ACTIVE FAULT SYSTEMS IN THE SHABLA REGION (BULGARIA) AS INTERPRETED ON GEOPHYSICAL AND SEISMICITY DATA*

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Shabla region is located in NE Bulgaria and belongs from the tectonic point of view to the south-eastern part of the Moesian Platform. The study area covers parts of the eastern slope of the North Bulgarian arch, having the Bulgarian–Romanian border to the north, Cape Kaliakra to the south, Dobrich city to the west, and the Black Sea shelf to the east. Block faulting, horsts and grabens of different rank are the typical structural features. The crustal-scale Intramoesian Fault, considered to separate the Moesian Platform in two main compartments, reaches the Black Sea continental shelf in Shabla region, its path being ambiguously located on maps, as it does not outcrop. Analysis of regional seismicity data available from ROMPLUS Earthquake Catalogue and EMSC Earthquake Catalogue, integrated with available tectonic and geophysical data, as well as with geological, geomorphological and neotectonic field observations, offered the possibility to interpret W–E, NE–SW and NW–SE active fault systems within the study area and build the grounds for a much more comprehensive understanding of this region's tectonics.

Key words: geophysical data interpretation, regional seismicity, active faults, regional tectonics, Moesian Platform.

1. INTRODUCTION

This study started during the bilateral scientific project MARINEGEOHAZARD carried out by geoscientists from Romania and Bulgaria, being proposed to its authors by project leaders of the Romanian part.

Since one of the main task for the project was the evaluation of tsunami hazard associated to onshore and offshore active tectonics along the Black Sea Romanian and Bulgarian shorelines, a more detailed map of fault systems and a better understanding on the active ones based on new, or newly released geophysical data, was considered of highest importance.

Analysis of regional seismicity data available from ROMPLUS Earthquake Catalogue (Oncescu *et al.*, 1999, updated) and EMSC Earthquake Catalogue (www.emsc-csem.org, 2016) illustrates the study area as being seismically active, with very strong historical earthquakes both onshore (Dulovo area) and offshore (Shabla area).

2. GEOTECTONIC AND GEOLOGICAL FRAMEWORK

2.1. GENERAL TECTONIC SETTING

Shabla region is located in NE Bulgaria and belongs from the tectonic point of view to the south-eastern part of the Moesian Platform. The study area covers parts of the eastern slope of the North Bulgarian arch (Zagorchev *et al.*, 2009), having the Bulgarian–Romanian border to the north, Cape Kaliakra to the south, Dobrich city to the west and the Black Sea continental slope to the east (Fig. 1). The North Bulgarian arch is also known as the North Bulgarian Uplift (*e.g.*, Tari *et al.*, 1997; Shanov, Radulov, 2010).

This ancient consolidated platform, called "Moesian" by E. Boncev (1946), represents a major structural unit of the Carpathian and Balkans foreland, with a folded and fractured pre-Palaeozoic basement and a faulted non-folded cover, with Upper Palaeozoic, Mesozoic and Neozoic sedimentary sequences (Paraschiv,

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1979; Săndulescu, 1984; Visarion *et al.*, 1988; Pulido-Bosch *et al.*, 1997a,b; Seghedi, 1998; Săndulescu, Visarion, 2000; Seghedi *et al.*, 2005 and references therein; Boutoucharov, Angelova, 2015). Block faulting, horsts and grabens of different rank are the typical structural features (Dabovski *et al.*, 2002; Zagorchev *et al.*, 2009).

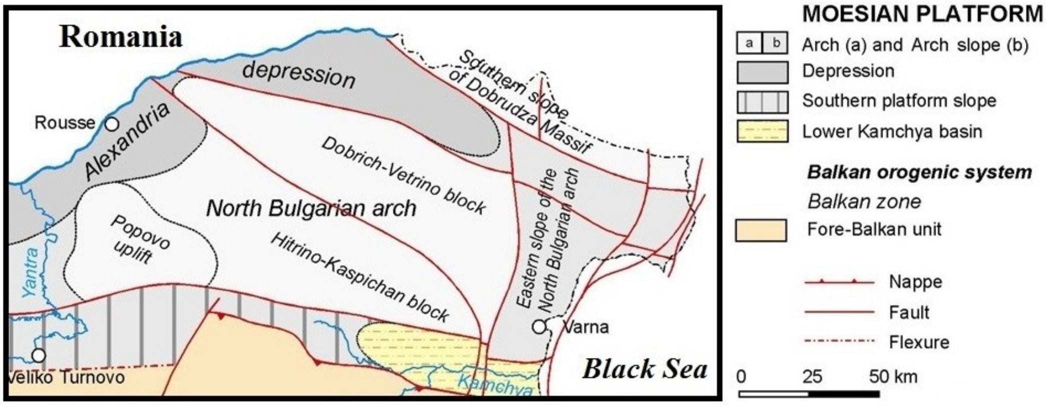

Fig. 1 – The study area located on the tectonic map of Bulgaria (modified after Zagorchev *et al.*, 2009).

2.2. MAIN FAULT SYSTEMS

Two main fault systems have been previously mapped based mainly on geophysical research (Kuprin *et al.*, 1980; Matova, 1999, 2000; Shanov *et al.*, 2005) within the Shabla region (Fig. 2):

- a system parallel to the Balkan orogen, having W–E direction: Charakman, Batovo and Forebalkan faults;
- a fault system having NNE–SSW or NE–SW directions: Balchik, Eastern Balchik, Touzlata, Krapets–Kavarna, Balgarevo, Tyulenovo and Kaliakra faults.

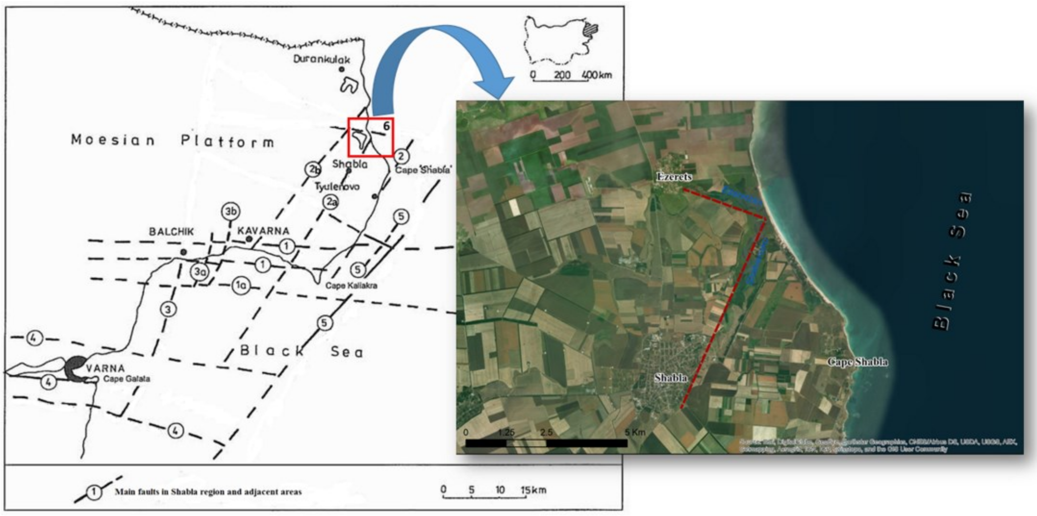

Fig. 2 – Main fault zones in Shabla region and adjacent areas (modified after Matova, 2000; Shanov *et al.*, 2005): 1 – Charakman faults; 1a – Batovo Fault; 2 – Tyulenovo Fault; 2a – Balgarevo Fault; 2b – Krapets-Kavarna Fault; 3 – Balchik Fault; 3a – Eastern Balchik Fault; 3b – Touzlata Fault; 4 – Forebalkan faults; 5 – Kaliakra Fault; 6 – Intramoesian Fault. Red square: detail on Ezeretzko and Shablensko firth lakes; red dashed line – interpreted Intramoesian Fault and Balgarevo Fault crossing.

The coastline between Shabla Cape and Kaliakra Cape is defined by the Tyulenovo fault, while the coastline between the Kaliakra Cape and Balchik is defined by the Charakman faults. Another fault system, important for its regional NW–SE development till the Carpathian Mts., is the Intramoesian Fault one. The Intramoesian Fault reaches the Black Sea continental shelf in the Shabla region, but as it is not exposed, its path was ambiguously located on various maps. This concealed tectonic structure is known in Bulgaria mainly under the name of the Silistra–Belgun Fault and presented on the geodynamic map of the Mediterranean region as an insecure active fault (Rogozhin *et al.*, 2009). The crustal scale Intramoesian Fault (Săndulescu, 1984; Visarion *et al.*, 1988) separates the Moesian Platform in two main domains, referred to as: Danubian and Dobrogean (Paraschiv, 1979), Vallachian/ Vallachian-Prebalkan and Dobrogean sectors (Săndulescu, 1984; Visarion *et al.*, 1988; Săndulescu, Visarion, 2000) or East and West Moesia (Oaie *et al.*, 2005; Seghedi *et al.*, 2005).

Shanov *et al.* (2005) emphasized the importance of the precise interpretation of the Intramoesian Fault's segmentation in this area: the length of the segments is of critical importance for evaluation of the maximum expected earthquake magnitudes. Failing this approach may lead to overestimation or underestimation of the seismic hazard both in Bulgaria and Romania.

