THE RELATIONSHIP BETWEEN THE ELECTROMAGNETIC PARAMETERS AND TECTONIC STRUCTURE OF THE TERRITORY OF BULGARIA

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Abstract. The results of magnetovariational sounding at the area of Rhodope Massif of the Republic of Bulgaria were examined. Magnetovariational response functions were calculated and the maps of - modulus and phases of the induction vectors were built based on the results. The comparison of these maps with the tectonic structure of the Rhodope was made. As a result it was shown that the MV parameters quite adequately reflect the tectonic features of the Rhodope region.

Key words magnetovariational sounding, induction vectors, conductivity anomalies, tectonic structures, Rhodope

Introduction

The present-day studies have shown that the Earth's tectonosphere consists of inhomogeneities of different ranks and structures, whose lateral position and position in the section do not always correlate with visible geologic structures. This necessitates mapping of deep-seated inhomogeneities in the crust and upper mantle in connection with the development of prognostic criteria for deep-seated oil, gas, and solid minerals and the compilation of new-generation maps for predicting concealed deposits (Shchukin, 2005).

The problem of the relationship between the crustal/mantle heterogeneities and surface structures is one of the key problems in the contemporary geology.

The electrical conductivity of the tectonosphere, which is studied by electromagnetic (EM) methods, is determined by a number of factors such as mineral and chemical composition of the rocks, porosity and pore connectivity, fluid or graphite content, and temperature. The conductivity at the crustal and upper mantle depths is predominantly determined by temperature and fluid content.

Importantly, the geoelectrical estimates of these parameters are independent of their estimates derived from seismic data. The EM soundings of the Earth which use the fields from natural and controlled sources provide a sufficiently large depth of investigation and have a specific sensitivity to the conductivity anomalies associated with these factors.

Presently, the EM soundings with natural sources have become a powerful instrument for exploring the geoelectrical structure of the Earth's interior. As the examples, we cite the EMSLAB, BEAR, EMTESZ-Pomerania, KIROVOGRAD international projects, the German soundings in the Andes, and the ambitious EARTHSCOPE и SYNOPROBE programs deployed in the USA and China.

Due to their particular sensitivity to the zones of high fluid saturation and thermal decomposition of the crustal/mantle material, the EM soundings are an important element in the family of geophysical methods for studying the structure of the tectonosphere in the geodynamical active regions.

In the eighties of the twentieth century, the efforts of the Bulgarian scientists of the Scientific Research Institute of Mineral Resources of the Ministry of Geology of Bulgaria and the Soviet geophysicists of the USSR Academy of Sciences (presently Russian Academy of Sciences) resulted in the extensive geoelectrical regional studies by the magnetotelluric and magnetovariational soundings on a number of the international geotraverses and linking their profiles which stretched almost across the entire territory of Bulgaria.

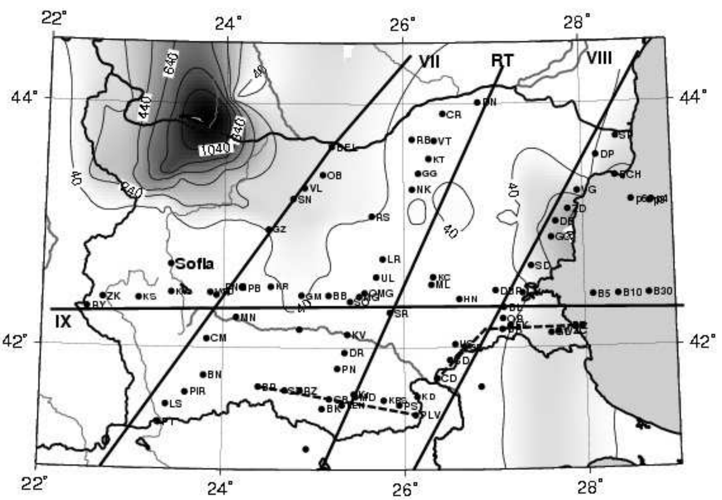

Fig.1. The map of the MT and MV soundings across geotraverses on the Bulgaria territory. Lines with numbers - values of the total longitudinal conductance of sediments S_s

These studies are essentially the first experience of a systematic study of the deep geoelectric structure of Bulgaria. Fig. 1 shows the points position for the observation of the long-period variation of the electromagnetic field at the territory of Bulgaria and the adjacent shelf. There were made more than 80 points of sounding in the wide interval of the variation periods: from 10 minutes to 24 hours.

