High resolution electromagnetic methods and low frequency dispersion of rock conductivity

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Abstract
The influence of frequency dispersion of conductivity (induced polarization) of rocks on the results of electromagnetic (EM) sounding was studied on the basis of calculation of electric field of vertical magnetic dipole above horizontally layered polarizable sections. Frequency dispersion was approximated by the Debye formula. Polarizable homogeneous halfspace, two, three and multilayered sections were analyzed in frequency and time domains. The calculations for different values of chargeability and time constants of polarization were performed. In the far zone of a source, the IP of rocks led to quasi-wave phenomena. They produced rapid fluctuations of frequency and transient sounding curves (interference phenomena, multireflections in polarizable layers). In the case of transient sounding in the near zone of a source quasistatic distortions prevailed, caused by the counter electromotive force arising in polarizable layers which may lead to strong changes in transient curves. In some cases quasiwave and quasistatic phenomena made EM sounding curves non-interpretable in the class of quasistationary curves over non-dispersive sections. On the other hand, they could increase the resolution and depth of investigation of EM sounding. This was confirmed by an experience of «high-resolution» electroprospecting in Russia. The problem of interpretation of EM sounding data in polarizable sections is nonunique. To achieve uniqueness it is probably necessary to complement them by soundings of other type.

Key words *electromagnetic sounding – induced polarization – frequency dispersion of conductivity – resolution of sounding – mathematical modelling*

1. Introduction

There are many publications devoted to the Low-Frequency Dispersion (LFD) of the conductivity and dielectric permittivity of rocks or to the phenomenon of Induced Polarization (IP), which is equivalent to it. Laboratory studies of rock samples within a wide frequency range (from fractions of Hz to tens of MHz) and time delays (from microseconds to tens seconds) have been carried out (Saint-Armant and Strangway, 1970; Komarov, 1980; Kormilzev, 1980; Klein *et al.*, 1984; Vinegar and Waxman, 1984; Olhoeft, 1985; Rusiniak, 1993). To some extent, though far from completion yet, this phenomenon has also been studied theoretically (Marshall and Madden, 1959; Sheinmann, 1969; Wait, 1982; Lima and Sharma, 1992). The basic electrophysical and electrochemical processes occurring in heterogeneous and polyphase media, which may result in and do result in the LFD of the electric parameters of rocks, have been found on the basis of theoretical and experimental data. The following processes are, apparently, the basic ones: processes of separation of charges in electrically heterogeneous mono-phase media,

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which is induced by an applied field (the Maxwell-Wagner effect); variations of the iono-diffusive potentials within the double layers on the boundaries of solid and liquid phases or occurring as a result of the change in the transport numbers of positive and negative ions in a porous medium (the membrane potentials); various types of electrochemical phenomena occurring on the boundaries of media with electronic and ionic conductivity. Apparently, the real processes in rocks also involves other electrophysical phenomena such as electrokinetic processes (electroosmosis, the filtration potential, electrophoresis, the precipitation potential), slow-acting adsorption and desorption, freezing, defrosting, dissolution, and crystallization potentials, and so on. These processes are, as a rule, of minor importance, but, under certain conditions, they can play a decisive role.

It is amply evident that strict and complete allowance for either of those phenomena in the solution of direct and, all the more, inverse electroprospecting problems is not feasible and even not necessary. In this case, the aim of the theory is to introduce certain effective parameters of a medium and approximating structures, characterizing the medium and processes occurring in it in a generalized way and disclosing useful information, when solving the inverse problems. A whole range of empirical approximations of the LFD of electric parameters of rocks has been proposed, which is, to some extent, in agreement with theoretical and experimental data (Shuey and Jonson, 1973; Pelton *et al.*, 1983). Although, the approximations do not answer the question of the physicochemical nature of the dispersion and specific properties of a geological medium, they nevertheless allow us to study, with the help of quite simple means, other quite important questions at the present time:

– To what qualitatively new phenomena does LFD of the electric parameters of rocks lead in the electromagnetic (EM) studies of the Earth?

– How can it influence on the results of the traditional interpretation of observed data?

– To what extent does it explain the facts of the deviations of experimental data, which have already been firmly established in field EM studies, from the classic theory of electroprospecting?

The non-monotonicity of the transient processes in coincident non-grounded loops is, for instance, among the latter. This phenomenon can not be explained in the framework of quasi-stationary electrodynamics of continuous media (Gubatenko and Tikshaev, 1979; Weidelt, 1982), but the explanation is invoked with allowance for the IP of a medium studied. In the recent years, some Russian publications have been devoted to the inexplicable high resolution of experimentally obtained Transient Sounding (TS) curves. These data show that TS curves may be complicated by small rapid fluctuations, which become noticeable, provided that the slow part of the transient process (agreeing with quasistationary electrodynamics) is excluded from the observed transient curves by any method. The fluctuations are, as a rule, in good agreement with seismic and log data and therefore they deliver useful new geophysical information and sharply increase the perspectives of application of EM methods in gas-oil field prospecting and in the solution of other geological tasks. Some examples of high-resolution electroprospecting are cited in the paper by Berdichevskiy (1994). It appeared natural that the high resolution of EM sounding found is associated with the influence of the polarizability of rocks. The given paper is just devoted to a test for this hypothesis and to systematic studies of peculiarities contributing in EM sounding curves by the polarizability of a medium. That is carried out by means of mathematical modelling.

2. Mathematical modelling of horizontally layered media

Horizontally layered polarizable sections were studied, as a rule, to fit grounded generator and receiving arrays (Seigel, 1959; Dey and Morrison, 1973; Lee, 1981; Wait, 1982). Some polarizable sections were investigated with reference to magnetotellurics (Patella, 1987; Mauriello *et al.*, 1996). In the case of non-grounded generator loops only homogeneous half-space and the simplest two-layer sections were studied (Lee, 1981; Flis *et al.*, 1989; Kaufman *et al.*, 1989). Below, attention is focused on non-grounded sources and the interaction of excited

EM fields and IP fields observed in the case of horizontally layered medium.