The Intramoesian Fault and the Balgarevo Fault appear to cross each other close to the shoreline, on the Shabla beach, and the Ezeretzko and Shablensko firth lakes seem to mark this faults junction (Fig. 2 – detail): Ezeretzko is NW–SE shaped, along the direction of the Intramoesian Fault, while Shablensko is NE–SW shaped, along the Balgarevo Fault.

2.3. GEOLOGICAL AND GEOMORPHOLOGICAL OBSERVATIONS

The Shabla area displays a monoclinal morphology, slightly elevated southward and westward and inclined towards N and NE. From the Bulgarian–Romanian border to Cape Shabla the coast is relatively low, with cliffs formed in Quaternary loess and loam deposits (Fig. 3) and beach strips like Dourankoulak and Shabla. Three firth lakes – Dourankoulashko, Ezeretzko and Shablensko – with an elevation of 50–80 cm above the sea level are located on the shoreline, at the end of SW–NE and NW–SE oriented drowned valleys.

From Cape Shabla to Kavarna bay and further southward, large outcrops of highly fractured Sarmatian (Miocene) limestone have been observed (Fig. 4), the coastline gradually increasing in height from Cape Shabla, up to 20 m at Tyulenovo, 60 m by Cape Kaliakra and then up to 120 m by the town of Kavarna (Fig. 5).

Fig. 3 – Quaternary loess deposits observed at Shabla Beach.

Fig. 4 – Large outcrops of highly fractured Sarmatian limestone observed along the coastline, south of Shabla.

Fig. 5 – Coastline increasing in height from Cape Shabla (left) to Cape Kaliakra (right).

2.4. NEOTECTONIC OBSERVATIONS

The study of the crustal movements in the area started in the mid 60's, being based on repeated topographic levelling measurements of marker heights.

The vertical crustal movements map published by Ciocârdel & Esca (1966) highlights the presence of crustal uplift of the North-Bulgarian arch.

Within the study area, characteristic is a decrease in the uplift intensity from South (+2 – +3 mm/y, Balchik and Kaliakra Cape) to North (0 mm/y, Mangalia). Such tendency of Earth's surface lowering is considered by Alexiev (2000) as result of a regional extensional regime.

Crustal uplifts in the Shabla region have been illustrated also on the Hristov *et al.* (1973) map of recent vertical movements in Bulgaria, which illustrates Shabla region as an uplifting tectonic block (ca 2 mm/y), as opposed to crustal subsidence along the Romanian littoral zone.

The Shabla–Kaliakra coast plunges in steps into the Black Sea (Fig. 6) on fractures parallel to the coastline. Graben structures were observed at Russalka on NE–SW trending, parallel to the coastline, and at Bolata on NW–SE trending, cutting the coastline (Fig. 7). The graben structures may suggest a recent extensional regime in this area.

2.5. HYDROGEOLOGICAL OBSERVATIONS

From hydrogeological point of view, the Shabla region represents the easternmost sector of the Low Danubian Artesian region (Benderev *et al.*, 2016), with high geothermal water occurrences along the coastline and in Kavarna area.

The main geothermal reservoirs are situated in carbonate rocks of Jurassic, Lower Cretaceous, Middle Triassic and Upper Devonian age. They consist of up to 1 000 m thick artesian aquifers, built up of strongly fractured limestone and dolomite, with high permeability (Pulido-Bosch *et al.*, 1997a,b; Nador, 2014).

The water temperature in the Shabla region ranges between < 25°C at Shabla and 25°C–50°C at Durankulak, with a flow rate exceeding 40 l/s and the maximum recorded on Bulgarian territory: 1039 l/s, in the Upper Jurassic–Lower Cretaceous aquifer (Benderev *et al.*, 2016). The high density of thermomineral occurrences is associated by Alexiev (2000) with an increased heat flow, determined by extensional stresses in the lithosphere.

Fig. 6 – The Shabla–Kaliakra coastline plunges in steps into the Black Sea (view from Iailata).

Fig. 7 – Graben structure observed at Bolata.

3. GEOPHYSICAL DATA

3.1. GRAVITY DATA

The anomalies contoured on the Bouguer Gravity Map of northern Bulgaria (Fig. 8) illustrate a regional decrease of intensity from NE to SW. The large north-eastern gravity high is associated with the North Bulgarian Uplift tectonic structure, uplifted high density Palaeozoic sedimentary formations covering a crystalline basement not yet reached by boreholes.

In the studied area two high gravity anomalies are contoured: a) a W–E trending anomaly between Shabla and the border Bulgaria–Romania; b) a NW–SE trending anomaly located west of Dobrich. These high gravity anomalies are separated almost completely by a low gravity "corridor" trending NW–SE toward Silistra.

When looking for faults using Bouguer gravity anomalies most useful data processing is the horizontal gradient, the elongated high anomalies showing lineaments where the density contrast determined by the fault displaced compartments are reflected in rapid variations of gravity. The horizontal gradient anomalies for Bulgaria have been computed by Trifonova *et al.* (2013), their interpretation illustrated in Fig. 9 showing gravity effects of faults trending mostly W–E, NE–SW and NW–SE. In the Shabla area two faults were interpreted, their direction being NE–SW and WNW–ESE.

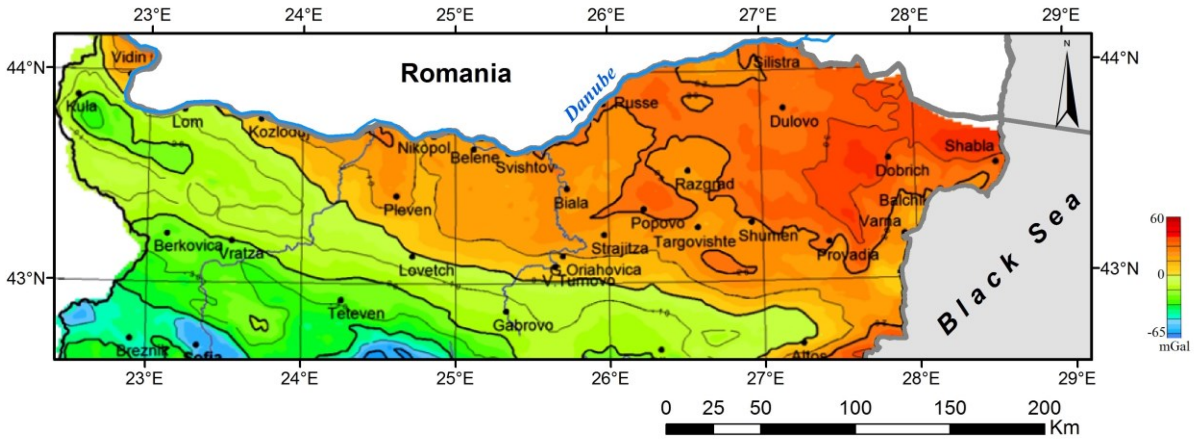

Fig. 8 – Bouguer gravity anomalies in northern Bulgaria (modified, from Trifonova *et al.*, 2013).

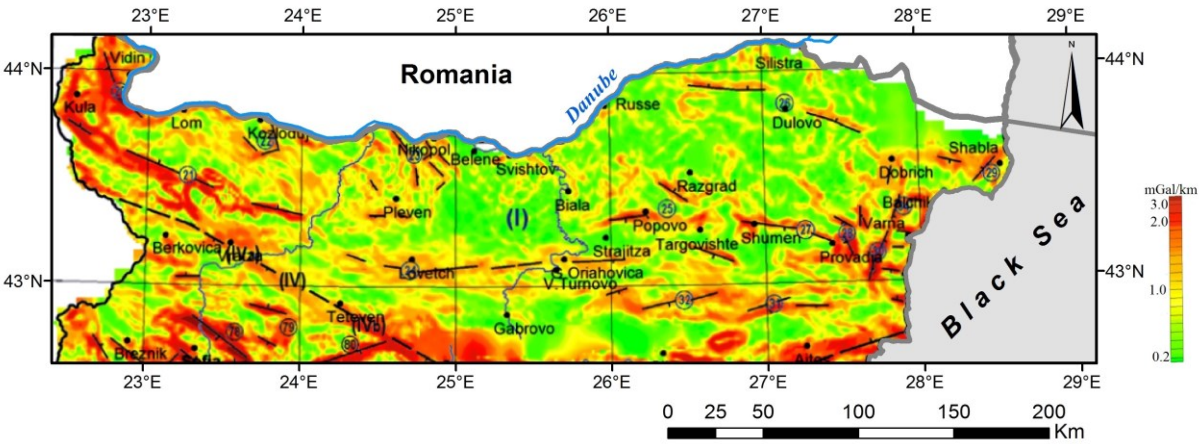

Fig. 9 – Horizontal gradient of Bouguer gravity anomalies in northern Bulgaria (modified, from Trifonova *et al.*, 2013).

