REFERENCES

ADÁM, A. (1978), *Geothermal effects in the formation of electrically conducting zone and temperature distribution in the Earth*, Phys. Earth Planet. Inter. *17*, 21–28.

CHEN MOXIANG, HUANG GESHAN, and ZHANG WENYEN (1982), *Distribution characteristics of the geothermal resources in the northern area of the North China Plain*, Institute of Geology, Academia Sinica, Research on Geology *1*, 72–89.

GOUBAU, W. M., GAMBLE, T. D., and CLARKE, J. (1978), *Magnetotelluric data analysis: Removal of bias*, Geophysics *43*, 1157–1169.

GUO SHOUNIAN, ZHU ZUOQUAN, and LIN CHANGYOU (1985), *Relationship between the crustal and upper mantle conductive layers and seismicities*, (in press).

JIN GUANGWEN, WANG JIAYIN, and WANG TIANSHENG (1982), *A method for computing MT tensor impedance*, Acta Geophysica Sinica 25, Supplement, 650–659.

LI LI and JIN GUOYOUN (1985), *MTS report on the crustal and upper mantle conductivity in Pan-Xi an Longmenshan mountain areas*, (in press).

LIU GUODONG (1985), *Cenozoic rift system of North China Plain and the deep internal processes*, Research on Recent Crustal Movement (1), Continental rifts and deep internal processes, Institute of Geology, State Seismological Bureau (Seismological Press, Beijing) pp. 17–25.

LIU GUODONG, GU QUN, SHI SULIN, SUN JIE, SHI ZHANGSONG, and LIU JINHAN (1983), *The electrical structure of the crust and upper mantle and its relationship with seismicity in the Beijing-Tianjin-Tangshan Region and adjacent area*, Acta Geophysica Sinica 26, 149–157.

LIU GUODONG, and LIU CHANGQUEN (1983), *Structures of crust and upper mantle and their relation to Cenozoic tectonism in northern part of North China*, Scientia Sinica *26*, 550–560.

LIU GOUDONG, SHI SHULIN, and WANG BAOJUN (1984), *Conductive layer in the crust in North China and its relation to crustal tectonism*, Scientia Sinica 27, 1093–1104.

LU ZAOXUN (1985), *Progress of geophysical prospecting study on the deep structure of Halcheng earthquake area*, Earthquake Research in China *1*, (1), 56–65.

SHEN XIANJIE, DENG XIOYUE, KAN WENHUA, (1985), *Corrections to the heat flow values measured in South-Xizang (Tibet) and the results*, Acta Geophysics Sinica *28*, Supplement (1), 80–92.

SIMS, W. E., BOSTICK, F. X., Jr., and SMITH, H. W. (1971), *The estimation of magnetotelluric impedance tensor elements from measured data*, Geophysics *36*, 938–942.

SONG ZHONGHE (1985), *P Wave velocity structure of the upper mantle in Chinese continent and its marginal areas*, (in press).

TENG JIWEN (1985), *An introduction to geophysical study on the Tibetan plateau area*, Acta Geophysica Sinica, *28*, Supplement (1), 11–15.

WANG TIYANG, WANG JIAN, (1985), *Geothermal measurements in Liaohe basin*, Kexue Tongbao *30*, 1008–1010.

WANG JUN, and LIU GUODONG (1985), *Terrestrial heat flow and deep geology in South China*, Acta Geophysica Sinica, (in press).

WU QIANFAN, XIE YIZHEN, ZU XINHUA, and WANG DOU (1985), *Terrestrial heat flow and seismicity in North China*, Research on Recent Crust Movement (1), Continental rifts and deep internal processes, Institute of Geology, State Seismological Bureau (Seismological Press, Beijing) pp. 133–141.

ZHANG RUHAI, XEI ZHENGWEN, WU JIXIN, and XEI YIZENG (1982), *The distribution of heat flow values in Tangshan and its surrounding*, Seismology and Geology 4, (0), 57–68.

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Application of Space Analysis of Electromagnetic Fields to Investigation of the Geoelectrical Structure of the Earth

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Abstract—Lateral composition inhomogeneities of the Earth's deep geoelectric structure require special consideration for any conductivity evaluation of a region. This paper presents a review of some theoretical techniques for determining both the vertical and horizontal conductivity profiles of a region using a spatial distribution of observed electromagnetic fields at the Earth's surface. Effects of shallow positioned anomalies upon a deep conductivity determination are also considered. An application of the procedure is illustrated by a conductivity study in the Soviet Carpathians.

Key words: Electromagnetic induction, Earth electric conductivity, electromagnetic anomalies, Soviet Carpathians.

Of all the geophysical methods used to study the terrestrial structure, those involving deep electromagnetic sounding are of particular concern. They provide data on the distribution of electrical conductivity in the interior of the Earth, which in turn convey exceedingly important information about the thermodynamic and phase states of deep-lying earth formations, hardly accessible to other geophysical techniques. That is why deep electromagnetic soundings are of great applied value.