2.1. *Preliminary notes*

An inevitable consequence of the frequency dispersion of the electric parameters of a medium is that they become complex values. A complex value of the conductivity of a medium is conveniently presented by the following formula:

$$\check{\sigma}_{ef}(\omega) = \sigma_{ef}(\omega) - i\omega\varepsilon_{ef}(\omega) \qquad (2.1)$$

where $\sigma_{ef}(\omega)$ and $\varepsilon_{ef}(\omega)$ are the effective real values of the conductivity and dielectric permittivity (harmonic oscillations are written in the form of $\exp(-i\omega t)$). Regardless of a concrete physicochemical nature of the effective values of the conductivity σ_{ef} and dielectric permittivity ε_{ef}, their phenomenological role remains the same as they play in the electrodynamics of continuous media: the conductivity determines the irreversible losses of the energy of an EM field related to its transfer in other forms (not only in the heat energy but in chemical, mechanical, and other forms as well), and the dielectric permittivity characterizes the feasibility to store the energy of this EM field convertibly (not only in the EM form but in chemical, mechanical, and other forms as well). Let us choose the Debye formula as an expression approximating LFD of the electric properties of rocks that is written for the complex conductivity of a medium in the formula

$$\check{\sigma}(\omega) = \frac{\sigma_0 - \sigma_\infty i\omega\tau_\sigma}{1 - i\omega\tau_\sigma} - i\omega\varepsilon_\infty = \sigma_\infty\left(1 - \frac{\eta}{1 - i\omega\tau_\sigma}\right) - i\omega\varepsilon_\infty. \qquad (2.2)$$

Here σ_∞ and σ_0 are values of the conductivity at very high frequencies (the «true» conductivity of a non-polarized medium) and at direct current (a completely polarized medium), respectively; ε_∞ is the dielectric permittivity at very high frequencies; $\eta = (\sigma_\infty - \sigma_0)/\sigma_\infty$ and τ_σ are the chargeability and time constant of the polarizability; $\omega = 2\pi f$ is an angular frequency of an applied field. Using the approximation of LFD by Debye, one obtains

$$\sigma_{ef} = \sigma_0\left[1 + \frac{\eta}{1-\eta}\cdot\frac{\omega^2\tau_\sigma^2}{1+\omega^2\tau_\sigma^2}\right],$$
$$\varepsilon_{ef} = \varepsilon_\infty + \frac{\sigma_\infty\eta\tau_\sigma}{1+\omega^2\tau_\sigma^2}. \qquad (2.3)$$

It follows from the formulas that the conductivity of a dispersive medium decreases and its dielectric permittivity increases as frequency decreases. Such dependence extends the possibility of the processes inherent in the $\varepsilon - \sigma$ and $\varepsilon - \mu - \sigma$ media to the domain of not too rapidly proceeding processes (in the low frequency domain). The processes in the $\varepsilon - \sigma$ medium proceed in the absence of significant interactions between electric and magnetic fields; they are of a quasi-static character and are revealed in the charge and discharge of polarizable elements through the conductive medium. The processes in the $\varepsilon - \mu - \sigma$ medium are connected with the exchange of the stored energy between the electric and magnetic fields and cause quasi-wave phenomena to rise.

Excluding the term $-i\omega\varepsilon_\infty$, practically not playing a role in our study, the Debye formula presents a particular case of a more general and widely used approximation of LFD of the electrical parameters of rocks, the Cole-Cole formula. For complex resistivity, it has the formula

$$\check{\rho}(\omega) = \frac{\rho_0 + \rho_\infty(-i\omega\tau_\rho)^C}{1+(-i\omega\tau_\rho)^C} = \rho_0\left[1 - \eta\frac{(-i\omega\tau_\rho)^C}{1+(-i\omega\tau_\rho)^C}\right], \quad C \le 1. \qquad (2.4)$$

At $C = 1$ and $\tau_\rho = \tau_\sigma/(1-\eta)$, the formula (2.4) coincides with the reciprocal reduced Debye formula. The difference in the time constants τ_σ and τ_ρ in formulas (2.2) and (2.4) is not accidental: it reflects the different rate of decay of the IP processes in current when switching off the applied voltage (τ_σ) and, by contrast, in voltage when switching off the applied current (τ_p). In view of this, it is more convenient to use expression (2.2) in case of inductively excited fields in the near zone, and expression (2.4) in the case of the galvanic current delivery into the Earth and in the far zone of the sources. We will be guided by this rule when using the time constants τ_a and τ_p in this paper.

The Debye formula coincides with the expression for the effective value of the complex conductivity of a two-component plane-layered heterogeneous, but mono-phase, medium, in a transverse electric field (the Wagner formula) (Berdichevskiy *et al.*, 1995)

$$\check{\sigma}(\omega) = \frac{\check{\sigma}_1 \cdot \check{\sigma}_2}{\alpha \check{\sigma}_2 + (1-\alpha)\check{\sigma}_1} = \tag{2.5}$$

$$= \frac{\dfrac{\check{\sigma}_1 \, \check{\sigma}_2}{\alpha \check{\sigma}_2 + (1-\alpha)\check{\sigma}_1} - i\omega\varepsilon \dfrac{\alpha\sigma_1 + (1-\alpha)\sigma_2}{\alpha\sigma_2 + (1-\alpha)\sigma_1}}{1 - i\omega\varepsilon \dfrac{1}{\alpha\sigma_2 + (1-\alpha)\sigma_1}} - i\omega\varepsilon.$$

Here the conductivities and permittivities of the layers are σ_1 and σ_2, ε_1 and $\varepsilon_2 = \varepsilon_1 = \varepsilon$, respectively, $\check{\sigma}_1 = \sigma_1 - i\omega\varepsilon$, $\check{\sigma}_2 = \sigma_2 - i\omega\varepsilon$ and $\alpha = d_1/(d_1 + d_2)$ is the relative thickness of the first layer. If we designate

$$\sigma_0 = \frac{\sigma_1 \sigma_2}{\alpha\sigma_2 + (1-\alpha)\sigma_1}; \; \sigma_\infty = \alpha\sigma_1 + (1-\alpha)\sigma_2;$$

$$\tau = \frac{\varepsilon}{\alpha\sigma_2 + (1-\alpha)\sigma_1}; \; \varepsilon_\infty = \varepsilon,$$

then the formulae (2.2) and (2.5) will coincide. LFD of effective conductivity (Re σ) or permittivity (ε) of such heterogeneous medium is an example of the well known Maxwell-Wagner effect. The Wagner formula allows us to provide a particular, but informative interpretation of the Debye formula parameters and to estimate their possible values. For example it follows that in the case of cracked-porous rocks, the microstructure of which can be approximated by a two-layer Wagner model, their time constants τ can approach arbitrarily close to the time constants of the high-resistive interlayers, that is, to reach values of 10^{-4} to 10^{-3} s (when the resistivity of the interlayers $\rho = 10^6 - 10^7$ Ohm) and the chargeability η can be arbitrarily close to 1. Theoretical studies of other processes and laboratory experimental data expand the possible range of the change of τ from fractions of microseconds to tens of seconds and minutes and confirm the possible high values of the chargeability, at least, for rapidly proceeding processes. This does not contravene the results of IP field studies since usual field IP measurements start with tenth fractions or first units of seconds when rapid processes are, in fact, completed. All these reasons as well as the aspiration to study the influence of LFD in an amply complete form determined the range of τ and η, which was utilized in the modelling.

A homogeneous polarizable half-space and horizontally layered sections involving polarizable layers were chosen as the basic models. The electric field E_φ of a vertical magnetic dipole in frequency domain (Frequency Soundings, FS) and time domain (Transient Soundings, TS) was computed. Particular attention was paid to the comparative analysis of the observed phenomena in the far and near zones.