During the land experiments were carried out synchronous measurements by a 5-component stations IZMIRAN-5. They measured the D (east), H (north) and Z (downward) magnetic field and Ex (north) and Ey (east) electrical field components.

A special magnetic instrument complex installed at the Panagyurishte observatory was in operation during the whole period of the observations. This station ensured the synchronization of the EM field measurements conducted during different years.

For the experimental data processing a software complex for the analysis of time series was applied (Ashirova et al., 1989). Regarding to the research, the spectral processing involved the calculation of the complex functions of the electrical conductivity, including the determination of the parameter R and the relationship of the coincident horizontal magnetic field components in a wide range of variations periods from 10 minutes up to 3 hours.

The qualitative interpretation of the data along the Petrich--Nikopol profile was carried out. The main result of the research was the discovery of the asthenosphere layer of the increased conductivity at the top of the mantle.

The chronology and preliminary results of the work described in (Abramova et al., 1994).

The further studies in this direction were broken by the known dramatic events that changed the political and social landscape of our countries.

In this paper we have tried to make the revision and additional processing of materials, the analysis of which has been postponed until better times, and may offer a new contribution to the problem of using sensing MV data.

Definitions and theoretical prerequisites

The variations of the magnetic field of the Earth which are generated by the electrical currents flowing in the near-Earth environment induce the secondary solenoidal currents in the conductive layers of the crust and upper mantle. These fields and currents are employed in the different EM sounding methods for estimating the conductive properties of the rocks composing the crust and asthenosphere.

The magnetovariational sounding (MVS) and magnetovariational profiling (MVP) methods are based on the amplitude ratio between the spatial harmonics of the vertical and horizontal components of the magnetic variations. These methods are used for searching for and exploring the large horizontal heterogeneities in the electrical conductivity of the Earth's crust and upper mantle through the separation and analysis of the anomalous part of the field of magnetic variations (Schmucker, 1970; Gough and Ingham, 1983).

In the MVS and MVP methods, all the procedures for processing the measurements at a separate observation point and on the profile employ the linear relationship that links the horizontal components of the EM field of magnetic variations H_x (T) and H_y (T) at period T with the vertical component H_z

$$H_z (T) = A H_{\mathbf{x}} (T) + B H_y (T) \qquad (1)$$

At each observation point, the induction vectors **C** (Schmucker, 1970) are calculated (and then plotted as the maps) from the magnetic tensor components in the following way:

$$\mathbf{C} = Ai + Bj, \tag{2}$$

with i and j pointing North and East, respectively. The induction vectors are constructed separately from the real (**Cu)** and imaginary **(Cv)** parts of the coefficients A and B for the selected periods.

As a result of data processing at each observation point, the components of the magnetic tensors and complex induction vectors were calculated in the interval of the periods of the magnetic variations from 15 min to 3--4 h. For the section along the Petrich--Nikopol profile, the one-dimensional (1D) and two-dimensional (2D) geoelectrical models were calculated, and the comprehensive interpretation of the obtained results with the allowance for the additional geological and geophysical parameters was carried out (Abramova et al., 1994).

The overall structure of the EM field along the profile was characterized by the following features.

1. The amplitudes of the vertical magnetic component and, hence, the components of the induction vectors $C_{\mathbf{u}}$ and $C_{\mathbf{v}}$, within the southern part of the profile are lower than in its northern part. This looked somewhat odd, considering the fact that the distance between the northern and southern segments of the profile was at most 150 km. Due to this, it was natural to hypothesize that the behavior of the EM field in Rhodope is largely contributed by the electrical conductivity of the underlying basement layers, which smoothed out the conductivity contrast.

2. The orientation of the EM field as characterized by the layout of the induction vectors did not always agreed with the *surface* structural plan of the key tectonic units and indicated a probable misalignment between the surface and deep boundaries of the geological crustal objects.

3. The total longitudinal conductance of sediments S_s estimated during the interpretation was ~1000--1700 S in the entire territory of the observations. The value of S_s in the Rhodope region was nearly identical to S_s within the Moesian platform covered by the thick sedimentary strata. This was noticeably different from the S_s-map for the territory of Bulgaria which was constructed by Iovka Borisova based on the geological and geophysical data available at that time (Fig. 1). On the first glance, this was surprising since the Rhodope in their subsurface portion are composed of the Precambrian or Early Paleozoic crystalline schists and granitoids with very high resistivities (Dachev, 1988).

