

Magnetotelluric Soundings for Estimating the Oil- and-Gas Content of the Mesozoic Complex in Western Kazakhstan

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Abstract—The results of electrical exploration carried out using the method of magnetotelluric sounding at a deposit in Western Kazakhstan are presented. Based on processing and interpretation of the electrometric data, a digital geoelectric model of the exploration area is developed and a geoelectric section of the test profile is constructed. It is shown that MT soundings, along with a seismic survey and well-log data, can be effectively used to define a geological structure and to identify prospective oil-and-gas bearing segments in Mesozoic terrigenous-sedimentary complexes.

Keywords: magnetotelluric soundings, oil-and-gas content, Western Kazakhstan, impedance tensor, geoelectric section

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Introduction. Magnetotelluric (MT) sounding is based on simultaneous measurement of variations in the electric (telluric) and magnetic fields of the Earth. The main values measured are the electric (E_x and E_y) and magnetic (H_x , H_y , and H_z) components. The medium resistivity is calculated from the impedance, which represents the ratio of the horizontal components of the electromagnetic field, electric to magnetic (E_x/H_y) and (E_y/H_x) at different periods (frequencies) of the field vibrations. In the conventional scheme of electromagnetic soundings that use a magnetotelluric field, the MT sounding method plays a key role for the medium stratification, geoelectric zoning, tracking of horizontal changes in electrical conductivity, and the identification of conducting layers in the upper and lower layers of the Earth's crust (Berdichevskii and Dmitriev, 2009).

The procedure and technique of MT studies. In Kazakhstan electrical exploration works at hydrocarbon deposits using the MT method have been performed since 2005 by the TOO Geoken Scientific Production Center. We consider the results at one of the segments in Western Kazakhstan (Fig. 1).

The geoelectric model of the medium that is constructed as a result of MT data interpretation contains information on the physical and geological properties of the section under study (conductivity, lithology, fluid saturation, etc.) (Daukeev et al., 2002).

MT soundings of the segment were performed in order to study and define the geological structure of the Mesozoic complex of deposits, to estimate the productivity of the structures revealed by seismic surveys, and to select the segments of the profiles with better reservoir properties (Istekova and Umirova, 2014), as well as to develop recommendations for detailed electrical exploration and other geophysical studies.

Drilling parametric, prospecting, and exploratory wells opened Upper Paleozoic, Triassic, Jurassic, and Lower Cretaceous deposits. The major productive complexes are represented by the Middle Jurassic deposits and the Neocomian Lower Cretaceous deposits, where the Yu-I oil reservoir horizon and the Neocomian A horizon are found. These oil reservoirs are classified as bedded, lithologically and tectonically screened (Umirova et al., 2015).

The field works were performed using state-of-the-art hardware and software complexes and technologies. The electromagnetic field was recorded via 5-channel stations (MTU-5, Phoenix Geophysics LTD, Canada).

Processing and interpretation of MT data. During the analysis of the MT data, we studied different spatial-frequency characteristics of the impedance tensor. This analysis included:

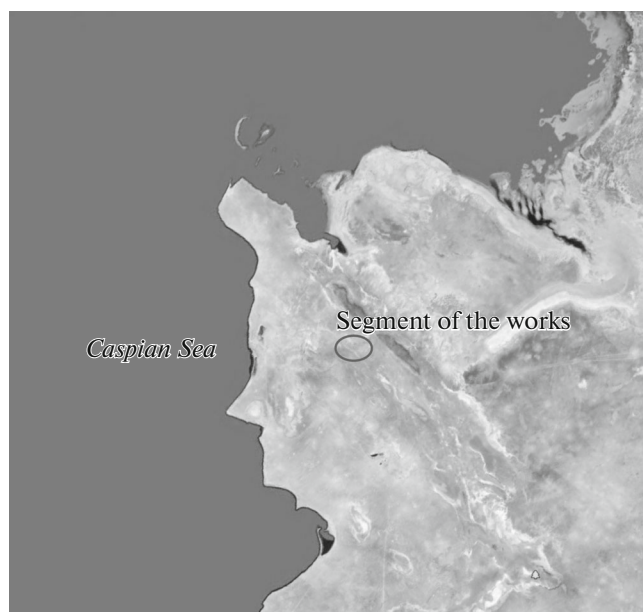


Fig. 1. The position of the exploration area.