2.2. *Homogeneous polarizable half-space*

As mentioned above, LFD expands the range within which conductivity and dielectric permittivity take a joint part in the formation of an EM field, to the low frequency domain. This is reflected in the frequency response of the modulus of the electric field E_φ over a homogeneous polarizable half-space (fig. 1). The plots are constructed as dependencies of the apparent resistivity ρ_ω in the far-zone normalization ($\rho_\omega = E_\varphi \cdot 2\pi r^4/3M$, r is the distance between the magnetic dipole with the moment M and a measurement point) on the non-dimensional parameter $\sqrt{T/\tau_0}$, where $T = 1/f$ is the period of the field and τ_0 is «the electrodynamic time constant» $\tau_0 = \mu r^2/\rho_0$. The term «far-zone» is thought usual in the sense that $\mu\omega r^2/\rho_0 = 2\pi\, \tau_0/T >> 1$. Two plots of the normal field, corresponding to non-

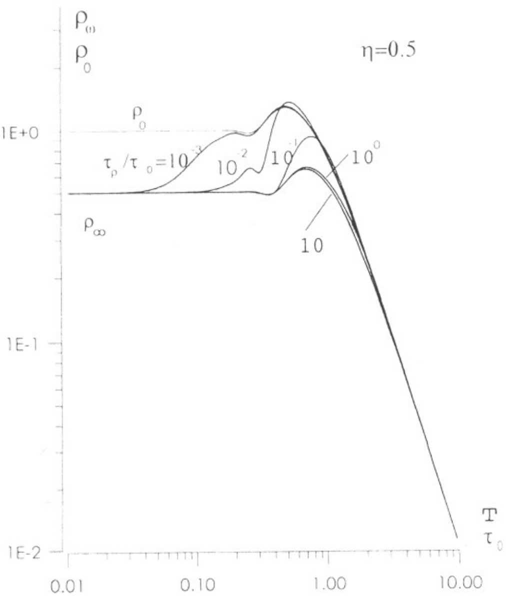

Fig. 1. Frequency sounding curves above a homogeneous polarizable half-space in a far zone.

dispersive half-spaces with the resistivities ρ_0 and $\rho_\infty < \rho_0$ are shown in this figure. The chargeability of the medium was chosen equal to 0.5, *i.e.* $\rho_0/\rho_\infty = 2$. The frequency responses of the field over the dispersive half-space pass from one plot of the normal field to the other. The lower the time constant τ_ρ, the higher the frequencies where this transition occurs. It is most clearly expressed in the high-frequency range. When this transition falls on the low-frequency range, it becomes practically imperceptible. This is the result of masking of polarization phenomena by the primary field of the source. If the part proportional to frequency is excluded from the electric field, then the polarization phenomena in the low-frequency range become more expressive.

The influence of the polarizability in the time domain is more pronounced (fig. 2). The plots are constructed in the same way as in fig. 1, as normalized far-zone apparent resistivity ρ_τ ($\rho_\tau = E_\varphi \cdot 2\pi r^4/3M$) *versus* the non-dimensional parameter t/τ_0. When time increases, the transient responses over a polarizable half-space at low time constants τ_ρ of the polarizability also pass from the normal field plot, corresponding to the resistivity ρ_∞, to the plot corresponding to ρ_0. With increasing τ_ρ, the late stage of the transient process ceases to be monotonous and, beginning from certain values of $\tau_\rho \approx \tau_0$, an area of negative values appears on the transient response of the field. The phenomenological nature of the sign change is associated with opposite directions of the electromotive force of the polarization and of electrodynamic electric field, and with a more rapid decay of the polarization with time than the decay of electric field of pure electrodynamic origin. At relatively high values of τ_ρ/τ_0 the change in the sign of the transient response of the field proceeds irrespective of the value of the chargeability η (at arbitrarily low values of η). In the same time, with reducing η, this transition is observed at still later times.

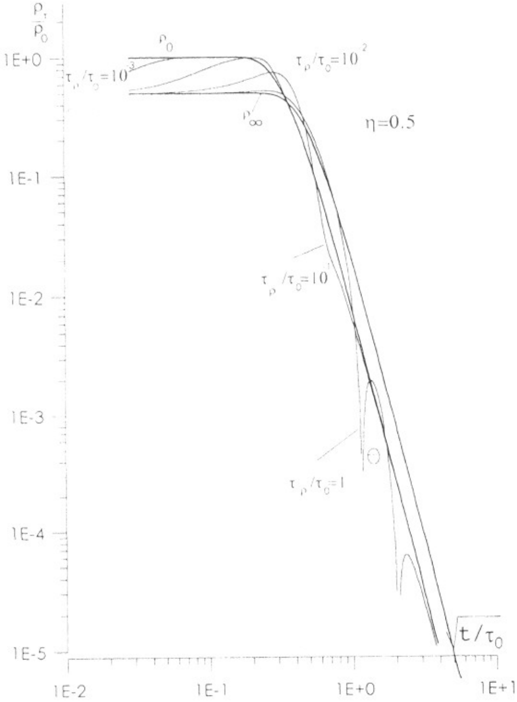

Fig. 2. Transient sounding curves above a homogeneous polarizable half-space.