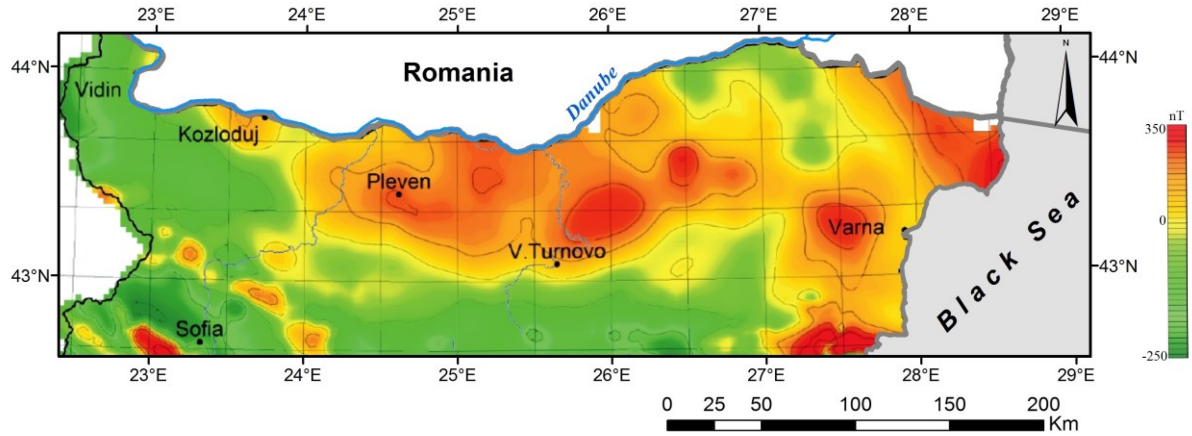

Fig. 10 – Anomalies of the vertical component of the geomagnetic field (ΔZ_a) in northern Bulgaria (Trifonova *et al.*, 2012).

3.2. MAGNETOMETRIC DATA

The map with anomalies of the vertical component of the geomagnetic field (ΔZ_a), published by Trifonova *et al.* (2012), reveals within the Moesian Platform (northern part of Bulgaria) high magnetic anomalies located close to the Black Sea (Shabla–Varna area) and south of the Danube river.

The high magnetic anomalies trending NW–SE in the Shabla–Kavarna–Dobrich area may be considered as associated with metamorphic rocks of the uplifted crystalline basement structures, most probably pierced by intermediate to basic magmatic intrusions (Fig. 10).

3.3. REFLEXION SEISMIC DATA

Results of a high resolution marine seismic survey over the Shabla offshore carried out in 1995 by MMS Petroleum plc, through its subsidiary Balkan Explorers Ltd. (Bulgaria), presented by Bottomley, Pritchard (1998) revealed the development of a NE–SW fault system on strike with the Tyulenovo structural trend, crossing an N–S fault system (Fig. 11).

The marine seismic survey carried out by Finetti *et al.* (1988) in the western Black Sea area interpreted offshore Shabla numerous faults at top Cretaceous, most of them trending NE–SW. North of Shabla the faults direction changes to NNW–SSE, while close to the shoreline their trend is N–S.

3.4. SEISMOLOGICAL OBSERVATIONS

The scientific literature describes Shabla region as a major seismic zone with impact both on the territories of Bulgaria and Romania. The high seismicity of the area stands out with strong earthquakes ($M \geq 7$) historical recordings (*i.e.*, 1901), although not with high frequency of repetition.

There are scattered seismic events on the entire study area, with some local clusters of earthquakes (Fig. 12). Seismological recordings showed as active seismic the area situated in front of the Bulgarian Black Sea coast, generating offshore Shabla strong earthquakes within the Moesian Platform. The strongest earthquake historically mentioned in this area was 7.2 M_w, 14 km depth (1901/03/31), in the close vicinity of Cape Shabla.

The analysis of the seismic events depth distribution (Fig. 13) showed that the earthquakes in the Shabla region occurred within the Earth's crust. The hypocenters are mainly located in the upper crust and only a few events are related to the lower crust. The maximum depth reached is about 30–35 km.

The maximum density of seismic events involves the 5–15 km depth interval, while the magnitude is usually ranging between 3 and 5. The strong earthquakes (magnitude 6–7) have hypocenters at 14–15 km depth. Also, there is a 25–35 km depth cluster of earthquakes of magnitude 4–5.

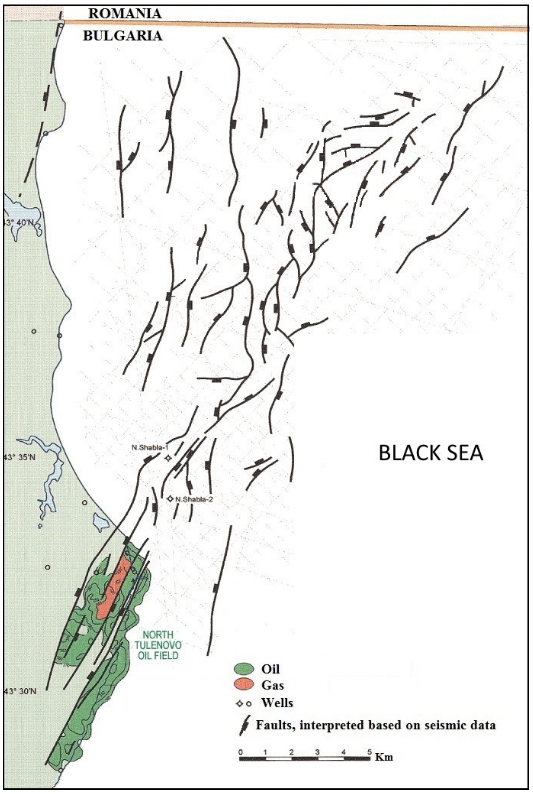

Fig. 11 – The NE–SW fault system, shown on strike with the Tyulenovo structural trend, and the N–S fault system, both depicted at top Valanginian carbonate based on reflexion seismic data interpretation (modified after Bottomley & Pritchard, 1998).

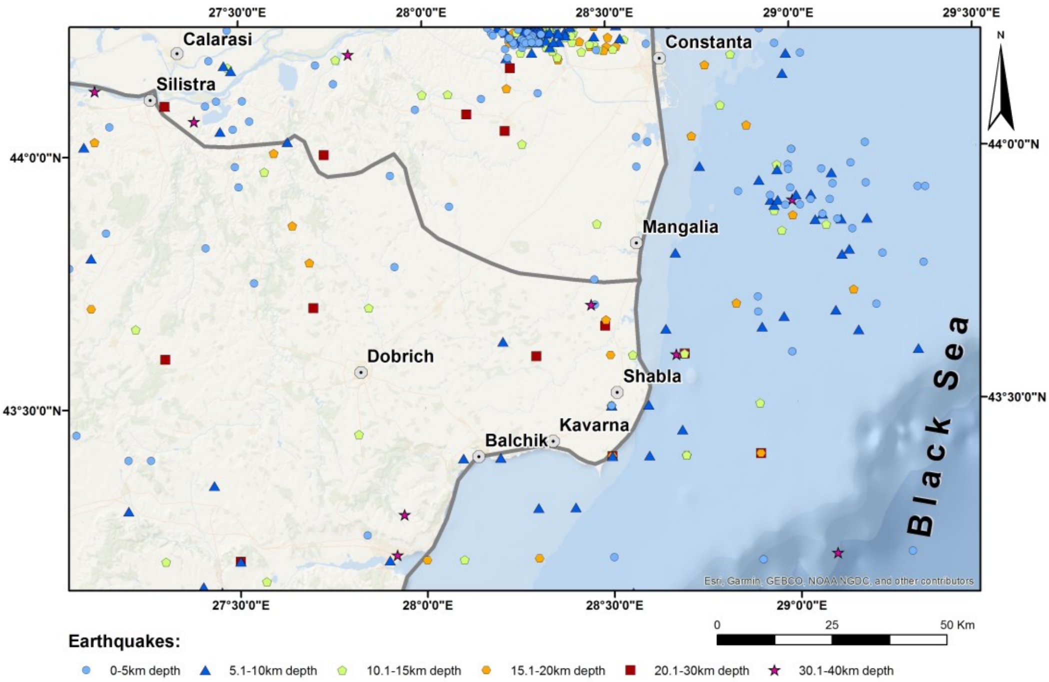

Fig. 12 – Seismic epicenters location within the Shabla region. Seismological data from ROMPLUS Earthquake Catalogue (Oncescu *et al.*, 1999 – updated) and EMSC Earthquake Catalogue (http://www.emsc-csem.org, 2016).

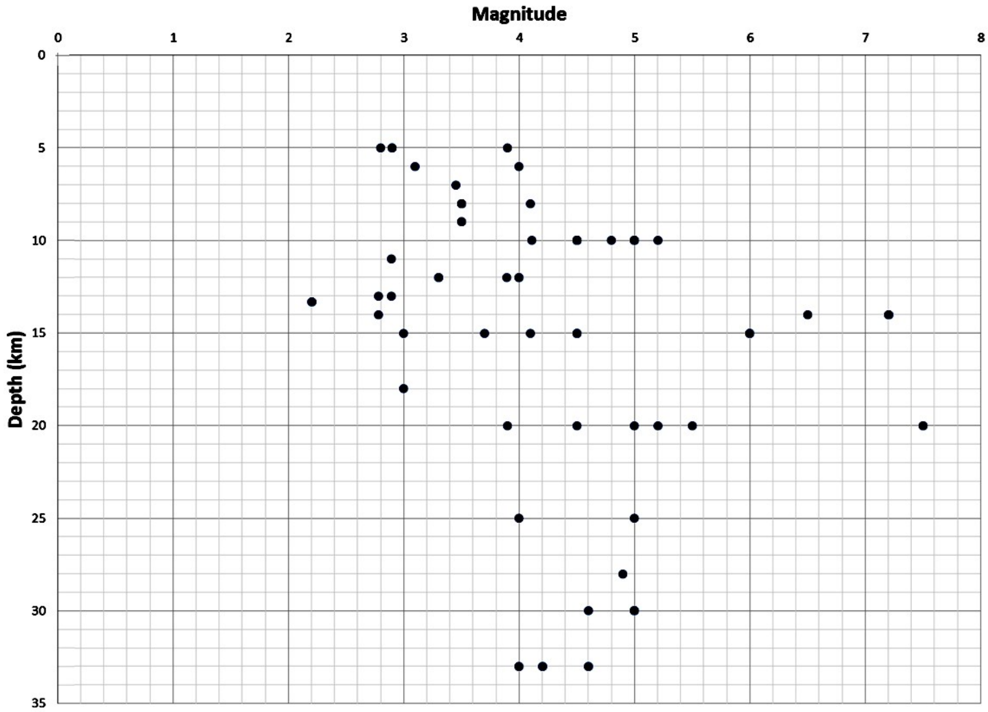

Fig. 13 – Magnitude vs Depth graph for the earthquake recordings in the Shabla region. Seismological data from ROMPLUS Earthquake Catalogue (Oncescu *et al.*, 1999 – updated) and EMSC Earthquake Catalogue (http://www.emsc-csem.org, 2016).