It must be mentioned that interpretation of electromagnetic sounding data has long relied on simple one-dimensional models of geoelectrical sections wherein conductivity varies only with depth. Recent findings have revealed, however, that formal interpretation of electromagnetic sounding data, within one-dimensional models, may hardly yield faithful information about the electrical conductivity distribution in the Earth. Moreover, electromagnetic sounding curves plotted for isolated observation points are, as a rule, distorted markedly, due to the effect of horizontal geolectrical (both surface and deep) inhomogeneities and, hence, their formal one-dimensional interpretation may indicate false geologic structures. The only way to eliminate ambiguous interpretation of isolated point sounding data is to combine sounding and profiling. This means, eventually, application of a single method of deep electromagnetic investigations relying on simultaneous observation of components of the electric and magnetic fields (of natural or artificial origins)

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along certain lines or over an area in a wide time or frequency range. The result of such observations is a space-time pattern of the electromagnetic field at the Earth's surface which makes it feasible, in principle, to reconstruct the behavior of electrical conductivity, both in the vertical and in the horizontal. Yet, this approach calls for quite different interpretation techniques, compared to the conventional procedures related to point electromagnetic soundings. The new interpretation methods are substantially similar to those employed in gravimetry and magnetometry and can be regarded as a kind of extension of geopotential field interpretation procedures to the electromagnetic case. These methods are based on space analysis of the fields, which relies on their integral and spectral transformations (BERDICHEVSKY and ZHDANOV, 1984).

Figure 1 is a general scheme of interpretation of electromagnetic data obtained above horizontally inhomogeneous geoelectrical sections. According to this scheme, interpretation of deep electromagnetic sounding data falls into two steps: (1) space analysis of the electromagnetic field, i.e., its separation into different parts, depending on the distribution of geoelectrical inhomogeneities; (2) solution of inverse problems, i.e., establishment of the parameters of an inhomogeneous geoelectrical section.

We will consider more closely the techniques employed in each step.

Step 1—Space Analysis of the Electromagnetic Field

This step of analysis includes separation of fields into external and internal, normal and anomalous, surface and deep parts (BERDICHEVSKY and ZHDANOV, 1984). Separation into external and internal parts is accomplished using the classical Gauss or Kertz-Siebert techniques. It merits remembering how the normal and anomalous components of the field are defined.

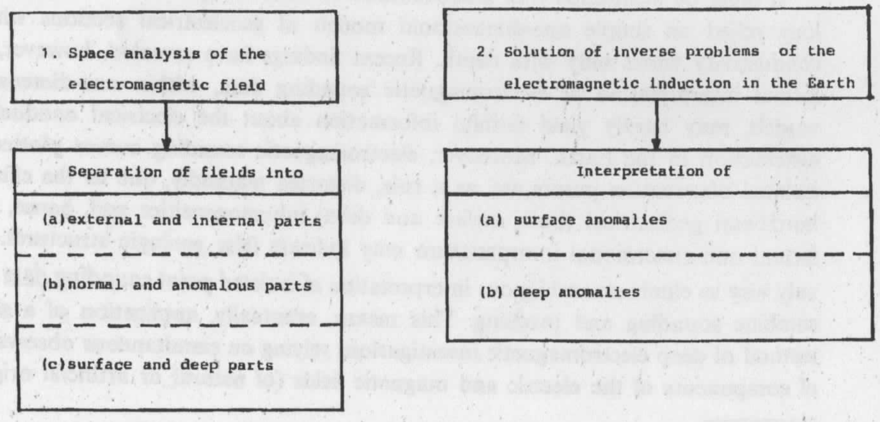

Figure 1
Scheme of interpretation of deep electromagnetic sounding data.

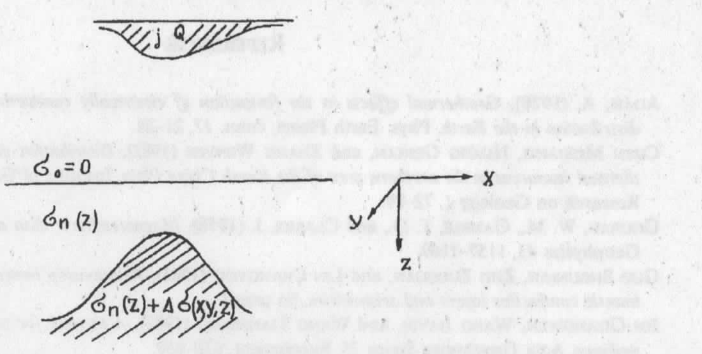

Figure 2
Geoelectrical model explaining the establishment of the normal and anomalous electromagnetic fields.

Take a model of Figure 2. Within this model, the horizontal plane $z = 0$ separates a nonconducting atmosphere, wherein extraneous electric currents j^Q are localized, from an inhomogeneous Earth of an arbitrary electrical conductivity distribution:

$$\sigma(x, y, z) = \sigma_n(z) + \Delta\sigma(x, y, z)$$

where σ_n and $\Delta\sigma$ are the normal and anomalous conductivities, respectively. The name of a normal electromagnetic field is ascribed to the field induced by an extraneous current j^Q in a horizontally homogeneous Earth of a conductivity $\sigma_n(z)$ varying only with depth. The normal field is distorted by horizontal geoelectrical inhomogeneities. These distortions are known as electromagnetic anomalies.