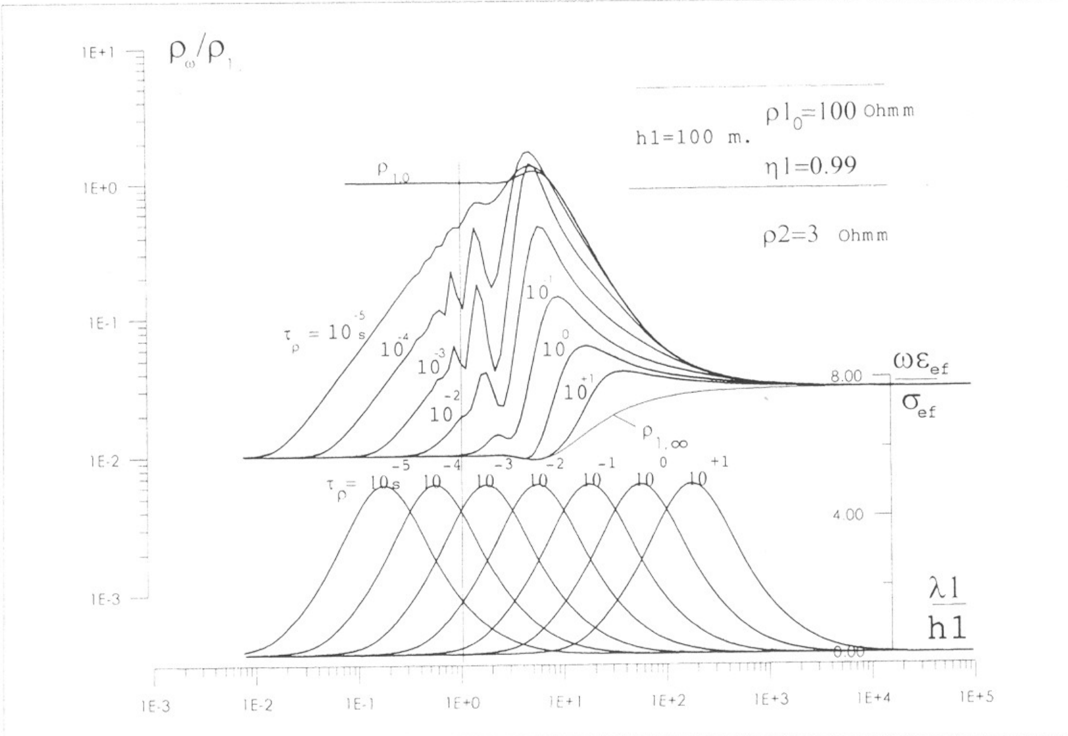

Fig. 3. Frequency sounding curves in a far zone above a two layer section with polarizable first layer. The maxima of the curves are given by $(1/2)\sqrt{\eta/(1-\eta)}$ and occur at $\omega\tau_\rho = 1/\sqrt{\eta/(1-\eta)}$.

2.3. *Horizontally layered polarizable medium*

In order to imagine better the phenomena observed in this case, let us first consider the results of the EM field calculations over a simplest two-layer section with the upper layer characterized by quite a high chargeability $\eta = 0.99$. FS and TS curves in the far zone of a source over such a section at various time constants of the upper layer polarizability are given in figs. 3 and 4. Sounding curves over the same section, but with frequency-independent resistivity of the upper layer ρ_∞ and $\rho_0 = \rho_\infty/(1-\eta)$, are shown for comparison purposes in the same figures. Note that here and in the following, the polarizable layers on the schemes of the sections studied are characterized by their resistivity at direct current $\rho_{1,0}$. The frequency dependence in the case of FS (fig. 3) is expressed by means of the effective wavelength in the first layer

$$\lambda_{1,ef} = 2\pi/\text{Re}\,\sqrt{i\omega\mu\check{\sigma}(\omega)}.$$

The sounding curves over the non-dispersive section, calculated, as usual, in the quasi-stationary approximation, are characterized by a smooth transition from the resistivity of the first layer ρ_1 to the resistivity of the basement. The curves over the polarizable section are remarkable for a much more complicated configuration. At the relatively low time constants $\tau_\rho = 10^{-5} - 10^{-3}$ s, they begin with $\rho_\omega = \rho_{1,\infty}$, then grow fluctuating as the period increases, and, at last, go monotonously to the resistivity of the basement. The location of the extrema of fluctu-

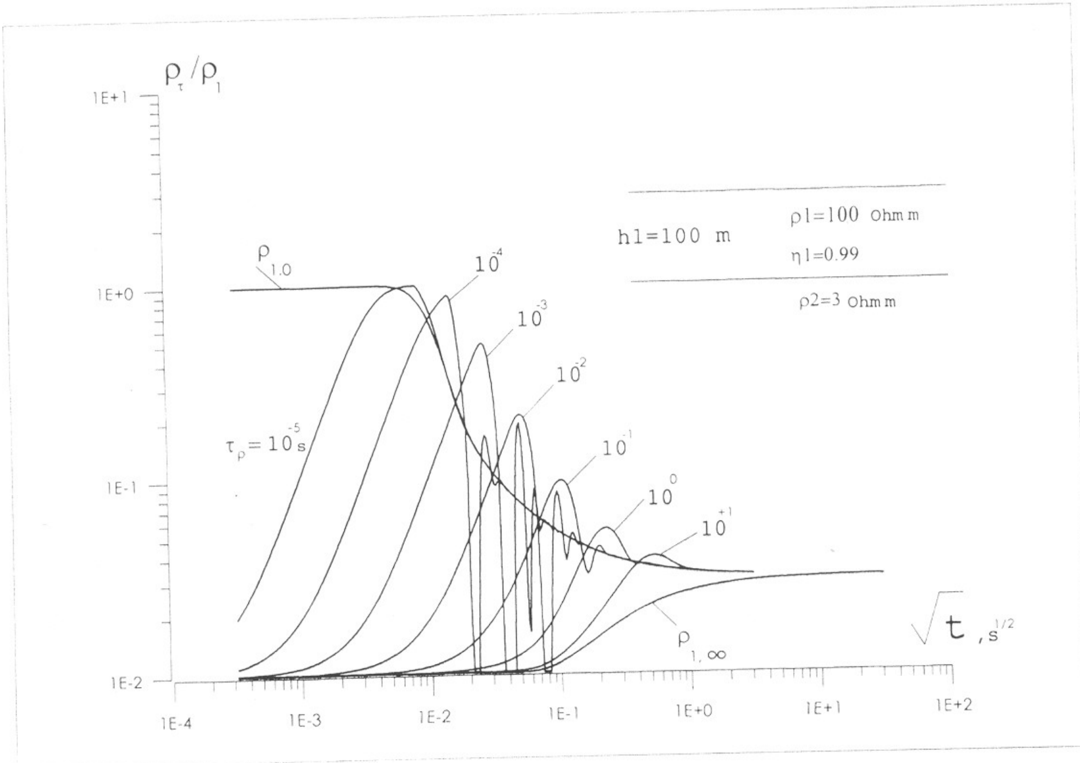

Fig. 4. Transient sounding curves in a far zone above two layers section with a polarizable first layer.

ations on the curves with various τ_ρ approximately obeys the relationship $h_1 = k\lambda_{1,\omega}/4$, where k is the integer number. This relationship characterizes an interference pattern observed in a wave field at the wave reflection from the basement of a layer with thickness h_1. The fluctuation extrema are strongly pronounced only in that area, where the ratio between the effective displacement current and conductive current is not too small. The dependence of the ratio on wavelength is illustrated by plots situated below the FS palette. For the section the ratio reaches 5. Note that in the same, but non polarizable, section and in the same frequency band the ratio cannot exceed 10^{-3}. All this is evidence of a quasi-wave character of the phenomena proceeding in a frequency-dispersive medium and associated with the complexity of its conductivity. In the domain of large time constants of polarization, the quasi-wave peculiarities on the sounding curves vanish; at the same time, however, the transition from $\rho_{1,\infty}$ to ρ_2 proceeds faster reflecting the simultaneous grow of the resistivity of the first layer with the increase in period. Note, in passing, that the frequency sounding curves correspond, in this case, to the two-layer section $\rho_{1,\infty} < \rho_2$, while the result of direct current sounding will be the section with $\rho_{1,0} > \rho_2$. If we try to interpret the FS curves at not too large time constants without allowance for their fluctuations (by smoothing them), then we may obtain a three-layer section of the K type.