4. DATA INTERPRETATION

4.1. HORIZONTAL GRADIENT OF BOUGUER GRAVITY ANOMALIES

In view of enhancing the possibility that gravity data reflects the presence of faults in the Shabla zone, the horizontal gradient anomalies computed by Trifonova *et al.* (2013) and presented in Fig. 9 have been interpreted in a more detailed manner (Fig. 14).

Besides the most intense anomalies of horizontal gradient of Bouguer gravity anomalies, interpreted as important faults by the Bulgarian geophysicists, less intense and shorter lineaments have been also considered in this study, considering that smaller density contrasts between fault compartments may occur in places due to variations of lithology in the geological structures and fault vertical displacement.

A large number of horizontal gradient anomalies have been interpreted as faults in the studied region (Shabla–Silistra–Veliko Turnovo–Varna), the main fault systems trending W–E, NE–SW and NW–SE. The Shabla–Varna area, most important in this study for its active tectonics and seismic hazard, is dominated by the W–E (*i.e.*, Dobrich–Shabla fault) and NE–SW (*i.e.*, S and W of Shabla faults) fault systems; long tectonic lineaments, depicted along Provadia–Varna–Dobrich, displaying a NNW–SSE trending.

4.2. VERTICAL COMPONENT AND TOTAL FIELD MAGNETIC ANOMALIES

Aiming to interpret in terms of local tectonics the available magnetometric data, both onshore and offshore, the study area was enlarged to Shabla – Constanţa (Romania) – Silistra – Balchik, the geophysical sources used to compile the map presented in Fig. 15 being as follows:

– Airinei *et al.* (1983) – Anomalies of the vertical component of the geomagnetic field (ΔZ_a) in Romania;
– Trifonova *et al.* (2012) – Anomalies of the vertical component of the geomagnetic field (ΔZ_a) in Bulgaria;

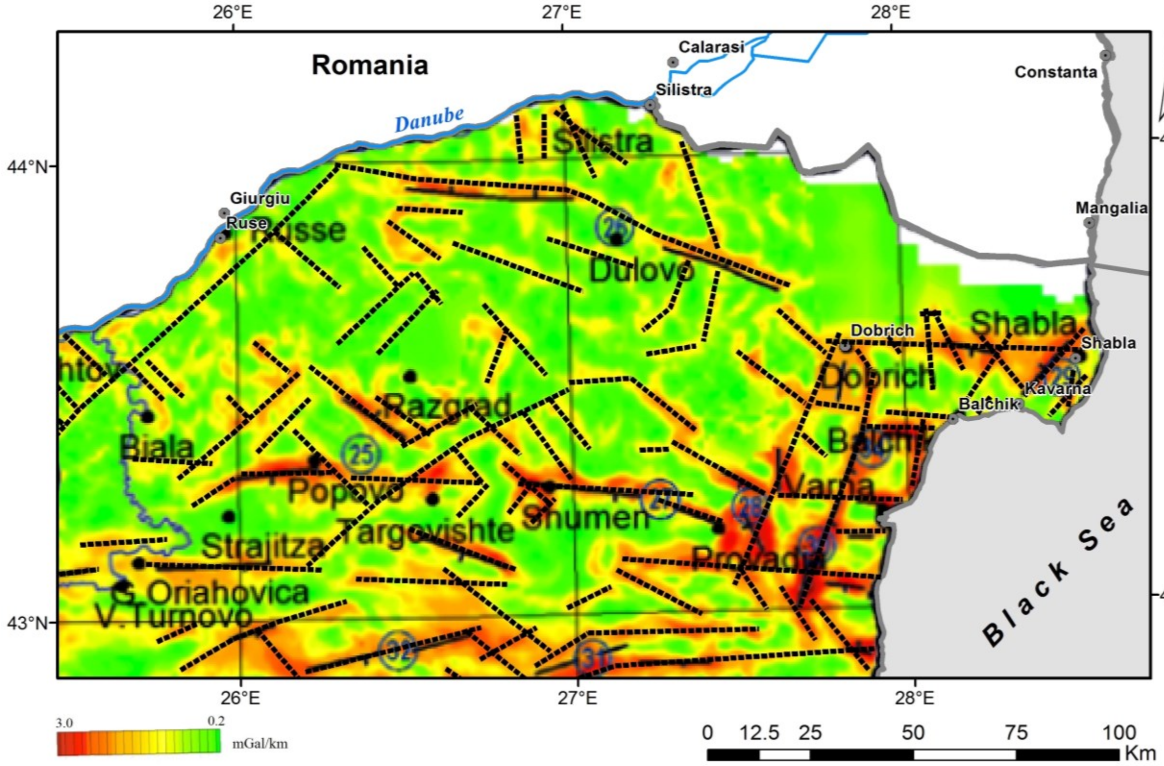

Fig. 14 – Horizontal gradient of Bouguer gravity anomalies in the Shabla area.
Black lines: faults interpreted by Trifonova *et al.* (2013); Black dotted lines: faults interpreted in this study.
Horizontal gradient anomalies: detail from Trifonova *et al.* (2013).

– Dimitriu *et al.* (2016) – Anomalies of the total geomagnetic field (ΔT_a) in the western Black Sea shelf (offshore Romania and Bulgaria).

Trifonova *et al.* (2012) and Dimitriu *et al.* (2016) maps were georeferenced and digitized using Global Mapper, and re-plotted using Oasis Montaj software. Separate grids of the magnetic anomalies map (ΔZ_a) of Bulgaria and the magnetic anomalies (total geomagnetic field) for the western Black Sea continental margin (Romanian–Bulgarian sector) were exported from Oasis Montaj and used for interpretation within the ESRI Arc Map georeferenced environment. In order to complete de mosaic of the magnetometric map of the Shabla area, Airinei *et al.* (1983) map was georeferenced and used within ESRI Arc Map as well.

The magnetic anomaly in the area of Constanţa (Romania) is caused by magnetite accumulations of BIF type (banded iron formation) in the crystalline basement situated at several hundred meters depth (*e.g.*, Visarion *et al.*, 1979).

Most probably, the high magnetic anomalies NW, E and SE of Shabla have as geological cause large magmatic intrusions deeply located, probably of dioritic petrographic type, not yet geologically maped or penetrated by boreholes. This interpretation is geophysically based on the magnetic anomalies dimensions, shape and intensity (Fig. 15) as well as upwelling hot upper mantle, as suggested by the low velocity seismic tomography anomaly located below this region (Stanciu, Ioane, 2018; Stanciu, 2020).

Such an interpretation is geologically supported by the great number of high temperature thermomineral aquifers explored by hydrogeological wells and on hydrothermal minerals (quartz, calcite) and hydrothermal alterations (silicification) observed in the outcropping Sarmatian limestone, in the region between Balchik and the border between Bulgaria and Romania.

The faults have been mostly interpreted in the studied area using the composite magnetic map

(Fig. 15) on lineaments of rapid variation of magnetic anomalies and along boundaries between closely situated high and low magnetic anomalies (dipolar magnetic anomalies).

Three main fault systems have been detected this way: W–E, NE–SW and NW–SE. Considering the onshore area Shabla–Kavarna and its eastward offshore continuation, these three fault systems highly tectonized the area due to numerous faults crossings. Since in this area have been mapped the highest size and intensity of magnetic anomalies, interpreted in this study to be associated with large magmatic intrusions, it is likely that the dense fault network was generated during magma upwelling and subsequent magma solidification.

