

Methods used in the U.S.S.R. to reduce near-surface inhomogeneity effects on deep magnetotelluric sounding

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The effects of near-surface inhomogeneities on deep magnetotelluric sounding are considered. Methods are suggested allowing for, and ruling out, the near-surface effects. Examples for practical application of these methods are given.

1. Introduction

Deep magnetotelluric (MT) soundings are carried out to study the electrical conductivity of the Earth's crust and upper mantle. The main targets of the studies are highly conducting zones in the crust and asthenosphere, originating from the dehydration and partial melting processes. In the interpretation of deep MT-sounding data three major problems are encountered:

(1) How can we separate deep and near-surface effects? Prior to analysing MT curves, an attempt should be made to remove or at least to reduce near-surface distortions introduced by the geoelectrical inhomogeneities in the sedimentary section and crystalline basement (or by bathymetric inhomogeneities in oceans).

(2) How can we identify crustal and asthenospheric conducting zones against the background of a monotonically increasing conductivity? The inverse MT problem is ill-posed due to its instability, and geophysically useful solutions call for a priori information about the deep geoelectrical section.

(3) When may we confine ourselves to a 1-D interpretation of MT curves? In the case of mod-

erate horizontal dimensions of a crustal or asthenospheric zone, the observed effects may differ from 1-D ones.

All of these problems have been examined in papers by the authors. Now we have endeavoured to summarize and expose systematically our view on the principles underlying the interpretation of deep MT-sounding data. This view has drawn very much on the work of I.I. Rokityansky, E.B. Fainberg, A.A. Kovtun, I.S. Feldman, V.N. Zharkov, U. Schmucker, J. Weaver, V. Haak, J.C. Larsen, and others. The paper is devoted to the first problem, i.e., to the effect of near-surface conductivity.

2. Screening effect of near-surface conductivity

The contribution of a near-surface conducting layer shows up primarily in the fact that it screens, to a particular degree, the deep conductivity. If the near-surface layer is rather homogeneous, its screening effect is quasi-1-D and can be analysed in terms of the Tikhonov–Cagniard classical theory. An investigation of theoretical MT curves has revealed that to identify deep highly conducting

zones positively, their conductance S_{cr} (crustal) or S_a (asthenospheric) should be at least more than the conductance S_1 of the near-surface layer (Vanyan and Shilovsky, 1982; Berdichevsky et al., 1984). The available data indicate that the S_{cr} value is tens and hundreds of Siemens in shields and platforms, and runs to 1000–2000 S in active regions. Hence, the regions whose sedimentary section conductance $S_1 = 1000\text{--}2000$ S (say, the central regions of the East European platform and Turan plate) are not favourable for studying the crustal highly conducting zone. With regard to an asthenospheric highly conducting zone of 4000–5000 S conductance, this can be detected in many regions of the U.S.S.R., and particularly in the East European platform and Turan plate.

It is helpful to have a criterion for evaluating the range of low frequencies over which the near-surface conductivity hardly affects the values of apparent resistivity related to deep conducting zones. Calculations suggest that the influence of S_1 is maximal on the ascending branch and vanishes on the descending branch (Vanyan and Butkovskaya, 1980). The boundary between the regions of strong and weak influence of S_1 is a maximum of the ρ_a curve related to the frequency $\omega_{max} = (\mu_0 S_1 h)^{-1}$, where h is the depth of the crustal conductor. The influence of S_1 can be virtually discarded if $\omega \leq 0.25 \omega_{max}$. Over this low-frequency range, variations in S_1 have almost no bearing on the telluric field strength observed at the surface. Physically, this means that the induction interaction of near-surface currents is negligible. Thus, the frequency $0.25 \omega_{max}$ is nothing but a lower limit of induction interactions of near-surface currents. This simple criterion is applicable to practical ρ_a curves having a distinct descending branch related to the highly conducting crustal zone of $S_{cr} \gg S_1$. For instance, if $S_1 = 100$ S and the conducting zone depth $h = 15$ km, we have $\omega_{max} = 0.5 \text{ s}^{-1}$, i.e., the near-surface conductivity effect dies away over periods > 12 s.

3. Effect of 2-D near-surface inhomogeneities

The mechanism by which near-surface conductivity affects the deep sounding results is more

complicated if the surface layer is inhomogeneous. Two-dimensional inhomogeneities have been studied closely by Berdichevsky and Dmitriev (1976a, b). The main conclusions are as follows:

(1) If the current flow is parallel to near-surface structures, the only source of distortions is induction interaction of currents running in the upper layer. Analogous to the horizontally homogeneous model, we can assume that the induction effects die away for $\omega \leq 0.25 (\mu_0 S_{max} \cdot h)^{-1}$, where S_{max} stands for a maximum value of inhomogeneous near-surface conductance, while h is the depth to the conducting basement. Over this low-frequency range, apparent resistivity is hardly dependent on the variations in the near-surface conductivity and it reflects the deep geoelectrical section.

(2) If the current flow is normal to near-surface structures, the induction phenomena in the upper layer are less pronounced. Here the major distortion is due to the galvanic mechanism which is lacking in the Tikhonov–Cagniard model. Inhomogeneities will have charges whose density is proportional to the strength of an exciting, i.e., a normal telluric field. Evidently, over a low-frequency range, with no skin effect in the upper layer, the anomalous and the normal fields are equally frequency dependent. As a result, inhomogeneities of near-surface conductivity show up in the vertical shift of the low-frequency portion of the transverse ρ_a^\perp curves generally preserving their normal shape. The conformity of the shape of low-frequency branches of ρ_a^\perp curves is a characteristic feature of galvanic effects. The shift of the low-frequency branch of apparent resistivity curves is governed by variations in the near-surface conductance. As the S value decreases, the ρ_a^\perp low-frequency branches shift upwards, while an increasing S value corresponds to the downward shift. This effect has been given the name ‘ S effect’. If a ρ_a^\perp curve is distorted by the S effect, the influence of the upper layer inhomogeneities cannot be eliminated merely by frequency reduction. It is interesting, however, that in this case the low-frequency branches of phase curves approach normal ones.

