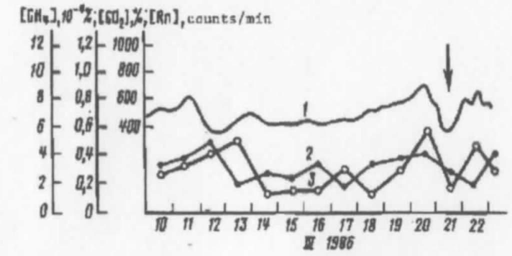

Fig. 3. Behavior of concentrations of radon (1), CO_2 (2) and methane (3) in subsoil air during preparation of Ura-Tyube earthquake of March 21, 1986, M = 4.6, about 80 km from observation site. Measurements made in the zone of North Ferghana deep fault (at Leninabad).

and CO_2 and CH_4 (Fig. 3) suggests that the earthquake focus was at a shallow depth and that the deformation that accompanied the propagation of the main crack was rapid. Third, the high energy density (or fluid content) of the rock medium in the North Ferghana fault zone during stress relaxation produced embayment-type anomalies in the subsoil radon distribution, similar to hydrodynamic anomalies [8]. Fourth, the earthquakes and accompanying rock deformations in the epicentral zone liberated new portions of radon, which were carried into the subsoil atmosphere by carrier gases in brief bursts that occurred after the embayments on the curve. Last, there occurred a smooth restoration of the background concentration or radon emanation, a process governed primarily by stabilization of the discharge of carrier gases into the subsoil atmosphere.

The above description is consistent with the theory of stagewise evolution of the focal zones of shallow-focus crustal earthquakes, developed by Myachkin et al. [5]. The entire description is very applicable to the development of the radon anomaly associated with the aftershocks of the Kayrakkum earthquake of October 13, 1985. There also seems to exist no fundamental difference in the mechanisms that produced the radon anomalies at Leninabad and were due to the shallow, solitary 1986 and 1985 earthquakes whose epicenters were at Ura-Tyube.

REFERENCES

1. Abduvaliyev, A.K., V.K. Adreyev, G.I. Voytov and N.K. Sergeyev. Dokl. Akad. Nauk SSSR, 271, No. 1, pp. 72-75, 1983.
2. Abduvaliyev, A.K., G.I. Voytov and V.P. Rudakov. Ibid., 291, No. 4, pp. 924-927, 1986.
3. Rudakov, V.P. Geokhimiya, No. 9, pp. 1337-1342, 1986.
4. Sadovskiy, M.A. Dokl. Akad. Nauk SSSR, 247, No. 4, pp. 829-831, 1979.
5. Myachkin, V.I., B.V. Kostrov, G.A. Sobolev and O.G. Shamina. In: Poiski predvestnikov zemletryaseniy (The Search for Earthquake Precursors), Donish Press, Dushanbe, pp. 121-131, 1976.
6. Lange, K.O. and G.N. Pshenin. Dokl. Akad. Nauk SSSR, 295, No. 6, pp. 1339-1343, 1987.
7. Abdulvaliyev, A.K., G.I. Voytov and V.P. Rudakov. Ibid., 300, No. 6, pp. 1737-1340, 1988.
9. Sadovskiy, M.A., F.I. Monakhov and A.N. Semenov. Ibid., 236, No. 1, pp. 50-53, 1977.

UDC 550.837.6

DEEP ELECTROMAGNETIC SOUNDING IN BULGARIA[1]

M.S. Zhdanov, L.M. Abramova, I.M. Varentsov, A.A. Belev,
N.G. Golubev, Kh. Y. Dachev, S.I. Sanin and V.S. Shneyer

Institute of Terrestrial Magnetism, the Ionosphere, and
Radio Wave Propagation (IZMIRAN), USSR Academy of Sciences,
Troitsk, Moscow Oblast; Institute of Minerals,
Committee on Geology (NIPI), Sofia, Bulgaria
(Presented by Academician Ye. P. Velikhov, March 27, 1989)

1. Teams of our two organizations have recently conducted deep electromagnetic soundings (DEMS) in Bulgaria on a system of international geotraverses. These investigations represent the first attempt at systematic study of the deep geoelectric structure of the Balkan region.

The DEMS technique combines magnetotelluric sounding (MTS) and magnetic variation profiling (MVP) and is generally based on multicomponent, multifrequency areal or profile electromagnetic measurements, which are used to determine the spatial distribution of electrical conductivity in the crust and the upper mantle [1, 2].

The effectiveness of this approach was recently demonstrated [2] in the interpretation of the Carpathian geomagnetic anomaly along the KAPG[2] geotraverse II.