Thus, the electromagnetic field E,H can be represented as a sum of the normal E^n,H^n and anomalous E^a,H^a fields:

$$E = E^n + E^a, \qquad H = H^n + H^a. \tag{1}$$

The first problem in the analysis is to separate fields into normal and anomalous parts. This operation can be effected by means of various types of integral transformations of the field. In the general case, the integral transforms can be represented in the form:

$$H^{n,a}(x, y) = \iint_{-\infty}^{+\infty} \hat{G}_H^{n,a}(x - x', y - y')\, H(x', y')\, dx'\, dy',$$
$$E^{n,a}(x, y) = \iint_{-\infty}^{+\infty} \hat{G}_E^{n,a}(x - x', y - y')\, E(x', y')\, dx'\, dy' \tag{2}$$

where $\hat{G}_{H,E}^{n,a}$ stands for the matrices of the kernels of the relevant integral transforms. These kernels imply space windows through which the observed fields are transmitted. We will show, as an example, calculation of the kernels of integral transforms for two-dimensional situations (in the most interesting case of E-polarization, where the field is uniform and the medium is homogeneous along the Y-axis) (BERDICHEVSKY and ZHDANOV, 1984).

$$\hat{G}^a_H(x) = \begin{bmatrix} G^a_{xx} & G^a_{xz} \\ G^a_{zx} & G^a_{zz} \end{bmatrix} = \frac{1}{2\pi}\int_{-\infty}^{+\infty} \mathscr{G} e^{-i\alpha x}\, d\alpha \tag{3}$$

where

$$\mathscr{G}^n = \begin{bmatrix} \dfrac{R^*|\alpha|}{R^*|\alpha| + n_1} & -\dfrac{i \operatorname{sign} \alpha\, n_1}{R^*|\alpha| + n_1} \\ \dfrac{i R^* \alpha}{R^*|\alpha| + n_1} & \dfrac{n_1}{R^*|\alpha| + n_1} \end{bmatrix} \tag{4}$$

Here α is the spatial frequency along the x-axis;

$$n_j = \sqrt{\alpha^2 + K_j^2}, \qquad j = 1, 3, \ldots, \mathscr{N}$$

is the wave number of the j-th layer of a normal geoelectrical section;

$$R^* = cotanh\left\{ n_1 d_1 + arctanh\left[\frac{n_1}{n_2}\, cotanh\left(n_2 d_2 + \ldots + arctanh\, \frac{n_{N-1}}{n_N} \right) \ldots \right) \right] \right\}.$$

Expressions (3) and (4) show that the kernels of integral transforms (3) and (4) imply space windows through which the observed fields are transmitted. Take, for instance, the plots describing the shape of space windows within the model of a homogeneous Earth (Figure 3). It is evident from these plots and from formulas (3) and (4) that the size of the windows is determined by the parameters of a normal geoelectrical section as well as by the field variation period. The width of space windows is found (ZHDANOV and PLOTNIKOV, 1981) to range from 60 to 150 km. This dictates a desirable area of field observation, when it is to be separated into normal and anomalous parts.

Thus, the prime advantage, making the suggested methods of field separation into normal and anomalous parts superior to the conventional techniques of field separation into external and internal parts, is a narrower width of space windows of the corresponding integral transforms. This permits a practical solution of the problem of separating fields measured in limited areas.

Another problem tackled in the first step, i.e., in the course of space analysis of electromagnetic fields, is their separation into surface and deep parts.

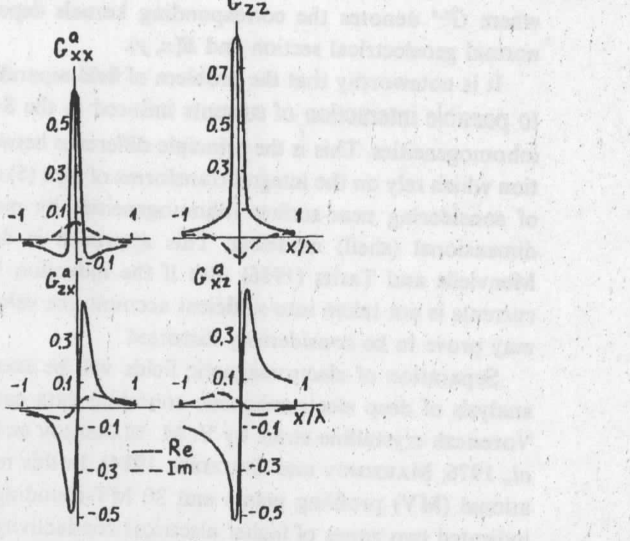

Figure 3

Plots of the kernels of integral transforms of geomagnetic fields used to separate the fields into normal and anomalous parts (electromagnetic wave length λ for σ_n = const).

