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Two-Dimensional Film Interpretation of South Tien Shan Geomagnetic Field Anomaly

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It is proposed that surface and crustal conductivity anomalies, distributed in area, be interpreted by film models: the upper part of the section, including the sedimentary cover, poorly conducting basement and crustal conducting layer, is approximated by inhomogeneous thin layers. Simple relations are given which make it possible to ascertain integral conductivity *S* of the upper part of the section. Typical two-dimensional models illustrate the possibilities of the proposed method. The described approach made it possible to make a two-dimensional interpretation of the known South Tien Shan magnetic anomaly. The *S* distribution in the crustal layer along the profile cutting the anomaly was found. Two maxima are discriminated in this distribution. The *S* value attains 12,000 mho.

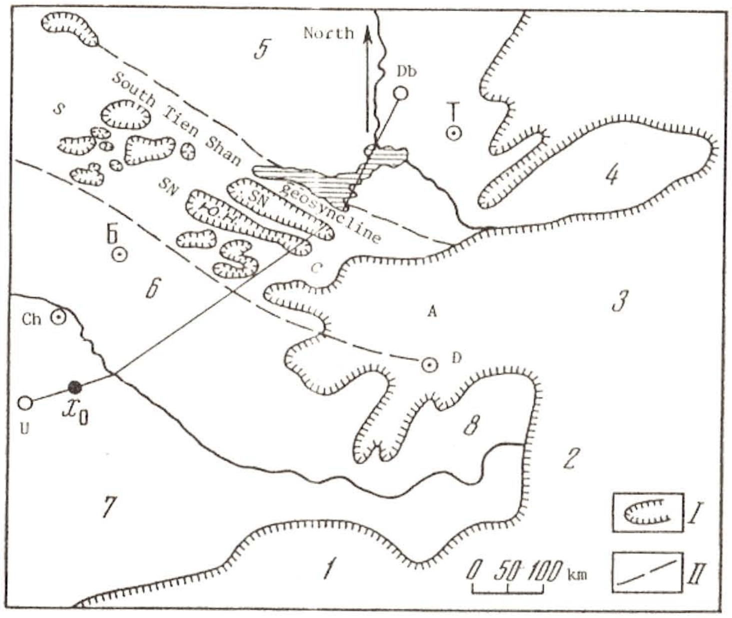

Fig. 1. Tectonic diagram of Western Uzbekistan. I) Outcrops of Paleozoic basement, II) deep faults; *1*) Hindukush, *2*) Pamirs, *3*) Alay Range, *4*) Fergana, *5*) Syrdarya syneclise, *6*) Amudarya syneclise, *7*) Murab depression, *8*) Afghan-Tadzhik depression. T—Tashkent, D—Dushanbe, B—Bukhara, Ch—Chardzhou, U—Uch-Adzhi, Db—Darbaza, NN—Northern Nuratau, SN—Southern Nuratau, x_0—Repetek base point.

Introduction

During recent years, numerous crustal conductivity models have been discovered and investigated in different regions of our planet. The South Tien Shan conductivity anomaly (STCA), discovered in 1979 - 1983 in the territory of Western Uzbekistan, is one of the largest (Fig. 1). Its extent is more than 1000 km and its width in individual zones exceeds 100 km. According to a preliminary interpretation, the anomaly is formed by carbonaceous matter, whose presence in many regions is regarded as an indicator of ore formation [1, 2]. This allows new prospects for the prediction of ore deposits in Uzbekistan; accordingly, the study of STCA is of great interest.

The formal interpretation of data from magnetotelluric (MT) and magnetovariation (MV) observations revealed a contradictory picture. The evaluations obtained by using mean MT sounding curves within the framework of a two-dimensional model indicated that the upper edge of the anomaly is situated at a depth of 5 to 10 km and that its total longitudinal conductivity S attains 350,000 mho [2]; the resistivity of the rocks forming the STCA attains 0.05 ohm·m.

