porreca et al. (2018) is reported at the bottom of the figure. For densities (ρ) and magnetic susceptibilities (k) not provided for blocks in (c), please refer to the values at the bottom of the figure. The star projects the Mw 6.5 30 October 2016 event from Chiaraluce et al. (2017). ρ and k for the modeled units are given in the figure (see the text and the table T1 for further details). CdN: Castelluccio di Norcia basin, AQS: Acquasanta thrust, MSt: Mount Sibillini thrust. ρ of the turbidites range from 2300 kg m^{-3} in the central part of the section, to 2400 kg m^{-3} east of the MSt to 2250 kg m^{-3} further east from 41 km to end of the section. Lower ρ (2480 kg m^{-3}) for the carbonates are found between 8 and 20 km along section model and between the Norcia and CdN basins and from surface to ~0 km in depth. Dashed line in (a) represents the retrieved anomaly with a magnetic susceptibility of 0.001 (SI) for the entire lower crust (i.e. without the high-k body at the base of the crust). Black dashed line in (c) locates the Curie isotherm (600 °C). Vertical-to-horizontal scale ratio in (c) is 0.4. Gravity data stations are on surface, magnetic data stations are at 2500 m altitude (Caratori Tontini et al., 2004).

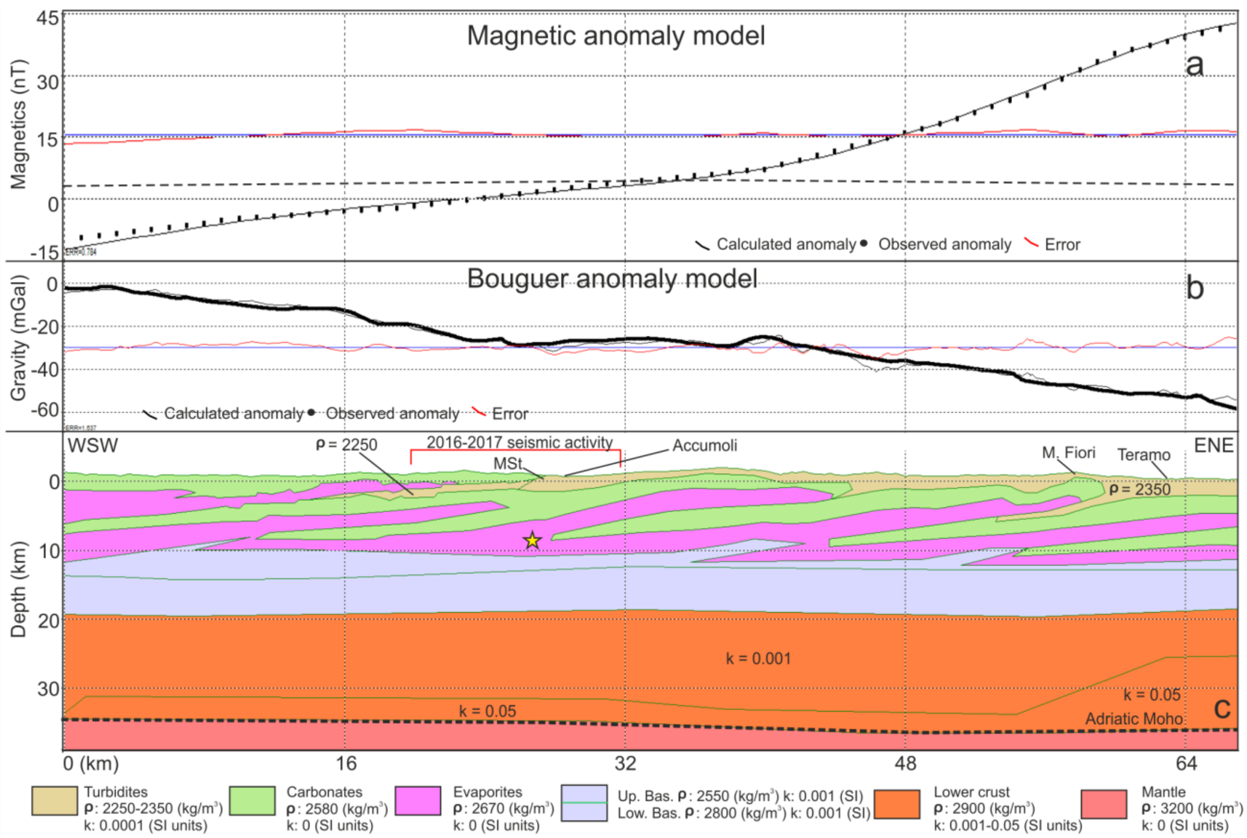
The resulting models for sections 1 and 3 (figures 4 and 5) show the best-fitting solutions considering the surface geology, the observed and calculated gravity and magnetic anomalies and the structural model tested in modeling of section 2. Across all sections (Figures 3-5), the magnetic and gravity anomalies show opposite overall trends, with magnetic values increasing and gravity values decreasing eastward. The AD Moho ranges between 30 and 35 km. Its spatial trend and transition with the TLP Moho, that was observed only in section 1 (Figure 4c), are comparable with previous observations (e.g. Ponziani et al., 1995; Pontevivo & Panza, 2002; Piana Agostinetti & Amato, 2009; Di Stefano et al., 2011) and models (Scarascia et al., 1998). The Curie depth is found between 30 and 35 km across all sections.