4. The regional seismic studies along the Petrich--Nikopol profile VII revealed a waveguide in the upper crust at a depth of 5--10 km (Fig. 2) (Dachev et al., 1985).

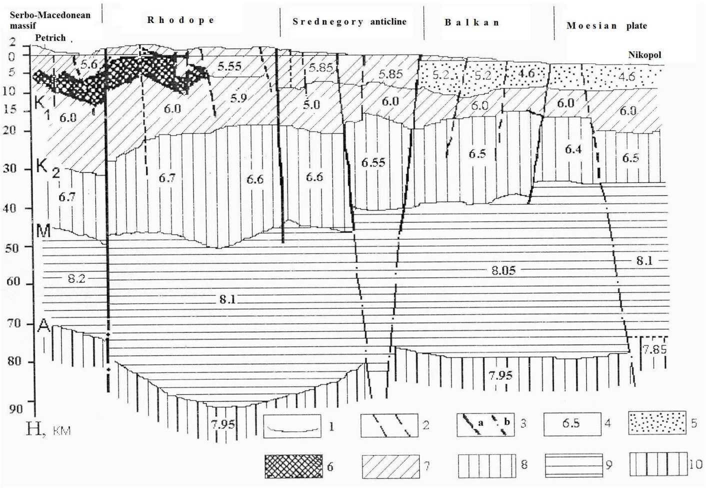

Fig.2 The Petrich-Nikopol section of the Earth crust.1 –seismic boundaries; 2-3 faults: 2 – crustal, 3- mantle (a –certain, b –possible); 4 – leer velocity values, km/s; 5 – sedimentary layer; 6 – low velocity layer; 7 – "granite" layer; 8 – "basalt" layer; 9 – uppermost mantle; 10 – asthenosphere layer (?)

The thickness of the waveguide is 8--9 km beneath the Rhodope. The top surface of the waveguide deepens southwards, and its thickness diminishes to 5--6 km in this direction. North of the Rhodope, the top surface of the waveguide also deepens, and its thickness decreases to 6 km.

These features in the behavior of the EM and seismic fields suggested the existence of highly conductive layers in the crust and probably in the conductive asthenosphere.

In the present work, we analyze the example of Rhodope for exploring the relationship between the parameters of the EM field and the tectonic structure of the region. This segment of the Bulgarian territory is covered by the densest EM field observations along a number of the electromagnetic profiles.

The geological and geophysical settings

The Balkan territory pertains to the Alpine folded zone, a part of the Balkan--Asia Minor orogeny (Velchev et al., 1970; Dachev, 1988). This arc-shaped edifice is elongated in the NW--SE direction in its western part and in the EW direction in its eastern part. It continues up to the Pontides in the east and up to the southern portions of the Carpathians in the west.

The Moesian platform, Balkan folded system, and Rhodope zone are the main geological--tectonic elements of the region. The post-Cretaceous evolution of these territories was marked by the formation of the numerous thrusts of different ages, often with significant amplitudes of the displacement (Ivanov R., 1981, 1984; Ivanov Zh. et al., 1984; Iosifov et al., 1994; Zagorchev, 2001).

The Rhodope massif which spreads over the territories of Bulgaria, Greece, and Serbia, is a unique geological object with a complicated tectonic structure and sharply anomalous behavior of the geophysical fields, a high hydrothermal and seismic activity, and a wide range of the ore and non-ore mineral deposits.

According to the modern understanding, the Rhodope region has undergone a profound Alpine rejuvenation including the formation of the Rhodope deep nappe and overthrusting of the Serbian--Macedonian massif over the Rhodope region (Ivanov R., 1981; Dachev, 1988; Zagorchev, 2001).

The existence of the Rhodope nappe is supported by the following body of evidence.

(i) The seismic and gravimetric data reveal the thick (45--55 km) crust beneath the Western Rhodope, which is the thickest among all the Balkan alpides; its thickness decreases northwards to 30 km in the region of the Moesian platform (Volvovsky et al., 1987; Dachev, 1988). This can probably be caused by the presence of the large thrust slices (thrust nappe) which augment the crust.