By surface anomalies we mean the anomalies caused by the near-surface inhomogeneous geoelectrical layer formed by the coastal water of seas and oceans as well as by the inhomogeneity of the continental sediments.

Deep anomalies are attributed to conducting zones in the consolidated Earth' crust and upper mantle; whose origin is related to hydrothermal processes and partial melting of crustal formations at high temperatures and pressures.

As a rule, in practice we observe electromagnetic anomalies caused by the total effect of both surface and deep inhomogeneities. It is remarkable that when we study the deep structure of the Earth, surface anomalies act as an interfering factor, distorting the information about the deep section. Therefore, separation of anomalies of the surface H^s, E^s and deep H^d, E^d origins is one of the most important problems of analysis. This problem can be solved, provided the geoelectrical parameters of the near-surface inhomogeneous layer of the Earth are available. The most convenient model of this layer may be an inhomogeneous highly conducting thin Price layer. To separate fields within this model, one must know the integral conductivity $S(x, y)$ of the thin layer. Consequently, the procedure of field separation reduces, just as in the case of distinction between the normal and anaomalous components, to integral transformations of the field (BERDICHEVSKY and ZHDANOV, 1984):

$$\begin{Bmatrix} H^{s,d} \\ E^{s,d} \end{Bmatrix} = \iint_{-\infty}^{+\infty} G^{s,d}(x - x^1, y - y^1) \begin{Bmatrix} H(x^1, y^1) \\ E(x^1, y^1) \end{Bmatrix} dx^1\, dy^1 \tag{5}$$

where $\hat{G}^{s,d}$ denotes the corresponding kernels dependent upon parameters of the normal geoelectrical section and $S(x, y)$.

It is noteworthy that the problem of field separation is solved with due reference to possible interaction of currents induced in the S-layer and in deep geoelectrical inhomogeneities. This is the principle difference between the methods of field separation which rely on the integral transforms of type (5) and the conventional techniques of considering near-surface inhomogeneities by means of numerical quasi three-dimensional (shell) modeling. This approach is developed, in particular, by M. Menvielle and Tarits (1986). But if the induction interaction of surface and deep currents is not taken into sufficient account, the value of separated anomalous fields may prove to be considerably distorted.

Separation of electromagnetic fields will be exemplified by the results of space analysis of deep electromagnetic sounding data carried out in the territory of the Voronezh crystalline strate by V. M. Maksimov and V. N. Gruzdev (Maksimov *et al.*, 1976; Maksimov and Gruzdev, 1984). In this region, they had 62 magnetovariational (MV) profiling points and 30 MT-sounding points. The experimental data indicated two zones of higher electrical conductivity, which were clearly manifested in the behaviour of the induction vectors and characterized by an increased intensity of the horizontal components; as well as by the sign reversal of the vertical component of the field of bay-like perturbations.

The total longitudinal conductivity of the sedimentary section in the region of interest ranges from 10 to 3000 S, which argues in favor of allowance for the effect of near-surface inhomogeneities on the results of deep investigation. To this

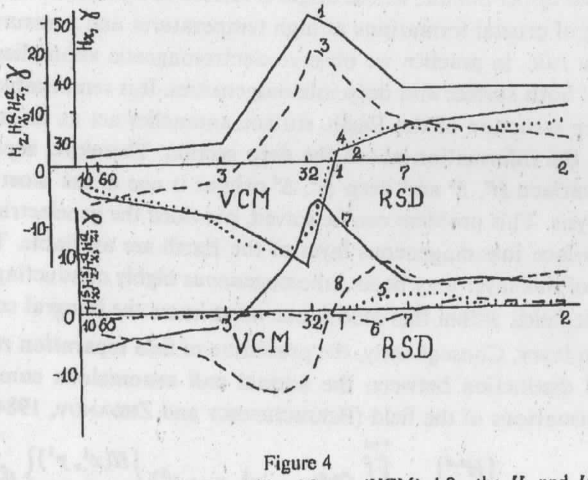

Figure 4

Geomagnetic anomaly in the Voronezh Crystalline Masses (VCM): 1,2—the H_x and H_z components of the observed field; 3,4—the H^a_x and H^a_z components of the anomalous field; 5,6—the H^s_x and H^s_z components of the surface anomalous field.

end, anomalies of the electromagnetic field were separated, using the above procedure, along one of the lines crossing the Voronezh Crystalline Masses.

At a glance Figure 4 shows the amplitude of the horizontal component of the magnetic field, H_x along this line increases markedly (curve 1) and the vertical component H_z of the observed field is inverted (curve 2). Meanwhile, the maximum values S related to the conducting sediments of the Ryazano-Saratovsky depression are not spatially consistent with the anomalous behaviour of the geomagnetic field. Separation of the total field into normal and anomalous parts made it possible to identify the normal background in the H_x and H_z components (H^n_x, H^n_z) and anomalous fields (H^a_x, H^a_z, curves 3 and 4 in Figure 4) characterized by a local extreme value of the horizontal component H^a_x and by the inversion of the vertical component H^a_z.

