Pattern Recogn. Phys., 1, 25–36, 2013
www.pattern-recogn-phys.net/1/25/2013/
doi:10.5194/prp-1-25-2013

Pattern Recognition in Physics
Open Access

Regional pattern of the earth's crust dislocations on the territory of Bulgaria inferred from gravity data and its recognition in the spatial distribution of seismicity

P. Trifonova[1], D. Solakov[1], S. Simeonova[1], M. Metodiev[1], and P. Stavrev[2]

[1]National Institute of Geophysics, Geodesy and Geography, Bulgarian Academy of Sciences, Acad. G. Bonchev St., bl.3, 1113 Sofia, Bulgaria
[2]University of Mining and Geology, St. Ivan Rilski, Sofia, Bulgaria

Correspondence to: P. Trifonova (p.trifonova@abv.bg)

Received: 14 February 2013 – Revised: 4 April 2013 – Accepted: 5 April 2013 – Published: 29 April 2013

Abstract. Deformations in the earth's upper layer can be mapped using a variety of methods and techniques. This paper examines the regional pattern of linear structures on the territory of Bulgaria using Bouguer gravity anomalies. The gravity data were analyzed using integrated gradient interpretation techniques, such as the Total Horizontal Gradient (THG) and Vertical Gravity Gradient (VGG). Derived gravity maps reveal persistent lateral changes in density caused by faults, thrusts or dislocated block borders. We thoroughly examine and describe the observed lineation pattern and relate it to the existing tectonostratigraphic information. Several decades after the earliest attempts of potential field data application for revealing first order faults and crustal blocks in the Bulgarian territory, we take advantage of improved techniques and high quality gravity and seismological data for more reliable estimation of the seismogenic potential of faults and thrust structures in the earth's crust. The interpreted structural elements are compared with the epicentral map and epicentral density function of the examined area, to evidence relations between the revealed structures and seismicity. The study indicates possible seismological significance of these lineations and motivates the interest of further quantitative investigations for the purposes of seismic hazard assessment.

1 Introduction

The main objective of the present study is to use the capability of gravity anomalous field data for revealing of buried structures in the earth's crust and to examine the correlation between spatial distribution of seismicity and the pattern of geophysical lineaments. As it is shown in similar studies, geophysical data provide a window to understand the tectonic and structural fabric of the region and to correlate it with earthquake distribution (Murthy, 2002).

During the last decades a number of investigations have been focused on the analysis and interpretation of the observed gravity field in Bulgaria. They resulted in an outline of the main features of the gravity zoning and classification of the Bouguer gravity anomalies for the whole territory as well as in its structural parts (see Dobrev and Schukin, 1974; Yossifov, 1977; Dachev, 1988; Dobrev et al., 1990; Stavrev et al., 2009).

It is well known that dislocations of different scales in the earth's crust can be recognized by steep gradients of anomalous gravity intensity. These anomalies of transition type are observed along the strike of various geological structures such as faults, flexures, thrusts, borders of dislocated blocks and vast intrusions, horsts and grabens, and others, creating significant rock density contrast in horizontal plane (Blakely and Simpson, 1986; Mikuska et al., 2006; Petrishchevsky, 2007). Localizations of abrupt lateral changes in density can be directly obtained from gravity measurements and they represent an independent source of information for identification of seismogenic structures – critical

Published by Copernicus Publications.

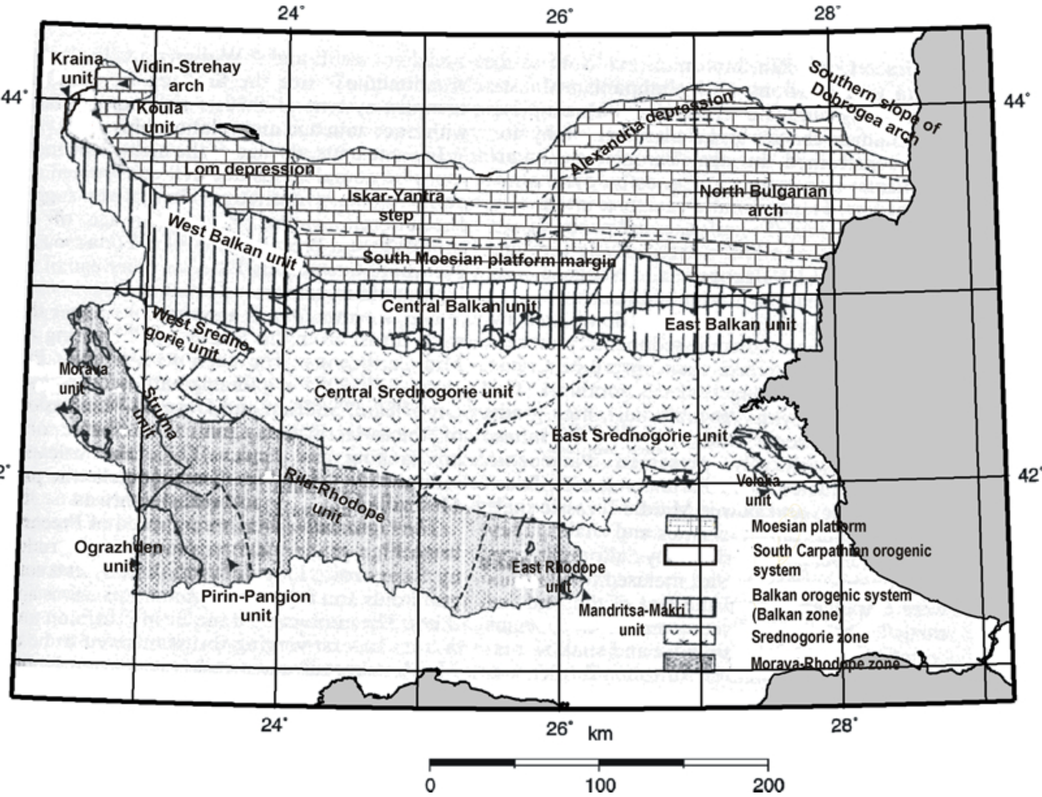

Figure 1. Tectonic scheme of Bulgaria (modified from Dabovsky et al., 2002). Alpine thrust belt (to the south) and Moesian Platform (to the north) are divided into units and subunits. In this model tectonic units represent rock bodies characterized by specific assemblage (lithology, stratigraphy, magmatism, metamorphism) and deformational events (age, resulting structures).

input for seismic hazard assessment. Geological maps and cross sections reflect mainly the near-surface manifestation of the faults which may have different depth extensions; although they are invaluable display tools, they do not provide unambiguous information on the 3-D geometry of the geological structures.

Spatial distribution of seismicity is crucial for detection of seismogenic structure and has the power to constrain the earthquake fault geometries (Kagan and Knopoff, 1980). For the purposes of the study, we present the spatial distribution of seismicity in Bulgaria by means of seismicity map and map of epicenter density function. We compare them with the generated gravity gradient maps searching for strong correlations between delineated gravity gradients and regions with increased seismicity.

2 A regional framework

Bulgaria is situated in the Balkan Region and comprises an element of the Eurasian continental margin. Its territory covers parts of two major tectonic units: (1) the northern part of the Alpine thrust belt on the Balkans and (2) its foreland – the Moesian Platform (Fig. 1).