At the Moscow University, voluminous albums of 2-D models of the ‘horst’, ‘graben’, and ‘scarp’ types have been collected (Dmitriev et al., 1971,

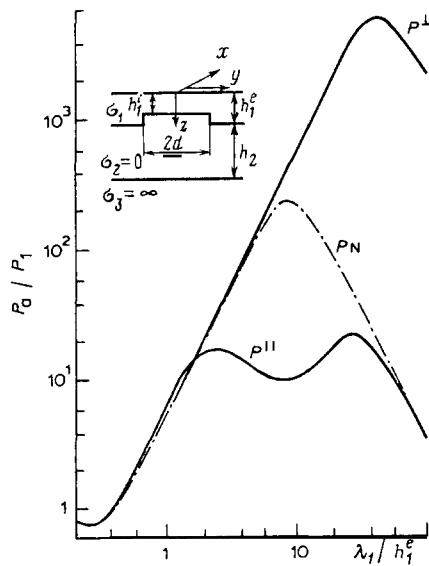


Fig. 1. Magnetotelluric sounding over the middle of a horst.

1972, 1975a–c). Figure 1 gives, as an example, ρ_a curves taken over a horst. The longitudinal curve ρ^{\parallel} (the telluric field is parallel to the horst) has a minimum, which is attributed to the induction effect of near-surface conducting zones surrounding the horst. As the frequency decreases, this induction effect dies away and the descending branch of the ρ^{\parallel} curve, reflecting the highly conducting basement, merges with the normal curve ρ_N , calculated for a 1-D model. Obviously, formal (i.e., 1-D) interpretation of the ρ^{\parallel} curve yields an accurate depth to the highly conducting basement. The transverse curve ρ^\perp (the telluric field is normal to the horst) has an extended ascending branch and its descending branch is distorted by the S effect and shifted upwards. Formal interpretation of the ρ^\perp curve indicates a false depression in the conducting basement.

These relationships can be applied to linearly extended structures whose longitudinal dimensions exceed the cross-section many times. These structures are treated as quasi-2-D. The criterion for quasi-two-dimensionality has been established (Berdichevsky and Dmitriev, 1975b; Berdichevsky et al., 1985). A distinction is made between two cases: (a) minimum S_1 and (b) maximum S_1 . A minimum S_1 has a slight bearing on low-frequency

branches of quasi-longitudinal MT curves if the length is 8–10 times the width. For a maximum S_1 , the conditions of quasi-two-dimensionality are determined by the ratio S_{\max}/S_0 , where S_0 is the surrounding conductance. To keep the effect of a maximum S_1 at a low level, the length should exceed the width by a factor of $8 S_{\max}/S_0$.

4. Effect of 3-D near-surface inhomogeneities

Clearly, in nature the most common inhomogeneities are 3-D near-surface inhomogeneities. Theoretical analysis of their effect has been initiated only quite recently. The earliest simplified models were considered by Berdichevsky and Dmitriev (1976a, b). Substantial progress has been achieved thanks to the works by Debabov (1976), Weaver (1979), Singer and Fainberg (1980), and Egorov (1982). These efforts cleared the way for the high-volume calculation of thin-sheet models, where the near-surface layer underlain by a horizontally layered medium is approximated by an inhomogeneous S plane and the 3-D problem is reduced to a simpler, 2-D one. Physical modelling was also of great importance for gaining insight into three-dimensional effects (Moroz et al., 1975; Kovtun, 1980). This provided the basis for compiling a library of models describing elementary geoelectrical situations (single isometric and extended maxima and minima of S_1). Today we are able to answer many questions concerning 3-D inhomogeneities of the near-surface layer (Golubtsova, 1981, 1982; Vanyan et al., 1984; Berdichevsky et al., 1985). A generalizing analysis has been made by Vanyan in a collective monograph (Vanyan et al., 1984) and by Haak (1978).

Three-dimensional near-surface effects, in the same way as 2-D ones, can be classified into galvanic and induction types. But in 3-D models these effects manifest themselves jointly and interact with one another.

The galvanic type includes the S effect and the flow-around and channelling effects (the current flows around poorly conducting zones and runs into highly conducting zones). It is noteworthy that the flow-around and the channelling effects tend to reduce the S effect and the latter is not as

pronounced as in a 2-D model. For instance, over an isometric minimum S_1 , the ρ_a value only increases as much as four-fold, while within a 2-D model this shift can be arbitrarily large. Another important feature of the flow-around and the channelling effects is that near an isometric inhomogeneity the ρ_a curves oriented along the inhomogeneity and towards its centre shift in opposite directions, so that the effective curve ρ_{eff} is close to a normal one (Berdichevsky and Dmitriev, 1976b). Here $\rho_{\text{eff}} = |Z_{\text{eff}}|^2 / \omega \mu_0$, where $Z_{\text{eff}} = \sqrt{Z_{xx} \cdot Z_{yy} - Z_{xy} \cdot Z_{yx}}$.