- the study of the amplitude and phase curves of MT soundings;
- the detection and suppression of the influence of local near-surface heterogeneities;
- the construction and the analysis of frequency sections of the impedance tensor parameters that show the correspondence between the real medium and the 1D-, 2D-, or 3D-model;
- the construction and the analysis of maps of the amplitude and phase polar plots of the impedance tensor at typical periods.

1D- and 2D-inversions are standard methods to interpret profile data of magnetotelluric soundings. It was stated in (Persova et al., 2012) that 1D inversion can be used only for reconstruction of the uppermost part of the section, which is usually characterized by horizontal stratification. 2D-inversion can provide a result that corresponds to reality in the case where all meaningful heterogeneities are elongated, mostly orthogonally to the profile. If the heterogeneities are not elongated, 2D inversion may lead to the generation of false deep anomalies. When 2D inversions are used, false anomalies may also occur due to the influence of “lateral” heterogeneities that fall outside the profile. As well, 2D inversion may create segments where a required level of discrepancy cannot be reached, which quite definitely points to the 3D-nature of the medium under study (Persova et al., 2012).

In the area of the works, the interpretation of the electrical exploration data was performed in two stages: (1) quantitative interpretation of the MT sounding curves resulted in the creation of geoelectrical sections and (2) subsequent geological interpretation of the geoelectrical sections resulted in the con-

struction of the geological–geophysical sections. The geological interpretation was performed using resistivity sections obtained based on the generalized information on the wells (Istekova et al., 2015).

The graph of the quantitative interpretation was selected on the basis of the analyzed MT data for the detailed stratification of the Jurassic–Cretaceous part of the section.

To obtain the first approximation and to identify the main features of the geoelectric structure of the sedimentary cover, we performed 1D inversion of the apparent resistivity and impedance phase curves using the MTSPInv software. The next step of the quantitative interpretation was 1D manual selection using IPI_2D_WIN_MT. At this stage, we used the results of automatic 1D inversion as a starting model, as well as information on the geometry of the main seismic horizons and the well logs.

The analysis of the shape of the resultant curves at the segment of the works indicate that all curves of the main components are consistent with each other in amplitude and phase and are similar in shape. Small discrepancies between the curves are observed up to $\sqrt{T}$ at about $10 \text{ s}^{1/2}$. At the beginning of the different curves, the apparent resistivity ρ_T is found within the range from 0.3 to 0.5 ohm m, which corresponds to relatively low-resistivity near-surface deposits (Fig. 2).

We then recorded a flat ascending branch on the curves ρ_T , having a bend corresponding to the manifestation of higher-resistivity Upper Cretaceous rocks. The minimum at $\sqrt{T} \approx 2 \text{ s}^{1/2}$ conforms to the conducting deposits of the suprasalt complex; the minimum values of ρ_T amount to 0.6–5.0 ohm m. High-resistivity deposits are shown on the curves as a steep ascending branch. One broad minimum on the curves indicate that the section contains low-resistivity deposits of the suprasalt complex. The rocks from the lower complexes down to the basement have high resistivity.

The impedance tensor components Z_{XY} and Z_{YX} almost coincide, except for the very end of the curve and the region of the broad maximum, where the structural elongation affects the low-resistivity deposits of the suprasalt complex in some segments.

At this stage, the MT sounding curves were also normalized to suppress the influence of the S-effect, which manifests itself due to the objects that cannot be taken into account within the framework of this interpretation model. The goal of normalization was first of all to avoid the influence of local near-surface heterogeneities.

