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# Geophysics

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## Abstract

## Full Text

### *Geophysics*

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# ON ELECTROMAGNETIC SOUNDING OF THE DEEP LAYERS OF THE EARTH

1. The possibility of studying the structure of the Earth's interior by observing and analyzing variations of the natural electromagnetic field, used as a powerful source of energy, was first shown in the work of A. N. Tikhonov in 1950 <sup>(1)</sup>, as well as in the works of Cato and Kikuchi and of Cagniard <sup>(2, 3)</sup>. A number of investigations in subsequent years—theoretical and experimental <sup>(4-9)</sup>—considerably broadened our ideas about the possibilities of the method. The use of the broad range of frequencies occurring in the Earth's natural field—from several hundred hertz to diurnal oscillations—makes it possible to apply this method both to the investigation of the upper layers of the Earth's crust, which are of great importance for prospecting for useful minerals, and to the study of deep layers submerged to hundreds of kilometers, which is of great interest in investigating the structure of the Earth's mantle.

The principal reason delaying the development of electromagnetic sounding of great depths has been the difficulty of recording the horizontal components of magnetic variations in the range of periods from seconds to several hours. At present this problem is being solved with the aid of magnetic microvariometers <sup>(10, 11)</sup>.

2. The main experimental material for carrying out deep sounding consisted of: 1) records of the Earth's natural electromagnetic field obtained at the geophysical station "Alushta" (Crimea) of the Institute of Physics of the Earth, Academy of Sciences of the USSR; 2) records of telluric currents at the "Shatsk" station (Ryazan oblast) and of the magnetic field at the Central Magnetic Observatory "Moscow" of the Institute of Terrestrial Magnetism and Radio-Wave Propagation, Academy of Sciences of the USSR.

Registration of the magnetic field at the "Alushta" station was carried out in the range of periods from 10 sec to 3 hours with quartz magnetic microvariometers developed in the electrometry division of the Institute of Physics of the Earth, Academy of Sciences of the USSR, jointly with the Institute of Terrestrial Magnetism and Radio-Wave Propagation <sup>(12)</sup>. The scale value was 0.1 gamma/mm;

the tape speed was 90 mm/hour. Registration of the electric field with the same time sweep was carried out on a standard telluric-current installation of the type used at stations of the Soviet Union operating under the MGT program (13)\*.

In processing the records, the apparent values of the amplitudes and periods of individual synchronous oscillations of all four field components ( $E_x, E_y, H_x, H_y$ ) were determined. From the amplitudes found, the impedance  $I = E_x/H_y$  or  $E_y/H_x$  was calculated for various periods  $T$ , and the values of the apparent resistivity  $\rho_k$  were determined from the formula

$$\rho_k = \frac{T}{5} |I(\omega)|_{\text{om}}^2.$$

The values of  $\rho_k$  found were statistically averaged. In Fig. 1 the dependence of  $\lg \rho_k$  on  $\lg \sqrt{T}$  is presented. The magnitude of the mean error does not exceed—

\* Maintenance of the measuring installations was carried out by the staff of the “Alushta” station under the direction of the station chief N. S. Rybalchik.

exceeds 20–25% of the quantity under consideration. The values of  $\rho_k$ , calculated from two pairs of different field components ( $E_x, H_y, E_y, H_x$ ), agreed with one another within the indicated accuracy.

Since at the “Alushta” station there were no records at low frequencies, we considered it expedient to compare this curve with observations obtained at the nearest points, namely: records of the electric field at the “Shatsk” station (registration of telluric currents was organized in 1950 by V. V. Novysh) and of the magnetic field at the “Moscow” Observatory (a La Cour installation with a sweep of 22 mm/hour).

We constructed the diurnal variation for quiet days over two months of 1950 for the components  $E_x, E_y, H_x, H_y, H_z$ , and carried out its harmonic analysis. The values of the apparent resistance, calculated for diurnal, semidiurnal, and 8-hour periods, are presented in Fig. 1 by circles (for February) and crosses (for March).

The points for “Shatsk” lay fairly well on the right asymptote of the curve for “Alushta,” which allowed us to combine the points for “Alushta” and for “Shatsk” into one curve and to interpret it as a single whole. The superposition of the points shows that the structure of the deep part of the section in the horizontal direction changes rather slowly. The absence of a segment of the curve in the region of periods less than 16 sec, as shown below, does not interfere with the interpretation of this curve.

3. Let us note the following features of the interpretation of apparent-resistance curves:

- 1) If an arbitrary packet of horizontal layers with total thickness  $h$  lies on a highly conducting basement, then the curve  $\rho_k$ , plotted on a bilogarithmic

scale ( $\xi = \lg \sqrt{T}$ ,  $\eta = \lg \rho_k$ ), has, in the region of large periods, a descending asymptote with angular coefficient equal to  $-2$ , whose equation has the form

$$\eta + 2\xi = \lg \frac{4\pi^2}{5} + 2 \lg h, \quad (1)$$

i.e., it contains the value  $h$  and does not depend on the other parameters of the section.