Other S evaluations were obtained in [3], where an analysis of MV anomalies was made within the framework of a two-dimensional model: it was shown that the resistivity of the inhomogeneity is an order of magnitude greater and that it lies at a depth 15 to 20 km. According to [3], the detected contradiction may be related to the existence of three-dimensional inhomogeneities leading to galvanic distortions of MT sounding curves, and as a result, an incorrect S evaluation. To estimate the possible galvanic distortions, the authors of [3], using the known Kertz formula, scaled the distributions of the vertical component of the magnetic field H_z along the Karabekaul-Arnasay profile to the electrical field and then to the impedance Z. A comparison of the observed and computed Z values demonstrated that the scaled values greatly exceed the values determined directly from the measured electrical and magnetic fields. The total longitudinal conductivity, determined within the framework of the two-dimensional model in accordance with methods for normalization to the internal field, described in [4], was equal to (8 - 10) × 10^3 mho; the conductivity maximum falls in the region between the Northern and Southern Nuratau (see Fig.

The estimates obtained in [2] as a result of the processing of MV data by the moments method and using the empirical Rokityanskiy formula $S=45T_{max}^{1.25}/L$ (where T_{max} is the period of the frequency characteristic maximum, L is the width of the anomaly in km) gave $S \approx 20\,000$ and 11,000 mho, respectively, which is at least an order of magnitude less than the MT estimates. The discrepancy between the MT and MV estimates was perceived by the authors of [2] as an indication of a more complex structure of STCA than was postulated on the basis of mean MT sounding curves.

At the present time, investigations of the STCA are being made in several directions at the same time. Field work is continuing in Uzbekistan and in contiguous territories for the purpose of better definition of the anomaly and more precise determination of its parameters. These studies, in particular, confirm the assumption made in [2] that there is an easterly continuation of the STCA within the limits of the Fergana megasyncline, where, according to [5], there is a layer of increased conductivity whose top lies at a depth of 5 to 10 km. Two-dimensional models taking into account both the local characteristics of the MT and MV fields and available geological-geophysical data on the structure of the region are being further developed. Numerical simulation methods are being used in studying the influence of the more complex structure of the anomaly (for example, its three-dimensionality) on the results of interpretation within the framework of a two-dimensional model. New methods are being developed for interpreting the experimental data pertaining to the STCA. These further developments are proceeding for the purpose of more precise determination of the most general integral characteristics of the section and determination of new anomaly parameters.

This article gives the first results of interpretation of the STCA within the framework of film models widely used during recent years in deep geoelectrics in solving direct problems of electromagnetic induction in inhomogeneous media [6].

2. South Tien Shan Anomaly in MV Field

The regional Uch-Adzhi-Darbaza profile (Fig. 1) runs in a submeridional direction and intersects the Amudarya syneclise, the South Tien Shan geosynclinal system, and the Syrdarya syneclise. The total longitudinal (integral) conductivity of the sedimentary cover changes from 2000 to 3000 mho along the profile in the most submerged central parts of the Amudarya syneclise and Fergana depression, and decreases to 20 - 40 mho at the edges of the Amudarya and Syrdarya syneclises. A detailed description of the region and data from MT and MV observations is given in [2]. Here we note only that work on systematization of available extensive MT data has not been completed. Therefore, this article gives an analysis only of profile MV observations. Taking into account the elongation of the anomaly, it is possible to hope that acceptable evaluations of the distribution of integral conductivity of anomalous features can be obtained by an interpretation of profile observations within the framework of a two-dimensional film model. A cross-scaling of the vertical component of the magnetic field to the horizontal component and vice versa was carried out for checking the legitimacy of application of the two-dimensional model.

As is well known [7], in a two-dimensional situation with longitudinal (E) polarization of