During the processing, we analyzed the sections of the impedance tensor parameters of the test profile. The analysis considered the values of the heterogeneity parameter N on the different periods, the Swift asymmetry parameters (Skew_S , amplitude parameter), and the phase parameter Skew_ϕ . The amplitude parameter N shows that the geoelectric section differs from one-dimensional. For the test profile, the amplitude parameter is $N \geq 0.1$ –0.2, which points to the

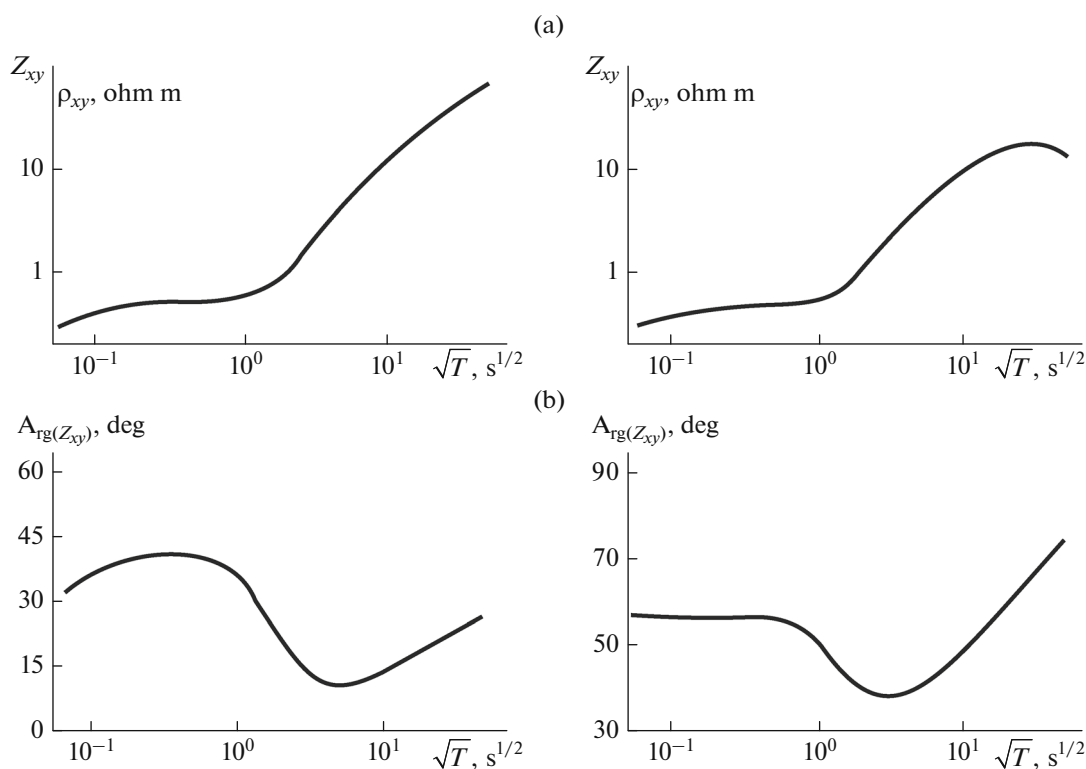


Fig. 2. (a) The apparent resistivity and (b) impedance phase curves for test profile 1.

horizontal stratification of the section. A small increase in the amplitude parameter N was recorded at $\sqrt{T} > 10 \text{ s}^{1/2}$, which is related to the influence of regional heterogeneities.

The amplitude Skew_S and phase Skew_B parameters indicate the difference between the geoelectric and two-dimensional sections. In our case, the values of the parameters Skew_S and Skew_B were 0.1–0.2 and somewhat exceeded 0.2 in the region of regional heterogeneities noted above. This means that the geoelectric section has a two-dimensional nature.

This one-dimensional situation in general in the upper part of the section enables us to move from the apparent resistivities in the two perpendicular directions (XY and YX) to the geometric average resistivity. Figure 3 presents the resultant geoelectric section of test profile 1.