Induction interaction of near-surface currents is a kind of horizontal skin effect (the current is concentrated near the edge of a highly conducting zone). The skin effect contributes to the effective resistivity of highly conducting zones and, hence, reduces the flow-around and the channelling effects. The lower limit of induction phenomena is evaluated in a way similar to a 2-D model. If $\omega \leq 0.25 (\mu_0 S_1 h)^{-1}$, the horizontal skin effect virtually disappears and there remain only galvanic effects which shift the low-frequency branches of the ρ_a curves, without affecting their shape. In this low-frequency range, phase curves approach normal ones.

Figure 2 gives ρ_a curves calculated for a thin-sheet model containing a near-surface inhomogeneity in the form of an isometric minimum S_1 .

In this figure the flow-around effect is seen very well. Geometrical averaging of the ρ_a curves obtained at the edge of an inhomogeneity yields a ρ_{eff} curve whose descending branch is close to a normal one. At the centre of the inhomogeneity, the descending branch of the curve is shifted appreciably upwards (the S effect).

So far we have ignored the near-surface current leakage into underlying poorly conducting layers. Yet this galvanic effect may prove very important, since the current redistribution in the vertical reduces telluric anomalies caused by near-surface inhomogeneities and normalizes the MT curves. It is evident that development of the leakage effect calls for sufficiently long horizontal distances. It follows from the analysis of thin-sheet models that MT curves are normalized over distances markedly exceeding $\sqrt{\tilde{S}_1 T_2}$, where \tilde{S}_1 is the mean conductance of an inhomogeneity and $T_2 = h_2 \rho_2$ is the transverse resistivity of the layer separating the S shell from the conducting basement. Take, for example, a model with $S_1 = 1000$ S, $\rho_2 = 10^4 \Omega \text{ m}$, and $h_2 = 100$ km. Here $\sqrt{S_1 T_2} = 1000$ km. In this example, the adjusting distance is rather large.

5. Ways to allow for near-surface inhomogeneities

The most comprehensive system of interpretation of deep MT-sounding data, taking account of the distorting effect of near-surface inhomogeneities, could be constructed using methods suggested by Berdichevsky and Zhdanov (1981, 1984). These methods rely on the Fourier analysis of the field. The spectral approach is attractive because it yields readily to formalization, does not require solution of direct problems and gives normalized MT-sounding curves reflecting the deep geoelectrical section. To employ this approach, one needs information about the distribution of near-surface conductivity (e.g., electrical prospecting and drilling data, bathymetric data in oceans). The Fourier transform is possible, however, in the case of simultaneous field observations with a fairly dense coverage of a vast territory. These methods have found application in magnetovariation investiga-

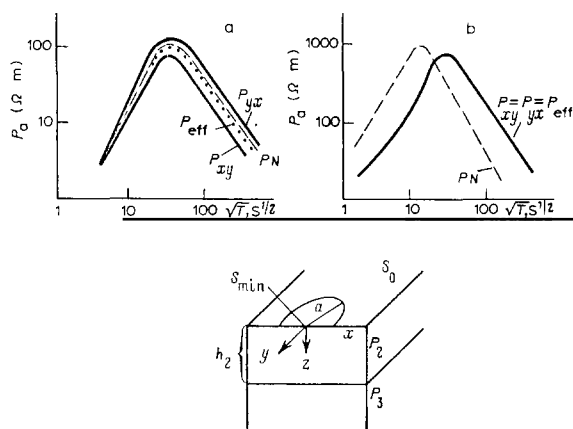


Fig. 2. Magnetotelluric soundings over an isometric minimum of conductivity of the upper layer: (a) at the edge of the minimum; (b) over the centre of the minimum. $S_n = 1000$ S, $S_{\text{min}} = 100$ S, $\rho_2 = 10^4 \Omega \text{ m}$, $\rho_3 = 1 \Omega \text{ m}$, $h_2 = 225$ km, radius of the minimum $a = 5$ km; ρ_N is the normal curve.

tions but they seem too unwieldy and cumbersome, from the organization and economic viewpoints, for MT soundings. To allow for near-surface inhomogeneities in current MT practice we use the following more or less simple methods:

(1) analysis and elimination (at least in part) of near-surface effects by means of criteria of distortion theory;

(2) modelling of near-surface inhomogeneities;

(3) statistical smoothing of small near-surface distortions;

(4) reduction of MT curves to the surface of the crystalline basement;

(5) correction of MT curves using a regional or global standard apparent resistivity curve.

6. Analysis of near-surface effects by means of criteria of distortion theory

Investigations of simple models describing elementary geoelectrical situations have led to the advent of theory classifying distortions according to their physical nature and establishing their characteristic features. This diagnostic theory has been given the name of the theory of distortions. It has been thoroughly developed for 2-D models (Berdichevsky and Dmitriev, 1976a, b) and its further substantial progress is attributed to the successes of 3-D modelling (Golubtsova, 1981, 1982; Vanyan et al., 1984; Berdichevsky and Golubtsova, 1985). The main concepts of distortion theory were outlined in sections 3 and 4 dealing with the effect of 2-D and 3-D inhomogeneities. Using the criteria of distortion theory, we can identify quasi-2-D situations, separate the induction and the galvanic effects, evaluate the S effect and the leakage effect, delineate flow-around and channelling zones, trace the effect of conducting faults and highly resistive surroundings, and detect irregular geological noise introduced by small folding, intrusions, and permafrost lenses. This preliminary work has very much in common with qualitative interpretation of MT data and does not need any external information about near-surface conductivity. Thus, we can discern near-surface distortions and, in favourable conditions, separate slightly distorted MT curves. For

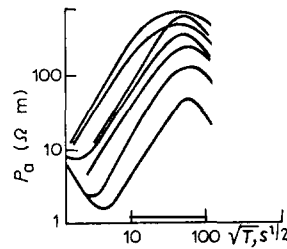


Fig. 3. Example of the S effect (northwest of the East European platform); descending branches of these curves are shifted owing to variations in conductance of sediments.

example, in regions having linearly extended structures the least distorted are the low-frequency branches of quasi-longitudinal ρ_a^{\parallel} curves. Meanwhile, near isometric uplifts and depressions it is the ρ_{eff} curves that experience a minimum distortion (Berdichevsky and Dmitriev, 1976b).