Figures 4 and 5 should be inserted here, in colors



Caption for figure 4: Joint gravity and magnetic model of section 1 (north). (a) Observed and predicted magnetic anomalies. (b) Observed and predicted Bouguer gravity. (c) Modelled blocks. For densities (ρ) and magnetic susceptibilities (k) not provided for blocks in (c), please refer to the values at the bottom of the figure. The star projects the Mw 5.9 26 October 2016 event from

Chiaraluce et al. (2017). ρ and k for the modeled units are given at the bottom of the figure (see the text and Table T1 for further details). MSt: Mount Sibillini thrust. Higher ρ (2350 kg m^{-3}) for the turbidites are found between model coordinates 34 and 53 km. Lower ρ (2480 kg m^{-3}) for the carbonates are found between 20 and 40 km along section model and from surface to ~1 km in depth. Dashed line in (a) represents the retrieved anomaly with a magnetic susceptibility of 0.001 (SI) for the entire lower crust. Black dashed line in (c) locates the Curie isotherm (600 °C). Vertical-to-horizontal scale ratio in (c) is 0.4. Gravity data stations are on surface, magnetic data stations are at 2500 m altitude (Caratori Tontini et al., 2004).



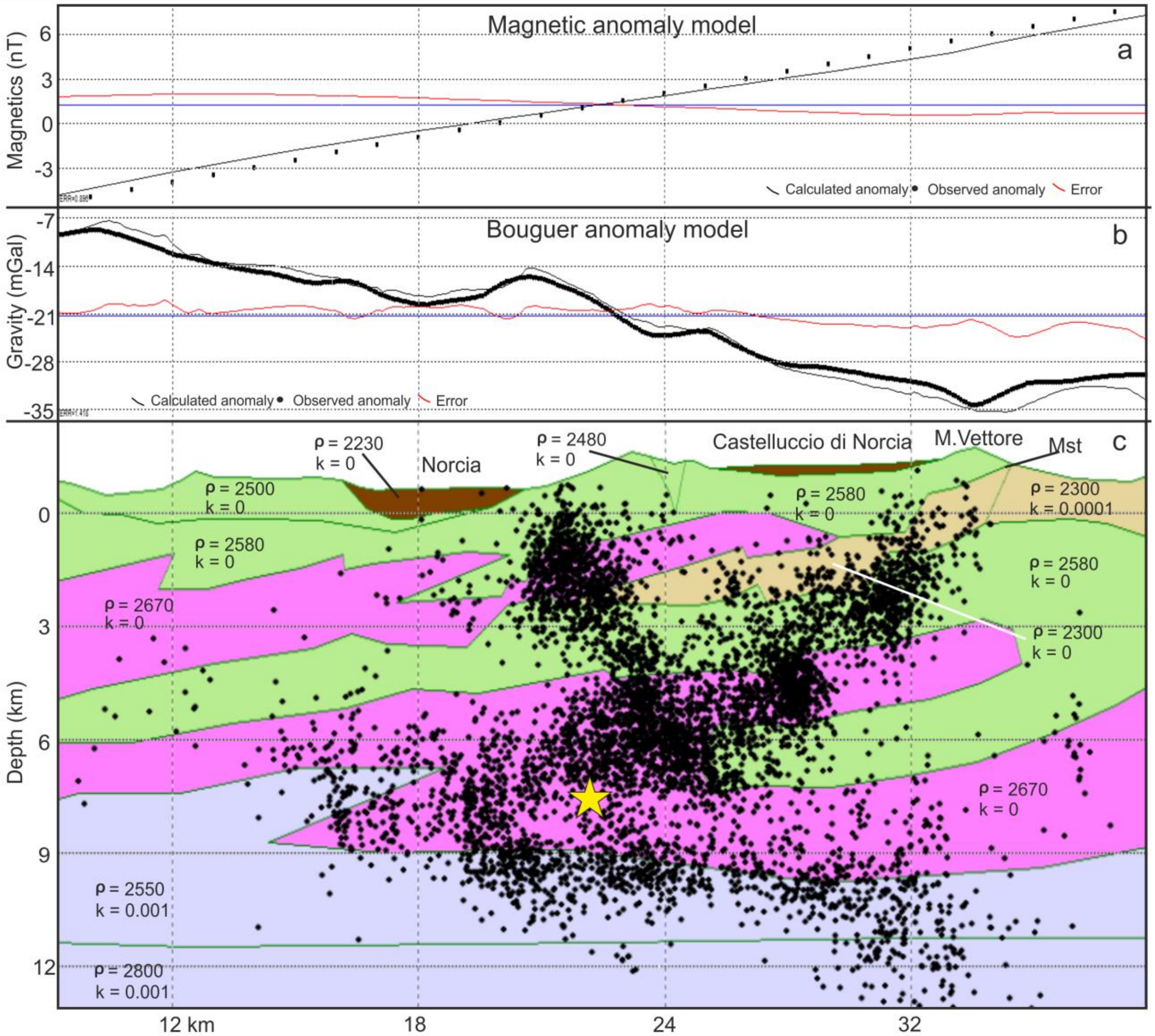
Caption for figure 5: Joint gravity and magnetic model of section 3 (south). (a) Observed and predicted magnetic anomalies. (b) Observed and predicted Bouguer gravity. (c) Modelled blocks. For densities (ρ) and magnetic susceptibilities (k) not provided for blocks in (c), please refer to the values at the bottom of the figure. The star projects the Mw 6.0 24 August 2016 event from Chiaraluce et al. (2017). ρ and k for the modeled units are given in the figure (see the text and the table T1 for further details). MSt: Mount Sibillini thrust. ρ of the turbidites range from 2250 kg m^{-3} under the chain, between model coordinates 15 and 25 km, to 2350 kg m^{-3} east of the MSt to the end of the section. Dashed line in (a) represents the retrieved anomaly with a magnetic susceptibility of 0.001 (SI) for the entire lower crust. Black dashed line in (c) locates the Curie isotherm (600 °C). Vertical-to-horizontal scale ratio in (c) is 0.4. Gravity data stations are on surface, magnetic data stations are at 2500 m altitude (Caratori Tontini et al., 2004).