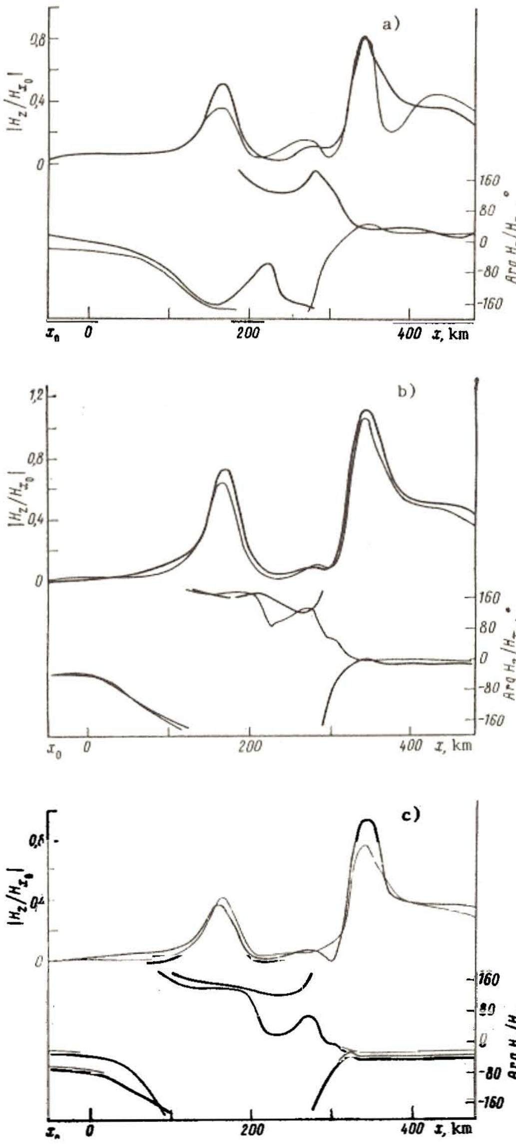

Fig. 2. Distribution of modulus and phase of vertical component H_z/H_x of magnetic field along Uch-Adzhi-Darbaza profile: a) period 1200 s, b) 3600 s, c) 10,000 s. The thick curves are spline approximations for the observations; the thin curves correspond to solutions of the direct problem.

the electrical field the vertical $H_z^{(a)}$ and horizontal $H_x^{(a)}$ components of the anomalous magnetic field at the Earth's surface are related by the Kertz transform:

$$H_x^{(a)}(x)=\frac{1}{\pi}\int_{R_1}\frac{H_z^{(a)}(x')}{x'-x}dx', \qquad (1)$$

where the integral is taken for the real straight line and is understood in the sense of the main value. The magnetic field level $H_x^{(n)}$ in the southern part of the profile is used as the normal level. There the MTS curves coincide with the normal curve for the southern part of the Turan plate [8]. According to [2], the maximum of the frequency characteristic $|H_z/H_x|$ is noted in the range of periods ~3000 s; accordingly, field scaling was for periods 1200, 3600, and 10,800 s. The results of the computations indicated that for periods 3600 and 10,800 s the mean relative discrepancy of the measured and scaled fields is ~10% that is, the main part of the MV anomaly can be examined within the framework of a two-dimensional model.

Thus, in the first approximation, the South Tien Shan MV anomaly can be regarded as two-dimensional. Since magnetic field vertical component is more sensitive to inhomogeneities, it was decided to use it as a basis for interpreting the STCA. The H_z/H_{x0} distributions along the profile for the considered periods are illustrated in Fig. 2. Repetek, where the field is least distorted by local anomalies, was selected as the base point x_0. The figure shows that the anomaly is clearly discriminated in both the modulus and phase H_z/H_{x0}.

3. Inverse Problems in Film Models

By the "inverse problem in geoelectrics" is meant the problem of ascertaining conductivity $\sigma(x, y, z)$ or its integral characteristics from the electromagnetic field observed at the Earth's surface. However, the complexities arising in solution of the problem in such a general formulation lead to the need for additional assumptions concerning the nature of the distribution of conductivity $\sigma(x, y, z)$. The nature of the assumptions is determined, in particular, by available *a priori* information on the section and by the part of the section that is of interest to the interpreter.

At the present time, the most commonly used method for solving the inverse method is the trial-and-error method, whose basic idea is a description of the geoelectric section by a finite number of parameters with a subsequent purposeful search for such values of the parameters for which the difference between the computed model and experimental fields is minimized. The effectiveness of the trial-and-error method is essentially dependent on the number of sought-for parameters and how successfully they describe the investigated section. Experience in solving inverse problems reveals that on a realistic basis it is possible to count on a stable determination of 5 to 10 parameters. This number of parameters is adequate, for example, for simple isolated anomalies against a background of a horizontally homogeneous section or for more precise determination of the values of individual parameters in an already known complex section. In these same cases when the object of research is surface structures with a complex spatial distribution, poorly described by a small number of parameters (such as the distribution of total longitudinal conductivity of the sedimentary mantle or a series of crustal anomalies), the use of the trial-and-error method is ineffective. In such cases, the use of film models is desirable because they make possible a direct scaling of the distributions of electromagnetic fields into integral conductivity (or resistivity) distributions.