(ii) The anomalously high position of the top surface of the asthenosphere and clear traceability of the related seismic waves testify to the specific state of this region, which is caused by the redistribution of stresses in the hot thermodynamic conditions. The existence of the waveguide zone established from seismic data is associated with the thick sediments buried in this area (Volvovsky et al., 1987).

As a reference for analyzing the probable correlation between the tectonic structures and EM field, we used the study of R. Ivanov (1981) where the author explored the tectonic structure of the Rhodope region (Fig. 3, adopted from the cited paper).

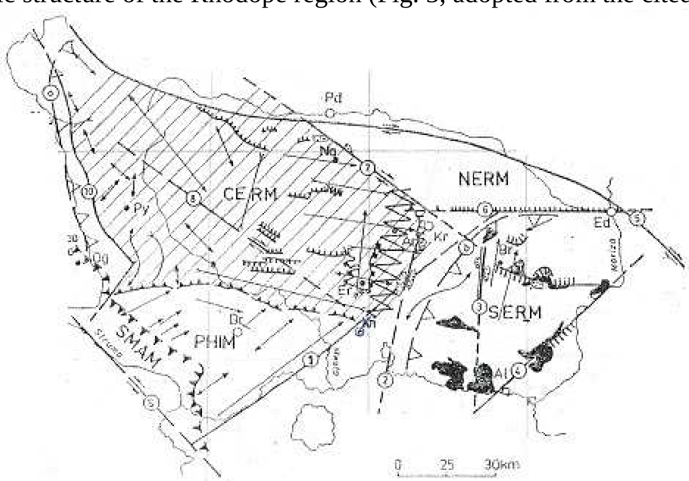

Fig. 3. Structure of a part of the Late-Alpine Rhodope massif (Ivanov R., 1981). Great faults and sliding zones: SMV- Simvolon, SZH -Snezhin, MAR - Maritsa, AD – Asenovgrad -Diadovo, STF – Struma, RF – Rhodope fault. M-N - the Madan-Nedelino intraformational glide. Towns:Pd – Plovdiv, Ed - Edrine (Odrin), Kr – Kardzali. Areas: Er –Erma-reka, Py – Pirin, Na – Norh-Rhodope Anticline.

The Rhodope massif is a territory of the metamorphic rocks and granites partially overlain by the Tertiary molasses and volcanics. The Tertiary molasse depressions and the related faults divide the massif into several "partial" submassifs: the North-East Rhodope Massif (NERM), South-East Rhodope Massif (SERM), Central Rhodope Massif (CERM), including the Rila and Pirin mountains, PHIM – the autochthonous part of the CERM, and Serbian--Macedonian Massif (SMAM), (Fig.3) (Ivanov R., 1981).

Just as the Aegean Sea and Western Turkey, the southern Bulgaria is characterized by the high heat flow (> 2 mCal/cm^{2}s against the average flux of 0.88 mCal/cm^{2}s over the Eastern Mediterranean (Macris, 1977)). One of the probable explanations of this phenomenon conjectures that the Aegean region has a heated upper mantle due to the convective motion of the hot asthenospheric material which penetrates into the lithosphere. It is presumed that beneath the Aegean region there is a large lithothermal dome which originated from the asthenospheric trough. This hypothesis is supported by the works on seismic tomography (Spakman et al., 1988).

At a depth of about 200 km is the low-speed area, due, apparently, to melting zone upper mantle rocks. In the area of southern Bulgaria there is a continuation of this zone. High heat flow values under the territory of the Rhodope testify to this. Province of Southern Balkan is characterized typically unsteady and heterogeneous thermal field, which is typical for activated alpine (Kutas, 1978; Velinov, Boyadjieva, 1981).

Interpretation

For the purposes of the present study, we revisited the old data and carried out the partial processing of the EM field observations by the modern software system (Varentsov, 2013). As a result of this work we built the curves of the magnetic parameters and estimated their accuracy. All the data are represented in the form of the maps showing the distributions of the key invariant complex parameters for the periods of magnetic variations ranging from 15 min to 3 h over the territory of Bulgaria.

According to the theory, the parameters of the amplitudes and directions of the induction vectors reflect the position and strike of the surface and buried deep structures. The example in Fig. 4 a, b shows the two panels of the parameters of the magnetovariational responses (induction vectors): the amplitude (modulus) of vector **C** (Fig.4a) and its direction Dir C (Fig.4b) in the southern segment of the Bulgarian territory. The maps are presented for three periods: 2200 s, 5400 s. and 8500 s. We chose these values of the periods as adequately reflect to the individual parts of the frequency characteristics.