2. Figure 1 is a summary diagram of long-term measurements of variations in the natural electromagnetic field between 1983 and 1987 along the KAPG system of geotraverses. In 1973, work was performed over the entire length of the Bulgarian segment of geotraverse VII, which runs from north to south across the Mysian platform, the Balkan fold belt, and the Rhodope block. Twelve observation stations equipped with 3- and 5-component quartz variation sets designed by IZMIRAN were set up on the 280-km traverse. In 1984 the measurements were continued on the 200-km geotraverse VIII, also crossing the Mysian platform and the Balkans and part of the Rhodope block. There were 11 stations on this traverse, which is near the Black Sea coast of Bulgaria, about 230 km east of geotraverse VII. In 1985, investigations in southeastern Bulgaria were made along the so-called "connecting traverse," which adjoins geotraverse VIII and cuts across the Strandzha region and the Rhodope block. Nine observation stations were operated on this traverse. In 1986-87, measurements were made on traverse IX, crossing Bulgaria from west to east: 24 deep magnetotelluric soundings were made.

Various electromagnetic measurements were made with buoy and bottom stations on the shelf of the Black Sea between 1980 and 1984. The marine measurements have been published [3]. In 1981-87, a total of 60 deep electromagnetic stations were operated.

During the entire observation period, a base station was in operation at the Panagyurishche observatory (Fig. 1), which synchronized all the electromagnetic measurements. The data were processed with a set of programs for analyzing magnetotelluric (MT) and magnetic variation time series, developed by IZMIRAN, the Institute of Geology, Turkmen SSR, and the Interdepartmental Geophysical Commission, USSR Academy of Sciences [4-6].

In this paper we present results based on the electromagnetic measurements on geotraverses VII and VIII. At each observation site we determined the transfer function of the electromagnetic field at periods between 10 minutes and 3 to 4 hours (or for up to 24 hours at some locations), including the components of the impedance tensors, the induction vectors, and of the telluric and magnetic tensors.

3. Qualitative analysis of the data identified the general structural patterns of the electromagnetic field in Bulgaria.

A. The amplitude of the vertical component of the magnetic field and the amplitudes of the induction vectors are small over practically the entire area, other than certain marine and shore sites ($|H_z/H_\tau|$ is a maximum of 0.15 to 0.2), and they are virtually independent of the frequency; the horizontal component of the magnetic

---

[1] Translated from: Glubinnyye elektromagnitnyye zondirovaniya v territorii Narodnoy Respubliki Bolgarii. Doklady Akademii Nauk SSSR, 1990, Vol. 312, No. 6, pp. 1338-1343.

[2] Commission on Planetary Physics of the Academies of Science of the Socialist Countries.

ISSN0012-494X/90/0003-0069$7.50/D

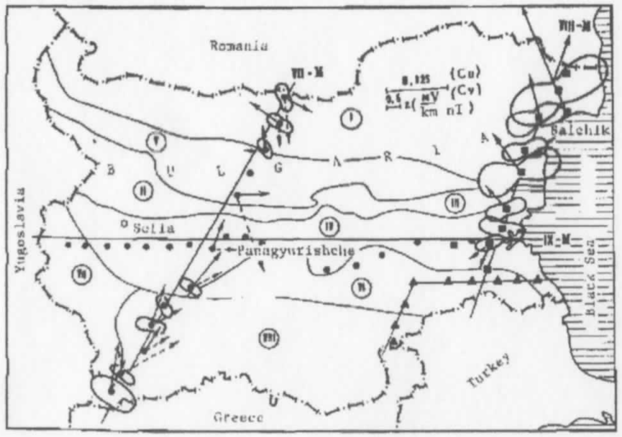

Fig. 1. Summary diagram of joint studies in 1983-1987.

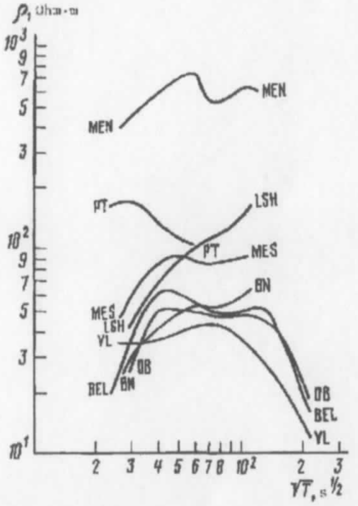

Fig. 2. Highest-value ρ_T curves on KAPG geotraverse VII. LSN, Leshnitsa; BN, Bansko; MEN, Menenkovo; VL, Vladinya; BEL, Belene; OV, Obnova; MES, Ch. Mesta; PT, Petrich.

field also contains no pronounced anomalies. This result indicates either that there are no sharp lateral geoelectric inhomogeneities or that they are screened by highly conductive layers.