Figure 3 is an example of MT curves whose descending branches are distorted by the S effect. These ρ_{eff} curves were obtained in the northwestern part of the East European platform. As the sedimentary conductance decreases, the descending branches of the ρ_{eff} curves shift upwards, which is precisely the characteristic feature of the S effect.

The situation typical of linear tectonic regions is depicted in Fig. 4. The quasi-transverse and the quasi-longitudinal curves ρ^{\perp} , ρ^{\parallel} were recorded in the Ciscaucasian foredeep. On approaching the

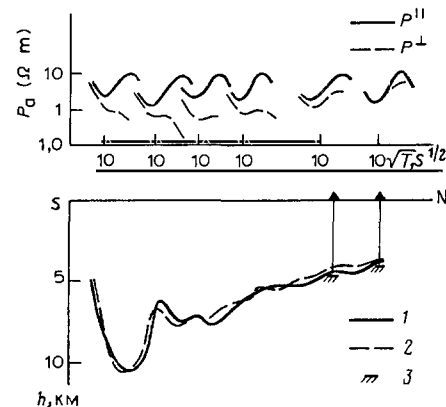


Fig. 4. Example of the edge effect in the Ciscaucasian foredeep: 1—relief of the basement, according to MT-sounding data, 2—the same, according to seismic prospecting data, 3—drill holes.

Caucasus, the quasi-transverse ρ^\perp curves are deformed: their ascending branches flatten, while the descending branches go down. This behaviour is characteristic of the edge effect normally observed on the steep slopes of elongated depressions (as the frequency decreases, the telluric field becomes polarized along the depression and its transverse component becomes smaller). The quasi-longitudinal ρ^\parallel curves are slightly distorted: here there is no edge effect and the S effect is hardly noticeable. It can be claimed that these curves convey sufficiently reliable information about the deep geoelectrical section.

Thus, an analysis involving the criteria of distortion theory shows the contribution of a near-surface inhomogeneity in the shaping of MT curves. Its objective is to diagnose near-surface distortions. In aggravated situations, where the distortion theory criteria prove to be too approximate or insufficient, it is necessary to resort to modelling.

7. Modelling of near-surface inhomogeneities

Near-surface inhomogeneities are modelled mostly on the S plane (using Price thin-sheet approximation). Since we are interested in anomalies resulting from the inhomogeneity of the upper layer, it is generally underlain by a horizontally homogeneous medium simulating the deep geoelectrical section. Regional and local models on a scale of tens and hundreds of kilometres permit the leakage effect to be ignored. This simplifies calculations very much, because the problem reduces to a scalar one for the current function. Confining ourselves to a low-frequency range we may also discard the induction interaction of near-surface currents. These simplifications make it possible to conduct calculations with reasonable computer time. Today we have at our disposal computer programs facilitating development of thin-sheet models with a rather complex distribution of S . The program of Singer and Fainberg (1980) ignores the leakage effect, while the program of Egorov (1982) takes account of neither the leakage nor the induction effects. From this standpoint, the most comprehensive programs al-

lowing for the two effects are those suggested by Debabov (1976) and recently by Singer and Fainberg (1985). Using one of these programs we can calculate the MT field and MT curves for any region in which an S map has been produced using shallow electrical prospecting data. A weak point in these calculations is the necessity for introducing a homogeneous surrounding and specifying a 'normal' field therein. Therefore, arbitrariness is unavoidable here, and positive information is expected only about relative field anomalies (with respect to the normal field) and about relative variations of MT curves (with respect to the curves derived for homogeneous surroundings). Usually, this information is sufficient to ensure a confident diagnosis of near-surface effects: comparing experimental and model data we can reach a conclusion regarding the deep or near-surface origin of the observed effects.

Let us illustrate this point by results obtained in the South Caspian depression (Vanyan et al., 1983). Here MT-sounding data have been interpreted for many years without due reference to the regional S effect which lowers the low-frequency branches of the ρ_a curves. These branches were assumed to be the result of the highly conducting asthenospheric zone absent in the area surrounding the depression. To test this hypothesis, a thin-sheet model of the depression with a non-conducting underlying basement was constructed. The S_1 values were made to vary from 2000 S in the area surrounding the depression to >10 000 S in the depression. Figure 5 shows maps of the major axes of experimental and model impedance diagrams. The experimental data coincide with the model so well that there is no doubt that in the anomaly studied the near-surface part (the regional S effect) dominates. Obviously, the old interpretation should be revised.