A similar pattern is observed for the TS of the same section in the far zone (fig. 4). At the same time constants τ_ρ of polarization, at which the interference was observed on the FS curves,

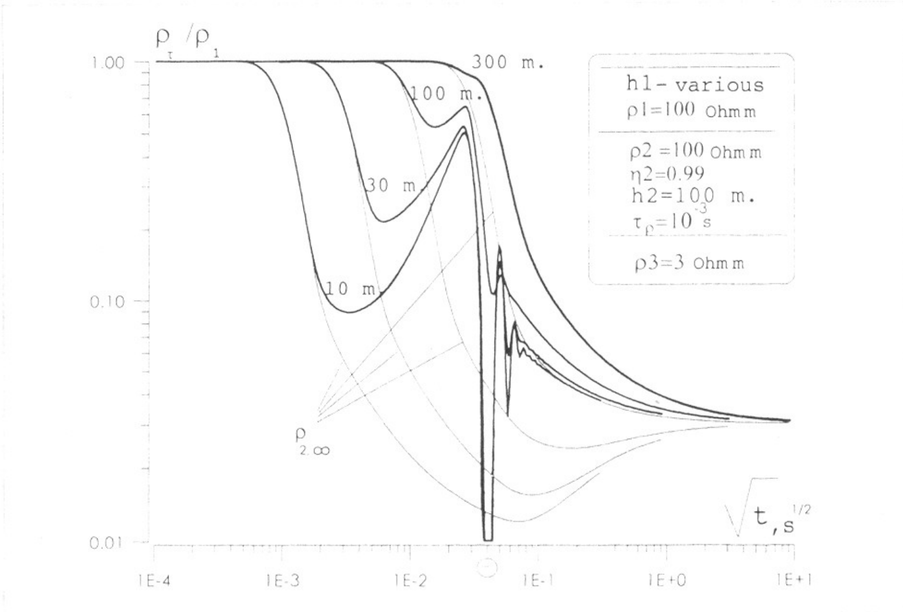

Fig. 5. Transient sounding curves in a far zone above a three layer section with a polarizable second layer. Different thicknesses of a first layer.

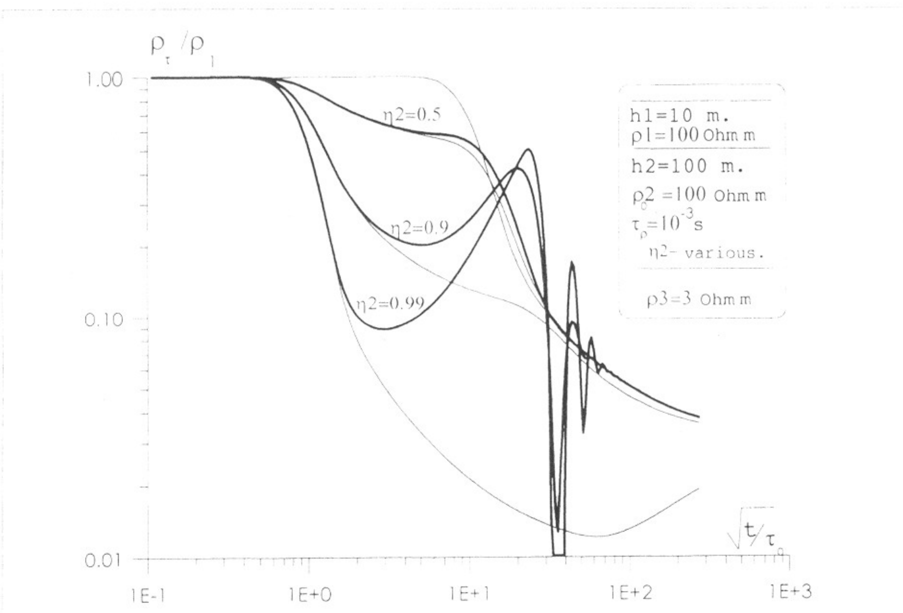

Fig. 6. Transient sounding curves in a far zone above a three layer section with a polarizable second layer. Different chargeabilities of a second layer.

the TS plots acquire a fluctuating character changing its sign at certain τ_p. In the given case, this is associated with multireflections of the quasi-wave field at the boundaries of the polarizable layer. Such TS curves cannot be interpreted in the class of non-polarizable sections. In attempting to carry out an approximate interpretation of them in such classes, the same errors may arise as in the case of FS.

Distortions of EM sounding curves in the far zone, associated with LFD, rapidly decrease with the growth in thickness of the deposits overlying the polarizable layer (fig. 5). At the limited thickness of the overlying layer, TS curves at small times correspond to a three-layer section with $\rho_2 = \rho_{2,\infty}$. With increasing time, ρ_τ increases reflecting the growing role of the counter electromotive force of polarization and then oscillating tends to the basement resistivity. The dispersion distortions become imperceptible at the thickness of the overlying deposits exceeding the thickness of a polarizable layer by 2 to 3 times. The distortions of that kind also rapidly diminish with decreasing chargeability of the layer (fig. 6). The location of characteristic dispersion distortions on sounding curves is determined not only by the electrodynamic parameters of a section (by the thickness and resistivity of layers), but also by the time constant and chargeability value of a dispersive medium (figs. 3 to 6).

The action of the polarizability of a section is revealed very differently and especially strongly in TS in the near zone ($t/\tau_0 = t\rho_0/\mu r^2 << 1$). An example of curves of TS in the near zone over a three-layer section with a polarizable second layer (η = 0.5) for a set of time constants τ_n is shown in fig. 7. In contrast to the far zone, the electric field is proportional not to resistivity but to conductivity of a homogeneous half-space. Therefore it is more convenient to use an apparent conductivity which is introduced by the expression

$$\sigma_\tau = \left(\frac{40E_\varphi}{Mr}\right)^{2/3} \frac{\pi t^{5/3}}{\mu^{5/3}}.$$

This expression is followed from electric field near-zone asymptotics above homogeneous half-space. As in the case of a homogeneous half-space (fig. 2), the counter electromotive force of polarization results in decreasing the transient process. σ_τ starts decreasing at transient times close to the time constant of polarizability. The divergence with the transient process over a non-polarizable section at small time constants grows as value of τ_n increases changing, at $\tau_n \approx 5 \times 10^{-5}$ s, even its sign. In order to show this circumstance more clearly in fig. 7 and some following figures, a separate log scale for the negative values has been added. Absolute values of the negative values increase downward in order to fit better the representation of the plot σ_τ to the character of the transient process.