The models are consistent with a top of the basement between 8 and 12 km of depth, with a slight eastward-deepening trend observed across all the sections. The involvement of the top of the basement by major thrusts as derived from the reference geologic model, is compatible with the observed gravity and magnetic anomalies across all models. The basement reaches its maximum depth (~12 km) at the eastern end of section 3 (Figure 5c).

The contribution to the magnetic anomaly is mostly given by the basement and deep crust with minor contribution from Turbidites, whose susceptibility (0.0001 SI) is in agreement with values proposed by previous works (Speranza & Chiappini, 2002). In particular, the basement and the upper portion of the deep crust contributes with moderate susceptibilities (0.001 SI units) while the major contribution to the magnetic anomaly has a deep origin at the base of the crust with an anomalous body with high susceptibility (0.05 SI units). This anomalous body is as much as ~10 km thick (i.e. ranging in depths from 25 to 35 km) in the eastern part of the sections and its thickness decreases northward (i.e. from section 3 to section 1) and westward across all models (Figures 3-5).

Short-wavelength (< 10 km) gravity anomalies are mainly found in the central part of the sections (Figure 3-6), within or near the area involved by the 2016-2017 seismic sequence. The Quaternary Norcia and Castelluccio continental basins correspond with negative gravity anomalies (≤ 7 mGal; Figure 6). The gravity lows are fit by the shallow continental sediments – i.e. gravels, sands and clays (e.g. Calamita & Pizzi, 1992; Blumetti et al., 1993; Coltorti & Farabollini, 1995) infilling the basins, having the lowest ρ (2230 kg m^{-3}) across all models.

Figure 6 should be inserted here, in colors



Caption for figure 6: Detail of the joint gravity and magnetic model of section 2. (a) Observed and modeled magnetic anomalies. (b) Observed and modeled Bouguer gravity. (c) Modelled blocks. The star projects the Mw 6.5 30 October 2016 event from Chiaraluce et al. (2017). Black dots mark the aftershocks from the same catalogue projected with a buffer of 3 km north and south of the section. Coordinates at the base of the figure refer to model coordinates in Figure 3. Vertical-to-horizontal scale ration in (c) is 1.

5 Discussion

The availability of several geological, geophysical and petrophysical data of the Central and Northern Apennines, allowed us the investigation of the post-orogenic extension dynamics in a detailed and multidisciplinary approach. Using established methods (i.e., forward modeling of gravity and magnetic anomalies) in a constrained approach, allowed us to define crustal geometries and properties beyond depths probed by geological models, contributing in understanding the role played by post-orogenic stratigraphy on the extensional phase.

Geometries retrieved from the reference geological model used on section 2 are compatible with the observed gravity and magnetic anomalies from the surface to ~12 km of depth. Considering the good fit obtained across both models, the resulting best-fitting geometries for sections 1 and 3 are in agreement with the structural model proposed on section 2. In fact, both magnetic and gravity anomalies predicted along these sections fit the observed anomalies producing errors with magnitude similar to those obtained on the geologically-constrained section 2. In our opinion, this approach further validates the initial geological model proposed by Porreca et al. (2018), which is consistently supported across the entire study area.

The top basement depth is consistent across the entire area, ranging between 8 and 12 km, slightly deepening toward the ESE. Only the major thrusts faults offset the basement across all the three sections. Layering of the basement is coherently represented across all the three sections with two basement layers contributing to the gravity and magnetic anomaly.

The resulting layering and petrophysical properties of the basement provides some suggestions about the nature of the basement in the area. In fact, the ρ and k of the upper layer are compatible with slightly metamorphosed continental deposits (phyllites) that may be related to the metamorphic units drilled by the Perugia 2 well (Figures 2a-b), ~25 km NW of the study area (e.g. Bally et al., 1986; Vai, 2001; Speranza & Chiappini, 2002). The main magnetic source is the high-k (0.05 SI units) body in the lower crust (25-35 km) whose thickness decreases both toward north and west. This result is in agreement with a recent study of the magnetic anomaly in the Central Apennines (Minelli et al., 2018) where a deep source (35-40 km) related to high k (0.05 SI units) materials was hypothesized without other contributions from middle or upper crust. Consistently, the Curie depth is found between 30 and 35 km across all sections, coinciding with the Moho discontinuity that marks a magnetic boundary without contributions to the magnetic anomaly coming from the mantle (Wasilewski et al., 1979; Wasilewski & Mayhew, 1992). To highlight the contribution of the deep high-k body to the magnetic anomaly, we show also the retrieved magnetic anomaly if a magnetic susceptibility of 0.01 is given to the entire deep crust – i.e. without the high-k body (dashed lines in Figures 3a, 4a and 5a).