The MV responses demonstrate the different behavior of the EM field at the different periods of the observations, which testifies to the vertical stratification of the geoelectrical section. The EM field at the relatively short periods reflects the properties of the geoelectrical section in the upper crustal layers, whereas with the growth of the period, the pattern of the field becomes increasingly dominated by the effects of the deeper structures.

The correlation between the tectonic structures and EM field is clearly observed in the case of the Central Rhodope Massif. The both panels in Fig. 4 show a zone that is confined to the position of the allochthonous CERM (Ivanov, 1981; 1984).

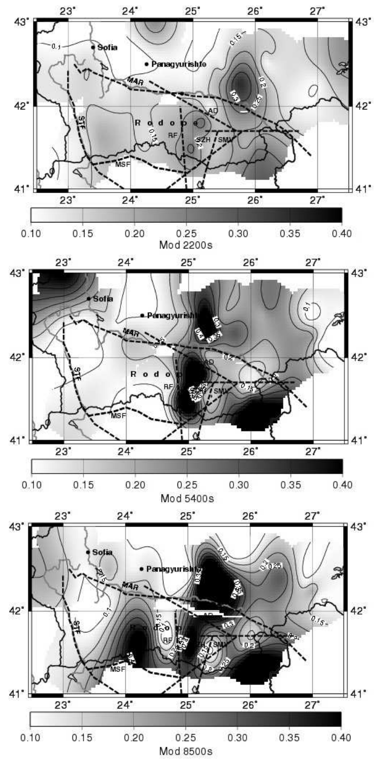

Fig. 4a. The maps of the of the magnetovariational response parameters: modulus of the induction vector **C.**

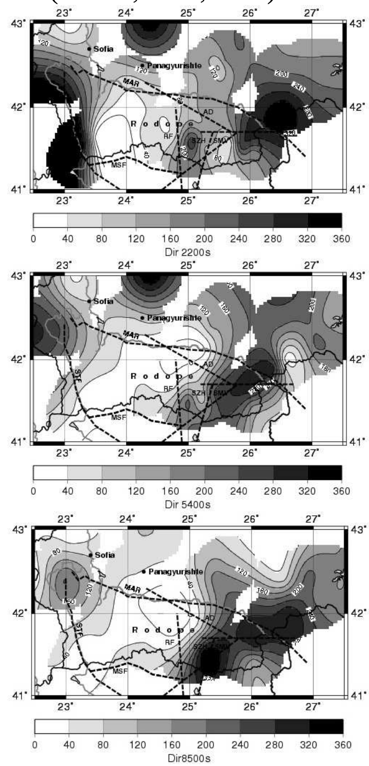

Fig. 4b. The maps of the of the magnetovariational response parameters: phases of the induction vector Dir C.

As seen from panel *a* of Fig. 4, the amplitudes of the induction vectors within the Western Rhodope (CERM territory) are low at almost all the periods of magnetic variations. In contrast, the amplitudes of the induction vector in the Eastern Rhodope (NERM and SERM areas) are, on average, noticeably higher, except for the separate local anomalies.

The low amplitudes of the induction vectors indicate that the crustal conductive layer which we previously revealed when interpreting the geoelectrical section along the Petrich--Nikopol geotraverse stretches beneath the entire CERM region.

The similar delineation of CERM territory by the directional parameters of the induction vectors, which is shown in Fig. 4b, is even more distinct.

This behavior of the vectors is well consistent with the hypothesis that the integral (whole) allochthonous plate constructed of the Rhodope series overlies almost the entire CERM region (the central Rhodope, Rila, and Pirin mountains). It is composed of highly metamorphosed rocks (almandin-amphibolites, migmatites, etc.).

The *western boundary* of this conductive layer just as the bend of the SW boundary of the Struma fault are clearly outlined by the EM parameters (Fig. 4b).

It is presumed that the western CERM boundary is hidden beneath the sediments of the Tertiary molasse depressions in the basins along the Struma River. West of this line, the rocks have the different properties and are described as the Serbian--Macedonian metamorphic series in Greece (Birk et al., 1970). The directions of the induction vectors fix this boundary by the sharp change in their directions.