The Moesian Platform, defined as an area of a stable tectonic development, is connected to the East European Platform trough the North Dobrogea and Scythian Platform. It is composed of slightly folded Paleozoic basement covered by relatively undeformed Mesozoic successions with thickness up to 4–5 km, buried beneath Paleogene, Neogene and Quaternary deposits (Dabovsky et al., 2002). It borders to the north, west and south on the Alpine orogeny, represented by the folded Carpathian and Balkanides systems. During the Alpine stage, this area was a mobile tectonic zone filled with numerous linear units with a block-fold structure (Fig. 1). Borders between the first order units of the Balakanides system are mainly marked by thrusts and reverse faults. There are also strike-slip displacements (as for example between Rodopean Massif and Srednogorie unit), which are usually interpreted in terms of thrusting or normal faulting (Solakov, 2008).

3 Data

Gravity data available cover almost 95 % of the Bulgarian territory with an average grid density of 2.51 points km^{-2}. After thirty years of field measurements, a rectified and digitized gravimetric database was completed in 2002 and put at

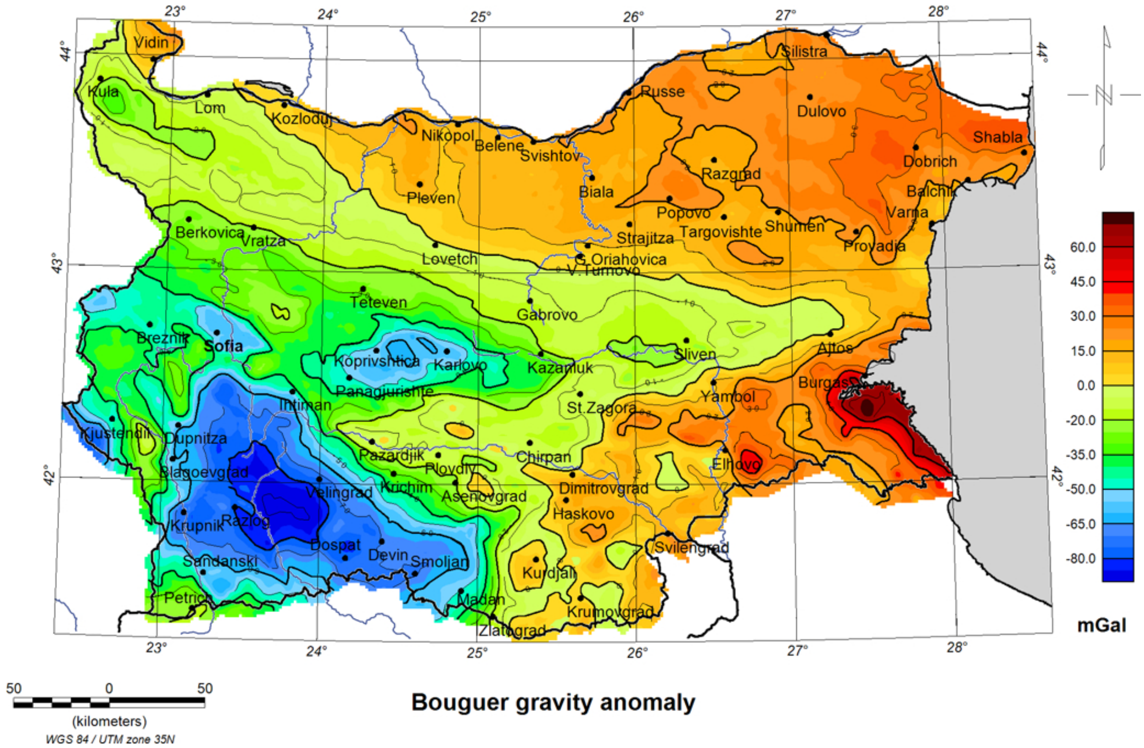

Figure 2. Map of the Bouguer gravity anomalous field of Bulgarian territory. Colors represent the observed intensity (minimum in blue and maximum in red), which is in the range of 176 mGal. Minimal values of the gravity anomalous field are obtained in the Rila–Rhodope unit, where the thickest earth crust is observed (51 km according to Boykova, 1999). Bouguer gravity maximum in the research area is well delineated in southeastern part of Bulgaria near Burgas (27.30° E; 42.20° N). The sources of this anomaly are huge Upper Cretaceous plutonic intrusions with basic and ultra basic composition (Dachev, 1988).

the disposal of the National Geofund of Bulgaria. This leveled gravimetric database allows more precise quantitative characterization of the distribution and specific parameters of the transition anomalies along the entire territory of Bulgaria. Figure 2 shows the spatial variations of the anomalous gravity field of Bulgaria.

The seismicity of Bulgaria and its near surroundings is mainly compiled from the following catalogues:

- Catalogue of earthquakes in Bulgaria and adjacent regions (Grigorova et al., 1979);
- New catalogue of the earthquakes in Bulgaria for the period from Vth century BC to XIXth century (1899) (Christoskov et al., 1979);
- Bulgaria catalogue of earthquakes in the period 1981–1990 (Solakov and Simeonova, 1993);
- Earthquake catalogue for Central and Southeastern Europe (Shebalin et al., 1998);
- Catalogue of earthquakes in Bulgaria and surroundings for the period 1991–2006 (available at funds GFI).

Data have been checked and complemented with the data from two other catalogues: first – a catalogue of earthquakes in the Mediterranean and surrounding area for the period 1901–2004 (Papazachos et al., 2005), and second – Seismicity of Europe and the Mediterranean (Karnik, 1996).

The compiled catalogue has been processed in the sense that duplicated events were removed, foreshocks and aftershocks were identified and tagged (using a space–time magnitude-dependent window as proposed by Christoskov and Lazarov, 1981, for the Balkan region), man-made and natural seismicity was discriminated (the aim was to exclude as precisely as possible quarry explosions and to catalogue only the tectonic events), and uniform magnitude and intensity scales were applied to all earthquakes. The intensity estimations are based on MSK intensity scale and the magnitude estimations are equivalent to M_S magnitude scale. The earthquake catalogue thus obtained for the territory of Bulgaria consists of about 25 000 earthquakes, which were used for all the following analyses of the regional seismicity.

The Stepp's (1971) test indicates that the catalogue can be considered complete in the last 400 yr for magnitudes larger or equal to 7.0, the last 250–300 yr for magnitudes larger than 6.0, 120 yr for $M_S > 5.0$ and after 1900 for $M_S > 4.0$. The test results imply that it is possible to create homogeneous data samples by determining intervals over which earthquakes in different magnitude classes are completely reported.