We are conscious that modelling potential fields has intrinsic limitations due to the non-uniqueness of the retrieved geometries and depths of sources. Detecting gently-dipping lateral contrasts of density or magnetic susceptibility is another limitation of the method *per se*, but including external constraints such as geologic models and independent geophysical models – e.g. Moho depth from receiver functions (e.g. Piana Agostinetti & Amato, 2009) and depth of magnetic sources retrieved from Euler deconvolution (Minelli et al., 2018), certainly increases the reliability of the retrieved models. In those cases where constraints are limited or not available (e.g. the composition and physical properties of the basement with moderate k) we preferred to maintain the geometry as simpler as possible and use parameters (density and magnetic susceptibility) as much homogeneous as possible. For these reasons, the slight misfits between the observed and predicted magnetic anomaly observed in model 1 (between model coordinates 50 and 55 km) and model 2 (at model coordinate ~50 km) were not fitted. However, these slight misfits (± 3 nT) can be attributed to local variations in depth or geometry of the magnetic source and/or of the magnetic susceptibility of modeled bodies.

The results from the magnetic models suggest that the Central and Northern Apennines have been built above a cold and thick crust with an average thermal gradient across the modeled sections of ~17 ° km^{-1}, roughly calculated assuming a Curie temperature of 600 °C and an average Curie depth of 34 km. This thermal gradient is in agreement with surface heat flow observations, with the rheology and location of seismic events in the area (Chiaraluce et al., 2017), and with models produced for the L'Aquila and Sulmona basins area (Minelli et al., 2018). The values of k used for the basement, the lower crust and the anomalous source at the base of the lower crust also provide some information about the nature of these bodies. In fact, they are compatible with a low metamorphic grade basement and lower crust, overlying a high-k volume. Considering its depth, the nature of this anomalous high-k volume is uncertain, but similar values of k were measured in some lower crust gneisses and mafic and ultramafic rocks from the Lofoten area (Schlinger, 1985), in the Ivrea-Verbano deep crust (Rochette, 1994) and were more recently hypothesized also in the Southern Apennines (Minelli et al., 2018). However, the k values used in this work exclude the possibility of a granitic composition for the high-k modeled bodies (Punturo et al., 2017). Moreover, in the Lofoten samples it was argued against a significant contribution of the Natural Remanent Magnetization (NRM) of the lower crust on a regional scale because of its polymetamorphic nature and the unstable and viscous signature of the NRM in the studied samples (Schlinger, 1985 and references therein).

The lower ρ, required for the carbonates (sections 1 and 2) and the turbidites (sections 2 and 3) under the Apennines chain (Figure 6) to fit the observed short-wavelength gravity anomalies may possibly represent the effect of a higher fluid content in tectonically-induced fracturing of the shallow units (e.g. Stierman, 1984). This interpretation is supported by the evidence that the lowest ρ values for the turbidites are found in sections 2 and 3 – i.e. the only sections where turbidites are found beneath the chain, in the seismically active region (Figures 3, 5 and 6). On the other hand, the range of ρ assigned to the turbidites east of the chain, shows a general eastward-decreasing trend (sections 1 and 2). This tendency may be the result of local fracturing and compaction affecting the initial ρ values. Similar causes can explain the misfit between observed and calculated gravity anomaly of the turbidites east of the MSt in section 2 (Figure 3b). However, to best isolate the cause of these features will certainly require further detailed and local investigation, possibly removing the regional trend in order to highlight these short-wavelength anomalies.

Seismic events of the 2016-2017 sequence have been plotted in the models of sections 1-3 and mainshocks of Mw > 5.5 fall within the deep evaporite unit (Figures 3-6) immediately overlying the basement. Considering the maximum depth of the seismicity across the area – i.e. 10-12 km (Chiaraluce et al., 2017) and the spatial distribution of the top of the basement from our models, we believe that these models, by constraining the top of the basement in the area, provide an explanation of the seismicity cutoff for the 2016-2017 sequence. These findings, coupled with the low thermal gradient retrieved from the Curie depth, highlight the lithologic control exerted by the post-orogenic stratigraphy on the extensional seismogenic layer which is mainly confined in the Mesozoic-Cenozoic sequences across the entire area. In fact, if the seismicity distribution at depth was driven by temperature, the brittle-ductile transition should have been deeper and, in turn, deeper events should have been observed.

6 Conclusions

The first joint gravity and magnetic models of the Central and Northern Apennines were produced across three cross-sections in the region struck by the 2016-2017 seismic sequence. The models were constrained by geologic surface observations and by a recent subsurface geological model for the central part of the area.

The best-fitting potential field models, based on the structural model proposed by Porreca et al. (2018), namely a combination of thick- and thin-skinned styles with thrusts involved in the compressional tectonics and seismicity mostly confined above the basement, provides new constraints on the structural setting of the area. These models provide likely physical properties that can be related to the composition of the basement and lower crust across the area. In fact, the modeled ρ and k values of the upper basement are compatible with slightly metamorphosed continental deposits, while k values used for the lower basement and lower crust are compatible with a moderately-magnetic composition overlying a mafic or ultra-mafic volume at the base of the crust beneath the eastern part of the study area. The nature and origin of this anomalous high-k body should be framed in the early geodynamic evolution of the Adria crust. These results imply a cold crust model with an average thermal gradient of ~17 ° km^{-1} that fits the low surface heat flow observations, the maximum depth of seismicity and previous models of the Central Apennines.

Resulting models provide support of the geological and geophysical understanding of the area and help evaluate the parameters controlling the seismicity distribution at depth. In particular, the correlation of the maximum depth of seismicity and the modeled top of basement suggests that the mechanical stratigraphy of the upper crust influences the thickness of the seismogenic layer, whose base grossly coincides with the top of the basement across the entire area, as also shown in the northermost part of the extensional belt (Barchi, 2002; Mirebella et al., 2008; Latorre et al., 2016). In fact, all earthquakes of the 2016-2017 sequence with Mw > 5.5 are found within deep evaporites, above the top of the basement.