The conditions for the applicability of film models in describing geoelectric structures are discussed most completely in [6] and are not examined in this article. Some possibilities of determining the parameters of the geoelectric section (integral conductivity of the sedimentary mantle, transverse resistivity of the reference horizon, conductivity of deep layers of the crust and upper mantle) in a class of film models when there is *a priori* information concerning the section and when there are data from synchronous measurements of electrical and magnetic fields at the Earth's surface were examined in [4, 6, 9 - 11]. A model with an inhomogeneous surface S layer is of the greatest interest for an interpretation of the South Tien Shan anomaly.

Model with Inhomogeneous Surface S Layer

In this section, we examine a model containing an inhomogeneous surface layer with the integral conductivity $S(\mathbf{r})$. The medium over the S layer (atmosphere) is assumed to be nonconductive ($\sigma = 0$), and the conductivity of the section under the S layer $\{\sigma(z)\}$ is assumed to be dependent on a single coordinate—depth z. The model is excited by an arbitrary external field.

The problem we must solve is formulated in the following way: Assuming the conductivity $\{\sigma(z)\}$ to be known, determine the distribution of integral conductivity $S(\mathbf{r})$ on the basis of the tangential components of the electrical and magnetic fields $\mathbf{E}_\tau(\mathbf{r})$ and $\mathbf{H}_\tau(\mathbf{r})$ observed at the Earth's surface $z = 0$. We note at once that everywhere in the text which follows, the electromagnetic fields are assumed to change harmonically with time $\exp(-i\omega t)$; and the permeability of the medium $\mu = \mu_0 = 4\pi \times 10^7$ henry/m. The influence of displacement currents, magnetic polarization of the medium, and frequency dispersion are neglected. In the S layer, the electrical field tangential component remains continuous, whereas the magnetic field tangential component experiences a jump, determined by current density [12, 13]:

$$\delta\mathbf{E}_\tau = 0, \quad \mathbf{n}\times(\mathbf{H} \quad \mathbf{H} \quad = S\mathbf{E}_\tau, \tag{2}$$

where $\mathbf{n}$ is the upward directed vector of the unit normal to the Earth's surface, $\mathbf{H}_-$ is the tangential component of the magnetic field on the lower side of the S layer.

Since

$$i\omega\mu_0 H_n = -\mathrm{div}_\tau(\mathbf{n}\times\mathbf{E}_\tau),$$

then the continuous and vertical component of the magnetic field also remains continuous in the S layer.

According to [6, 14], the electromagnetic field in a laterally homogeneous medium can be described using the two scalar potentials V and W

$$\mathbf{E}_\tau = i\omega\mu_0\mathbf{n}\times\nabla_\tau V + \nabla_\tau\left(\sigma^{-1}\frac{\partial W}{\partial n}\right) \tag{4}$$

$$\mathbf{H}_\tau = -\nabla_n\frac{\partial V}{\partial n} - \mathbf{n}\times\nabla_\tau W, \tag{5}$$

$$H_n = \Delta_\tau V, \quad j_n = -\Delta_\tau W \tag{6}$$

where H_n and j_n are the vertical components of the magnetic field and the current respectively. The potential V of the induction mode is a solution of the equation

$$\left\{\frac{d^2}{dz^2} \quad \Delta_\tau \quad i\omega\mu_0\sigma(z)\right\}V(\mathbf{r}, z) = 0,$$

tending to zero when $z \to \infty$. Similarly, the potential of the galvanic mode is a solution of the equation

$$\left\{\frac{d}{dz}\frac{}{\sigma} \quad \frac{}{}\Delta \quad i\omega\mu_0\right\}W(\mathbf{r} \quad = 0. \quad (8$$