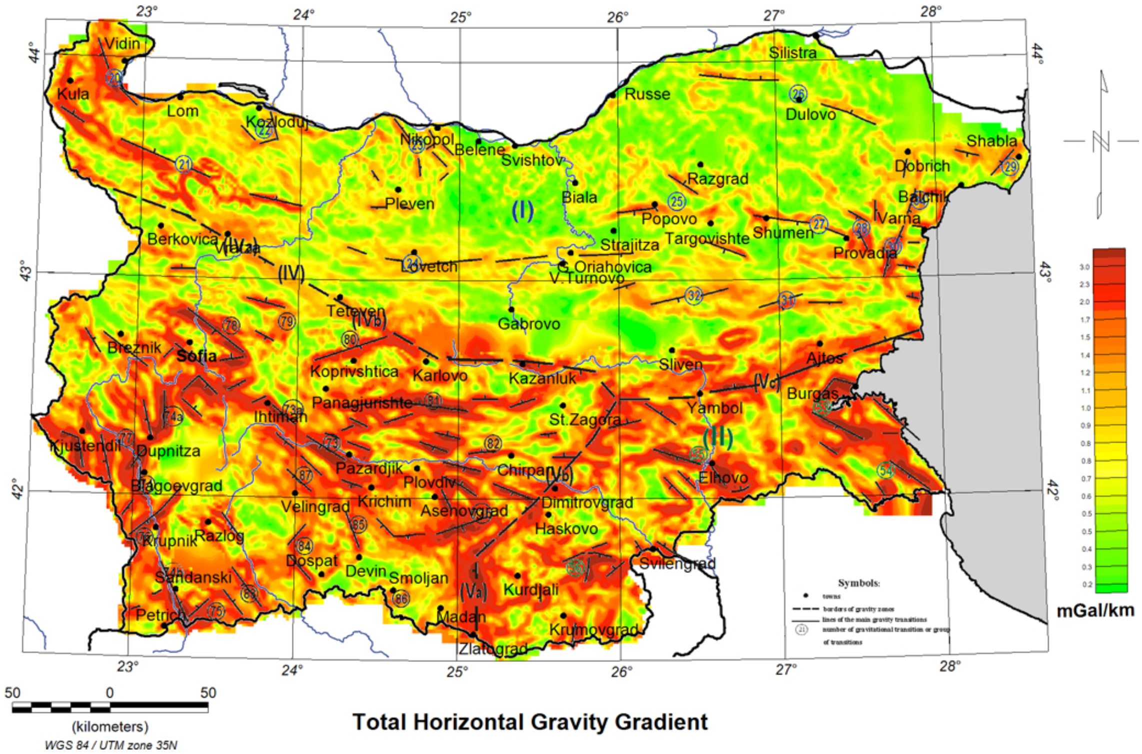

Figure 3. Map of the modulus of total horizontal gradient (THG) of Bouguer gravity anomalous field in Bulgaria. The calculated total horizontal gradients have values up to 8 mGal km^{-1}. Main gravity transitions are delineated, oriented, numbered and described in the text. Axes of steep gravity transitions are indicated by the lines of maximum gradient values, given in red and brown colors. The most intensive among them are marked by long black lines. The short black lines perpendicular to the axes show the direction of field value decreasing and expected deepening of the faults, flexures and other dislocation structures responsible for the observed gravity steep gradients.

4 Methods

4.1 Directional derivatives of the Bouguer gravity anomalous field

The well-known method of first gravity derivatives can be applied according to the existing experience (Stanley, 1977; Grauch and Cordell, 1987; Marson and Klingele, 1993; Blakely, 1995; Ioane, 1999). The basic idea of this study is to exploit this characteristic of gravity anomalies in order to locate steep lateral changes in density. The gravity anomalies of transition type can be easily identified by using the modulus of the Total Horizontal Gradient (THG). The horizontal derivatives of the anomalous gravity field in Bulgaria along two orthogonal axes have been calculated and geometrically summed (Fig. 3). When applied to a two-dimensional survey, the THG tends to place narrow ridges over abrupt changes in density and locating maxima can be done by simple inspection or automated procedure (Blakely and Simpson, 1986).

The calculated Vertical Gravity Gradient (VGG) reflects in other way the above mentioned transition anomalies (Fig. 4). The spatial distribution of the vertical derivative of the gravity field is similar to the distribution of the vertical component Z of magnetic anomalies caused by the same structures in the case of their vertical magnetization, according to Poisson's theorem (see e.g. Blakely, 1995, or Dimitrov and Stavrev, 1986). A comparison between the maps of THG (Fig. 3) and VGG (Fig. 4) shows the same lines of distribution. However, while the THG reflects intensity and orientation of the transition anomalies, the VGG map additionally points out on the character of the transition and respective structures' slope (down or up depending on the position of vertical derivative's positive part). In the case of normal increasing of rock density with depth, VGG can be used to show the direction of structure deepening. An alternative, less suitable way, is to use the map displaying the horizontal gradient vector.

The amplitude, width, length and coordinates of the gradient anomalies can be specified from the two gravity gradient maps mentioned above. Simple gravity models of fault structures like thin semi-infinite layer (sheet) and thick horizontal slab (e.g. Telford et al., 1990), and their possible alternation in depth, show that the amplitude of gradients depends on the density contrast created by the dislocation, and on the ratio between the depths of the upper and lower surfaces of the slab. The width of a gradient anomaly reflects mainly the depth to the average surface of dislocation(s) in a reciprocal way. The length of a gradient anomaly follows the

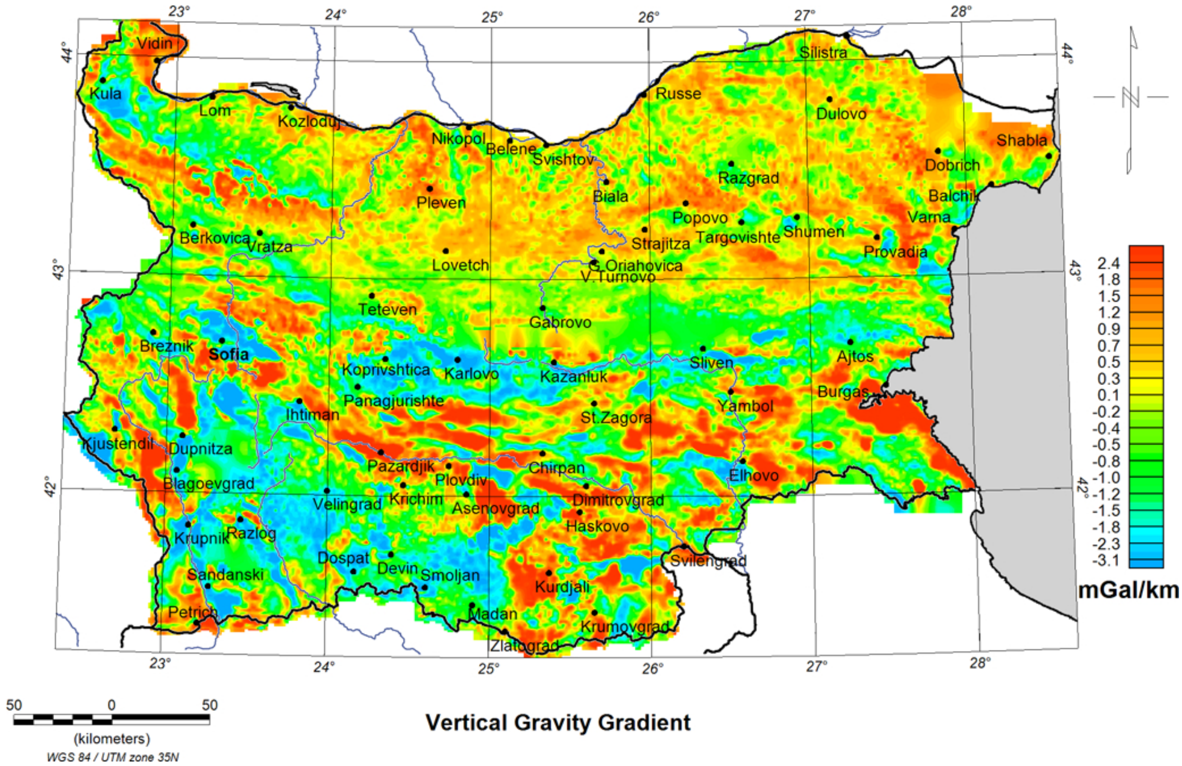

Figure 4. Map of the vertical gravity gradient (VGG) of Bouguer gravity anomalous field in Bulgaria. The positive (red) and accompanying negative (blue) gradients represent single gradient anomaly.

horizontal size of the geological dislocation. In the case of close structures, an interference picture appears that complicates the estimation of the above characteristics of the target dislocations.