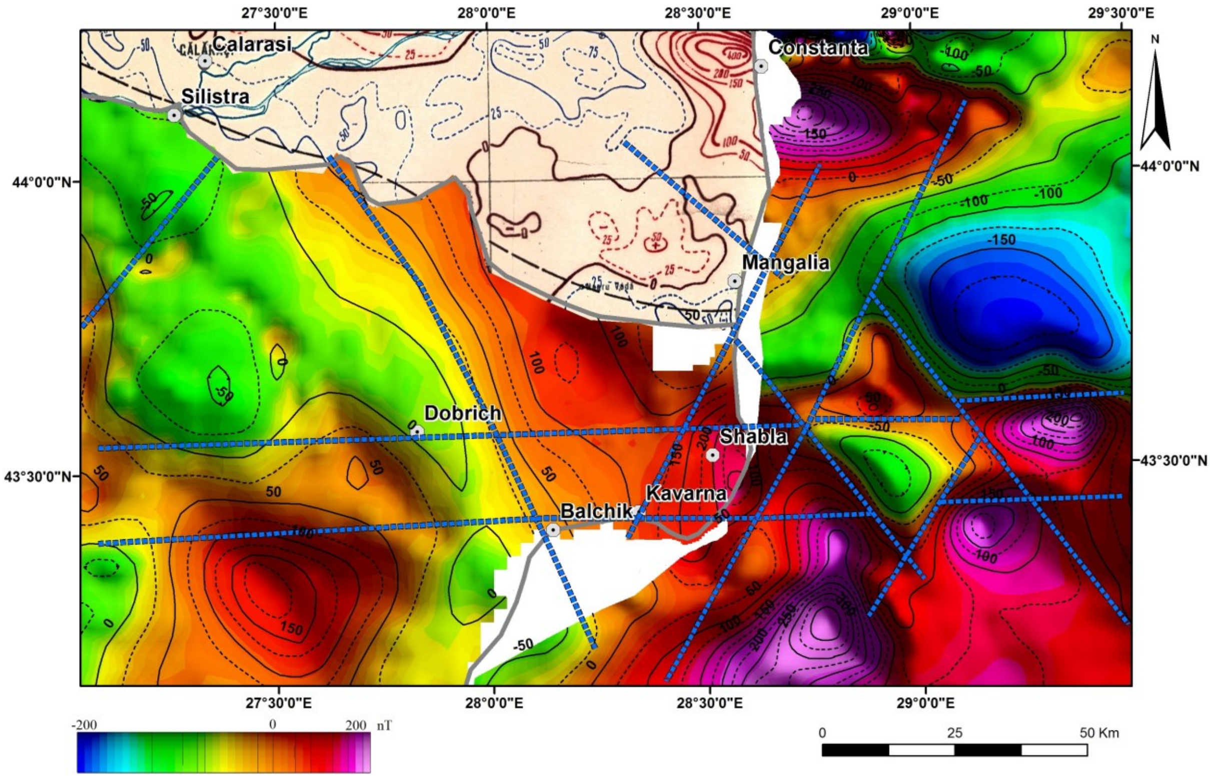

Fig. 15 – Anomalies of the geomagnetic field in the Shabla area. Magnetic data: Onshore – vertical component of the geomagnetic field (Bulgaria – Trifonova *et al.*, 2012; Romania – Airinei *et al.*, 1983); Offshore – total geomagnetic field (Dimitriu *et al.*, 2016); Blue dotted lines: interpreted faults and tectonic contacts.

4.3. BATHYMETRIC DATA

The bathymetric map published by Dimitriu *et al.* (2016) was obtained from offshore multi-beam bathymetry measurements on the Romanian and Bulgarian Black Sea shelf carried out by GeoEcoMar researchers within the project MARINEGEOHAZARD – "Set-up and implementation of key core components of a regional early-warning system for marine geohazards of risk to the Romanian–Bulgarian Black Sea coastal area".

The sea bottom morphology in front of Cape Shabla (Fig. 16) displays a N–S oriented steep slope, showing a fast decrease on the bathymetric map from 30 to 60 m depth, crossed by a W–E lineament along the 70 m sea bottom depth isoline. Eastward, NE–SW and NNE–SSW lineaments of fast increasing of sea bottom depth have been interpreted as normal faults involved in the western Black Sea opening and possibly, in present day, in tectonic extensional processes.

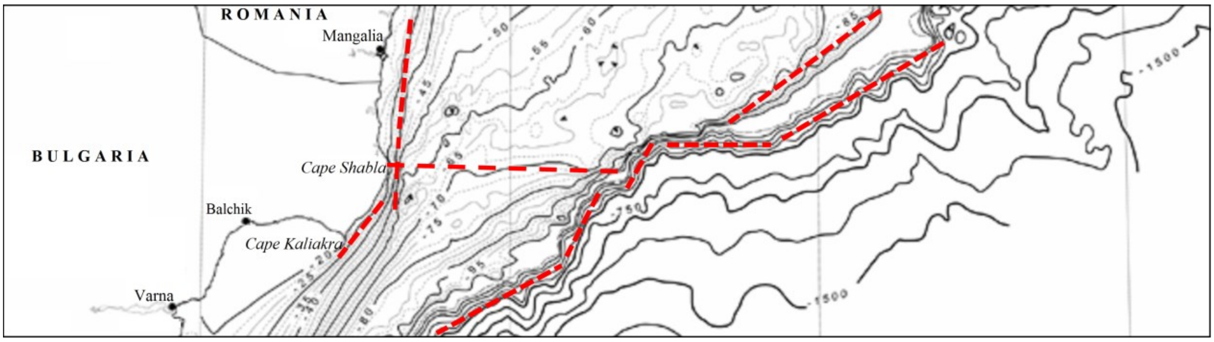

Fig. 16 – Interpreted faults (red dotted lines) on the bathymetric map of the Bulgarian Black Sea offshore in front of Shabla region (modified, after Dimitriu *et al.*, 2016).

4.4. SEISMICITY DATA

Considering that earthquake epicenters along lineaments of various length and trend may reveal fault lines and fault systems in areas characterized by active tectonics, the seismicity data represented in Fig. 12 have been interpreted for the region located, onshore and offshore, around Shabla zone (Fig. 17). In areas where the epicenters of seismic events are sparse, their interpretation has been supported by the faults and fault systems trending as resulted from the analysis of gravity and magnetic anomalies (Figs. 14 and 15) and considered as "expected continuation of fault line".

The main fault systems resulted from regional seismicity data interpretation are W–E, NE–SW and NW–SE, significant crossings of these fault systems being noticed in the Shabla area (onshore and offshore), E Mangalia area (offshore) and Călărași–Silistra area (onshore).

Of special interest might be the horizontal displacements of NE–SW faults along a NW–SE trending regional fault (sinistral strike-slip fault?) in the Shabla area, which may be associated with the seashore shape in a geodynamical sense north and south of Cape Shabla.

The high seismicity recorded in the Shabla and Mangalia areas, mostly offshore, are in good agreement with the high density of faults belonging to the W–E, NE–SW and NW–SE fault systems, and especially, to the high density of faults crossings (Fig. 17).

4.5. INTEGRATED INTERPRETATION OF GRAVITY, MAGNETIC AND BATHYMETRIC DATA

The main target of this study was represented by the onshore and offshore active fault systems in the Shabla region, responsible for the region's high seismicity and capable of strong and destructive earthquakes. To do that, within this section of the study will be selected the most relevant results obtained from the interpretation of each geophysical dataset.

The Bouguer gravity map illustrates in NE Bulgaria a large gravity high trending NNE–SSW between Dobrich and Varna, displaying the highest gravity values in the W Dobrich and W Varna areas as NW–SE local anomalies. Another large Bouguer gravity high is developed NNW–SSE between Silistra and Shabla, its highest values being contoured north of Shabla, in a local W–E trending gravity anomaly.

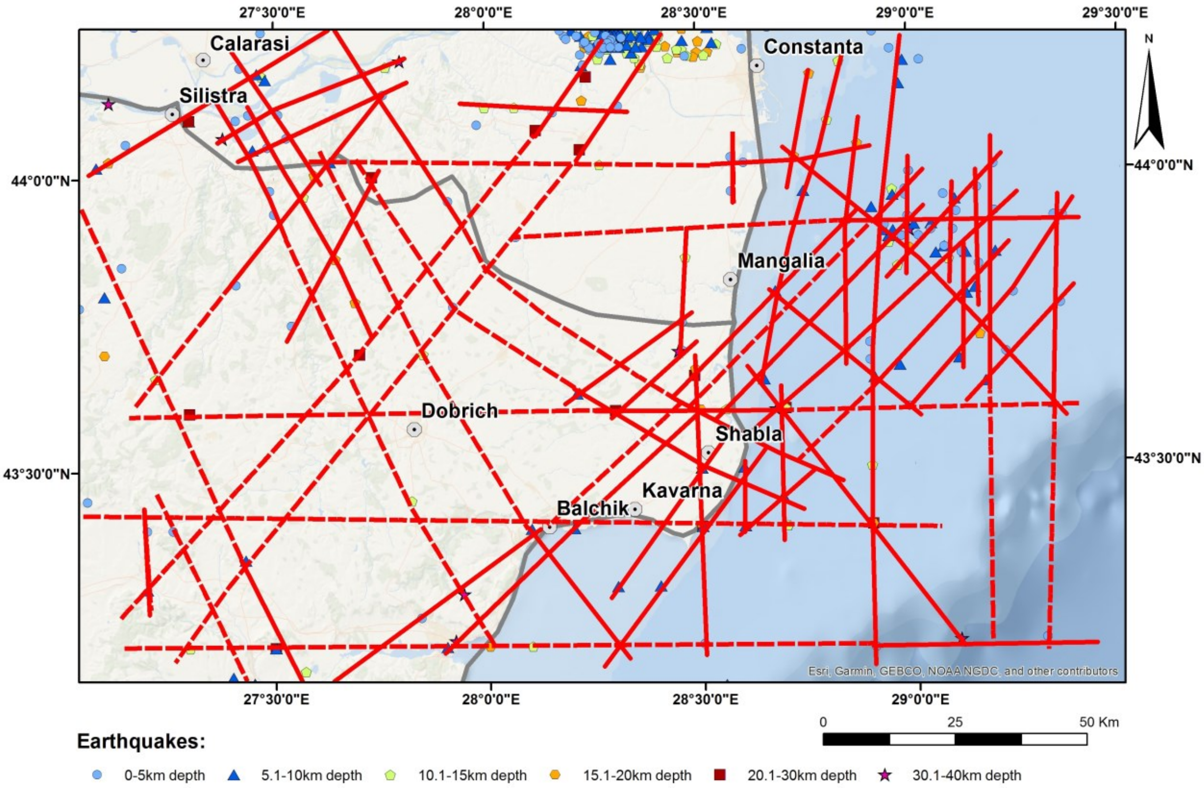

Fig. 17 – Interpretation of seismicity data in the Shabla seismic area. Red lines: interpreted fault lines; dotted red lines: expected continuation of fault lines.Seismological data from ROMPLUS Earthquake Catalogue (Oncescu *et al.*, 1999, updated) and EMSC Earthquake Catalogue (http://www.emsc-csem.org, 2016).