Combining these results with those obtained for the 1997-1998 Umbria-Marche sequence (e.g. Barchi & Mirabella, 2009 and references therein), we confirm that lithology plays a major contribution in controlling the depth of seismicity across the entire Umbria-Marche Apennines. In fact, mainshocks of the Umbria-Marche 1997-1998 and 2016-2017 sequences are always found in the deep evaporites unit, above the basement.

The multidisciplinary modeling approach used in this work, embracing potential field methods, surface geology and structural models, has proven to be robust and should be adopted to investigate other post-orogenic extensional scenarios.

7 References

Anelli, L., Gorza, M. Pieri, M. & Riva, M. (1994). Subsurface well data in the Northern Apennines (Italy). Memorie della Società Geologica Italiana, 48, 461-471.

Arisi Rota, F & Fichera, R. (1987). Magnetic interpretation related to geo-magnetic provinces: the Italian case history. Tectonophysics 138, 179-196.

Bally, A. W., Burbi, L., Cooper, C., & Ghelardoni, R. (1986), Balanced cross-sections and seismic reflection profiles across the Central Apennines. Memorie della Società Geologica Italiana, 35, 257-310.

Barchi, M. R., Minelli, G. & Pialli, G. (1998). The CROP 03 profile: a synthesis of results on deep structures of the Northern Apennines. Memorie della Società Geologica Italiana, 52, 383-400.

Barchi, M. R., Landuzzi, A., Minelli, G., & Pialli, G. (2001). Outer northern Apennines. In anatomy of an orogen: The Apennines and adjacent Mediterranean Basins (pp. 215–253). Netherlands: Springer.

Barchi, M. R. & Mirabella, F. (2009), The 1997-98 Umbria-Marche earthquake sequence: “Geological” vs. “seismological” faults. Tectonophysics, 476, 170-179. doi:10.1016/j.tecto.2008.09.013

Barchi, M. R. (2010), The Neogene-Quaternary evolution of the Northern Apennines: crustal structure, style of deformation and seismicity. Journal of the virtual explorer 36 (10), doi:10.3809/jvirtex.2010.00220

Bigi, S., Casero, P., & Ciotoli, G. (2011). Seismic interpretation of the Laga basin; constraints on the structural setting and kinematics of the central Apennines. Journal of the Geological Society, 168(1), 179–190. https://doi.org/10.1144/0016-76492010-084

Blumetti, A. M., Dramis, F., & Michetti, A. M. (1993). Fault-generated mountain fronts in the central Apennines (Central Italy): Geomorphological features and seismotectonic implications. Earth Surface Processes and Landforms, 18(3), 203–223. https://doi.org/10.1002/esp.3290180304Boccaletti, M., Conedera, C., Dainelli, P. and Gocev, P.

(1982). The recent (Miocene-Quaternary) regmatic system of the western Mediterranea region. J. Petrol. Geol. 5, 31–49

Calamita, F. & Pizzi, A. (1992). Tettonica quaternaria nella dorsale Appenninica Umbro-Marchigiana e bacini intrappenninici associati. Studi Geologici Camerti, volume speciale (1992/1), 17–25.

Caratori Tontini, F., Stefanelli, P., Giori, I., Faggioni, O. & Carmisciano C. (2004). The revised aeromagnetic anomaly map of Italy. Annals of Geophysics 47(5), 1547–1555.

Carminati, E. & Doglioni, C. (2012). Alps vs. Apennines: the paradigm of a tectonically asymmetric Earth. Earth-Science Reviews, 112(1-2), 67-96.

Carta Geologica Regionale 1:10000 – Regione Marche (2014). Regione Marche – P. F. Urbanistica, Paesaggio e Informazioni Territoriali. Retrieved from http://www.ambiente.marche.it/Territorio/Cartografiaeinformazioniterritoriali/Archiviocartograficoeinformazioniterritoriali/Cartografie/CARTAGEOLOGICAREGIONALE110000.aspx

Carta Geologica Regionale 1:10000 – Regione Umbria (2016). Geoportale WebGis Regione Umbria. Direzione Ambiente, Territorio e Infrastrutture Servizio Geologico e Sismico. Retrieved from http://storicizzati.territorio.regione.umbria.it/Static/GeologiaKmz/GeologiaKmz/Index_kmz.htm

Cassano, E., Anelli, L., Cappelli, V. & La Torre P. (2001), Magnetic and gravity analysis of Italy. In: Anatomy of an orogen: the Apennines and adjacent Mediterranean basins. By Vai G. B. & Martini I. P. (eds.), 53-64 Kluwer Academic Publishers.

Cassinis, R., Pialli, G., Broggi, M. & Prosperi, M. (1991), Dati gravimetrici a grande scala lungo la fascia del profilo: interrogativi sull'assetto della crosta e del mantello. Studi Geologici Camerti, volume speciale 1991/1, 41-47.

Centamore, E., Adamoli, L., Berti, D., Bigi, G., Bigi, S., Casnedi, R., Cantalamessa, G., Fumanti, F., Morelli, C., Micarelli, A., Ridolfi, M. & Salvucci, R. (1992). Carta geologica del bacino della Laga e del Cellino e delle zone limitrofe. Selca, Firenze.