The calculation procedures of derivatives include well-known direct and spectral algorithms. These operations are unstable with respect to the noise, therefore tools for suppressing the field components due to technical and near surface sources creating high wavenumber noise were applied.

For the present research a grid of 1.5×1.5 km is prepared from the Bouguer gravity database. The step size of this grid is larger than the distance between the observation points but it is sufficient for the regional scale of the investigation and it helps with the filtration of existing noise. Using these data and the Fourier spectral techniques, the total horizontal gradient and vertical gravity gradient have been calculated and analyzed (see Figs. 2, 3 and 4).

4.2 Spatial distribution of seismicity

In many studies, smoothed seismicity approaches (e.g. Kagan and Jackson, 1994; Frankel, 1995; Helmstetter et al., 2007; Zechar and Jordan, 2010) are applied for different purposes – earthquake density estimation, seismic hazard estimation etc. Here we use a kernel smoothing technique for earthquake density evaluation.

Earthquake occurrence can be statistically regarded as a point process in a five-dimensional space defined by the following parameters: latitude, longitude, depth, origin time, and magnitude. Assuming that the earthquake generation process is quasi-stationary the spatial distribution of earthquakes in a region is well represented by the epicentral density function. A density function is generated as follows. Each earthquake is considered as a random two-dimensional variable with truncated normal distribution, having as mean value $(\mu_x,\ \mu_y)$ the earthquake coordinates from the catalogue, and lying within the interval $\mu_x - 3\sigma_x \le \mu_x \le \mu_x + 3\sigma_x$, $\mu_y - 3\sigma_y \le \mu_y \le \mu_y + 3\sigma_y$, the considered standard deviations and correlation are $\sigma_x = \sigma_y = \sigma$ and $\sigma_{xy} = 0$, respectively.

Thus the probability that a given epicenter E is located in an area Q is given by

$$P(E \in Q) = \iint_Q f(x,y)\mathrm{d}x\mathrm{d}y, \tag{1}$$

where $f(x,y)$ is the density of the truncated normal distribution.

As a density function of the epicenters we consider the function

$$\Phi(x,y) = \sum_i P(E_i \in Q(x,y)), \tag{2}$$

where E_i is the i-th earthquake and $Q(x, y)$ is a square with central point (x, y) and size $A\,\text{km}^2$.

In this application we select a square of 10×10 km size (concerning the average accuracy of earthquake parameters determination in the considered catalogue), i.e. $A = 100\,\text{km}^2$ and $\sigma_x = \sigma_y = 10$ km. The procedure could be considered as smoothing with two-dimensional isotropic Gaussian kernel governed by a single parameter (Zechar and Jordan, 2010) with smoothing distance $\sigma = 10$ km.

The density function is calculated at a grid interval of 0.01° latitude and 0.01° longitudes and is normalized to 1 yr.

5 Application and results

5.1 Analysis of gravity anomalies

The Bouguer anomalous field on the Bulgarian territory (Fig. 2) shows intensity in the range of 176 mGal from negative values in the southwestern part of Bulgaria to positive values at the Black Sea coast.

Three main gravity zones can be separated, taking into account the specific characteristics of the field distribution (names after Dachev, 1988): (I) *Moesian gravitational zone*: covers the area of Moesian Platform in northern Bulgaria, Fore Balkan region (South Moesian Platform margin), Central Balkan structural zone and northern parts of the East Srednogorie unit; (II) *Thracian gravitational zone*: occupies part of the East Rhodope and East Srednogorie units; and (III) *Rhodopean gravitational zone*: the zone displaying the most intensive gradient anomalies, which includes Rila–Rhodope unit, Ograzhden, Struma, and West and Central Srednogorie structural areas. All geologic units mentioned above are named after Dabovski et al. (2002). Although a good correspondence between gravity field distribution and the existing tectonic zonation (Fig. 1) is not observed, the derivative calculations have the power to reveal features that cannot be detected by direct observations.

The map of THG, shown in Fig. 3, indicates the axes of steep gravity transitions by the lines of maximum gradient values, given in red and brown colors. The outlined gravity gradients in the three main gravity zones show close relations with the known geological data and interpretations of regional tectonic settings on the territory of Bulgaria. The number of gravity transitions with lengths greater than 5 km is larger than 110. The dominant orientation of their axes is WNW–ESE following the axes of the main known structures of Bulgarian geological space.

5.1.1 Moesian gravitational zone

More than 30 gradient anomalies with mainly W–E orientation are delineated in Fig. 3. Some of them, (21)–(24), outline the southern boundary of the Moesian Platform, while (25)–(30) indicate borders of blocks in the North Bulgarian arch.

Tracing the gravity anomalous map from west to east, the first highlighted region inside this structural unit is Vidin positive anomaly (44.1° N, 22.9° E). It is part of a wider anomaly extending to the Romanian territory, which represents uplifted blocks (amplitude of about 2 km) in the southwestern periphery of the Moesian Platform. Block edges are outlined in the TGH map as the transition anomaly (20). The western Fore Balkan strip of gravity maxima follows the Belogradchik anticlinorium (43.6° N, 22.5° E), whose magmatic formations outcrop on the surface. The northern border of this structure is marked by an elongated gravity transition (21) comprising density contact of fault or flexure type. In the northeastern part of the zone the mosaic pattern of the anomalies is related to large transposed blocks inside the North Bulgarian arc and neighboring depressions. Block borders are mainly of fault type and those showing significant density contrast are marked by gravity transitions (25)–(30). Vertical displacements along the fault planes could reach several kilometers as the boreholes evidenced in the case of Venelin–Axakovo–Dobrich fault, which is approximately parallel to the Black Sea coast in eastern Bulgaria. The depth distribution of intra-block faults is presumed to be much larger (Dachev, 1988).

Going to the south towards the Balkan zone, the gravity transitions (28) and (30) are caused by faults related to the Mirovo salt body, which is outcropped on the surface. Three other structures are delineated on the map in Fig. 3: the South Moesian gravity transition (step) (24), Varbitza transition (31) and Kotlen transition (32). They are borders of the main structures of the Moesian Platform and have equatorial direction. Gradient (24) coincides with the geologically determined boundary between the Moesian Platform and the Fore Balkan transition zone, and is caused by the increase of sediment thickness and changes in the rock composition.

5.1.2 Thracian gravitational zone

More than twenty gradient axes here follow mainly linear structures of young magmatic activity. Looking from north to south and from east to west, the first anomaly in this zone is the East Balkan maximum, which could be traced farther to the Black Sea shelf. It is caused by anticline structure and a rupture basic intrusion. the Burgas group of positive anomalies (42.3° N, 27.5° E), which have complicated configurations and high intensities, is a result of large plutonic bodies with high density and ultra-basic composition located at average depths between 3 and 8 km and expanding down to more than 15 km (Dobrev et al., 1990). The borders of the magmatic ensemble are delineated by gravity transitions (53) and they enclose an area of 50×80 km in size. Gravity transitions (54) are related to thrust and fault structures inside the Strandzha block. Following to the east, Elhovo gravity transition (55) marks the junction with the Sakar block structures. East Rhodope gravity gradient anomalies (56 and others) follow structures with north–south orientation. They are caused by metamorphic bodies and can also be traced to the south on the territory of Greece.