Figure 4 also depicts components of the surface anomalous field (H^s_x—curve 5 and H^s_z—curve 6), which have relatively small amplitudes (not exceeding $\frac{2}{3}$ nT). Thus, a conclusion can be reached that the deep anomaly H^d_x, H^d_z (curves 7 and 8) determines, first of all, the anomalous nature of the field observed which is seemingly due to the local conducting zone found in the consolidated Earth's crust.

Let us present brief characteristics of the methods employed in the second step-interpretation of data (Figure 1).

Step 2—Solution of Inverse Problems of Electromagnetic Induction in the Earth

In this step of data interpretation we deal with two groups of methods: interpretation of surface and deep anomalies. The methods used to study surface anomalies have been developed rather comprehensively by U. Schmucher (1971). They rely largely on approximation of surface inhomogeneities by thin Price shells. It is generally assumed in surface anomaly interpretations that consideration is given to the range of periods wherein the field does not penetrate an area of developed deep geoelectrical inhomogeneities and, hence, their effect can be discarded.

Proceeding to a longer-period range of variations, the effect of surface inhomogeneities is taken into account by separating fields in the above manner. As a result, the main problem here is to establish the parameters of the deep geoelectrical section, which is just to be solved below.

Interpretation of deep electromagnetic anomalies involves three groups of methods (Figure 5): (1) approximate express methods of localizing a deep inhomogeneity; (2) methods of reconstructing the shape of an inhomogeneity; (3) automated methods of producing a geoelectrical section of a given inhomogeneous area.

The approximate express methods of localizing a deep inhomogeneity include, initially, analytical continuation of the field. The basis for the theory of these methods is closely treated by M. S. Zhdanov and M. N. Berdichevsky (Zhdanov, 1984; Berdichevsky and Zhdanov, 1984). Now we will outline the essentials underlying

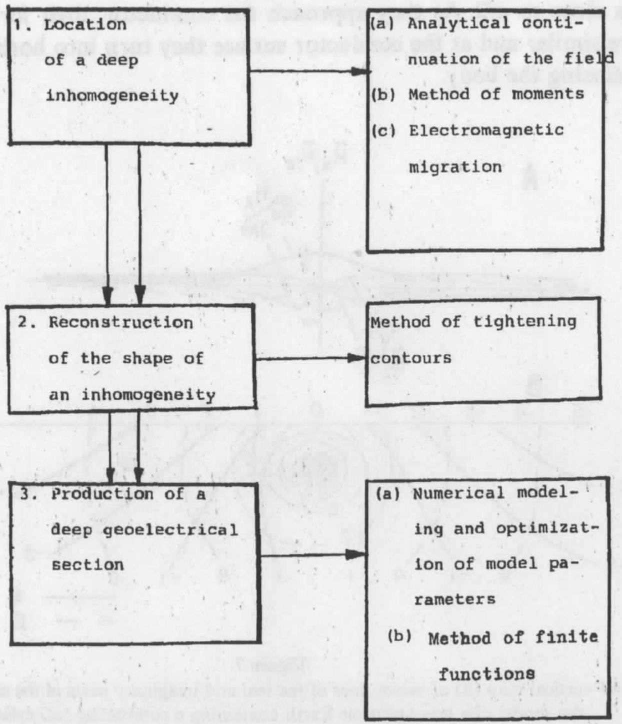

Figure 5
Methods of interpretation of deep electromagnetic anomalies.

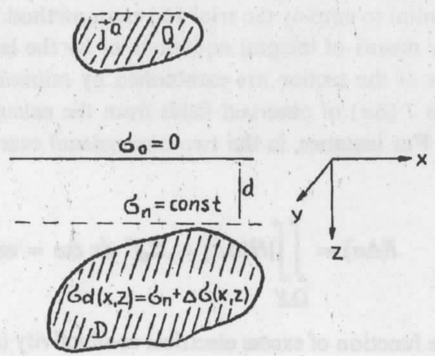

Figure 6
Analytical continuation of the electromagnetic field down to a deep inhomogeneity D.

the procedure of analytical continuation, using as example two-dimensional electromagnetic fields (the case of E-polarization). The model of the section is given in Figure 6.

A homogeneous well conducting Earth of a constant normal electrical conductivity σ_n contains an inhomogeneous deep domain D with an arbitrary two-dimensional distribution of conductivity $\sigma_d(x, z) = \sigma_n + \Delta\sigma(x, z)$. At the Earth's surface there are specified variations in the magnetic field H_x and H_z. It requires a continuation of this field analytically into the Earth right to the horizontal layer $0 \leqslant z \leqslant d$ (d being the distance from the Earth's surface to the domain D). To solve the problem, we pass to the spatial spectra h_x, h_z satisfying, as is known, within the homogeneous layer $0 \leqslant z \leqslant d$ the one-dimensional Helmholtz equations:

$$h_x'' = n^2 h_x, \qquad h_z'' = n^2 h_z$$

where

$$n = \sqrt{d^2 - i\omega\mu_0\sigma n}.$$

The last equation implies, in particular, the following representation for h_z:

$$h_z(z) = h_z^+ e^{nz} + h_z^- e^{-nz} \tag{6a}$$

whence

$$h_z'(z) = n(h_z^+ e^{nz} - h_z^- e^{-nz}) \tag{6b}$$

Taking $z = 0$ in equations (6a) and (6b) we derive two equations for two unknown coefficients h_z^+ and h_z^-:

$$h_z(0) = h_z^+ + h_z^-, \qquad h_z'(0) = n(h_z^+ - h_z^-). \tag{7}$$

Solving these equations we find

$$h_z^\pm = \frac{1}{2n}(nh_z(0) \pm h_z'(0)). \tag{8}$$

According to the third Maxwell equation div $H = 0$, we have for spectra

$$h_z' = i\alpha h_x. \tag{9}$$

Substituting (9) into (8) we write

$$h_z^\pm = \frac{1}{2\pi}(nh_z(0) \pm i\alpha h_x(0)). \tag{10}$$

Thus, we have found the unknown coefficient in formula (5). Upon substitution of (10) into (6a) and some transformation, we obtain in the final form

$$h_z(z) = cosh(nz)h_z(0) + i(\alpha/n)sinh(nz)h_x(0). \tag{11}$$

The corresponding expression for the spectrum of the horizontal component is derived from (11) by differentiating with respect to z and by allowing for (9)

$$h_z = (1/i\alpha)h_z' = cosh(nz)h_x(0) - i(n/K_x)sinh(nz)h_z(0). \tag{12}$$

The obtained formulas yield a solution to the problem of analytical continuation of the magnetovariational field into a horizontal layer. Indeed, taking the inverse Fourier transform of (11) and (12) we define the fields themselves inside the Earth:

$$H_x(x, z) = \frac{1}{2\pi} \int_{-\infty}^{+\infty} \left[h_x(0) cosh(nz) - ih_z(0) \frac{n}{\alpha} sinh(nz) \right] e^{-i\alpha x} \, d\alpha$$

$$H_z(x, z) = \frac{1}{2\pi} \int_{-\infty}^{+\infty} \left[h_z(0) cosh(nz) + ih_x(0) \frac{\alpha}{b} sinh(nz) \right] e^{-i\alpha x} \, d\alpha. \tag{13}$$

Note that analytical continuation of the field into the lower half-plane is a typical example of an ill-posed problem. Indeed, with an increasing depth of continuation z, the exponents e^{nz} included in (13) point out high spatial frequencies in the field spectra, i.e., the high-frequency interference unavoidably present in practical observations is enhanced. To preclude this effect, it is desirable to resort to suitable regularizing algorithms which reduce, in a simple case, to low-frequency filtering of the observed field.

Analytically continued fields can be interpreted using two techniques: method of singular points and method of analysis of vector lines of the field in the vertical plane.

The method of singular points lies in finding singular points of the analytically continued field (i.e., points of focusing of the isolines of the continued field) and in locating therefrom anomaly-forming bodies.

The method of field vector lines involves construction of maps of vector lines of the real and imaginary vectors of the magnetic field, ReH and ImH, in the vertical plane. These maps represent the magnetic field in a clear-cut manner.

Assume that the domain D is highly conducting. Then, according to the boundary conditions on the boundary of the domain D, the normal component of the magnetic field is close to zero. Let us examine how this fact appears in the maps of vector lines of the real and imaginary parts of H.

In the whole space (except for the surface of a perfect conductor), the magnetic field is polarized elliptically. The vectors being conjugate radii of the polarization ellipse are not colinear and the corresponding vector lines intersect. At the surface of a perfect conductor, where $H_n = 0$, the magnetic field is linearly polarized. Hence, the vectors ReH and ImH are colinear, while the field vector lines ReH and ImH run together and coincide with the contour of a body. Thus, to delineate a body, it is sufficient to find the vector line ReH confluent with the vector line ImH. In practice, these lines are found visually. Therefore, the region occupied by a body is located somewhat roughly.

Consider, for example, a model within which the Earth, excited by an E-polarized plane wave, containing a horizontal conducting half-cylinder. Figure 7 is a vertical map of vector lines of the real and imaginary parts of the field. The vector lines ReH and those away from the conductor have different configurations and ImH intersect at angles close to $\pi/2$. As they approach the conductor, their forms become more and more similar and at the conductor surface they turn into horizontally extended ovals enclosing the body.