Chiaraluce, L., et al. (2017), The 2016 Central Italy Seismic Sequence: A First Look at the Mainshocks, Aftershocks, and Source Models. Seismological Research Letters, 88(3), 757–771. https://doi.org/10.1785/0220160221

Coltorti, M. & Farabollini, P. (1995). Quaternary evolution of the "Castelluccio di Norcia" basin (Umbro-Marchean Apennines, Central Italy. Il Quaternario 8(1), 149-166.

Cosentino, D., Asti, R., Nocentini, M., Gliozzi, E., Kotsakis, T., Mattei, M., et al. (2017). New insights into the onset and evolution of the central Apennine extensional intermontane basins based on the tectonically active L'Aquila Basin (central Italy). GSA Bulletin, 129(9–10), 1314–1336.

Della Vedova, B., Bellani S., Pellis G. & Squarci P. (2001), Deep temperatures and surface heat flow distribution. In: Vai G. B. & Martini I. P. (Eds.): Anatomy of an orogen: the Apennines and adjacent Mediterranean basins. Kluwer Academic Publishers:65-76, Dordrecht, The Netherlands.

Di Luzio, E., Mele, G., Tiberti, M. M., Cavinato, G. P. & Parotto, M. (2009), Moho deepening and shallow upper crustal delamination beneath the central Apennines. Earth and Planetary Science Letters 280, 1-12, doi:10.1016/j.epsl.2008.09.018

Di Stefano, R., Bianchi, I., Ciaccio, M. G., Carrara, G. & Kissling E. (2011), Three-dimensional Moho topography in Italy: New constraints from receiver functions and controlled source seismology. Geochem. Geophys. Geosyst., 12, Q09006, doi:10.1029/2011GC003649.

Düzgit, Z., Hisarli, M., Sayin, N. & Orbay, N. (2006). Correlation between gravity and magnetic anomalies of Western Anatolia and its relation to tectonic structures. Earth Planets Space 58, 943-949.

Fourier, J. (1822). Théorie analytique de la chaleur. Firmin Didot Père et Fils, Paris.

Frost, B. R., & Shive, P. N. (1986). Magnetic mineralogy of the lower continental crust. Journal of Geophysical Research, 91(B6), 6513–6521. https://doi.org/10.1029/JB091iB06p06513

Garland, G. D. (1951). Combined analysis of gravity and magnetic anomalies. Geophysics, 16(1), 51-62. https://doi.org/10.1190/1.1437650

Gualtieri, L. & Zappone, A. (1998). Hypothesis of ensialic subduction in the Northern Apennines: a petrophysical contribution. Memorie Società Geologica Italiana 52, 205-214.

Isaaks, E. H., and Srivastava, R. M. (1989), An Introduction to Applied Geostatistics, Oxford University Press, New York, 561 pp.

Koopman, A. (1983). Detachment tectonics in the central Apennines, Italy. Geologica Eltraiectina, 30, 1–155.

Larocchi, L., Gualtieri, L. & Cassinis, R. (1998), 2D lithospheric gravity modeling along the CROP 03 profile. Memorie Società Geologica Italiana 52, 225-230.

Lavecchia, G. (1985). Il sovrascorrimento dei Monti Sibillini: Analisi cinematica e strutturale. Bollettino della Societa Geologica Italiana, 104, 161–194.

Lavecchia, G., Brozzetti, F., Barchi, M., Keller, J., & Menichetti, M. (1994). Seismotectonic zoning in east-central Italy deduced from the analysis of the Neogene to present deformations and related stress fields. Geological Society of America Bulletin, 106, 1107–1120.Lazzarotto, A., Aldinucci, M., Cirilli, S., Costantini, A., Decandia, F.A., Pandeli, E., Sandrelli, F. & Spina, A.

(2003). Stratigraphic correlation of the Upper Paleozoic- Triassic successions in the southern Tuscany, Italy. Bollettino della Società Geologica Italiana – Volume Speciale 2, 25–35

Luiso, P., Paoletti, V., Nappi, R., Gaudiosi, G., Cella, F. & Fedi, M. (2018). Testing the value of a multi-scale gravimetric analysis in characterizing active fault geometry at hypocentral depths: the 2016-2017 Central Italy seismic sequence. Annals of Geophysics, 61. Doi:10.4401/ag-7852.

Malinverno, A. & Ryan, W.B.F. (1986). Extension in the Tyrrhenian sea and shortening in the Apennines as result of the arc migration driven by sinking of the lithosphere. Tectonics 5, 227-245

Mancinelli, P., Minelli, G., Pauselli, C., & Federico, C. (2015), Magnetic and gravimetric modeling of the central Adriatic region. Journal of Geodynamics, 89, 60-70, doi: 10.1016/j.jog.2015.06.008.

Marson, I., Cernobori, L., Nicolich, R., Stoka, M., Liotta, d., Palmieri, F. & Velicogna, I. (1998), CROP-03 profile: a geophysical analysis of data and results. Memorie Società Geologica Italiana 52, 123-137.

Martinis, B. & Pieri, M. (1964) Alcune notizie sulla formazione evaporitica dell'Italia centrale e meridionale. Mem. Soc. Geol. Ital., 4, 649–678.

Mattei, M., Sagnotti, L., Faccenna, C. & R. Funiciello, R. (1997). Magnetic fabric of weakly deformed clayey sediments in the Italian peninsula: Relationships with compressional and extensional tectonics. Tectonophysics, 271, 107–122.

Milli, S., Moscatelli, M., Stanzione, O. & Falcini, F. (2007). Sedimentology and physical stratigraphy of the Messinian turbidites deposits of the Laga Basin (central Apennines, Italy). Bollettino della Società Geologica Italiana, 126, 37–48.