5.1.3 Rhodope gravitational zone

This is the zone presenting the most intensive gradient anomalies. Two orientations of the gradient anomalies dominate: first, anomalous groups (73) and (82) along Maritsa River outline the deep Maritsa dislocations, as well as the set of faults in the heterogeneous basement of the upper Thracian depression to the north; and second, steep gradients (74) along the Struma River and gradients (83) along the Mesta River, all of them crossed by several gradient extrema, e.g. the prominent fault (76) near the Kresna–Krupnik area. The Maritsa transition (73) reflects the gravity effects of a deep linear dislocation extending in depth to more than 20 km. The gravity effect is partly caused by concomitant plutons and basic intrusions fed from that magma-conducting fracture. The Struma transition (74) coincides with the Struma fault zone, characterized by various orientations of the dislocation lines. Density contrasts are caused by the high-density metamorphic complex of Struma diorite formation and the "lighter" granite masses to the east. Transversal to the main direction of Struma line the Krupnik gravity transition (76) can be traced, as it's well defined by its intensity and size. The total displacement of density boundaries is estimated at 3 km. Several anomalous zones are delineated inside the Rila–Rhodope unit, and the related transitions are displayed in the THG map. They are the N-NW striking Mesta transitions (83) along the Mesta graben which is filled with young volcanic rocks; it shows weakening zones through which magmatic material has penetrated during Oligocene. Gradients of group (78) indicate border faults of Sofia depression in the West Srednogorie unit. In the Central Srednogorie unit gravity transitions (80) and (81) are related to deep density discontinuities having sub-vertical direction.

Two other elongated chains of intensive gravity transitions, the Balkan gravity transition (IV) and Zlatograd–Yambol gravity transition (V), are outlined in Fig. 3 (named by Dachev, 1988). The first one marks the northern boundary of the Rhodope gravitational zone and it has surface as well as deep sources. Its western part (IVa) is related to the deep faults of the West Balkan front line caused by overlaps and thrust belts. Going to the east, the observed gravity gradients (IVb) reflect the boundary between Central Balkan and Central Srednogorie tectonic units. Zlatograd–Yambol gravity transition (V) has different sources for its three components. The Central Rhodopean transition (Va) is caused by overthrust structures from the west, which are located at a depth of 8–10 km. The second element of this transition (Vb) is complicated by smaller transverse gradient anomalies and it reflects elongated detachment fault in the heterogeneous basement below the sediments of Upper Thracian graben structure. The third part (Vc) follows the boundaries of the magmatic formations towards the East Srednogorie unit.

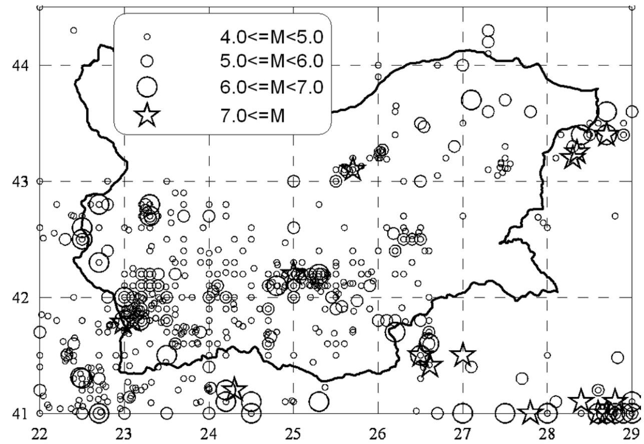

Figure 5. Spatial pattern of seismicity on and near the territory of Bulgaria (the earthquakes (historical and instrumental) with $M_S \geq 4.0$ that occurred in the region up to 2006 are displayed); symbols represent the values of the surface wave magnitude.

5.2 Spatial distribution of seismicity

The spatial pattern of the seismicity on and near the territory of Bulgaria (within a space window of41–44.5° N and 22–29° E) is shown in Fig. 5. The figure represents the epicentral map of the earthquakes (historical and instrumentally recorded) with $M_S \geq 4.0$ that occurred in the study area. The magnitude symbols are given in the upper left corner. The figure demonstrates the pronounced nonuniformity in the spatial distribution of the earthquakes in the considered region. Significantly more earthquakes with $M_S \geq 4.0$ occurred in southern Bulgaria than in its northern part. No events were generated in northwestern Bulgaria. Earthquake clustering is observed in several areas situated both in the southern and northeastern parts of the country extending to the Black Sea coast.

From the analysis of the depth distribution (Sokerova et al., 1992 and Dachev et al., 1995) it follows that all of the earthquakes in the considered region are of shallow depth, and occur in the earth's crust down to 50 km. The hypocenters are mainly located in the upper crust, and only a few events are related to the lower crust. The maximum density of seismicity involves the layer between 5 and 25 km depth.

Seismicity maps (although they are an invaluable display tool) do not provide explicit information in the context of nonuniformity in the spatial distribution of earthquakes. Therefore the density function approach is applied in the study to detect spatial pattern peculiarities that are not directly noticeable.

Figure 6 shows the spatial distribution of the calculated density function in the study region. Only the earthquakes with surface magnitude $M_S \geq 4.0$ that occurred in Bulgaria after 1900 were considered. The time period is chosen according to estimated completeness of the catalogue for quakes with M_S greater than or equal to 4.0.