Can thin-sheet models be employed to make corrections for near-surface inhomogeneities? To do this, we must choose a normal field. The normal field can be naturally established by multi-step modelling: at first a global (spherical) model is constructed and the field distribution obtained is transferred, as a normal one, to continental and more detailed regional models (Fainberg, 1983). But this method is rather problematic because of

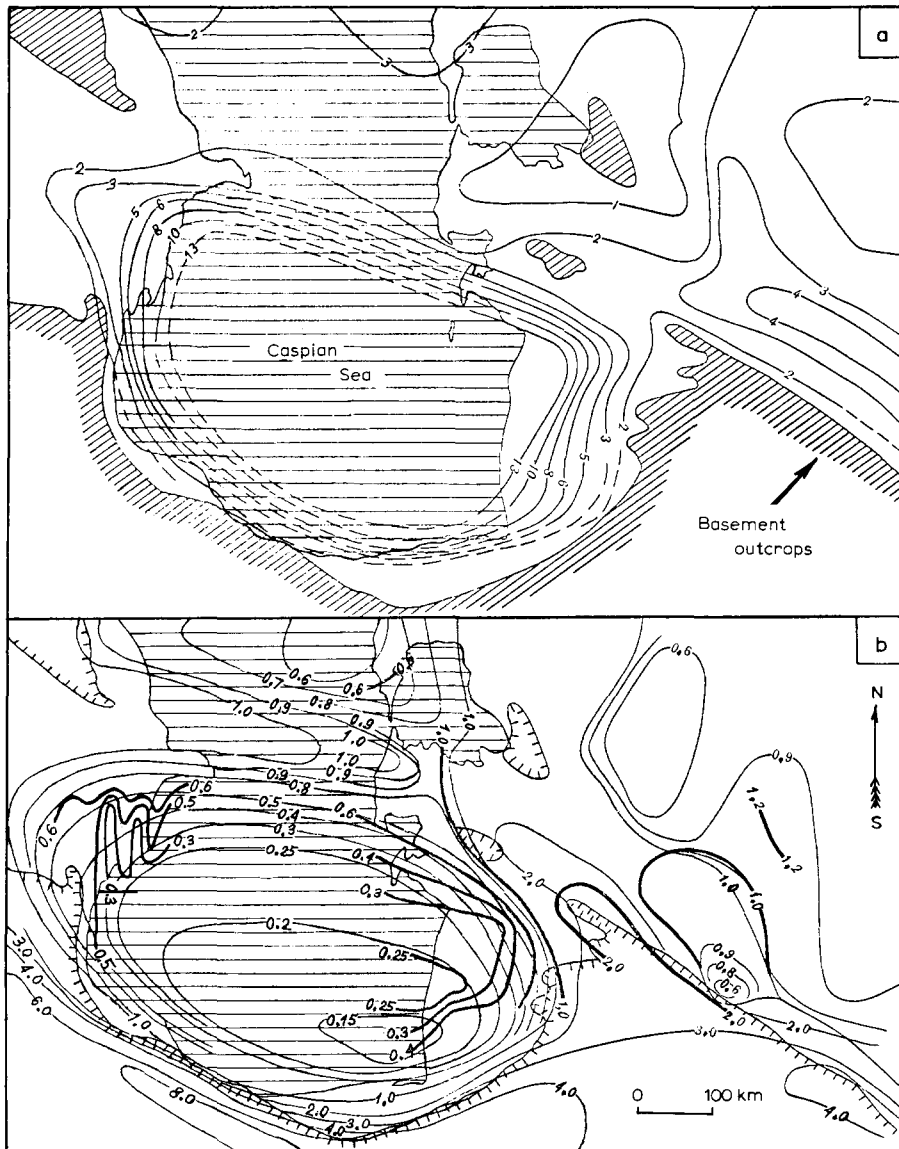


Fig. 5. Three-dimensional S effect in the South Caspian depression. (a) Scheme of conductance of the sedimentary section; S in thousands of Siemens; dashed where uncertain. (b) Comparison of the field measurements (thick lines) and model calculations (thin lines); relative values are those of the major axes of the impedance diagrams.

arbitrariness in the choice of external excitation and insufficient information about the transverse crustal resistance determining the rate of near-surface current leakage into the crystalline basement. Furthermore, errors may arise from ignorance of the normalizing effect of deep faults conductively connecting the near-surface layer to

conducting layers in the Earth's crust and upper mantle. An alternative solution to the problem is to check the normal field against the standard apparent resistivity curve (see section 10) and to evaluate the degree of distortion of MT curves obtained in the surrounding area of the homogeneous model. This promising approach will be

discussed in the last section of the paper. Here, however, we will only remark that in favourable conditions thin-sheet models controlled by a standard apparent resistivity curve may help not merely to recognize but also to remove the near-surface effects.

Evidently, the scale of thin-sheet models should be consistent with the details of information on near-surface conductivity of a studied region. To model regional distortions at a scale of many hundreds of kilometres, we can use maps of conductance of the sedimentary section and water layer, which have been recently published in the U.S.S.R. (Fainberg, 1978). Local distortions can be analysed if a studied region has been subjected to electrical prospecting. The worst case is with small inhomogeneities (geological noise) whose structure is not known in detail. Then, a solution is provided by the statistical approach.

8. Statistical smoothing of small near-surface distortions

Geological noise is made up of small anomalies introduced by intrusions, effusions, permafrost lenses and other small-size structures. The hori-

zontal dimensions of near-surface anomalies are far smaller than distances over which deep conductivity can change appreciably. Thus, we arrive at the problem of separating the regional background, which does not differ in principle from similar problems in gravimetry and magnetometry. Here it is natural to employ a statistical approach assuming a random distribution of near-surface anomalies with a mathematical expectation corresponding to a normal field. No theory has yet been elaborated for this approach, but numerous analyses indicate a lognormal distribution of apparent resistivities, which is typical of many natural processes (Kolmogorov, 1941; Berdichevsky et al., 1980).