On further increasing τ_n, however, this monotonic dependence on the time constant at a certain part of the TS curve breaks down associated with a strong slowing down of the decay of the electrodynamic transient process when reaching the more conductive basement of the section. The further increase in τ_n leads again to the growth of distortions of TS curves and to the local change of their sign (for the section considered it occurs at $\tau_n \geq 1$ s). It is important to note that the location of the characteristic polarizability distortions on the near-zone TS curve is associated with its time constant τ_n rather than with the depth of deposition of a polarizable layer.

Figure 8, based on the same section as in fig. 7, illustrates dependence of near-zone TS curves on the chargeability of a layer at the fixed τ_n = 0.02 s. At small times $t << \tau_n$, the near-zone TS curve reflects a section with the «true» conductivity of the second layer, which differs increasingly from the direct current conductivity, the higher the chargeability η ($\sigma_{2,\infty} = \sigma_{2,0}/(1-\eta)$). At times t close to τ_n, the apparent conductivity σ_τ decreases compared with the non-polarizable section (in this case absolutely not in that area of times, which characterizes the depth of a layer). With increasing the chargeability, the diminution of σ_τ becomes progressively stronger and, at a certain value η, the transient process changes the sign. In this case, as in the case of the far zone (fig. 6), the position of polarization distortions on the time axis does not depend on a value of τ_n. But it happens on condition that in the far zone τ_p is fixed and in the near zone τ_n does. It confirms the note made earlier on a

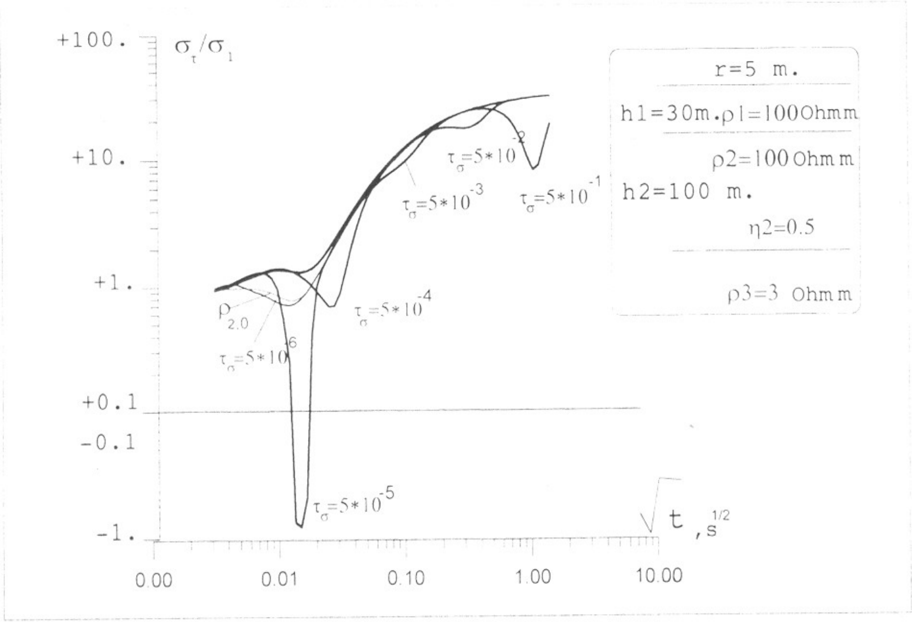

Fig. 7. Transient sounding curves in a near zone above a three layer section with a polarizable second layer. Different time constants of polarization

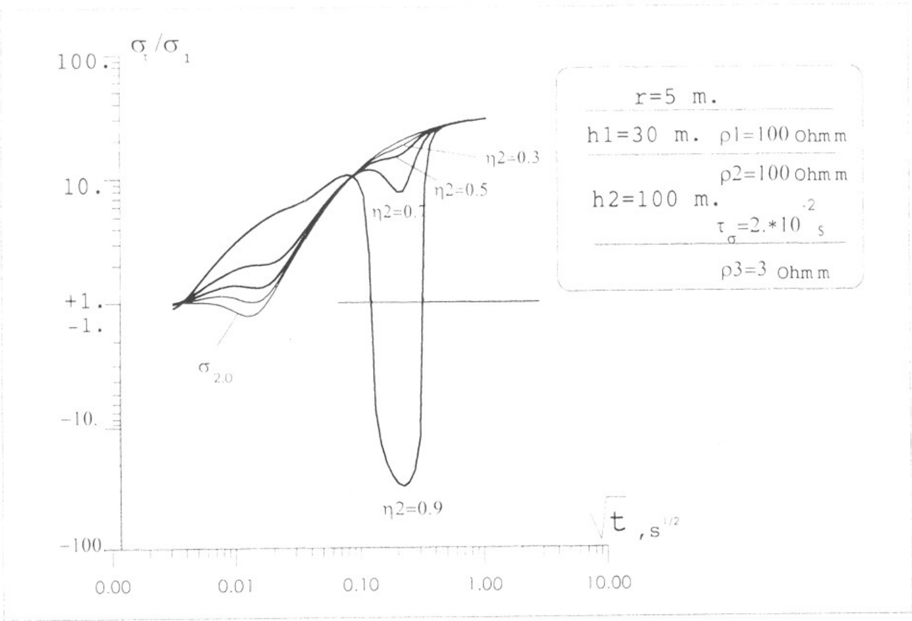

Fig. 8. Transient sounding curves in a near zone above a three layer section with a polarizable second layer. Different chargeabilities, τ_{σ} = const.

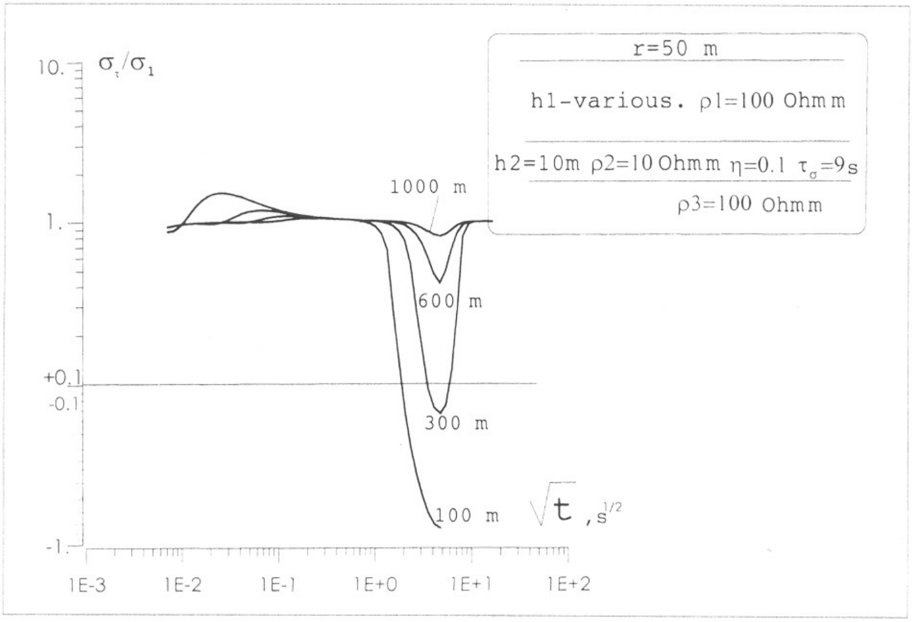

Fig. 9. Transient sounding curves in a near zone above a three layer section with a polarizable second layer. Different thicknesses of a first layer.

greater adequacy of the law of a frequency dispersion in the form (2.2) to the near zone and in the form (2.4) to the far zone of the source.