The vertical component of geomagnetic map contoured in NE Bulgaria two main high magnetic anomalies: a) in the Varna–Dobrich area, trending NNE–SSW; b) in the Shabla–Silistra area, trending NW–SE.

When integrating the results obtained using these two geophysical methods it is easy to observe that the regional gravity and magnetic anomalies are clearly overlapped, meaning that the deep geological structures are denser and have higher magnetic properties than the neighbouring ones.

Interpreting in geological terms, these high gravity and magnetic anomalies are determined by the North Bulgarian Uplift tectonic structure, which uplifted high density Palaeozoic sedimentary formations, covering a high density crystalline basement not yet reached by boreholes.

These uplifted sedimentary structures are pierced in both areas by large intermediate to basic magmatic intrusions, also not yet reached by boreholes. The trending of the analyzed regional gravity and magnetic anomalies is controlled by the main fault systems developed in the Shabla–Silistra–Varna region: NNE–SSW, NW–SE and W–E.

Lineaments resulted from the gravity (horizontal gradient anomalies), magnetic (vertical component and total geomagnetic field) anomalies and the bathymetric map analysis have been interpreted as faults and fractures (whether they are presently active or not), tectonic contacts or deep magmatic intrusions boundaries (Fig. 18).

There is not much overlapping onshore, between the lineaments interpreted on gravity horizontal gradient and magnetic data, the gravity ones referring mostly to tectonics of sedimentary formations, while the magnetic ones referring mainly to boundaries of magmatic intrusions. In cases when boundaries of magmatic intrusions represent tectonic contacts, implying also upward faulted sedimentary formations, such lineaments display a good correlation: W–E lineament between Dobrich and Shabla, or NE–SW lineaments in the Shabla, Kavarna and Balchik areas.

Better correlations may be noticed offshore, between W–E and NE–SW lineaments interpreted on magnetic and bathymetric maps, these fault systems extending eastward, offshore, within the submerged part of the Moesian Platform. The offshore NE–SW interpreted fault systems on bathymetric data reveals downlifted sea bottom sectors of the Black Sea shelf, these faults being considered to develop downward, into the sedimentary and magmatic geological formations.

The N–S lineament interpreted on bathymetric data between Shabla and Mangalia belongs to an N–S fault system, which tectonically controls the geometry of the Black Sea western margin. This fault system also controls the in steps seaward decrease of cliffs heights in the Kavarna and Balchik areas.

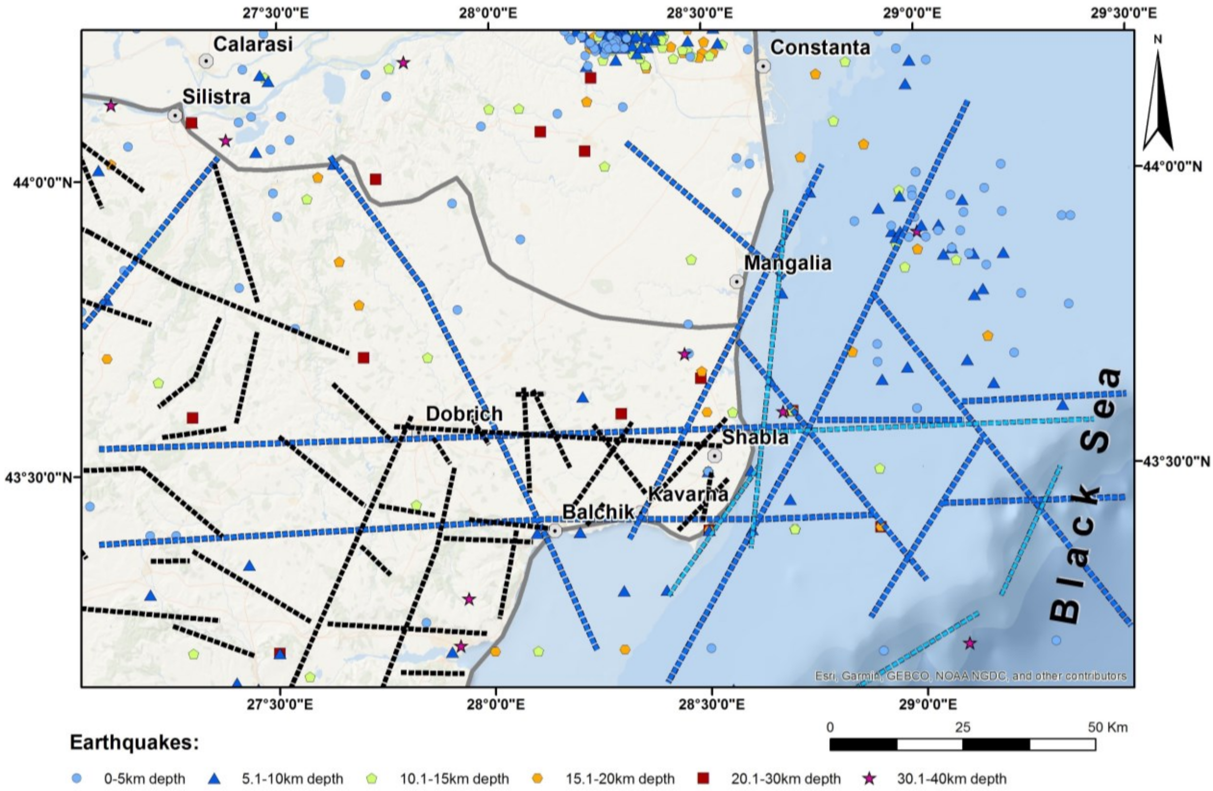

Fig. 18 – Faults interpreted in the Shabla region based on gravity, magnetic and bathymetric data. Black dashed lines: faults and tectonic contacts interpreted on gravity data; blue dotted lines: faults, fractures and magmatic intrusions boundaries interpreted on magnetic data; light blue dotted lines: offshore tectonic lineaments interpreted on bathymetric data. Seismological data from ROMPLUS Earthquake Catalogue (Oncescu *et al.*, 1999, updated) and EMSC Earthquake Catalogue (http://www.emsc-csem.org, 2016).

4.6. INTEGRATED INTERPRETATION OF MAGNETIC AND SEISMICITY DATA

Best for this study’s geophysical and tectonic objectives proved to be the lineaments interpreted on the regional magnetic and seismicity maps, these data covering both the onshore and offshore analyzed areas (Fig. 19).

When looking for active tectonics in a studied region most important are recently, or presently active faults and fault systems. Among all geophysical data interpreted, seismicity, considered as the regional occurrence of seismic events, is the method to offer this kind of information.

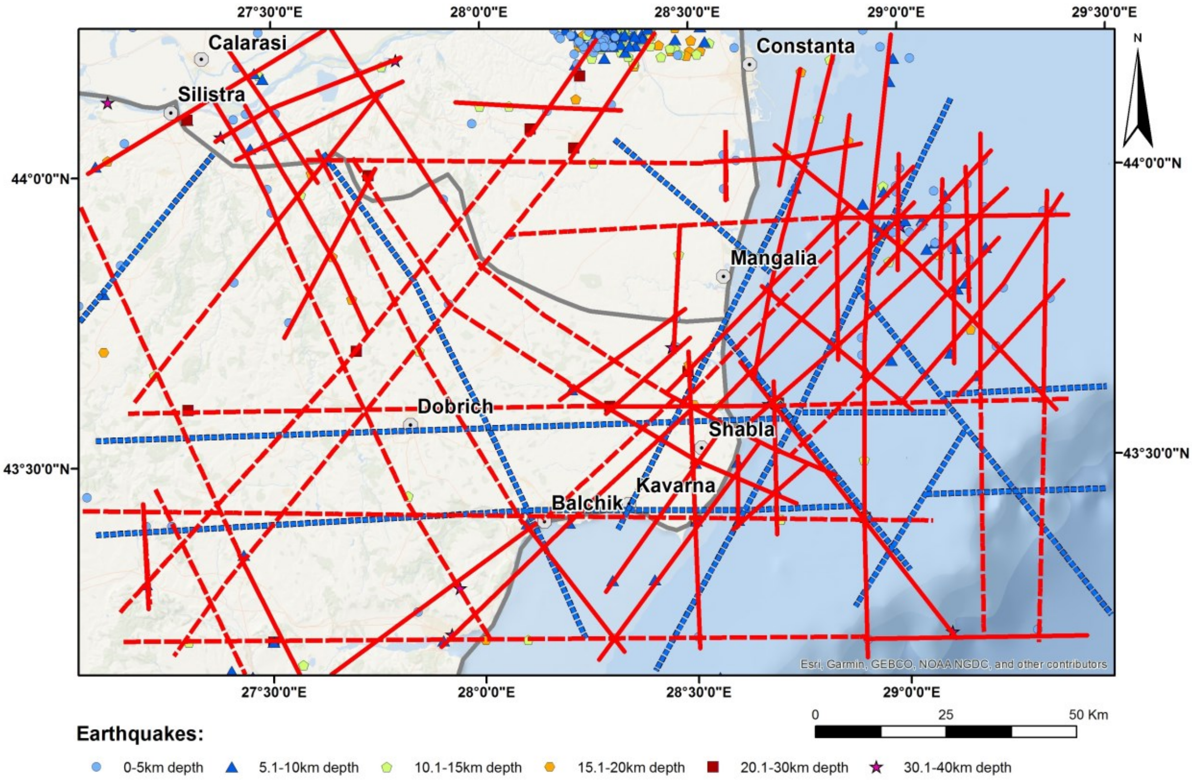

Fig. 19 – Faults interpreted in the Shabla region based on magnetic and seismicity data. Red lines: interpreted fault lines; dotted red lines: expected continuation of fault lines; blue dotted lines: faults, fractures and magmatic intrusions boundaries interpreted on magnetic data; Seismological data from ROMPLUS Earthquake Catalogue (Oncescu *et al.*, 1999, updated) and EMSC Earthquake Catalogue (http://www.emsc-csem.org, 2016).