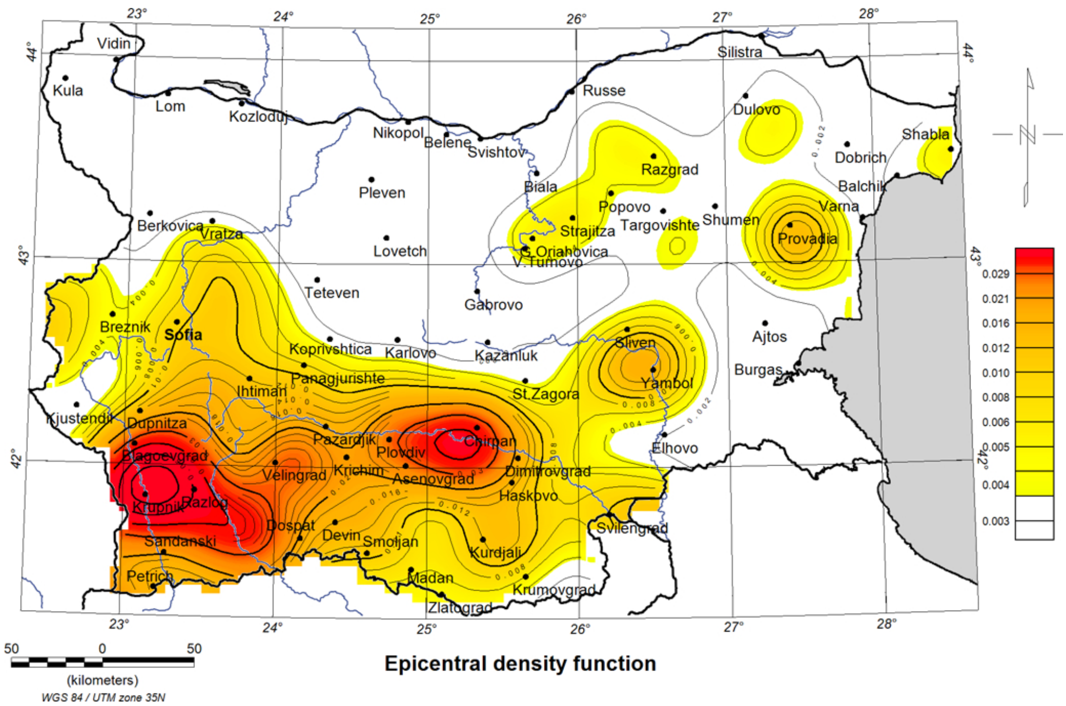

Figure 6. Spatial distributions of epicenter density function on and near the territory of Bulgaria (the density function is calculated on the basis of $M_S \geq 4.0$ earthquakes that occurred after 1900); colors represent the density function values.

Figure 6 demonstrates no uniformity in the spatial distribution of earthquakes in Bulgaria. Density function values vary between 0.003 and 0.03 earthquakes/per $100\,\mathrm{km}^2$ per year. The information carried by the values of the epicenter density function can be considered as an indicator of spatial clustering properties and rate of seismic activity in the region during the study time period.

Thus, the highest values of density function (above 0.029) that are observed in western and central parts of southern Bulgaria indicate a high rate of occurrence of clustered small-to-strong earthquakes. In contrast, low values of the density function (less than 0.004) in northern Bulgaria as a whole (with the exception of the region close to Provadia city) exhibit a low rate of occurrence of moderate-to-strong size events after 1900.

As seen in Fig. 6 earthquakes are concentrated in certain seismic zones that are outlined by higher (above 0.01) values of the density function. Specific tectonic, seismic, and geological features characterize each zone.

6 Interpretation

Generally, basic processing of the gravity and seismological data on the territory of Bulgaria emphasize correlations, which are illustrated by the gradient-epicentral map presented in Fig. 7.

The map is compiled using the gravity transitions delineated on the THG map (Fig. 3) and historical and instrumental seismicity map (Fig. 5) on and near the territory of Bulgaria. The earthquakes with $M_S \geq 3.0$ that occurred in the region after 1980, the year when the National Seismological Network was put in operation, are also included.

A comparison between Figs. 6 and 7 reveals several regions (as for example, close to Provadia, Sliven, Yambol, cities in Eastern Bulgaria, marked down in Fig. 6), exhibiting large values of the density function (up to 0.016), and juxtaposition between gravity transition and moderate seismicity ($M_S < 6.0$), characteristics pointing to a relatively high rate of occurrence of clustered small-to-moderate size events. In contrast, low values of the density function (varying in the interval 0.002–0.01) in the Sofia–Kjustendil region (marked down in Fig. 6), where strong historical earthquakes occurred ($M_S > 6.5$) and fairly good fit between gravity transition and seismicity is observed (Fig. 7), indicate that the moderate-to-strong earthquakes in the area are rare events.

Very clear is the superposition of the delineated gravity transition and the seismic zone near the town of Gorna Orjahovitza (43.1° N, 25.7° E). It is a segment of the South Moesian (North Fore Balkan) fault which separates the Moesian Platform from Stara Planina mountain. This region was reactivated during the Vlashka orogenic phase (the Pliocene-Quaternary threshold) and has remained active to present-day (Dachev et al., 1995). Detailed seismotectonic investigations have defined the seismogenic structure formed by a system of faults: two major faults with E–W orientation (confirmed by gravity transitions as well on Fig. 3) and several smaller ones

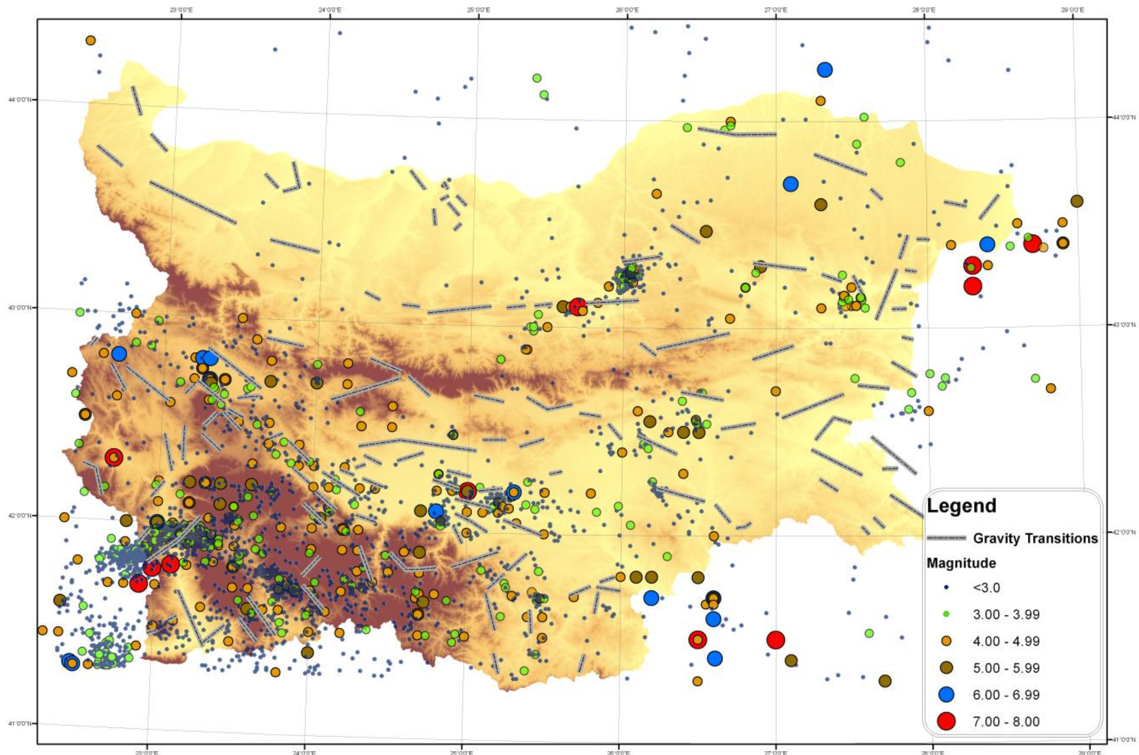

Figure 7. Gradient-epicenter map for Bulgarian territory; lines represent delineated gravity transitions, colors and size of the circles represent the values of surface wave magnitude. The yellow-brown background represents the topography of the region.

in NE–SW directions (Dachev et al., 1995). The strongest earthquakes were generated in the eastern part of the structure (see Fig. 7) with $M_S = 7.0$ (1913), and $M_S = 5.5$ and $M_S = 5.7$ (1986), while in the western part a number of small events were recorded ($M < 4.0$). The epicenter density function (Fig. 6) exhibits, on the other hand, rather low values in this area, due (most likely) to the low rate of occurrence of moderate-to-strong earthquakes during the study time interval.