Three layers are clearly identified in the resultant sections of apparent resistivity in profile 1:

- a homogeneous very low-resistivity layer in the upper part of the section having the resistivity values in the range from 0.1 to 0.4 ohm m;
- a layer with a slight increase in the resistivity from 0.6 to 1 ohm m;
- and a bottom layer with a region of gradient increase in resistivity up to 25 ohm m.

The identified layers can also be seen on the MT sounding curves.

The first and second low-resistivity layers in profile 1 of the section of the apparent resistivities are quite consistent. The impedance phase section is more informative. The first and second layers in this section are complicated by a series of linear heterogeneities. As an example, there is a quite extended zone of changes in the impedance phases between the MT sounding stakes at 2.5 and 4.5 km in profile 1. The third layer is next with a gradient increase in resistivity to 30–40 ohm m.

We made the following conclusions based on the simultaneous analysis of the distribution of rock resistivity in the section with respect to the lithological composition according to the well-log data.

The Jurassic–Cretaceous rocks show the following tendency in the distribution of geoelectric properties:

- clayey rocks have the least resistivity (0.1–1 ohm m on average);
- siltstone rocks have higher resistivity than clays (1–2 ohm m on average); and
- sandy rocks are characterized by the highest resistivity (3–10 ohm m on average).

Thus, the rocks are well classified on the basis of their resistivity: clays have the least resistivity, siltstones have an average level, sand and sandstones have high resistivity. Calcareous siltstones do not frequently occur. They have the same resistivity as sandy rocks. In general, siltstones and sandstones prevail in the section.

Using the basic seismic horizons, we obtained a set of intervals of increased resistivity that were obtained