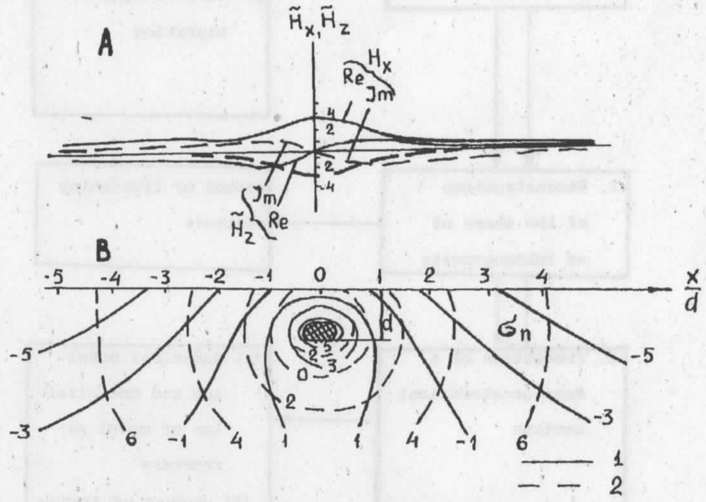

Figure 7

Plots (A) and vertical map (B) of vector lines of the real and imaginary parts of the magnetic field within the model of a homogeneous Earth containing a conducting half-cylinder.

Analytical continuation (in conjunction with the methods of moments (Bedrichevsky and Zhdanov, 1984) and of electromagnetic migration (Zhdanov, 1984)) provide only a crude location and shape of a deep inhomogeneous domain D.

To define the shape and distribution of electrical conductivity inside D definitively, it is essential to employ the trial and error method. Here the direct problem is solved either by means of integral equations or by the lattice-point method. The sought parameters of the section are established by minimizing the function of the standard deviation $I(\Delta\sigma)$ of observed fields from the calculations in the frequency and space ranges. For instance, in the two-dimensional case of an E-polarized field, we have

$$I(\Delta\sigma) = \iint_{\Omega X} |H(\Delta\sigma) - H_0|^2 \, dx \, d\omega = \min \tag{14}$$

where $\Delta\sigma$ is the function of excess electrical conductivity (against the background of a certain specified normal section); X is the line of observation; Ω is the recorded frequency interval.

To regularize the solution of inverse problem, we introduce a stabilization functional

$$S(\Delta\sigma) = \iint_D (\Delta\sigma - \Delta\sigma_0)^2 \, dS \tag{15}$$

where $\Delta\sigma_0$ is a certain initial distribution of excess electrical conductivity. Then the solution of the inverse problem reduces to minimization of the Tikhonov parametric function

$$M_\alpha(\Delta\sigma) = I(\Delta\sigma) + \alpha S(\Delta\sigma) \tag{16}$$

where α is the regularization parameter.

The above scheme is implemented in a set of computer programs intended basically for solution of the direct problem.

Application of the above procedure will be exemplified by the deep electromagnetic sounding data obtained in the Soviet Carpathians. The Carpathian region has long been an object of particular interest to geophysicists. The anomaly of the natural electromagnetic field found here is one of the most highly developed in the territory of the Soviet Union. It is related to concentration of currents in a region of higher electrical conductivity. The magnetotelluric and magnetovariation investigations performed by a representative group of Soviet scientists (A. P. BONDARENKO, M. N. BERDICHEVSKY, A. I. BILINSKY, M. S. ZHDANOV, S. N. KULIKOV, I. I. ROKITYANSKY, L. M. ABRAMOVA, V. S. SHNEER *et al.*) made it possible to trace the anomaly over most of the length of the Folded Carpathians. The Soviet Carpathians, Transcarpathians, and the adjacent part of the Eastern-European platform have been studied in the most detailed fashion: over 60 magnetovariational profiling points and 20 magnetotelluric sounding points have been interrogated on several lines (ZHDANOV *et al.*, 1986). Figure 8 presents a typical profile of observed values of variations in the geomagnetic field for a 1-h period.

The above method was employed to examine the electromagnetic field along a line, i.e., to identify the anomalous part of the field and to separate the latter into a surface and deep components (Figure 9). The deep component was found to be almost twice as large as the surface component. To locate the sources of the deep anomaly, the latter was continued analytically into the lower half-plane (Figure 9). The isolines of the continued field clearly indicate the location of a crustal zone of higher electrical conductivity lying at a depth of nearly 10–12 km in the joining zone of the Folded Carpathians and Transcarpathian depression. This information was allowed for while developing a model of the whole geoelectrical section. The structure of the crustal well-conducting zone and deep geoelectrical strata was optimized within the scope of the automated trial and error method using lattice-point algorithms to solve the direct problem (ZHDANOV *et al.*, 1986). The final model is depicted in Figure 10 and the corresponding calculation curves are plotted in Figure 8. The

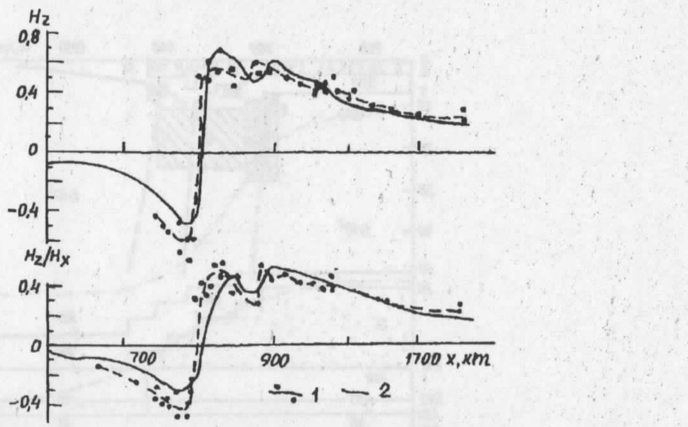

Figure 8

Geomagnetic anomaly in the Soviet Carpathians: The amplitudes of H_z and H_z/H_x for a variation period $T = 1$ hr: 1—observation results; 2—finite-difference modeling results for the section of Figure 10.