The statistical approach relies on the principle of spatial filtering, which enjoys great favour in the interpretation of geopotential field anomalies. The procedure of filtering MT soundings is developed rather well (Berdichevsky and Nechaeva, 1975). MT data are represented as a set of apparent resistivity maps for various periods. These maps are transformed using a low-pass filtering similar to that developed for removing small-scale gravimetric anomalies. Upon filtering we obtain maps with smoothed local anomalies. An example of filtering is presented in Fig. 6. The ρ_a values

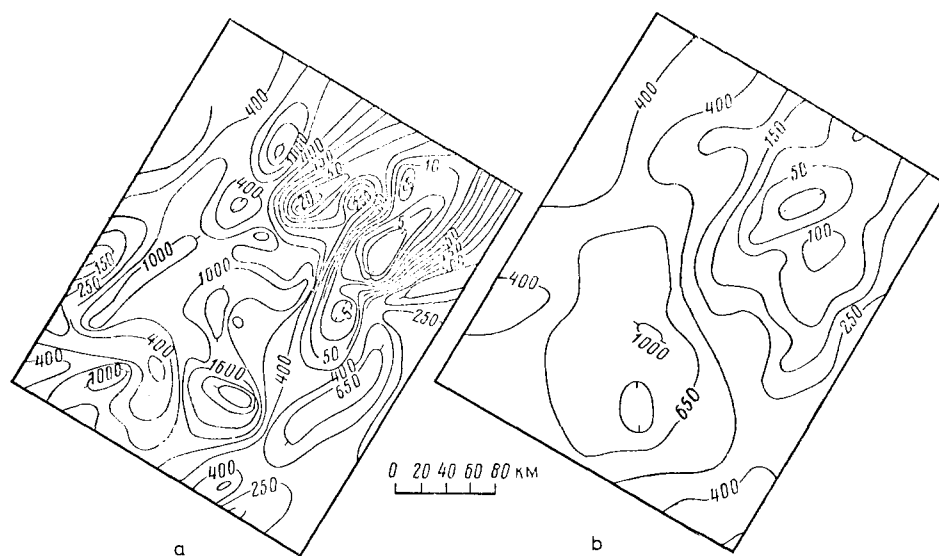


Fig. 6. Map of apparent resistivities for a 225-s period (Southern Yakutiya): (a) of initial data; (b) filtered data (values in Ω m).

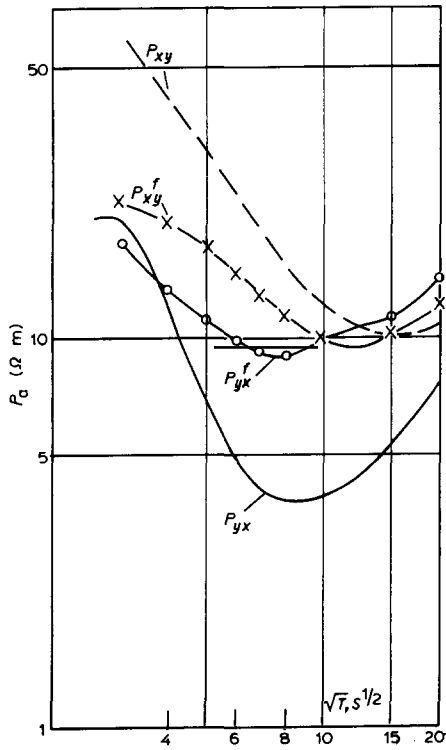


Fig. 7. Example of filtered MT curves: ρ_{xy} and ρ_{yx} are the initial curves, while ρ_{xy}^f and ρ_{yx}^f are the filtered curves.

from transformed maps are synthesized, thereby yielding filtered MT curves reflecting the regional regularities (Fig. 7). One can think that filtered

MT curves approach the 1-D model. It seems that the same idea is behind the electromagnetic array profiling proposed by Bostick (1986).

A somewhat different approach is taken when the terrain under consideration can be divided into zones of practically conformal curves. Here we confine ourselves merely to a logarithmic averaging within each zone. This technique was utilized, in particular, to interpret the MT-sounding data in the Baikal region, where the MT field has severe distortions due to intrusions and permafrost lenses. Averages were obtained in 10 zones covering the Irkutsk cirque and the Transbaikalian region (Fig. 8). Individual ρ_{eff} values differ from each other by a factor of $10 - 10^3$. However, the averaged ρ_{eff} curves lie nearer the same level and indicate a crustal highly conducting layer developed in the region of the Baikal rift.

Clearly, statistics entail substantial expenses, since the suppression of the geological noise requires a large amount of averaging. Unfortunately, this is the only way of gaining deep information in regions of severe geological noise.

9. Reduction of MT curves to the surface of the crystalline basement

The value of admittance observed at the Earth's surface (Y) is reduced to that at the bottom of the