- 2) If an arbitrary packet of horizontal layers with total longitudinal conductance

$$\Sigma_0 = \int_0^h \sigma(z) dz$$

lies on a basement of high resistance, then the curve  $\rho_k$ , plotted on a bilogarithmic scale ( $\xi = \lg \sqrt{T}$ ,  $\eta = \lg \rho_k$ ), has, in the region of large periods, an ascending asymptote with angular coefficient equal to  $2$ , whose equation has the form

$$\eta - 2\xi = \lg \frac{20}{(4\pi)^2} - 2 \lg \Sigma_0, \quad (2)$$

i.e., it contains the total longitudinal conductance and does not depend on the other parameters of the section.

Thus, by taking an arbitrary point on either of these asymptotes, we can directly obtain in the first case the total thickness, and in the second case the total longitudinal conductance.

4. The experimental curve  $\rho_k$  has two segments with angular coefficients close in modulus to  $2$ —the left one ascending and the right one descending. Substituting into (1) the coordinates of an arbitrary point of the right asymptote, we determine the depth of occurrence of the highly conducting basement, which turns out to be  $500$  km. Substitution into (2) of the coordinates of points of the left asymptote determines the value of the total conductance of the upper packet of layers:  $\Sigma_0 = 0.125$ .

Owing to the absence of records of field disturbances with periods below  $16$  sec, the curve  $\rho_k$  in the region of “small” periods could not be completed. According to logging data from a borehole in Yalta, passing through

the Tauride suite, the resistance of the latter ranges from  $30$  to  $50$  ohms. Taking its mean value to be  $40$  ohms, we find the total thickness of the upper packet to be  $5$  km.

The values  $h$  and  $\Sigma_0$ , determined from the asymptotic conditions, do not depend on the other parameters of the section.

5. The interpretation of the experimental data was carried out with the aid of specially calculated theoretical curves.

At the Computing Center of Moscow State University, programs are in operation that make it possible, for a given electrical section, to determine the apparent resistance for an incident plane monochromatic wave. In particular, there is a separate program for an eight-layer medium with constant conductivity of the layers.

After a preliminary rough interpretation of the experimental curve with the aid of a two-layer master chart, a series of four-layer theoretical curves was calculated, the parameters of which were varied and refined until a satisfactory agreement of one of the theoretical curves with the experimental points was achieved. The results of the interpretation are presented in Table 1. Below the 3rd layer, at a depth of 500 km, lies a highly conducting basement with a resistance of the order of 1 ohm.

**Fig. 1.** Curve of apparent resistance  $\rho_k$ . The solid line is the theoretical curve for the four-layer section corresponding to Table 1. The points are the mean values of experimental determinations of apparent resistance. The length of the vertical segments corresponds to the magnitude of the mean error in the determination of  $\rho_k$ .

**Table 1**

Electrical characteristics of the section obtained in interpreting the magnetic-telluric deep-sounding curve

Layers	Resistance, ohms	Thickness, km
1st	30–40	4–5
2nd	1500	150
3rd	250	350

With the aid of variations of the section parameters, the stability of its determination was studied. It turned out that changing the parameters of the 2nd and 3rd layers by 20% from the principal value causes a noticeable departure of the theoretical curve from the experimental points. Lack of space does not permit us to dwell on this in greater detail. Let us recall that the total thickness of the upper packet of layers is determined independently of the structure of this packet.

6. The use of diurnal variations, which constitute a disturbance traveling along a spherical layer with the velocity of the Earth' s rotation and with a wavelength comparable with the Earth' s radius, forced us to take into account the influence of the Earth' s sphericity and of the change in the

structure of the wave. As calculations showed (<sup>4</sup>), the magnitude of the corrections introduced by both factors is small and lies within the errors of the determination of  $\rho_k$ .

The absence of field records over the full frequency range at a single point, and the consequent need to combine observational materials from different stations on one curve, the influence of surface inhomogeneities (the proximity of the Black Sea), as well as shortcomings of the processing method, could have had some effect on the quantitative estimate of the results obtained. All this must be taken into account in subsequent work; however, one can be confident that it cannot introduce substantial changes into the character of the section of the region we have studied.

7. Until recent years, the only source of information on the distribution of electrical conductivity within the Earth was the results of analyses of variations of the geomagnetic field (<sup>14</sup>, <sup>15</sup>). On their basis, the average course of changes in conductivity with depth was established, characterizing the Earth as a whole. The parameters of the section that we have obtained are not in contradiction with these data. An interesting feature of magnetotelluric sounding is that it is carried out from field records made at a single point, and therefore its results are not an average and characterize the features of the Earth's structure in the region under investigation.

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*Note: Figure translations are in progress. See original paper for figures.*

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