B. Polar impedance diagrams constructed for geotraverse VII are in most locations elongated at directions of 120 to 150° (clockwise) relative to the geomagnetic meridian (Fig. 1). The induction vectors on geotraverse VII are of small magnitude (0.05 to 0.2), which makes it difficult to determine their orientation, but in most sites these vectors are parallel to the magnetic axis of the polar diagram, i.e.,

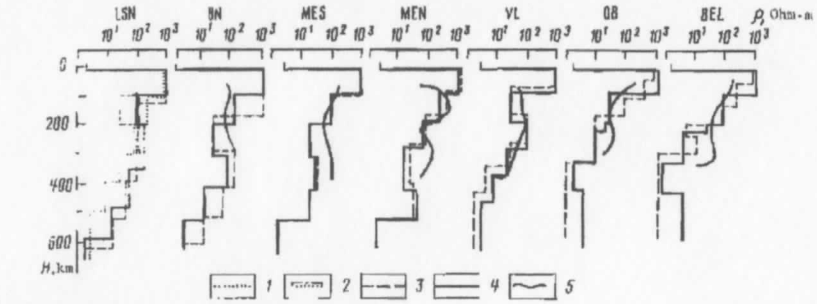

Fig. 3. 1) A priori model of a normal section lacking an asthenospheric layer. 2) A priori model of normal section with an asthenosphere; 3) 1D fitting of the seven-layer distribution ρ(H) into the a priori normal section 1; 4) 1D fitting of the seven-layer distribution ρ(H) into the a priori normal section 2, assuming values of h_1, h_2, and h_3; 5) Differential Molochnov transformations; 6) Inferred zone of occurrence of asthenosphere.

approximately parallel to geotraverse VII (Fig. 1). This orientation of the electromagnetic field is not entirely consistent with the structural layout of the main tectonic elements in Bulgaria, which generally have a sublatitudinal strike. This indicates that the structural layouts of the principal deep electromagnetic boundaries and geological entities in the upper stages of the crust may not be consistent with each other and that there exists a regional influence of tectonic zones in adjoining regions on the electromagnetic field. Such adjoining zones include the Carpathians in Romania, the Dinaric Alps, and the Black Sea and Sea of Mamara basins.

C. The orientations of the polar impedance diagrams on geotraverse VIII differ from those on geotraverse VII, primarily owing to the shoreline effect. The long axes of the polar diagrams have azimuths of 50 to 90°. The induction vectors are small (maximum absolute magnitude 0.2) and are generally perpendicular to the coastal slope.

4. In the quantitative interpretation stage, we constructed and analyzed plots of the MTS data and concurrent values of the electromagnetic field, as calculated at all sites on geotraverses VII and VIII on the basis of the telluric and magnetic tensors [1].

We begin by noting that on geotraverse VII, the least distortion is exhibited by the maximum ρ_T curves, determined from the direction of the major axis of the polar diagram, i.e., roughly perpendicular to the geotraverse; as a result, these curves may be regarded as longitudinal and as roughly consistent with the two-dimensional case of E-polarization. These curves have the characteristic type-K form, but their maxima are complicated by faint local minima (Fig. 2). The descending branches of these curves are rather consistent with the normal curve typical of stable regions [7].

On geotraverse VII, the least distorted are again the maximum curves, with the same characteristic K type, but owing to the shoreline effect, all of these curves lie above the normal curve.

The sounding curves with the highest values were used to evaluate the longitudinal conductivity of the near-surface sediments. This quantity ranges from 1000 to 1700 S on geotraverse VII and from 500 to 900 S on geotraverse VIII.

To obtain a regional representation of the characteristics of the geoelectric section at depth, we performed one-dimensional interpretation of the peak resistivity sounding curves, including differential transformation into a section at depth and automated fitting to layered models of the crust by means of regularized Newtonian optimization procedures. We used the INV 1D one-dimensional interpretation program developed by IZMIRAN [8].