The values of the spatial harmonics of the potentials V and W at the surface of the underlying S layer of the section are related to the values of the corresponding normal derivatives through the spectral impedañces of the induction and galvanic modes. Applying generalized functions, using (4) - (8) it is possible for one to derive an expression relating the tangential components of the electrical and magnetic fields at the surface of a laterally homogeneous section [15, 16]:

$$\mathbf{n}\times\mathbf{H}_\tau^-(\mathbf{r}) = \mathbf{E}_\tau(\mathbf{r})/Z_0^- + \int_{R^2} \quad \{\sigma\}, \mathbf{r}-\mathbf{r}' \quad \{\mathbf{E}_\tau(\mathbf{r}' \quad \mathbf{E}_\tau(\mathbf{r})\}d\mathbf{r}'$$

Here the integration is over the surface of the underlying section; Z_0^- is the impedance of the underlying S layer of the section. The explicit form of the tensor kernel $\hat{Y}(\{\sigma\}, \mathbf{r})$, which in essence is a spatial representation of the spectral admittance of the underlying section, was obtained in [16]:

$$(\mathbf{r}) = (\mathbf{n}\times\mathbf{e}_r)\otimes(\mathbf{n}\times\mathbf{e}_r)\left\{\frac{d}{dr}G'(r \quad G^g(r)\right\}$$
$$-\mathbf{e}_r\otimes\mathbf{e}_r\left\{\frac{d}{dr}G^g(r) + \quad \right\} \tag{10}$$

where $\mathbf{e}_r = \mathbf{r}/r$, the symbol $\otimes$ denotes the tensor product of the vectors $\mathbf{a}$, $\mathbf{b}$: $(\mathbf{a} \otimes \mathbf{b})_{ij} = a_i b_j$; i, $j = 1, 2$. The functions $G^i(r)$ and $G^g(r)$ are determined through Fourier-Bessel integrals:

$$G^i(r) = \int_0^\infty \frac{d}{dk}\left(\frac{1}{Z_k^i}\right) J_0(kr)\frac{dk}{2\pi r}$$
$$G^g(r) = \int_0^\infty \frac{d}{dk}\left(\frac{1}{Z_k^g}\right) J_0(kr)\frac{dk}{2\pi r} \quad (11)$$

where Z_k^i, Z_k^g are the spectral impedances of the induction and galvanic modes at the top of the underlying section.

Denoting the linear operator on the right-hand side of expression (9) by $\hat{\mathscr{L}}(\{\sigma\})$, we obtain

$$\mathbf{n}\times\mathbf{H}_\tau(\mathbf{r}) = \hat{\mathscr{L}}(\{\sigma\})\mathbf{E}_\tau(\mathbf{r}) + S(\mathbf{r})\mathbf{E}_\tau(\mathbf{r}) \quad (12)$$

Expression (12) makes it possible, using the MT field $\{\mathbf{E}_\tau, \mathbf{H}_\tau\}$ known at the Earth's surface, to ascertain the integral conductivity value $S(\mathbf{r})$.

We note that the problem of determining $S(\mathbf{r})$ from fields known at the Earth's surface and the stipulated structure of the underlying section can also be solved by other methods, such as on the basis of spectral representations of the electromagnetic field [4]. However, in such an approach, difficulties arise due to the need for computing the spectral transforms of electromagnetic fields along the entire Earth's surface on the basis of data measured in a restricted territory. In the proposed approach, this difficulty is overcome because of the local character of the admittance kernel $\hat{Y}(\{\sigma\}, \mathbf{r})$. The distance characterizing the rate of spatial attenuation of the induction part of the kernel is determined by the depth of field penetration into the underlying section $|\lambda_0| = |Z_0^-|/\omega\mu_0$; for the galvanic mode this distance can be considerably greater: $L_g = |\sqrt{\mathscr{T}/Z_0^-}|$, where $\mathscr{T}$ is the transverse resistance of the poorly conducting thickness of the section [16, 17]. Another difficulty in applying the method in [4] is related to the need for solving an integral equation of the first kind.

Since the problem of determining integral conductivity S on the basis of data from MT observations at the Earth's surface belongs to the class of incorrect problems, it is necessary to discuss the matter of the existence, uniqueness, and stability of its solution.