The position of the *northern boundary* of the nappe is expected to occur in the zone of Sredna Gora. The southeasterly striking Asenovograd--Dyadovo (AD) fault is presumed to be the boundary band of the CERM allochthon. To a certain extent, this is reflected in the parameters of the EM field in Fig. 4.

The *eastern boundary* of the nappe is covered by the thick strata of the Paleogenic molasses. Its surface is masked by the thick (>500 m) zone of slickenside diaphthoretic rocks. (Ivanov R., 1981). The strikingly pronounced gravimetric transition from the light masses of the CERM allochthon to the significantly heavier SERM masses is interpreted as the geophysical “Central Rhodope Deep Fault” (RF), which is probably the geological boundary between the different rocks of the blocks of the Central Rhodope autochthon nappe. This region is marked by the profound folding, diaphthoresis, and milinitization of the NNE zone with the thick serpentite layers at the CERM and SERM boundary-- the Snezhin synclinorium.

The position of this fault spatially corresponds to the sharp changes in the parameters of the EM field at almost all the periods of the amplitudes and directions.

The nature of the conductive layer in the Rhodope

The high-conductivity anomaly revealed in the western part of the studied territory is likely to be induced by the fluids ascending from the lithospheric plates which subside towards the southern portions of the Serbian-Macedonian and Rhodope massif. This geoelectrical structure of fluid--thermal origin is correlated to the low-velocity seismic structure (Fig. 2).

As noted above, the waveguide which is identified from seismic data in the upper portions of the crust at a depth of 5--10 km is associated with the thick buried sedimentary rocks in this part of the region. In the opinion of the Bulgarian geologists (Ivanov, Stanev, 1982), the autochthon in this thrust is formed by the thick marble layer which is treated by the hydrogeologists as a large, deeply seated artesian basin with hydrothermal karst. The allochthon composed of the Rhodope granitoid series serves as the water-resistant confining plate.

These scientists suggested the paleohydrogeologic approach based on studying the hydrothermal systems in the active volcanic area and substantiated the thermo-elision model of polymetallic metallogeny in Rhodope. This model can explain the origin of the conductivity anomaly revealed beneath the Rhodope.

An important fact is that during the Tertiary period, the Rhodope aquifer was a carrier of hydrothermal brines which penetrated into the Rhodope confining plate and formed the metasomatic tin -- zinc ore mineralization (the Erma River deposit).

Interestingly, the region of the increased crustal conductivity also quite accurately coincides in plan with the negative lithospheric anomaly of the constant magnetic field established from the CHAMP satellite data, which suggests the elevation of the Curie surface, and with the change in the sign of the lithospheric magnetic field in the region of the Central Rhodope deep thrust (see the paper: "Lithospheric magnetic anomalies in the Balkan region" in this Journal).

Conclusion

From the presented data it can be seen that the MV parameters quite adequately reflect the tectonic features of the Rhodope region.

The analysis of the EM data quite confidently suggests the presence of the buried crustal conductor beneath the western part of the Rhodope massif. The parameters of the EM field reflect the spatial distribution of the Central-Rhodope massif and the Central-Rhodope deep fault zone.

The Rhodope hydrothermal basin can be treated as the source and cause of the unique geoelectrical anomaly in the south Bulgaria.

The further interpretation of the revealed crustal geoelectrical anomalies with the allowance for the seismic velocity models, seismological data, geothermal reconstructions, potential field anomalies, geochemical and petrophysical notions, as well as the other geological and geophysical information will clarify the origin of these anomalies and elucidate their relationship with the geodynamical processes.

The modern interpretation technologies that have been developed in the world to date make it possible to build the volumetric geological models on different scales which could be of practical value for mineral prospecting, hydrogeological and hydrothermal resources evaluation, and seismicity assessment in the territory of Bulgaria.

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Връзката между електромагнитните параметри и тектонски структури на територията на България

Л. Абрамова, Ив. Варенцов, Д. Абрамова

Резултатите от магнитовариационните (MV) изследвания на територията на България са представени в статията. Изчислени са функциите на електропроводността и магнитните индукционните вектори. Построени са върху тях карти на модул и посоката на индукционните вектори. Сравнението на тези карти с тектонската структура на района на Родопския масив показва, че параметрите MV адекватно отразяват тектонските характеристики на региона на Родопите.