The next figure (fig. 9) illustrates an effect of shielding of a conductive and polarizable layer by overlying deposits. At given parameters of the section the layer is marked by two separate departures of the near-zone TS curve from that of the homogeneous half-space. In the t-interval corresponding to an electrodynamic excitation of the layer (as in the case of non polarizable section), it is marked by a regular increase in the apparent conductivity. The level of the increase is determined, to a significant degree, by the ratio of the longitudinal conductance of the layer and overlying deposit. At long times, when $t \approx \tau$, the departure from the constant value of σ_τ is related to pure polarization processes and results, as usual, in decreasing σ_τ. With increasing thickness h_1 of the deposits overlying the polarizable conductive layer, both the departures decrease and, in this case, the first of them becomes practically imperceptible at lower values of h_1 than the second one does. With increasing τ, this difference would be still more noticeable.

3. Resolution of EM soundings and ambiguity of their interpretation

The modelling results discussed above are evidence of the essential increase in resolution of EM sounding curves over polarizable sections. The curves change their configuration rapidly with frequency or transient time; they are characterized by additional peculiarities associated with the geoelectric section; polarizable layers, at the corresponding time constants and chargeabilities, can be revealed in the sounding curves at depths inaccessible for quasi-stationary geoelectric methods, and so on. Some of the peculiarities of the sounding curves over polarizable sections mentioned above rapidly fall with the decrease of the chargeability of the section and with the increase in the depth of the polarizable layers. First of all, this is related to quasi-wave phenomena. These phenomena can be, apparently, taken into account and utilized only in high-frequency and low-depth studies (in particularly, ground penetrating radar methods). The other peculiarities are of the quasi-static character and associated with the discharge of polarizable elements of a geoelectric section. They are well revealed in the time domain at certain ratios between the time constants of polarization and the time of measurement of the field and can be utilized to obtain new information in a wider range of geoelectric situations.

Let us consider from this point of view the results of modelling of TS over sections involving groups of thin polarizable layers. TS curves in the far zone over a section with five thin polarizable layers are shown in fig. 10. The sounding curves were constructed using a strongly stretched linear vertical scale. If the layers are non-polarizable, then the whole group of the layers are marked on the «a» sounding curve by the minimum of the apparent resistivity reaching 13 to 14%. With allowance for the chargeability of the layers ($\eta = 0.5$) (the «b» curve) the minimum slightly increases. The curve being the difference of these curves (the «c» curve) is characterized by fluctuations marking each of the layers by a local change in the transient process in tenth fractions of percent. Such an operation of subtracting a smooth calculated curve without allowance for dispersion from an observed transient curve corresponds to one of the accepted methods of data processing in high-resolution electroprospecting. The difference curve recalls experimental curves. However, such a modelling result for the far zone can be obtained only under quite strict limitations on the section; namely that the chargeabilities of the layers are high enough and that the distances between the layers and their time constants quite rapidly increase with depth. Without increasing of the time constants with depth, the layers are no longer distinguished separately.

A different situation arises in the near zone. The TS curve in the near zone over a section involving three thin conductive and polarizable layers is shown in fig. 11. The layers are separated 10 m from each other. The thickness of the overlying deposits exceeds many times the distance between the layers (by 200 times), and the longitudinal conductance of the deposits is much higher than the integral longitudinal conductance of the thin conductive layers (by 30 times). The section approximates, to a certain degree, the situation of oil-gas fields. In the case of absence of polarizability, a sounding curve, strongly stretched vertically, marks the whole group of the layers by the approximately one-percent rise in the apparent conductivity (the «a» curve). When the layers are polarizable, they are each marked by a separate fluctuation of the sounding curve («b») equal to tenth fractions of percent. In comparison with the analogous situation in the far zone (fig. 10), there is not so strict a limitation here on the distance between layers, and underlying layers can be characterized by a lower chargeability. Note, that as Russian experience shows, modern digital equipment with sufficient data accumulation and careful data processing can provide necessary accuracy to detect such small anomalies in sounding curves. With decreasing thickness or conductivity of the overlying deposits, similar results can be obtained at quite small values of the chargeability of the layers.

Thus, seemingly, a possible reason for the high resolution of experimentally obtained TS curves in the near zone, inexplicable in the framework of quasi-stationary geoelectric methods in oil-gas provinces is found: it is related to the polarizability (LFD) of rocks. However the situation is not so simple. It has already been mentioned above that the distortions of TS curves in the near zone associated with polarizability of a section are related mainly to the time constant of their polarization rather than to the depth of polarizable layers. This circumstance can cause serious errors to arising with the formal use of the principles of interpretation of transient (or frequency) responses (in particularly, EM sounding curves) in cases of polarizable sections. TS curves in the near zone calculated over the same sections as in fig. 11, but with the lower layer with its time constant placed on a shallow depth and characterized by a quite low chargeability ($\eta = 0.5\%$), are shown in fig. 12. The form of the TS curve has not significantly changed. However the surface layer in this case, in accordance with its time constant, reveals

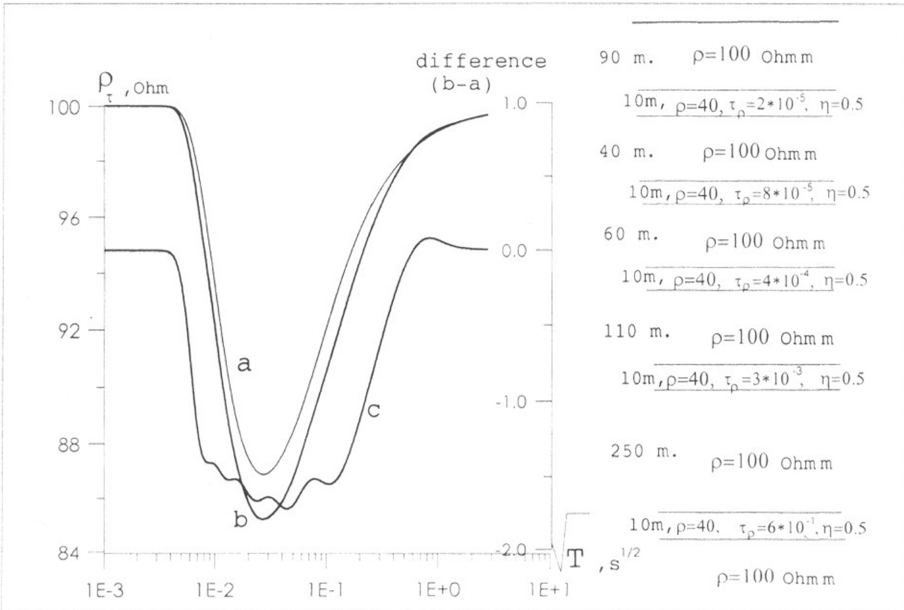

Fig. 10. Transient sounding curve in a far zone above a section with five thin polarizable layers.