In the class of film models, the MT field $\mathbf{E}_\tau(\mathbf{r})$, $\mathbf{H}_\tau(\mathbf{r})$ precisely stipulated at the Earth's surface corresponds to a unique $S(\mathbf{r})$ distribution, which very clearly follows from expression (12). Thereby a positive solution is found for the problem of the existence and uniqueness of solution of the formulated problem. With respect to the matter of stability in determining $S(\mathbf{r})$, as follows from (12), it can be reduced to the problem of stability of the operator $\hat{\mathscr{L}}(\{\sigma\})$. The solution of this problem is dependent on the form of those metrics in which the closeness of both the observed fields and the result of application of the $\hat{\mathscr{L}}(\{\sigma\})$ operator to them is considered. For example, taking into account the nature of the singularity of the induction part of the kernel $\hat{Y}(\mathbf{r})$ in (9) ($\hat{Y} \sim 1/r^3$ when $r \to 0$ [16]), it is possible to demonstrate a stability of the representation

$$\hat{\mathscr{L}}(\{\sigma\}) : C^2(\mathbf{R}^2; \mathbf{C}^2) \mapsto C^0(\mathbf{R}^2; \mathbf{C}^2) \quad (13)$$

and the instability of the representation

$$\hat{\mathscr{L}}(\{\sigma\}) : C^0(\mathbf{R}^2; \mathbf{C}^2) \mapsto C^0(\mathbf{R}^2; \mathbf{C}^2) \quad 13'$$

Here $C^k(\mathbf{R}^2; \mathbf{C}^2)$ is the metric space of complexly signed fields with a standard uniform metrics, determined on the real plane $\mathbf{R}^2$, taking into account not only the field itself but all its derivatives to the k-th order, respectively. Thus, for stable field scaling in accordance with (9), it is necessary to know the electrical field and its first two derivatives everywhere on the Earth's surface.

In actual practice, fields are measured only in a restricted and discrete network of points and with some error and, accordingly, the matter of stable S determination is essentially reduced to the problem of stable retrieval of fields and their first two derivatives. As is well known, the problem of retrieving fields and their derivatives is an incorrect problem and can be solved by regularization methods. The algorithm described above was embodied in a program.

5. Testing

Since a two-dimensional interpretation of the South Tien Shan anomaly will be presented below, this section gives an example of testing of a program for determining integral conductivity of the surface layer in a two-dimensional model. Testing was for an E-polarized field for a period $T = 1000$ s for a known model [18]. The model parameters are given in Fig. 3. The upper inhomogeneous layer with a thickness $h = 2.5$ km, simulating the water envelope and the sedimentary mantle, is regarded as a thin S layer underlain by a two-layer section. The fields at the model surface were computed using the Varentsov-Golubev finite-difference modeling program [19]. The results of retrieval of surface-layer conductivity are illustrated in this same figure together with its model distribution.

6. Film Interpretation of South Tien Shan Anomaly

As noted in Sect. 2, in the first approximation this anomaly can be considered

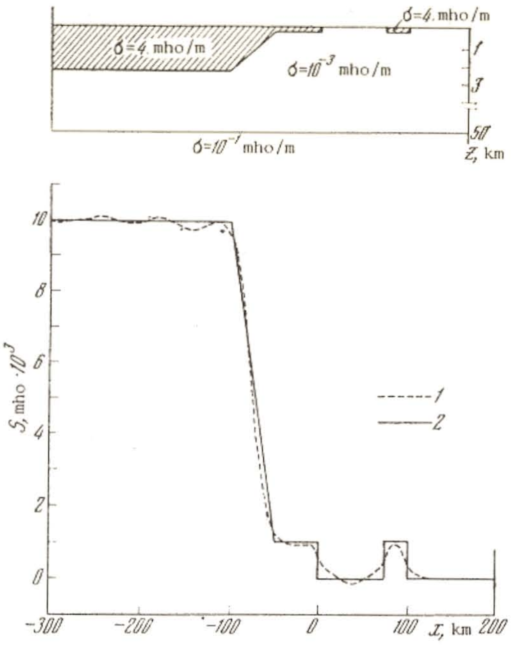

Fig. 3. Distribution of integral conductivity S for model of inhomogeneous surface layer: *1*) solutions of inverse problem, *2*) true S distribution.