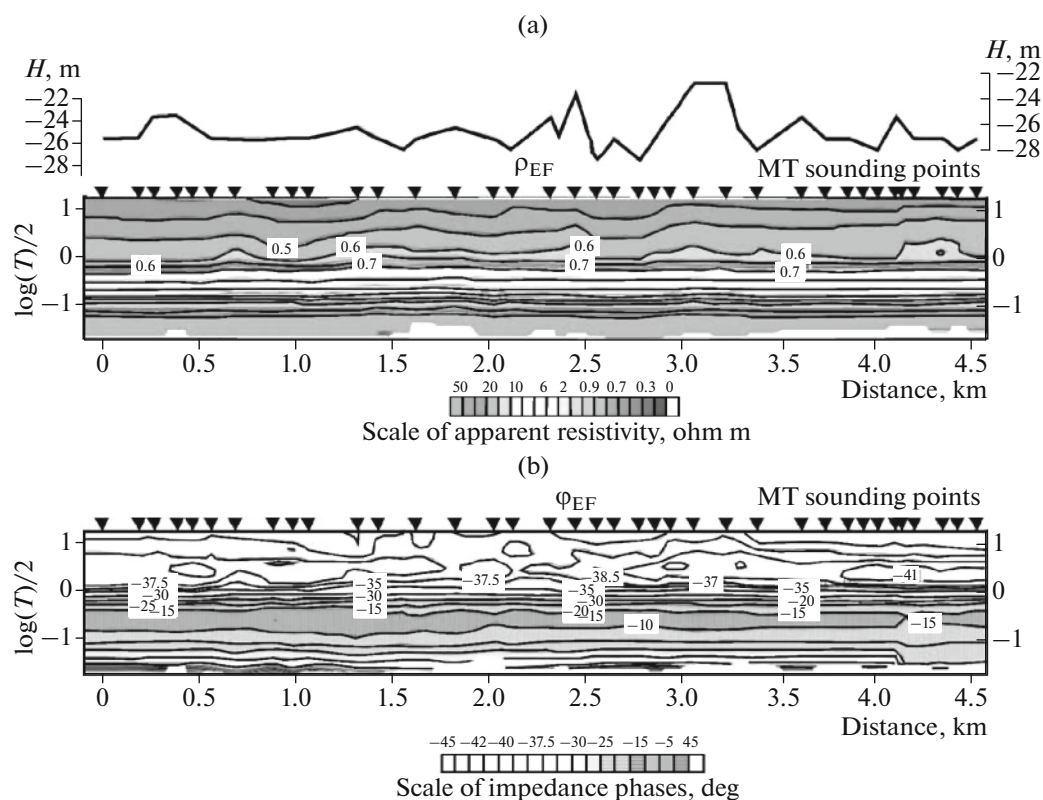


Fig. 3. The resultant geoelectric section of (a) the apparent resistivity and (b) the impedance phase for test profile 1.

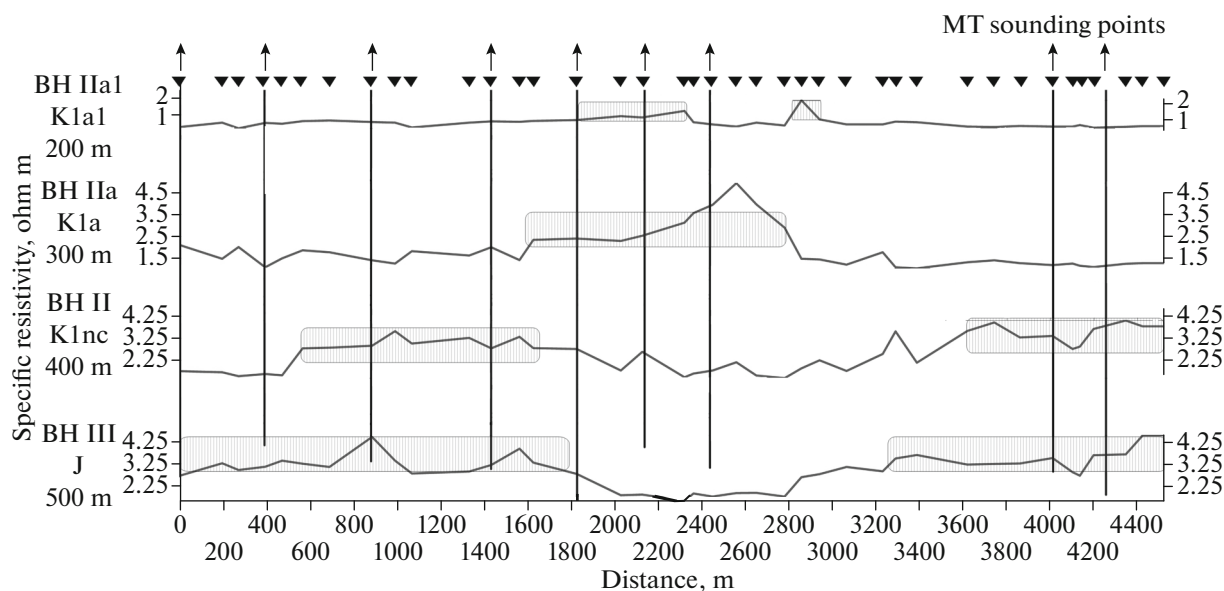


Fig. 4. Plots of the distribution of specific resistivities for the Jurassic–Cretaceous deposits of profile 1: K₁a₁, Albian deposits; K₁a, Aptian deposits; K₁nc, Neocomian deposits; and J, Jurassic deposits.

from the MT sounding data. Figure 4 presents the plots of the depth dependence of the resistivity values in the Jurassic–Cretaceous rocks.