As an example, Fig. 3 shows the results of Molochnov-Sekriyeru transformation [9] for the plots of ρ_T obtained on geotraverse VII. For comparison, we also show a normal section typical of the western slope of the Ukrainian Shield [2], a region which geodynamically is very similar to Bulgaria. The data were used to choose an initial approximation in one-dimensional automated model fitting. For example, in view of the presence of a local minimum on the transformed ρ_T curve at depths from

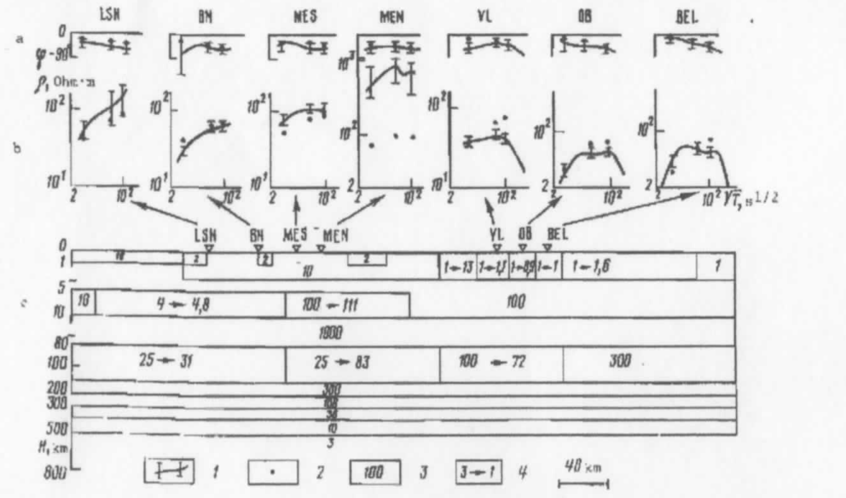

Fig. [illegible]. Two-dimensional geoelectric model along geotraverse VIII: a, b) Frequency curves for phase of impedance $\varphi_z(\sqrt{T})$ and apparent resistivity $\rho_a(\sqrt{T})$ at observation sites on geotraverse; c) Structure of the geoelectric section. 1) Plots of $\rho_a(\sqrt{T})$ and $\varphi_z(\sqrt{T})$, showing confidence intervals; 2) Curve-fitting values; 3) Resistivities of blocks, ohm-m; 4) Initial and final values for the optimized block.

100 to 200 km, we allowed in the initial model for the possible existence of an asthenospheric layer with a total longitudinal conductivity of up to 3000 S. We then selected a multilayer model that fitted the presence of conductive sediments, a nonconductive crust and nonuniform conductivity distribution in the mantle. As optimization parameters of the model we chose the resistivities of the layers, and in many cases the thicknesses of certain layers as well. The total number of optimized parameters was 2 or 3 in the first stage of fitting and as many as 10 to 15 in the final stage. Fitting to the model made it possible to approximate the measurements with an error of only a few percent. Thus we find that on geotraverse VII, the upper mantle has high conductivity, but the correlation between sections obtained at different locations is poor and no consistently present asthenospheric layer can be identified along any complete section. On geotraverse VIII, the selected models are rather similar to each other and to the initial model.

The one-dimensional interpretation results can be used to improve the conclusions derived from qualitative analysis. The low peak values of the apparent resistivity curves in the Rhodope mountains proved not to be attributable exclusively to the presence of conductive sediments and the crustal layer: we must also assume anomalous conductivity in the upper mantle. Analysis of the curves at the individual stations (Fig. 2) indicates that the asthenospheric layer may extend northward beneath the Balkan fold belt and the adjoining flank of the Mysian platform.

5. In the next stage of interpretation, we made a combined analysis of all sounding curves and of concurrent recordings of the electromagnetic field along the individual geotraverses, i.e., we solved the inverse problem on the assumption of a two-dimensional model of the section. Using the one-dimensional interpretation results and existing geodynamic hypotheses (see discussions in "Geologica Balcanica" [10]), we constructed for geotraverse VII a series of two-dimensional models, certain of whose parameters (the conductivities of particular layers and of two-dimensional blocks) were optimized with the INV 2D program for solving two-dimensional inverse problems in media of known geometry [8]. We performed simultaneous fitting of the resistivity values, the impedance phases and induction vectors at 11 points for three periods (900, 3600, and 1000 seconds). The best agreement between the magnetic data for the section and the apparent resistivities is obtained with a total longitudinal asthenospheric conductivity S_a = 2500 S, with a gradual tapering out beneath the central mountain region (Fig. 4).