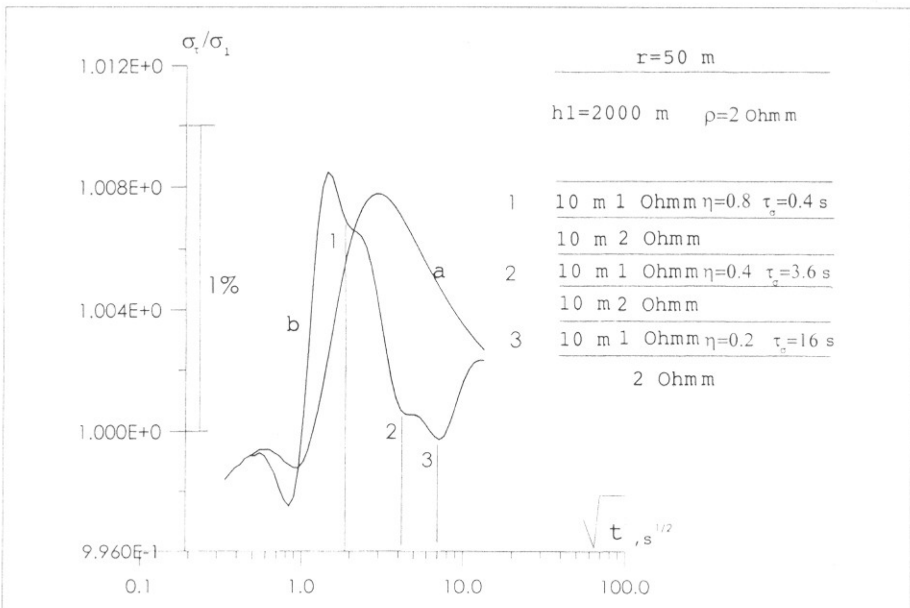

Fig. 11. Transient sounding curve in a near zone above a section with three thin polarizable layers at depth.

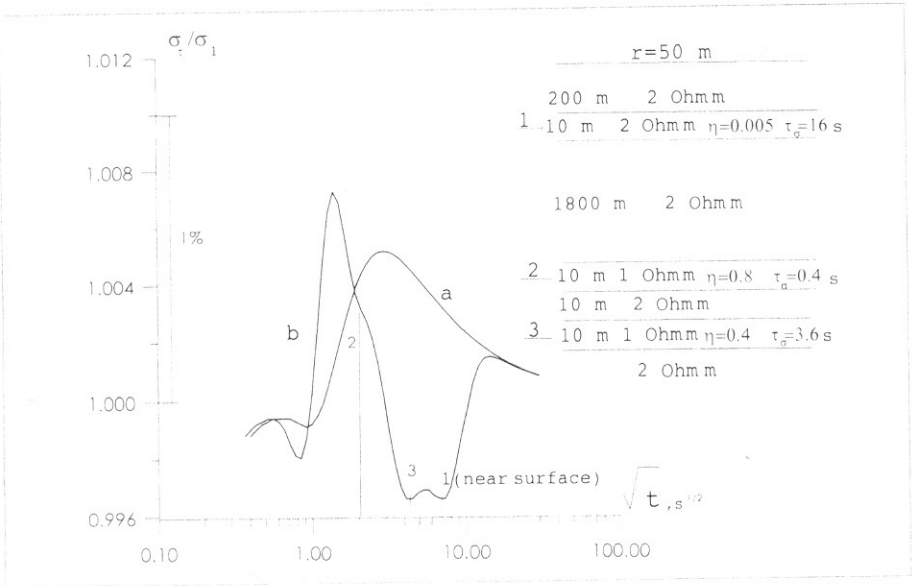

Fig. 12. Transient sounding curve in the near zone above a section with one shallow and two deep layers.

itself on the same times as in the first case (fig. 11) and can be taken for the deepest layer, as before.

Thus, in case of EM soundings over polarizable sections, we deal with a one-dimensional inverse geoelectric problem being by principle nonunique. This should not provoke astonishment since, in the given case, the section, even in the frameworks of the given law approximating LFD, is characterized additionally by two independent parameters – the chargeability η and the time constant τ. In order to determine the parameters as functions of depth, additional independent measurements of the EM field are necessary. EM soundings with a changing separation between the transmitter and receiver or direct current soundings can be the most natural complement of FS and TS. It is not inconceivable that the necessary independent information can be obtained carrying out EM soundings with different field sources (for instance, by electric and magnetic dipoles) and measuring different field components (magnetic and electric components). This will be the subject of further studies.

4. Conclusions

1) Low frequency dispersion of the conductivity (induced polarization) of rocks triggers quasi-wave and quasi-static processes in a polarizable medium, significantly changing the EM field. The quasi-wave processes are revealed on EM sounding curves by appearing in the far zone of characteristic fluctuations of an interference nature (FS) or associated with reflections of the EM field at the boundaries of polarizable layers (TS). Quasi-static processes are revealed in generating the counter electromotive force in polarizable layers which diminishes the inductive transient process and are even capable of changing its sign (TS in the near zone). The EM sounding also marks changes in the resistivity of polarizable layers with frequency or transient time. Such processes accompany both quasi-wave and quasi-static phenomena.

2) LFD of conductivity may lead to an increase in the depth of investigation and of the resolution of the EM sounding and, particularly for TS in the near zone. It explains many experimentally observed peculiarities of the curves of

such soundings, though not all. The theory of EM fields in a polarizable medium allows us to create the basis of more correct interpretation of data of «high-resolution» electroprospecting.

3) Distortions of EM sounding curves associated with LFD of conductivity makes them, in some cases, non-interpretable in the class of quasi-stationary curves over non-dispersive sections. The attempts of such an interpretation in case of high values of the chargeability of the layers or their time constants can result in a distortion of the real geoelectric section (in misjudging the conductivity and depth of the layers, in triggering «false» layers and so on).

4) The problem of interpretation of data of EM soundings in the case of a polarizable medium in their standard present-day implementation is nonunique in principle. To achieve the uniqueness of its solution, it is, probably, necessary to perform TS (FS) for different separations between the transmitter and receiver and to utilize different types of them.

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