Going to the south, West Srednogorie tectonic unit (Fig. 1) is noteworthy with its high seismic activity. The local gravity field is determined by the distribution of Cenonian volcano-sedimentary and intrusive complexes and rather thick Neozoic depositions (Dachev, 1988). The most prominent structure is the Sofia graben, which is developed between West Balkan neotectonic complex to the north and Maritsa graben to the south. The separation is marked through neotectonical active fault zones which are exhibited as the NW–SE striking gravity transition (78) in Fig. 3. The largest earthquakes which affected the area are those of 1858 (near the city of Sofia, 42.4° N, 23.2° E) and 1905 (near the town of Trun in the western part of the area). Both had surface wave magnitude larger than 6.0 (Solakov et al., 2001).

The delineated transitions of the Maritsa dislocation group (marked by numbers 73 and 81 in Fig. 3) are WNW–ESE oriented. The Maritsa deep fault was active during Upper Cretaceous stage and it became a transmitter of intensive magmatic activity through its multiple fragments in the upper part of the crust. They are part of the Upper Thracian depression, which is a neotectonic structure formed between the Rhodopean Massif and the Srednogorie zone, where a cyclic accumulation of Neogene-Quaternery sediments was pointed out (Zagorchev, 1992). The present seismotectonic activity is related to these fault systems that generated a large number of earthquakes over the centuries (see Fig. 7). The high values of epicenter density function (Fig. 6) indicate the high rate of occurrence of small-to-strong earthquakes during the last more than one hundred years. The strongest known earthquakes are those that occurred in 1928 (the Chirpan quake of 14 April 1928, $M_S = 6.8$ and the Plovdiv quake of 18 April 1928, $M_S = 7.0$).

Struma depression is a deep intra-mountain Neogene-Quaternary structure along the river stream with the same name. The amplitude of the neotectonic differentiating movements there amounted to 2500–3000 m (Dachev et al., 1995). A series of transverse dislocations such as Krupnik, Belasitsa, etc., are evidenced, some of them being clearly identified by gravity transitions (marked by numbers 74 and 76 in Fig. 3). Some of the strongest earthquakes in Europe during 20th century occurred near Kresna (41.8° N, 23° E) area which is a part of the Struma tectonic unit (Fig. 1) – the earthquakes of 4 April 1904 ($M_S = 7.2$ and $M_S = 7.8$). High rate of contemporary seismicity is exhibited by high values (in Fig. 6) of epicenter density function (more than 0.029). The deepest earthquakes in Bulgaria occurred in the Kresna seismic zone, where the crustal thickness is also large (under the western part of the Rhodopean Massif it reaches 45–50 km).

To the west of the deep Struma depression is located the Serbian-Macedonian neotectonic structure, which represents a mosaic configuration of highly elevated domes and deeply subsided graben depressions where Neogene sediments are thicker than 1000 m.

Several examples of juxtaposition of gravity transitions and moderate seismic activity are evident in the Rila–Rhodope unit (Fig. 7). These are: (I) the Central Rhodopean transition (marked as Va in Fig. 3) with its Kurdjali–Haskovo transition group (41.6°/25.5°). Its source is deep, probably Late Alpine thrusts composed of metamorphic rocks (amphibolites and ultrabasites) with high density, situated in fault-bend folds (Dachev, 1988). (II) Devin–Krichim (85) and Dospat–Velingrad (84) transitions which delineate borders of small depressions filled with young volcanic rocks. (III) Mesta transition (83) reflects borders of Mesta graben, where considerable displacements have been accommodated by the existing faults during the neotectonic activation phase (Zagorchev, 1992). The strongest earthquake that occurred here was in the West Rhodope seismic zone and had $M_S = 5.3$ (it occurred in 1977, near the town of Velingrad). Predominant thrust and overthrust tectonics in this area may support the small horizontal shift observed between delineated gravity transitions and zones of concentrated seismic activity. Nevertheless, the seismogenic source of the displayed seismic events may be correlated with the processed gravity anomalies, in most of the cases.

7 Conclusions

The main conclusions derived from this study can be summarized as follows:

I. Very clear superposition of delineated gravity transitions and seismicity is pointed out in the following zones:

   1. near the city of V. Turnovo and Gorna Orjahovitza (43.1° N, 25.7° E). Two major faults having E–W orientation, as well as several smaller in NE–SW directions are confirmed by gravity transitions. They are "responsible" for the large number of seismic events with magnitudes of up to $M_S = 7.0$. The low rate of occurrence of moderate-to-strong earthquakes in the area is exhibited by rather low values of the epicenter density function;
   2. over the Sofia graben, which is developed between West Balkan neotectonic complex to the north and Maritsa graben to the south (42.4° N, 23.2° E). The observed anomalies are caused by the distribution of Cenonian volcano-sedimentary and intrusive complexes and thick Neozoic depositions. The low rate of contemporary seismicity in the Sofia–Kjustendil region is displayed by the low values of the epicenter density function;
   3. delineated transitions of Maritsa dislocation group (42.2° N, 24.7° E). The Maritsa deep fault was a transmitter of intensive magmatic activity through its multiple fragments in the upper part of the crust. Present seismogenic activity is connected to these fault systems where a large number of events have been recorded (the strongest one occurred near the city of Plovdiv and had the magnitude $M_S = 7.0$). High values of epicenter density function represents earthquake (up to $M_S = 7.0$) clustering;
   4. Kresna region (41.8° N, 23° E), which is part of the Struma tectonic unit. A series of transverse dislocations such as Krupnik, Belasitsa, etc., are clearly identified by gravity transitions. The high values of the density function in the Kresna region, where one of the strongest earthquakes in Europe during the 20th century occurred ($M_S = 7.8$) indicate a pronounced rate of small to strong earthquakes after 1900.
   5. Several juxtapositions between gravity transitions and moderate seismic activity are evident in the Rila–Rhodope unit and eastern Bulgaria (near the cities of Velingrad, Dospat, Provadia, Sliven and Yambol). They are marked with rather large values of the epicenter density function (up to 0.016), and maximum magnitudes lower than 6, characteristics pointing to a relatively high rate of occurrence of clustered small-to-moderate size events.

II. The geophysical images enable the understanding of the tectonic and structural fabric of the region. The correlation of the earthquakes distribution with the geophysical lineaments in the study area is emphasized.

The obtained results in this paper open the way for further quantitative interpretations of the delineated gravity transitions and modeling of the targeted anomalous sources using forward and inverse techniques, which will give important information about the spatial parameters of the seismic sources in the investigated territory.

Acknowledgements. This work was carried out with the support of the Bulgarian Ministry of Regional Development and Public Works and Ministry of Environment and Water (National Geofund) under the project "Seismic zoning of Bulgaria according to the requirements of EC8".

We thank the editor Sid-Ali Ouadfeul, and the two reviewers Luminita Angela Ardeleanu, and one anonymous reviewer for the constructive criticism and comments that helped us to improve the manuscript.

Edited by: S.-A. Ouadfeul
Reviewed by: L. A. Ardeleanu and one anonymous referee

References

Blakely, R. J.: Potential theory in gravity and magnetic applications, Cambridge University Press, 1995.

Blakely, R. J. and Simpson, R. W.: Approximating of edges of source bodies from magnetic or gravity anomalies, Geophysics, 51, 1494–1498, 1986.

Boykova, A.: Moho discontinuity in central Balkan Peninsula in the light of the geostatistical structural analysis, Phys. Earth Planet. Int., 114, 49–58, 1999.