Analyzing the lineaments presented in Fig. 19, the correlation of the W–E, NE–SW and NW–SE interpreted fault systems based on magnetic and seismicity data is quite high, showing that most of the tectonic features geophysically detected and illustrated in this map, are presently active.

Besides the fault systems depicted by magnetic data interpretation, the N–S system as interpreted on seismicity data, both onshore and offshore between Constanţa (Romania) and Kavarna (Bulgaria), seems to be of particular interest when evaluating the seismic hazard in this region, especially at crossings with the NE–SW fault system.

4.7. INTEGRATED INTERPRETATION OF NEOTECTONICS AND FIELD OBSERVATIONS

Active fault systems have influences in slow ground displacements during neotectonic vertical or/and horizontal movements, or sudden ones, as a consequence of high magnitude earthquakes (Ioane *et al.*, 2014).

Interpreting results of repeated topographic levelling measurements, geological mapping and geomorphological observations, it may be considered that the regional geological structure along the Black Sea shore, in Bulgaria and Romania, was tilted during neotectonic crustal movements, uplifting southward Sarmatian limestone formations (at Kavarna, ca 120 m) and downlifting northward the geological formations up to the Danube Delta (Romania). At Portiţa (Razelm Lake, Romania), Pleistocene loess was reached by boreholes beneath a Holocene sandy bank at several meters depth suggesting that this regional tectonic tilting developed quite recently, during the Quaternary.

From Cape Shabla to Kavarna the outcropping Sarmatian limestone is highly fractured due to a dense network of N–S faults, this fault system determining the littoral shape from Cape Midia (N Constanţa, Romania) to Kavarna (Bulgaria).

Geomorphological observations showed that the Intramoesian Fault and the Balgarevo Fault cross close to the Black Sea shoreline, the Ezeretzko and Shablensko firth lakes marking these faults junction: Ezeretzko is NW–SE shaped, along the direction of the Intramoesian Fault, while Shablensko is NE–SW shaped, along the Balgarevo Fault.

When searching for concrete traces of regional and local seismicity in the studied area, the houses walls usually bear for scars as immediate consequences of active faulting and damaging earthquakes (Fig. 20).

Fig. 20 – Oblique cracks, considered to be due to active faulting, observed on houses walls in Shabla (left) and Ezerets (right) localities.

5. CONCLUSIONS

This study started during the scientific project MARINEGEOHAZARD carried out by geoscientists from Romania and Bulgaria, one of its main task being the onshore and offshore active tectonics along the Black Sea Romanian and Bulgarian shorelines.

Two main fault systems have been previously mapped based on geophysical research within the Shabla region:

– a fault system parallel to the Balkan orogen, having W–E direction;
– a fault system having NNE–SSW or NE–SW directions.

Two high Bouguer gravity anomalies have been contoured in NE Bulgaria, separated by a low gravity “corridor” trending NW–SE toward Silistra:

– W–E trending anomaly between Shabla and the border Bulgaria–Romania;
– NW–SE trending anomaly located west of Dobrich.

High anomalies of the vertical component of geomagnetic field, trending NW–SE in the Shabla–Kavarna–Dobrich area, may be considered as associated with metamorphic rocks of the uplifted crystalline basement structures, most probably pierced by intermediate to basic magmatic intrusions.

Marine seismic surveys over the Shabla offshore area detected a NE–SW fault system, similar to the onshore Tyulenovo oil field structural trend, which is crossing an N–S fault system. North of Shabla the faults direction changes to NNW–SSE, reaching the N–S trending close to the shoreline.

The sea bottom morphology in front of Cape Shabla displays an N–S oriented steep slope, showing a fast decrease on the bathymetric map, crossed by a W–E lineament. Eastward, NE–SW and NNE–SSW lineaments of sudden increasing of sea bottom depth have been interpreted as normal faults involved in tectonic extensional processes.

Shabla region is a seismic zone with impact both on the territories of Bulgaria and Romania. Scattered seismic events are located on the entire area, but seismological recordings showed that the most active seismic area is situated offshore Shabla.

Earthquake epicenters along lineaments may reveal fault lines and fault systems in areas characterized by active tectonics, such as the Shabla area. In areas where the epicenters of seismic events are sparse, the seismicity data interpretation has been supported by the faults and fault systems trending as resulted from the analysis of gravity and magnetic anomalies and considered as "expected continuation of fault line".

The main fault systems interpreted on regional seismicity are W–E, NE–SW and NW–SE, crossings of these fault systems being noticed in the Shabla area (onshore and offshore), E Mangalia area (offshore) and Călăraşi–Silistra area (onshore).

The horizontal displacements of NE–SW faults along a NW–SE trending regional fault (sinistral strike-slip fault) in the Shabla area, might be associated with the seashore shape north and south of Cape Shabla.

Integrating the results obtained using the gravity and magnetic methods the regional anomalies are overlapping, meaning that the deep geological structures are denser and have higher magnetic properties than the neighbouring ones. These high gravity and magnetic anomalies are determined by uplifted high density Palaeozoic sedimentary formations and a high density crystalline basement not yet reached by boreholes, pierced by large intermediate to basic magmatic intrusions. The trending of the regional gravity and magnetic anomalies is controlled by the fault systems developed in the Shabla–Silistra–Varna region: NNE–SSW, NW–SE and W–E.

Lineaments interpreted on the gravity (horizontal gradient anomalies), magnetic (vertical component and total geomagnetic field) anomalies and the bathymetric map have been considered as faults and fractures (whether they are presently active or not), tectonic contacts or deep magmatic intrusions boundaries. When boundaries of magmatic intrusions represent tectonic contacts, such lineaments display a good correlation: W–E lineament between Dobrich and Shabla, or NE–SW lineaments in the Shabla, Kavarna and Balchik areas.

Good correlations have been noticed offshore between W–E and NE–SW lineaments interpreted on magnetic and bathymetric maps, these fault systems extending eastward, within the submerged part of the Moesian Platform. The offshore NE–SW interpreted fault systems on bathymetric data reveals eastward downlifted sea bottom sectors of the Black Sea shelf, these faults being considered to develop downward, into the geological structures.

Best for the objectives of this study proved to be lineaments interpreted on the regional magnetic and seismicity maps, these data covering the onshore and offshore analyzed areas. The correlation of the W–E, NE–SW and NW–SE interpreted fault systems based on magnetic and seismicity data is quite high, showing that most of the tectonic features geophysically detected are presently active.

The N–S lineament interpreted on bathymetric and marine seismic data belongs to an N–S fault system, which controls the geometry of the Black Sea western margin. This fault system also controls the in steps seaward decrease of the cliffs heights in the studied area.

Based on results from topographic levelling, geological mapping and geomorphological observations, the regional geological structure along the Black Sea shore, in Bulgaria and Romania, is interpreted as tilted during neotectonic crustal movements: uplifting southward Sarmatian limestone formations and downlifting northward the geological formations up to the Danube Delta (Romania).

Geomorphological observations showed that the Intramoesian Fault and the Balgarevo Fault are crossing close to the shoreline Black Sea, the Ezeretzko and Shablensko firth lakes: Ezeretzko is NW–SE shaped, along the direction of the Intramoesian Fault, while Shablensko is NE-SW shaped, along the Balgarevo Fault.

Graben structures observed at Russalka and Bolata may suggest a recent extensional regime in this area.

An older extensional regime was possibly associated with magmatic intrusions in this area, considering the high magnetic anomalies onshore and offshore. This could also explain the high thermal waters observed in boreholes along the coastline, within Durankulak – Shabla area, as well as the sulphide seeps occurrences in Mangalia area (Romania).

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REFERENCES

AIRINEI, ŞT., STOENESCU, S., VELCESCU, G., ROMANESCU, D., VISARION, M., RĂDAN, S., ROTH, M., BEŞUŢIU, L., BEŞUŢIU, G. (1983), *Magnetic Anomalies Map (ΔZ_a) of Romania, scale 1:1000000*, Geological Institute of Romania, Bucharest (in Romanian).

ALEXIEV, G. (2000), The role of destructive taphrogenesis in shaping the morphostructural pattern of Bulgaria's territory. Revista de geomorfologie, Vol. 2, Bucuresti, pp. 9–14.

BENDEREV, A., HRISTOV, V., BOJADGIEVA, K., MIHAILOVA, B. (2016), *Thermal Waters in Bulgaria*. In: P. Papić (Ed.), Mineral and Thermal Waters of Southeastern Europe, Environmental Earth Sciences, DOI 10.1007/978-3-319-25379-4_3, pp. 47–64, Springer International Publishing Switzerland.