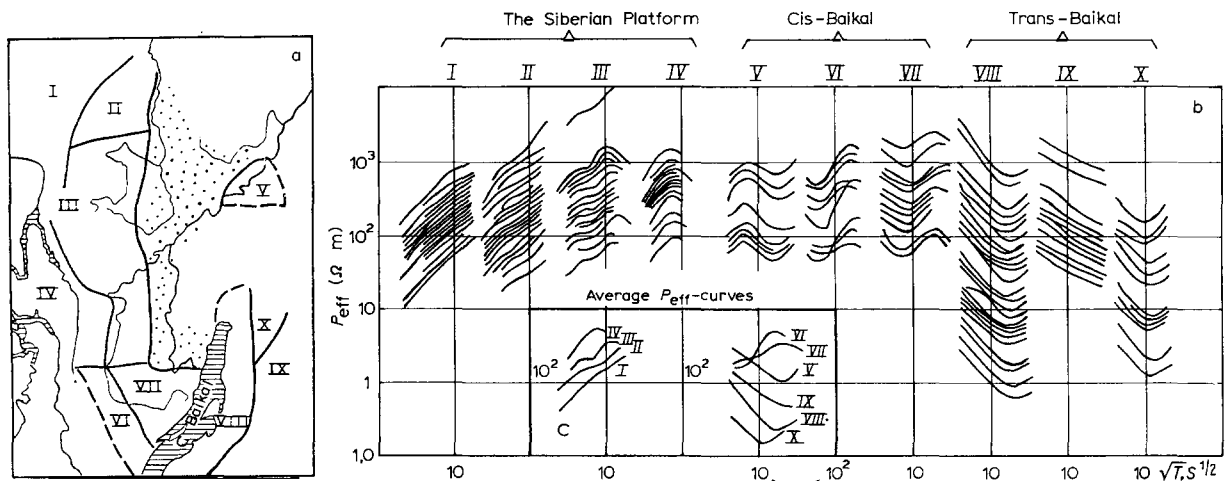


Fig. 8. Statistical smoothing of local anomalies in the Baikal region. (a) Zones of conformal effective apparent resistivity curves. (b) Sets of curves referring to particular zones. (c) Average effective curves.

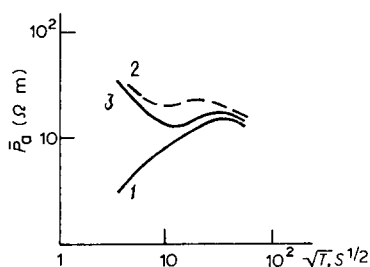


Fig. 9. Example of reduction of apparent resistivity to the surface of the basement: 1—initial curve; 2—reduced curve; 3—curve for a region of low sedimentary conductance values.

upper layer (Y^*) according to the relation

$$Y^* = Y - S_1$$

where

$$Y = H_y/E_x$$

which holds good for a horizontally homogeneous model. The reduction can be applied over a low-frequency range beginning with the ascending branch of MT curves. Thus, we obtain a curve of apparent resistivity $\rho_a^* = 1/\omega\mu_0(Y^*)^2$ reduced to the surface of the crystalline basement. Reduction renders the effect of inhomogeneities S_1 less pronounced, thereby simplifying MT data typification. Figure 9 shows average $\bar{\rho}_a$ curves taken in two regions of the Pannonian depression characterized by different S_1 values (Adam and Vanyan, 1984). Upon reduction they differ very little and attest to the occurrence of a deep highly conducting layer.

10. Correction of deep MT-sounding curves using a standard apparent resistivity curve

The idea of this method originated from Rokityansky (1975). It is assumed that at depths > 250 – 300 km conductivity varies slightly in the horizontal direction and it can be approximated by a spherically symmetric model. If this is the case, low-frequency branches of MT curves obtained in different tectonic provinces should be confluent and the discrepancy between them is evidence of the effect of upper layer inhomogeneities. Thus, there is a simple criterion for recogniz-

ing and allowing for near-surface effects. This criterion can be used if very-low-frequency data are available.

The assumption of insignificant variability of electrical conductivity at depths below 250–300 km is supported by the following considerations:

(1) The major factor responsible for marked anomalies in the mantle conductivity is a degree of partial melting. However, the basalt melt is likely to disappear below 250 km because the higher the pressure, the higher the solidus.

(2) According to geothermic and seismic data, the temperatures and seismic velocities under the continents and oceans level off at depths ~ 300 km. An exception to this may be regions of up-flowing hot mantle (e.g., ridges, rises and rifts) and zones of possible subduction of relatively cool lithospheric plates. But, even if geothermal anomalies occur in these regions, they will hardly have a pronounced bearing on the deep conductivity, since below 300 km the latter is largely determined by pressure (Zharkov, 1978). Besides, the resolution of MT sounding decreases dramatically with increasing depth. Assume that temperature inhomogeneities at depths of 300 km change the conductivity by a factor of 2–4 times. If the horizontal dimensions of such a zone are of an order of hundreds of kilometres, the anomaly in apparent resistivity is estimated to be several per cent or at best tens of per cent (Berdichevsky et al., 1984). Meanwhile, the ρ_a anomalies caused by near-surface inhomogeneities often run to 2–3 orders of magnitude. To correct for such drastic distortions, it seems possible to use a model with a spherical symmetry of electrical conductivity at great depths.

What data can be used to draw a reference (undistorted) apparent resistivity curve to be used as a standard characterizing a normal geoelectrical section of the Earth's interior? At present we see two sources of these data:

(1) Global magnetovariation sounding carried out in a world-wide network of geomagnetic observatories. This frequency sounding yields an apparent resistivity curve reflecting the mean geoelectrical section of the Earth (chiefly of the continents). The global sounding data over periods ranging from 6 h to 11 days (Rotanova and

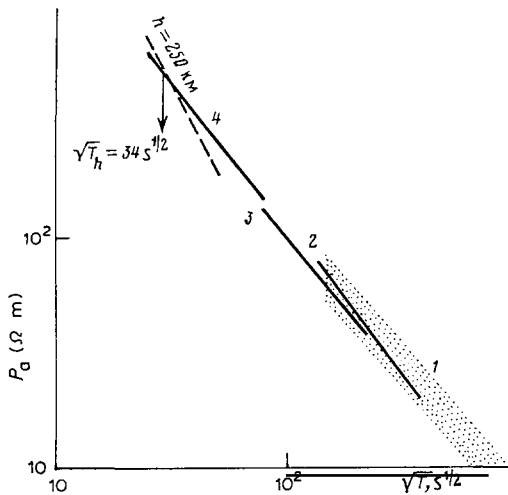


Fig. 10. Magnetotelluric and global magnetovariation data: 1—magnetovariation sounding; 2—MT sounding in the north-eastern part of the Pacific Ocean; 3—MT sounding in the south of the Turan plate; 4—MT sounding in the northwest of the East European platform. All the curves of MT sounding are reduced to the surface of the basement.