The analysis of these plots shows that the resistivity of rocks decreases in the area of magnetotelluric stud-

ies as the groundwater mineralization increases. The resistivity of sands and sandstones with high specific porosity significantly drops. Clays change their resistivity much more weakly, since they have small filtration potential and contain much “bound” water with low mineralization. At higher mineralization (>50 g/L) there

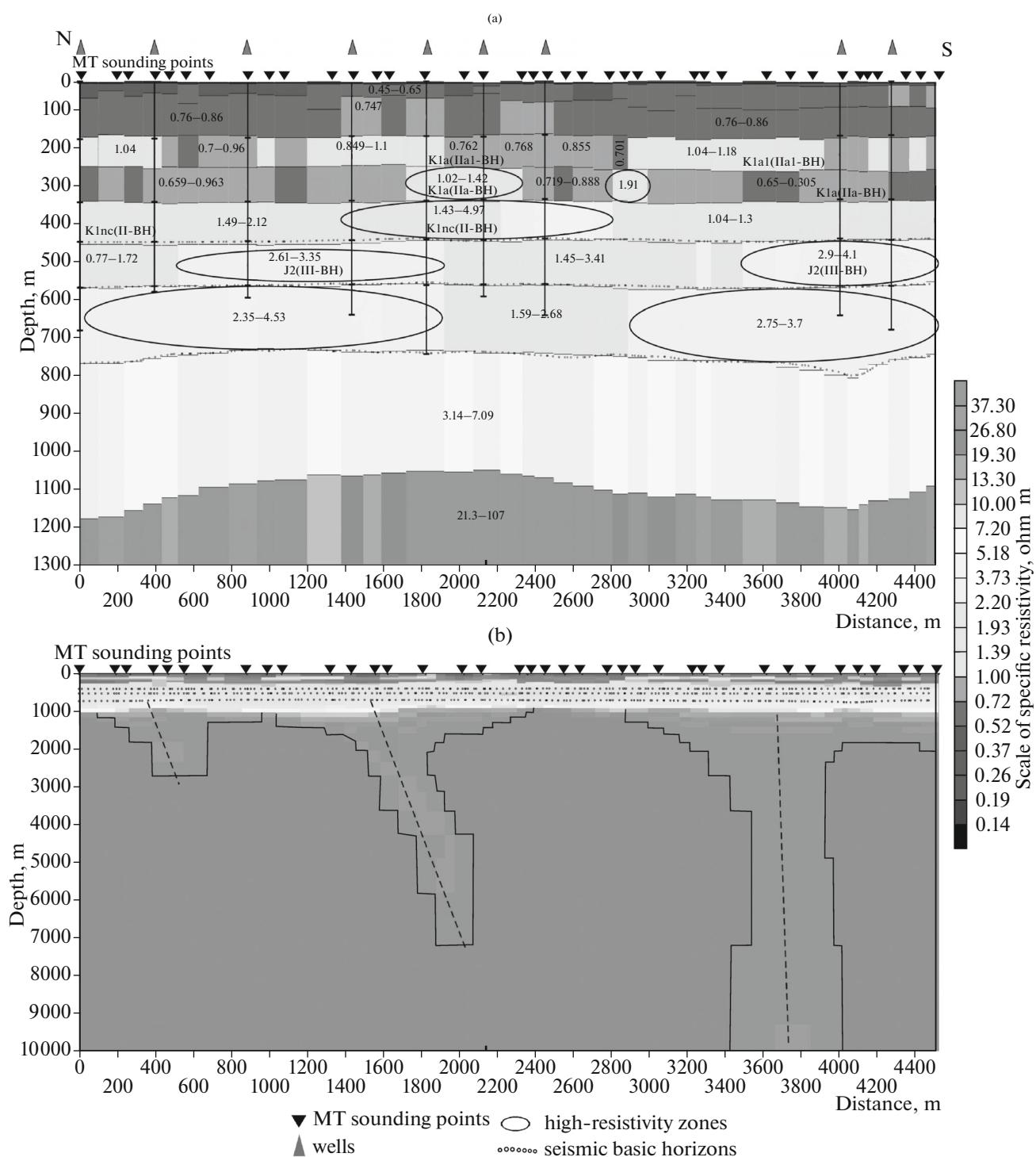


Fig. 5. The results of interpreting the MT sounding data for the (a) upper and (b) lower parts of the section of profile 1.

is an “inversion of resistivity” in the sandy–clayey deposits: water-saturated sands and sandstones become more conducting than clays.