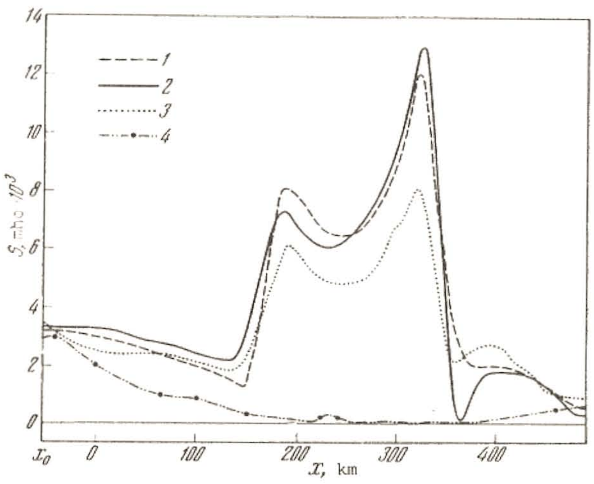

Fig. 4. Distribution of integral conductivity S along Uch-Adzhi-Darbaza profile: *1 - 3*) results of solution of inverse problem for periods 10,800, 3600, and 1200 s; *4*) distribution of integral conductivity S_1 of sedimentary cover.

two-dimensional. In this case, on the basis of the magnetic field vertical component $H_z(x)_0$ it is possible to compute its tangential component in accordance with (I) and the electrical field:

$$E_y(x)=E_y(x_0)+i\omega\mu_0\int_{x_0}^{x} H_x(x')\,dx', \qquad (14)$$

that is, in a two-dimensional situation the distributions of the magnetic field vertical component are adequate for determining surface layer integral conductivity. To determine the MT field, it is also sufficient to know the normal field level. In making the computations, as above, the field at the point x_0 (Repetek) was used as the normal field. The normal section of the southern Turan plate [8] was used as the underlying horizontally homogeneous section. Twenty-five experimental determinations of the H_z/H_{x0} ratio were available for the profile. The distributions of the modulus and phase H_z/H_{x0} along the profile, obtained as a result of a spline approximation, are shown in Fig. 2 by thick curves.

The results of S computations are given in Fig. 4, which also shows the S_1 distribution for the sedimentary mantle. It is evident that the $S(a) = S - S_1$ difference characterizes STCA strength. The figure shows that the S distributions, found for periods 3600 and 10,800 s, are close. The S value, obtained for a period 1200 s, is appreciably lower at the center of the profile. It can be assumed that for a period 1200 s the thin layer approximation in the anomalous region where the S values attain (8 - 12) × 10^3 mho is not satisfied adequately precisely. Some idea concerning the accuracy of solution of the inverse problem can be obtained from a comparison of the initial experimental data on H_z/H_{x0} with solution of the direct problem for a two-dimensional model with a thin surface layer whose integral conductivity was determined as a result of solution of the inverse problem for the period T = 10,800 s (Fig. 2, thin curves). The best agreement is observed for the two fundamental periods T = 10,800 and 3600 s, and a somewhat poorer agreement is observed for the period T = 1200 s. In general, the agreement is satisfactory, although on some profile segments the discrepancy attains 20%. The phases are in good agreement for those profile segments where the H_z values are great, and accordingly the phases of the H_z/H_{x0} ratio are determined most reliably. On the profile segment 180 - 300 km, the H_z value is small and the H_z/H_{x0} phases are determined with a great error. Accordingly, the modeling results are not consistent with the experimental data. Using (1), (14) it is easy to confirm that the H_z distribution on those profile segments where H_z is small exerts virtually no effect on the distribution of the electromagnetic field horizontal components, and therefore also on the results of solution of the inverse problem. It is interesting to note that a qualitative idea concerning the error in determining S can be obtained from an evaluation of the $|\mathrm{Im}\,S/\mathrm{Re}\,S|$ ratio. In actuality, the $|\mathrm{Im}\,S/\mathrm{Re}\,S|$ ratio, obtained as a result of solution of the inverse problem, does not exceed 20% for a period 1200 s and decreases to several percent for periods 3600 and 10,800 s.

The nature of the S distribution indicates the existence of two zones with maximal S^a values; the northern maximum is appreciably greater than the southern maximum. The maximal value $S^a \simeq$ 12,000 mho is consistent with the STCA evaluation determined from MV data. The conclusion drawn in [2, 3] that exaggerated S values, obtained using MT data, are caused by strong galvanic effects, for which full allowance is possible only within the framework of three-dimensional models, is confirmed.

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