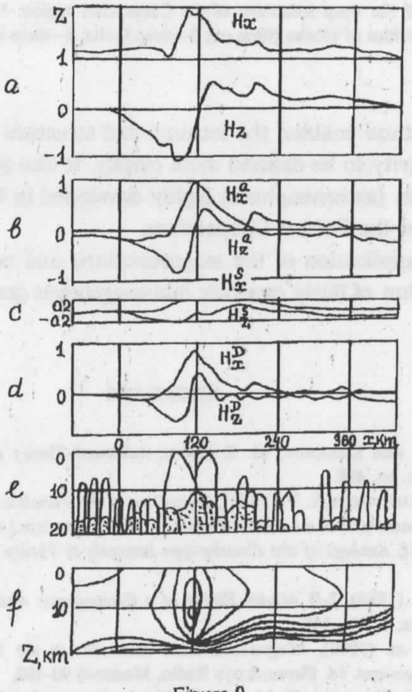

Figure 9

Space analysis of the geomagnetic field in the Soviet Carpathians: a: H_z, H_x—components of the total field; b: H^a_z, H^a_x—anomalous part of the field; c: H^s_z, H^s_x—surface anomaly; d: H^d_x, H^d_z—deep anomaly; e: analytical continuation of the vertical component H^d_z into the conducting Earth (map of isolines of the field H^d_z in the vertical plane); f: map of the flux function of the analytically continued field in the vertical plane.

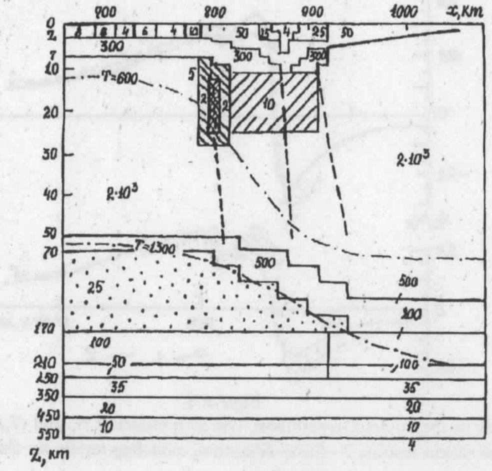

Figure 10

Geoelectrical model of the deep structure of the Carpathian region: 1—geoelectrical boundaries and resistivities of blocks (0hm.m); 2—deep faults; 3—deep isotherms (°C).

trial and error method enabled the location and structure of the crustal anomaly of electrical conductivity to be defined more closely. It also served to recognize a deep conducting stratum (asthenosphere) highly developed in the Pannonian basin and pinching out under the Folded Carpathians.

Thus, a joint application of the magnetotelluric and magnetovariation methods permits investigation of fairly complex inhomogeneous geoelectrical sections.

REFERENCES

BERDICHEVSKY, M. N. and ZHDANOV, M. S. (1984), *Advanced Theory of Deep Geomagnetic Sounding*. Amsterdam; Elsevier, pp. 408.

ZHDANOV, M. S. and PLOTNIKOV, S. V. (1981), *Separation of the Variations in the Geomagnetic Field into a Normal and Anomalous Parts in a Limited Territory*. Gheomagnetism i aeronomiya, *XXI* (6), 1064–1069.

ZHDANOV, M. S. (1984), *Analogs of the Cauchy-type Integrals in Theory of Geophysical Fields*. Moscow; Nauka, pp. 326.

ZHDANOV, M. S. *et al.* (1986), *2-D Model Fitting of a Geomagnetic Anomaly in the Soviet Carpathians*. Annales Geophysicae, *4*, 335–342.

MAKSIMOV, V. M. *et al.* (1986), *Magnetovariation anomalies in the Voronezh crystalline masses*. In *Geomagnetic Investigations. 16*, (Sovetskoye Radio, Moscow) 90–102.

MAKSIMOV, V. M. and GRUZDEV, V. N. (1984), *Oboyansk anomaly of geomagnetic variations and its relationship to the main geological and geophysical features of the structure of the Kursk magnetic anomaly*. In *Geophysical Investigations into the Kursk Magnetic Anomaly* (Publ. Voronezh State University) 21–29.

MENVIELLE, M. and TARITS, P. (1986), *The Andean Conductivity Anomaly Reexamined*. Annales Geophysicae *4*, 63–70.

SCHMUCKER, U. (1971), *Interpretation of Induction Anomalies Above Nonuniform Surface Layers*. Geophysics 36, 156–165.

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