When constructing predictive lithological sections of sandy–clayey Jurassic–Cretaceous deposits we

used the classical petrophysical dependences that were presented in nomograms in (Ryzhov et al., 1990).

According to the plots in Fig. 4, the sandstones from the area under study have resistivities somewhat higher than clays through the entire depth. Therefore,

we may suppose that the mineralization of ground waters is average in the exploration area. The analysis of the selected samples from the wells showed that the mineralization of the exploration area varies mostly from 20 to 30 g/L, but several samples have mineralization of 80 g/L.

The deposits of the underlying Jurassic–Cretaceous rocks have been studied less. The terrigenous Permian–Triassic deposits have comparatively high resistivity (several tens of ohm m). The zones of decreased values of resistivity are related as a rule to the tectonic structures in the area of the deposit.

The complex interpretation of seismic, electrometric, and well-log data is carried out using the modern software developed by the Severo-Zapad Company (Russia).

The upper part of the geoelectric section down to the depth of 1300 m was obtained as a result of one-dimensional layer-by-layer interpretation. It characterizes the change in the electrical resistivity of the Mesozoic–Cenozoic geological part of the section. The section (Fig. 5) shows the basic seismic horizons and the data acquired from the exploratory wells, which were used in selecting a geoelectric model.

The lower geoelectrical sections down to a depth of 10 km were constructed as a result of two-dimensional inversion. They have geoelectric heterogeneities in the Paleozoic part of the section.

Based on the generalization and the analysis of the data, we identified and substantiated the intervals of the section that have hydrocarbon potential (Fig. 5a). In Fig. 5a, these are shown by ovals.

Two weakly-sloped zones with low resistivity (Fig. 5b) that might be related to faults were identified for the Paleozoic part of the section based on the results of the 2D inversion. At these segments the decrease in the resistivity values is low but stable. In addition to it, the section shows quite a shallow “pocket” with low resistivity, whose nature is unknown. In the profile center, the Paleozoic part of the section contains a positive high-resistivity structure.

To identify the prospective zones in the Mesozoic part of the segment in the presented sections, we analyzed the well data from that location (the results of induction logging as the method closest to MT sounding) and the character of fluid saturation. As a result, typical anomalous aureoles of the increasing electrical resistivity were recorded in the prospective structures that had been identified based on the well drilling and log data. As well, a lateral change in the electrical resistivity clearly manifests itself in the region of these anomalies and in the reservoir itself (Fig. 5a). This is likely to be related to the fact that over a long geological period a cap of epigenetically changed rocks was formed above the reservoir due to the upflows of hydrocarbons and other fluids that gradually trickle

over the cover, which leads to a decrease in porosity and permeability of terrigenous rocks due to pyritization and calcitization. As a result, there is a total high-resistivity anomaly above the hydrocarbon reservoir. In general, the reservoir itself is a high-resistivity bed, whose bottom contains low-resistivity rocks filled with highly mineralized waters. This bed or the combination of the beds may be recorded by magnetotelluric soundings as a high-resistivity anomaly.

CONCLUSIONS

It was shown that MT sounding can be effectively used along with seismic surveying and well-log data in the studied segment of test profile 1 to fulfill exploration tasks. The complex interpretation of the MT sounding, well log, and seismic-survey data made it possible to define the geological structure of the Mesozoic deposits. The structure of the Paleozoic deposits was characterized and the prospective faults were identified. The potential segments identified in the Mesozoic terrigenous-sedimentary complexes of rocks are genetically associated with the zones of tectonic deformations. The well-log data were used to evaluate the productivity of the structures identified during the seismic survey and to outline the segments of the profiles with better reservoir properties. Based on the results of the MT studies, it is recommended that detailed works should be continued.

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