To summarize, we distinguish the following elements in the geological structure of the Balkans: 1) a deep platform-type sequence in north Bulgaria, similar to that

of the Carpathian flank of the Ukrainian Shield [2]; 2) a conductive sedimentary cover of the Mysian platform, with a resistivity $\rho \geq 2.0$ ohm-m and a total longitudinal conductivity ranging from a few thousand siemens near the Cis-Carpathian Downwarp to a few hundred siemens on the southern flank of the platform; 3) conductive sedimentary deposits in the intermontane basins of the Balkan system and the Rhodope block with resistivities $\rho \geq 2.0$ ohm-m and a total longitudinal conductivity of as much as 1100 S; 4) a conductive crustal layer at a depth of 3 to 10 km beneath the Rhodope block with a resistivity of at least 5 to 10 ohm-m and a total longitudinal conductivity (including the thin sedimentary cover) of up to 1000 S; 5) a conductive asthenospheric layer with $S_a \leq 3000$ S at depths of more than 60 to 80 km beneath the Rhodope block, tapering out toward the Mysian platform.

The geoelectric section obtained along geotraverse VII is well correlated with the seismologic section constructed by Vol'vovskiy, et al. [12] from deep seismic sounding data for Bulgaria. The crustal conductive layer beneath the Rhodope block represents either a water-saturated metamorphic carbonate complex or a buried sedimentary sequence; it shows up in the seismic section as a layer with low velocities. Some investigators attribute this complex to large-scale horizontal movements in the geological history of the Rhodope block [10].

The presence of a conductive asthenospheric layer beneath the Rhodope block in the zone of junction of the geothermally active regions of the Pannonian Basin and Alpine Asia Minor fold belt is suggested by the positive heat flux anomalies [13] and by seismologic data that indicate the absence of earthquake epicenters at depths greater than 60 km [14].

We thank R. Gavrilov, who was involved in organizing the field work in Bulgaria, and Ye. R. Martanus and Ye. Yu. Sokolova, who made the numerical calculations in the data processing and interpretation stage.

REFERENCES

1. Berdichevskiy, M.N. and M.S. Zhdanov. Interpretatsiya anomaliy peremennogo elektromagnitnogo polya Zemli (Interpretation of Anomalies in the Variable Terrestrial Electromagnetic Field), Nedra Press, Moscow, 1981.
2. Zhdanov, M.S. and M.N. Berdichevskiy. Dokl. Akad. Nauk SSSR, 295, No. 1, pp. 78-82, 1985.
3. Korotayev, S.M., I.L. Trofimov, M.S. Zhdanov, et al. Okeanologiya, <u>27</u>, No. 6, pp. 942-946, 1987.
4. Shimelevich, M.I. Metody obrabotki variatsiy yestestvennogo electromagnitnogo polya Zemli (Methods of Analyzing Variations in the Natural Terrestrial Electromagnetic Field), Moscow, pp. 37-54, 1983.
5. Ashirova, N.G., M.N. Berdichevskiy and V.G. Dubrovskiy. Izv. Akad. Nauk SSSR, Fizika Zemli, No. 10, pp. 69-76, 1981.
6. Semenov, V. Yu. Obrabotka dannykh magnitotelluricheskogo zondirovaniya (Processing of Magnetotelluric Sounding Data), Nedra Press, Moscow, p. 133, 1985.
7. Rokityanskiy, I.I. Issledovaniya anomaliy elektroprovodnosti metodom magnitovariatsionnogo profilirovaniya (Use of Magnetic Variation Profiling to Investigate Conductivity Anomalies), Nauka Press, Kiev, p. 279, 1985.
8. Varentsov, I.M. Proceeding of the IAGA. Symposium on Space-Time Structure of the Geomagnetic Field, HHI - Rep. No. 21, B., p. 123, 1987.
9. Molochnov, G.V. and V.G. Sekriyeru. Izv. Akad. Nauk SSSR. Fizika Zemli, No. 2, pp. 64-71, 1976.
10. Geologica Balcanica, No. 14, pp. 3-91, 1984.
11. Zhdanov, M.S., I.M. Varentsov, N.G. Golubev and V.V. Spichak. Matematicheskiye metody v geoelektrike (Mathematical Methods in Geoelectric Investigations), Nedra Press, Moscow, pp. 5-26, 1982.
12. Vol'vovskiy, I.S., Ch. R. Dachev, O.G. Popova, et al. Byul. Mosk. obshch. ispyt. prir., Otd. geol., <u>60</u>, No. 4, pp. 38-47, 1985.
13. Markis, J. Geophysical Investigation, Hamburg. Geophys. Einselschr., Series A, <u>34</u>, p. 124, 1977.
14. Velinov, T. and K. Boyadzhiyeva. Geotermichni izsledovaniya v B"lgariya (Geothermal Investigations in Bulgaria), Tekhnika Press, Sofia, 1981.