Catalog of earthquakes in Bulgaria and surroundings for the period 1991–2006, Archives of the Geoph. Inst., BAS, Sofia (unpublished).

Christoskov, L. and Lazarov, R.: General considerations on the representativeness of the seismological catalogues with a view to the seismostatistical investigations, Bulgarian Geophys. J., 3, 58–72, 1981 (in Bulgarian).

Christoskov, L., Sokerova, D., and Rijikova, S.: New catalogue of the earthquakes in Bulgaria for the period V century BC to XIX century (1899), Archives of the Geoph. Inst., BAS, Sofia, 1979 (unpublished).

Dabovski, C., Boyanov, I., Khrischev, Kh., Nikolov, T., Sapunov, I, Yanev, Y., and Zagorchev, I.: Structure and Alpine evolution of Bulgaria, Geologica Balkanica, 32, 9–15, 2002.

Dachev, Ch.: Structure of the Earth crust in Bulgaria, Technika, Sofia, 334 p., 1988 (in Bulgarian).

Dachev, H., Vaptzarov, I., Filipov, L., Solakov, D., Simeonova, S., Nikolova, S., Sokolova, P., Botev, E., and Georgiev, Tz.: Seismology, geology, neotectonics, seismotectonics and seismic hazard assessment for the PNPP Belene site, Report of Project: Investigations and activities for increasing of the seismic safety of the PNPP Belene site, Geoph. Inst., BAS, Sofia, 250 pp., 1995.

Dimitrov, L. and Stavrev, P.: Magnetic methods in geophysics, Publication of University of Mining and Geology, Sofia, p. 434, 1986 (in Bulgarian).

Dobrev, D., Stavrev, P., Yossifov, D., Raditchev, R., and Vikov, K.: Spatial distribution and morphology of covered magmatic massifs in Bulgaria according to geophysical data, Geologica Balkanica, 20, 59–70, 1990.

Dobrev, T. and Shchukin, Y.: Geophysical fields and seismicity of the eastern part of the Carpathian-Balkan region, Nauka, Moscow, 170 pp., 1974 (in Russian).

Frankel, A. D.: Mapping seismic hazard in the central and eastern United States, Seismol. Res. Lett., 66, 8–21, 1995.

Grauch, V. and Cordell, L.: Limitations of determining density of magnetic boundaries from the horizontal gradient of gravity or pseudogravity data, Geophysics, 52, 118–123, 1987.

Grigorova, E., Sokerova, D., Christoskov, L., and Rijikova, S.: Catalogue of the earthquakes in Bulgaria for the period 1900–1977, Archives of the Geoph. Inst., BAS, Sofia, 1979 (unpublished).

Helmstetter, A., Kagan, Y. Y., and Jackson, D. D.: High resolution time-independent forecast for $M > 5$ earthquakes in California, Seismol. Res. Lett., 78, 78–86, 2007.

Ioane, D.: Contributii metodologice si de interpretare la cercetarea gravimetrica, magnetometrica, spectrometrica gama si mercurometrica a mineralizatilor associate eruptivului neogen din Romania, Editura Carpatica, Cluj-Napoca, 174 pp., 1999 (in Romanian).

Kagan, Y. Y. and Jackson, D. D.: Long-term probabilistic forecasting of earthquakes, J. Geophys. Res., 99, 13685–13700, 1994.

Kagan, Y. Y. and Knopoff, L.: Spatial distribution of earthquakes: the two-point correlation function, Geophys. J. Roy. Astr. S., 62, 303–320, doi:10.1111/j.1365-246X.1980.tb04857.x, 1980.

Karnik, V.: Seismicity of Europe and the Mediterranean, Academic publishing house of Czech Republic, Prague, 1996.

Marson, I. and Klingele, E. E.: Advantages of using the vertical gradient of gravity for 3-D interpretation, Geophysics, 58, 1588–1591, 1993.

Mikuska, J., Pasteka, R., Marusiak, I., Bielik, M., Wibraniec, S., and Hajach, M.: Linear trends in complete Bouguer anomaly maps of Slovakia and neighbouring countries, 2nd Workshop on International Gravity Field Research, Smolenice, Slovakia, 80–85, 2006.

Murthy, I. S.: On the correlation of seismicity with geophysical lineaments over the Indian subcontinent, Curr. Sci., 83, 760–766, 2002.

Papazachos, B., Cominakis, P., Skordilis, E., Karakaisis, G., and Papazachos, C.: A catalogue of earthquakes in the Mediterranean and surrounding area for the period 1901–2004, Publ. Geoph. Lab. Univ. of Thessaloniki (computer file), 2005.

Petrishchevsky, A. M.: The Relation of Seismicity to Lithospheric Density Inhomogeneities in the Russian Far East, Volcanology and Seismology, 6, 60–71, 2007.

Shebalin, N., Leydecker, G., Mokrushina, N. G., Tatevossian, R. E., Erteleva, O., and Vassiliev, V.: Earthquake Catalogue for Central and Southeastern Europe 342 BC–1990 AD, Final Report to Contract No ETNU-CT93-0087 Bruddel (computer file http://www.bgr.de/quakecat), 1998.

Solakov, D. (Ed.): Project report: "Seismic zoning of Bulgaria according to EC8", Geophysical Inst.-BAS, Sofia, p. 187, 2008 (in Bulgarian).

Solakov, D. and Simeonova, S.: Bulgarian Catalogue of Earthquakes 1981–1990, Sofia Press, p. 40, 1993.

Sokerova, D., Simeonova, S., Nikolova, S., Solakov, D., Botev, E., Glavcheva, R., Dineva, S., Babachkova, B., Velichkova, S., Maslinkova, S., Donkova, K., Rizikova, S., Arsovski, M., Matova, M., Vaptzarov, I., and Filipov, L.: Geomorphology, neotectonic, seismicity and seismotectonic of NPP Kozloduy, Final Report (Summary) on IAEA Mission: Design basis earthquake for seismic upgrading of NPP Kozloduy, Sofia, 200 pp., 1992.

Solakov, D., Simeonova, S., and Christoskov, L.: Seismic hazard assessment for Sofia area, Ann. Geofis., 44, 541–556, 2001.

Stanley, J. M.: Simplified gravity interpretation by gradients – the geological contact, Geophysics, 42, 1230–1235, 1977.

Stavrev, P., Solakov, D., Simeonova, S., and Trifonova, P.: Regional set of dislocations in the Earth's crust of Bulgaria according to gravity data, CD Abstracts, Ref.# 6507, 5th Congress of the Balkan Geophysical Society, Belgrade, 2009.

Stepp, J.: An investigation of earthquake risk in the Puget sound area by use of the type I distribution of large extremes, Ph.D. thesis, Penns. Univ., 131 pp., 1971.

Telford, W. M., Geldart, L. P., and Sheriff, R. E.: Applied Geophysics, Cambridge University Press, p. 770, 1990.

Yossifov, D.: First class deep faults and Earth's crust blocks in the folded zones and activated regions of Bulgaria inferred from geophysical data, Geotectonics, 6, 48–65, 1977.

Zagorcev, I.: Neotectonics of the central parts of the Balkan Peninsula: basic features and concepts, Geol. Rundsch., 81, 635–654, 1992.

Zechar, D. and Jordan, T.: Simple smoothed seismicity earthquake forecasts for Italy, Ann. Geophys.-Italy, 3, 53, doi:10.4401/ag-4845, 2010.