Minelli G. & Menichetti M (1990). Tectonic evolution of the Perugia massifs area (central Italy), Boll. Soc. Geol. It., 109 (5), 445-453

Minelli, L., Speranza, F., Nicolosi, I., D'Ajello Caracciolo, F., Carluccio, R., Chiappini, S., Messina, A. & Chiappini, M. (2018), Aeromagnetic investigation of the central Apennine Seismogenic Zone (Italy): From basins to faults. Tectonics, 37. https://doi.org/10.1002/2017TC004953

Montone, P. & Mariucci, M. T. (2015), P-wave Velocity, Density, and Vertical Stress Magnitude Along the Crustal Po Plain (Northern Italy) from Sonic Log Drilling Data. Pure and Applied Geophysics, 172, 1547–1561. doi:10.1007/s00024-014-1022-5.

Patacca, E., Sartori, R. & Scandone, P. (1990). Tyrrhenian basin and Apenninic arcs: kinematic relations since Late Tortonian times. Mem. Società Geologica Italiana 45, 425-451.

Patacca, E. & Scandone P. (2001). Late thrust propagation and sedimentary response in the thrust-belt foredeep system of the southern Apennines (Pliocene-Pleistocene), in Anatomy of an

Orogen: The Apennines and Adjacent Mediterranean Basins, edited by G. Vai and I. Martini, pp. 441–454, Kluwer Acad., Norwell, Mass.

Pauselli, C. & Federico, C. (2003), Elastic modeling of the Alto Tiberina normal fault (central Italy): geometry and lithological stratification influlences on the local stress field. Tectonophysics 374, 99-113. Doi:10.1016/S0040-1951(03)00235-X.

Pauselli, C., Barchi, M. R., Federico, C., Magnani, M. B., & Minelli, G. (2006), The crustal structure of the Northern Apennines (Central Italy): An insight by the CROP03 seismic line. American Journal of Science, 306(6), 428–450. https://doi.org/10.2475/06.2006.02

Pauselli, C. & Ranalli, G. (2017), Effects of lateral variations of crustal rheology on the occurrence pf post-orogenic normal faults: the Alto Tiberina Fault (Northern Apennines, Central Itlay). Tectonophysics 721, 45-55.

Piana Agostinetti, N. & Amato A. (2009), Moho depth and vp/vs ratio in peninsular Italy from teleseismic receiver functions. J. Geophys. Res., 114, B06303, doi:10.1029/2008JB005899.

Pierantoni, P. P., Deiana, G., & Galdenzi, S. (2013). Stratigraphic and structural features of the Sibillini Mountains (Umbria–Marche Apennines, Italy). Italian Journal of Geosciences, 132, 497–520. https://doi.org/10.3301/IJG.2013.08

Pontevivo, A. & Panza G. (2002), Group velocity tomography and regionalization in Italy and bordering areas. Phys. Earth Planet. Inter., 134,1–15, doi:10.1016/S0031-92 01(02)00079-1.

Ponziani, F., De Franco, R., Minelli, G., Biella, G., Federico, C. and Pialli, G. (1995). Crustal shortening and duplication of the Moho in the Northern Apennines: a view from seismic refraction data. Tectonophysics 252, 391-418.

Porreca, M. et al. (2018), Seismic reflection profiles and subsurface geology of the area interested by the 2016-2017 earthquake sequence (Central Italy). Tectonics, doi: 10.1002/2017TC004915

Punturo, R., Mamtani, M. A., Fazio, E., Occhipinti, R., Renjith, A. R. & Cirrincione, R. (2017). Seismic and magnetic susceptibility anisotropy of middle-lower continental crust: Insights for their potential relationship froma study of intrusive rocks from the Serre Massif (Calabria, southern Italy). Tectonophysics 712-713, 542-556, doi.org/10.1016/j.tecto.2017.06.020.

Rybakov, M., Goldshmidt, V., Hall, J. K., Ben-Avraham Z. & Lazar, M. (2011). New insights into the sources of magnetic anomalies in the Levant. Russian Geology and Geophysics 52, 377-397. doi:10.1016/j.rgg.2011.03.001

Rochette, P. (1994). Comments on "Anisotropic magnetic susceptibility in the continental lower crust and its implication for the shape of magnetic anomalies" by G. Florio et al. Geophysical Research Letters, 21, 2773–2774.

Royden, L., Patacca, E. & Scandone, P. (1987). Segmentation and configuration of subducted lithosphere in Italy: An important control on thrust belt and foredeep basin evolution. Geology 15, 714-717

Santantonio, M. 1994. Pelagic carbonate platforms in the geologic record: their classification, and sedimentary and palaeotectonic evolution. AAPG Bulletin, 78, 122–141.

Scarascia, S., Cassinis, R. & Federici, F. (1998), Gravity modeling of deep structures in the northern-central Apennines. Memorie Società Geologica Italiana 52, 231-246.

Shive, P. N., Blakely, R. J., Frost, B. R., & Fountain, D. M. (1992). Magnetic properties of the lower continental crust. In D. M. Fountain, R. Arculus, & R. W. Kay (Eds.), Continental lower crust (pp. 145–177). New York: Elsevier Sci.

Schlinger, C. M. (1985). Magnetization of lower crust and interpretation of regional magnetic anomalies: Example from Lofoton and Vesterrålen, Norway. Journal of Geophysical Research, 90(B13), 11,484–11,504.