BONCEV, E. (1974), *Moesian Platform.* In: Tectonics of the Carpathian Balkan regions, Platforms of the foreland, pp. 449–453, Geological Institute of Dionyz Stur, Bratislava.

BOTOUCHAROV, N., ANGELOVA, M. (2015), *Thermal Maturity of Middle Triassic Rocks and Heat Flow Modeling in Agatovo-Suhindol Area (Central North Bulgaria).*

BOTTOMLEY, S., PRITCHARD, G. (1998), *Tyulenovo field holds key to new drilling in Bulgaria*. Oil & Gas Jurnal, **96**, Issue 9, http://www.ogj.com/

CIOCÂRDEL, R., ESCA, A. (1966), *Essaï de synthèse des données, actuelles concertant les mouvements verticaux recents de l'ecorce terrestre en Roumanie*. Rev. Roum. Geol., Geophys., Geogr., Serie de Geophysique, **10**, 1, pp. 5–32.

DABOVSKI, C., BOYANOV, I., KHRISCHEV, KH., NIKOLOV, T., SAPOUNOV, I., YANEV, Y., ZAGORCHEV, I. (2002), *Structure and Alpine evolution of Bulgaria*. Geologica Balcanica, 32.2 – 4, pp. 9–15, Sofia.

DIMITRIU, R.G., OAIE, G., RANGUELOV, B., RADICHEV, R. (2016), *Maps of the gravity and magnetic anomalies for the western Black Sea continental margin (Romanian – Bulgarian sector)*. The 16th International Multidisciplinary Scientific GeoConference SGEM – 2016, Vol. III, Book 1, pp. 537–544, DOI: 10.13140/RG.2.1.1401.2405

EMSC Earthquake Catalogue, http://www.emsc-csem.org, 2016.

FINETTI, I., BRICCHI, G., DEL BEN, A., PIPAN, M., XUAN, Z. (1988), *Geophysical study of the Black Sea*. Boll. Geofis. Teor. Appl., **30**, pp. 197–324.

HRISTOV, V., TOTOMANOV, I., VRABLIANSKI, B., BURILKOV, T. (1973), *Map of the recent vertical movements in Bulgaria*. Central Geodetic Laboratory BAS, Geological Institute BAS, Sofia.

IOANE, D., DIACONESCU, M., CHITEA, F., GÂRBACEA, G. (2014), *Active Fault Systems and Their Significance for Urban Planning in Bucharest, Romania*. In: Boştenaru, D., Armaş, I., Goretti, A. (Eds.), Earthquake Hazard Impact and Urban Planning, pp. 15–45, Springer.

KUPRIN, P., BELBEROV, Z., KALININ, A., KANEV, D., KRUSTEV, T. (Eds.) (1980), *Geological and geophysical researches in the Bulgarian Black Sea zone* (in Russian, with English abstract), Publ. House Bulg. Acad. Sc. Sofia.

MATOVA, M. (1999), *Some geoindicators of recent geological activity along the northern Bulgarian coast (NE Bulgaria)*. Geoindicators, Workshop in Vilnius, Lithuania, http://www.lgt.lt/geoin/topic.php?tid=vilnius

MATOVA, M. (2000), *Recent geological activity along the northeastern Bulgarian Black Sea coast*. Geological Quaterly, **44**(4), pp. 355–361, Polish Geological Institute, Warshaw, https://gq.pgi.gov.pl/article/viewFile/8109/pdf_215

NADOR, A. (2014), *Danube Region geothermal report* – Bulgaria, European Union Strategy for the Danube Region COM (2010) 715. Available at: http://www.danube-region.eu, pp. 35–36.

OAIE, G., SEGHEDI, A., RĂDAN, S., VAIDA, M. (2005), *Sedimentology and source area composition for the Neoproterozoic – Eocambrian turbidites from East Moesia*. Geologica Belgica, **8**/4, pp. 78–105.

ONCESCU, M.C., MÂRZA, V.I., RIZESCU, M., POPA, M. (1999, updated), *The Romanian earthquake catalogue between 1984–1996.* In: Vrancea Earthquakes: Tectonics, Hazard and Risk Mitigation (Eds. Wenzel F., Lungu D., Novak O.), Kluwer Academic Publishers, pp. 42–49.

PARASCHIV, D. (1979), *The Moesian Platform and its Hydrocarbon Reservoirs*. Romanian Academy Publishing House, Bucharest, 196 p. (in Romanian).

PULIDO-BOSCH, A., LOPEZ-CHICANO, M., MACHKOVA, M., VELIKOV, B., DIMITROV, D., PENTCHEV, P., CALAFORRA, J.M. (1997a), *Ecological problems of karst waters caused by overexploitation and contamination – On the example of North-East Bulgaria*. ERB-CIPA-CT93-0139 Project, coordinated by A. Pulido-Bosch, Professor of Hydrogeology University of Granada (Spain).

PULIDO-BOSCH, A., MACHKOVA, M., LOPEZ-CHICANO, M., CALVACHE, M.L., DIMITROV, D., CALAFORRA, J.M., VELIKOV, B., PENTCHEV, P. (1997b), *Hydrogeology of the Upper Aquifer, Dobrich Region (Northeastern Bulgaria)*. Hydrogeology Journal, **5**, 2, pp. 75–85.

ROGOZHIN, E.A., KARAZAKOVA, YU.V., GORBATIKOV, A.V., SHANOV, S., STEPANOVA, M.YU., MITEV, A. (2009), *The Structure and Contemporary Activity of the Intramoesian Fault in Northeastern Bulgaria obtained through a Complex of New Geological-Geophysical Methods*.

SĂNDULESCU, M. (1984), *Romanian Geotectonics*, Technical Publishing House, Bucharest, 450 p. (in Romanian).

SĂNDULESCU, M., VISARION M. (2000), *Crustal structure and evolution of the Carpathian-Western Black Sea areas*. First Break, **18**, EAGE, pp. 103–108.

SEGHEDI, A. (1998), *The Romanian Carpathian foreland.* In: Sledzinski, J. (Ed.), *Reports on Geodesy. Monograph of Southern Carpathians*. Warsaw University of Technology, Institute of Geodesy and Geodetic Astronomy, pp. 21–48.

SEGHEDI, A., VAIDA, M., IORDAN, M., VERNIERS, J. (2005), *Paleozoic evolution of the Romanian part of the Moesian Platform: an overview.* Geologica Belgica, **8**/4, pp. 99–120.

SHANOV, S., BOYCOVA, A., MITEV, A. (2005), *Intramoesian Fault on Bulgarian territory: available geophysical data*. 4th Congress of the Balkan Geophysical Society, 9–12 October 2005, Bucharest, Romania, Journal of the Balkan Geophysical Society, **8**, Suppl. 1, pp. 56–59.

SHANOV, S., RADULOV, A. (2010), *Seismotectonic model on geological data for 1892 Dulovo earthquake, Lower Danube valley*. Scientific Annals, School of Geology, Aristotle University of Thessaloniki, Proceedings of the XIX CBGA Congress, Special volume, **100**, pp. 191–196.

STANCIU, I.M. (2020), *Intramoesian Fault: geophysical detection and regional active (neo)tectonics and geodynamics*, PhD Thesis, University of Bucharest, Faculty of Geology and Geophysics (unpublished).

STANCIU, I.M., IOANE, D. (2018), *The Intramoesian Fault: tectonic contact at crustal and lithospheric depths?* GEOSCIENCE – 2018, Abstracts Volume.

TARI, G., DICEA, O., FAULKERSON, J., GEORGIEV, G., POPOV, S., ŞTEFĂNESCU, M., WEIR, G. (1997), *Cimmerian and Alpine stratigraphy and structural evolution of the Moesian Platform.* In: Robinson, A.G. (Ed.), *Regional and Petroleum Geology of the Black Sea and Surrounding Regions.* American Association of Petroleum Geologists, Memoir, **68**, pp. 63–90.

TRIFONOVA, P., SIMEONOVA, S., SOLAKOV, D., METODIEV, M. (2012), *Exploring seismicity in Bulgaria using geomagnetic and gravity data.* Comptes rendus de l'Académie Bulgare des Sciences, **65**, 5, pp. 661–668.

TRIFONOVA, P., SOLAKOV, D., SIMEONOVA, S., METODIEV, M., STAVREV, P. (2013), *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, Pattern Recogn.* Phys., **1**, pp. 25–36, doi:10.5194/prp-1-25-2013.

VISARION, M., MAIER, O., NEDELCU-ION, C., ALEXANDRESCU, R. (1979), *Structural model of the Palazu Mare metamorphites, as inferred from integrated analysis of geological, geophysical and petrophysical data.* St. Cerc. Geol., Geofiz., Geogr., Geophysics, **17**, 1, pp. 95–113.

VISARION, M., SĂNDULESCU, M., STĂNICA, D., VELICIU, S. (1988), *Contributions à la connaissance de la structure profonde de la plateforme Moésienne en Roumanie.* Stud. tehn. econ., Geofizica, **15**, pp. 68–92.

ZAGORCHEV, I., SABOVSKI, C., NIKOLOV, T. (Eds.) (2009), *Geology of Bulgaria*, Vol. 2 (PPT Presentation) https://www.researchgate.net/publication/266615718_Presentation_Geology_of_Bulgaria_vol_2_Mesozoic_Geology

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