Pushkov, 1982) are plotted in Fig. 10 by the stippled region. These data do not use telluric measurements and seem to be rather free of near-surface effects, owing to the low sensitivity of the low-frequency magnetic field to the upper layer inhomogeneities and high-volume averaging. This curve has been useful for several years in the interpretation of deep MT-sounding data.

The efforts to define this curve more accurately are still under way. Recently, Fainberg (1983) has suggested a new version in which he selects the most plausible data and endeavours to allow for the ocean effect.

(2) Deep magnetotelluric soundings carried out in stable regions with a homogeneous sedimentary section. The ρ_a curves should be characterized by the following features: (a) weak near-surface distortions; (b) lack of evidence of crustal and asthenospheric highly conducting zones; (c) consistency with the global curve and with the current ideas of the geoelectrical section of stable regions based on laboratory measurement and geothermal data.

The standard apparent resistivity curve plotted using the results of global sounding and of MT

soundings in the East European platform (Vanyan et al., 1980) and Turan plate (Avagimov et al., 1981) is also depicted in Fig. 10. For comparison, the same figure gives an MT-sounding curve recorded recently in the central part of the Pacific Ocean (Chave and Von Herzen, 1978). Its low-frequency branch is close to the standard curve. This corroborates the starting assumption of a spherical asymmetry of electrical conductivity at great depths.

The line $h = 250$ km intersects the standard apparent resistivity curve at a point with an abscissa $\sqrt{T} = 34$ s^{1/2}. Consequently, the range of depths characterized by a spherical symmetry of conductivity shows up over periods exceeding $T_h \sim 20$ min. Above this period the normal ρ_a curves should approach a standard curve. To improve the accuracy of estimation, allowance should be made for the conductance of the sedimentary section and of the crustal and asthenospheric highly conducting zones $S = S_1 + S_{cr} + S_a$. In such a model we have a normal ρ_a curve whose right descending branch manifests itself over periods $T > T_s$ ($\sqrt{T_s}$ being the abscissa of the point of intersection of the standard curve and of the S line). We choose the larger value of T_h or T_s and this is a boundary of the interval within which the normal ρ_a curves are close to the standard curve. For instance, for $S = 3000$ S we have $T_s \sim 10^4$ s. Here $T_s > T_h$. Hence, if the ρ_a curve is not distorted, it should coincide with the standard curve over periods mounting to several hours. This example is clear evidence of the importance of long-period variation recording.

In order to correct deep MT-sounding data, one should claim with certainty that the low-frequency portions of the curves reflecting the geoelectrical section of the Earth's crust and upper mantle are free of near-surface induction effects, i.e., that they have a normal shape. The frequency at which the induction effects virtually die away can be estimated using rough criteria given in sections 2 and 3. To have more accurate data, a thin-sheet model may be used to allow for the induction interaction of near-surface currents. Convincing evidence of the absence of induction effects is the conformity of low-frequency portions of the ρ_a curves taken under different orientations.

The most complicated situation occurs where soundings are carried out near deep highly conducting faults. As it is difficult to estimate the induction effect of faults (because of the lack of information on the fault geoelectrical structure), it is better to use a transverse MT curve.

Thus, we select the portion of an experimental ρ_a curve having a normal shape but shifted either upwards or downwards owing to the galvanic distortions (mainly, the S effect). Comparing the right descending branch of the ρ_a curve with the standard apparent resistivity curve, ρ_{st} curve, we establish the degree of galvanic distortion $\alpha = \rho_a / \rho_{st}$ and make appropriate corrections by moving the low-frequency portion of the ρ_a curve so as to superimpose its descending branch on the standard curve. The overall ρ_a curve is reconstructed by rough interpolation connecting its high- and low-frequency branches.

A theoretical example of correcting an MT curve by means of its shifting is given in the study of Mikhlin (1984). The model consists of a near-surface S sheet underlain by a four-layer medium with a conductor at the basement (Fig. 11). The sheet contains a circular poorly conducting inclusion. The ρ_a curve recorded over this inclusion has a normal shape but is shifted markedly upwards (the S effect). Moving the ρ_a curve so that its right descending branch might lie on the h -line we arrive at a normalized curve ρ'_a coinciding fairly well with the normal ρ_N curve.

The accuracy of correction may be enhanced on transition from the global standard curve ap-

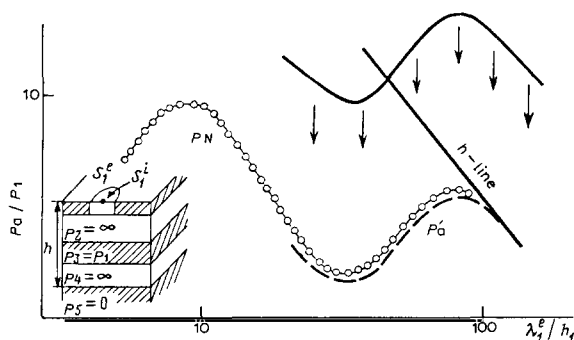


Fig. 11. Correction of the MT-sounding curve by shifting: ρ_N is the normal curve, ρ'_a is the shifted ρ_a curve.

plicable to all tectonic provinces to regional standard curves characterizing particular tectonic provinces, which is feasible on accumulation of certain interpretation experience.

11. Conclusions

The authors should like to stress the importance of using a combination of the above methods to separate deep information. Analysis in terms of distortion theory, numerical modelling, and correction by means of a standard apparent resistivity are essential steps in reducing the effect of near-surface inhomogeneities.

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