Speranza, F. & Chiappini, M. (2002), Thick-skinned tectonics in the external Apennines, Italy: new evidence from magnetic anomaly analysis. Journal of Geophysical Research, 107, doi:10.1029/2000JB000027.

Stierman, D. J. (1984). Geophysical and geological evidence for fracturing, water circulation and chemical alteration in granitic rocks adjacent to major strike-slip faults. Journal of Geophysical Research: Solid Earth, 89(B7), 5849-5857.

Tarquini, S., Isola, I., Favalli, M. and Boschi, E. (2007). TINITALY/01: a new Triangular Irregular Network of Italy. Annals of Geophysics, 50-3.

Tarquini S., Vinci S., Favalli M., Doumaz F., Fornaciai A., Nannipieri L., (2012). Release of a 10-m-resolution DEM for the Italian territory: Comparison with global-coverage DEMs and anaglyph-mode exploration via the web. Computers and Geosciences 38, 168-170. doi:10.1016/j.cageo.2011.04.018.

Telford W. M., Geldart L. P., Sheriff R. E. 1990. Applied geophysics. Cambridge University press.

Tiberti, M. M., Orlando, L., Di Bucci, D., Bernabini, M. & Parotto, M. (2005), Regional gravity anomaly map and crustal model of the central-southern Apennines (Italy). Journal of Geodynamics 40, 73-91, doi: 10.1016/j.jog.2005.07.014.

Tinti, E., Scognamiglio, L., Michelini, A., & Cocco, M. (2016), Slip heterogeneity and directivity of the ML 6.0, 2016, Amatrice earthquake estimated with rapid finite-fault inversion. Geophysical Research Letters, 43(20), 10,745-10,752. https://doi.org/10.1002/2016GL071263

Vai, G. B. (2001). Basement and early (pre-Alpine) history. In G. B. Vai & I. P. Martini (Eds.), Anatomy of an orogen: The Apennines and Adjacent Mediterranean Basins (pp. 121–150). Dordrecht, Netherlands: Kluwer Academic Publisher. https://doi.org/10.1007/978-94-015-9829-3_10

Wasilewski, P. J., Thomas, H. H. & Mayhew, M. A. (1979). The Moho as a magnetic boundary. Geophysical Research Letters 6, 7.

Wasilewski, P. J. & Mayhew, M. A. (1992). The Moho as a magnetic boundary revisited. Geophysical Research Letters 19, 22, 2259-2262.

Acknowledgments and data

We acknowledge the insightful and constructive comments by Fabio Caratori Tontini and two anonymous reviewers.

We thank eni for providing the gravity anomaly data covering the area.

The data integration was carried out using the MOVE 2017 © Midland Valley Exploration Ltd.

Data concerning the gravity and magnetic profiles used in the modeling are available from https://doi.pangaea.de/10.1594/PANGAEA.895034.

		Arisi Rota & Fichera, 1987	Cassinis et al., 1991	Mattei et al., 1997	Scarascia et al., 1998	Speranza & Chiappini, 2002	Pauselli & Federico, 2003	Di Luzio et al., 2009	Mancinelli et al., 2015	Montone & Mariucci, 2015	Pauselli & Ranalli, 2017	Minelli et al., 2018	This work
Holocene-to-Upper Miocene turbiditic and continental deposits	ρ	--	2450 (PP) 2500-2520 (F)	--	2450 (PP)	--	2390 (T)	--	2300 (PP)	2130 (Q), 2280 (P), 2350 (M), 2360 (F)	--	--	2250-2400
	k	0	--	0 - 0.0007	--	0.0001 (PP)	--	--	0	--	--	0.001-0.00002 (C)	0.0001
Lower Miocene-to-Jurassic carbonatic and marly sequences	ρ	--	2500-2650	--	2700	--	2660	2570-2670	2600	2660	2650	--	2480- 2580
	k	0	--	--	--	0	--	--	0.001	--	--	--	0
Triassic Units	ρ	--	2650 – 2670 (E)	--	2700	--	2800 (E)	2750	--	2730 (D) 2570 (V)	2650	--	2670
	k	0	--	--	--	0 (E)	--	--	0 (E)	--	--	--	0
Metamorphic basement	ρ	--	--	--	--	--	2570 (PH)	--	--	2550	--	--	2550
	k	0.009-0.02	--	--	--	--	--	--	--	--	--	--	0.001
Basement	ρ	--	2780	--	2700	--	2840	2750	2700	--	2650	--	2800
	k	0.009-0.02	--	--	--	0.002-0.008	--	--	0.038	--	--	--	0.001
Lower Crust	ρ	--	2780	--	2850	--	--	2850	2800	--	2850	--	2900
	k	--	--	--	--	0.008	--	--	--	--	--	0.05	0.001-0.05
Mantle	ρ	--	3200	--	3250	--	--	3320	3200	--	3250	--	3200
	k	--	--	--	--	--	--	--	--	--	--	--	--

Table T1. Density (ρ) and magnetic susceptibility (k) values derived from literature. ρ values are expressed in kg m^{-3} and magnetic susceptibilities are expressed in SI units. ρ values from the work of Montone & Mariucci, (2015) are derived from velocity observations in sonic well logs. Metamorphic basement refers to the phyllitic upper portion of the basement (Barchi et al., 1998).

PP – Plio-Pleistocene units, P – Pliocene, F – Flysch, Q – Quaternary, M – Messinian, T – Turbidites, C – Continental, E – Evaporites, D – Dolomites, V – Volcanic, PH – Phyllites.