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PROSPECTS OF HYDROCARBON DEPOSITS EXPLORATION USING THE METHOD OF INDUCED POLARIZATION DURING GEOMAGNETIC-VARIATION PROFILING

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Traditionally it is believed that the effect of induced polarization is an interfering factor for the measurement of electromagnetic fields and their interpretation during conducting works using magnetotelluric sounding and geomagnetic-variation profiling methods.

A new method is proposed for isolating the effects of induced polarization during geomagnetic-variation profiling aimed at searching for hydrocarbon deposits on the basis of phase measurements during the conduct of geomagnetic-variation profiling. The phenomenon of induced polarization is proposed to be used as a special exploration mark for deep-lying hydrocarbon deposits.

The traditional method of induced polarization uses artificial field sources, the powers of which are principally insufficient to reach depths of 3-5 km, which leads to the need to search for alternative - natural sources in the form of telluric and magnetotelluric fields.

The proposed method makes it possible to detect and interpret the effects of induced polarization from deep-seated oil and gas reservoirs directly, without relying on indirect signs.

Key words: effect of induced polarization, geomagnetic-variation method, hydrocarbon reservoirs, depth of exploration.

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Introduction. Geomagnetic-variation profiling (GVP) is traditionally used to study the deep structure of the earth's crust along with the generally recognized method of magnetotelluric sounding (MTS).

The main advantage of magnetotelluric sounding in the methodical field is the synchronism of measurements of magnetic and electric fields. This makes it possible to obtain objective characteristics of the studied medium by means of mathematical procedures. The MTS method makes it possible to determine the distribution of electrical conductivity in the earth to very large depths (of the order of 10-50 km). In the recent time GVP is actively used in the search for hydrocarbon deposits (HC) in combination with seismic prospecting. However, knowledge of the distribution of electrical conductivity is often insufficient for reliable forecasting and contouring of hydrocarbon deposits.

The need to measure the electric field significantly complicates and draw out to a great length the measurement process. One of the reasons for this is the polarization of the measuring electrodes. However, it is possible to propose a compromise solution consisting of a combination of a common technique for measuring the induced polarization (IP) in a phase modification with depth potentials of the GVP.

Formulation of a problem. Many authors have considered the influence of the induced polarization on the MTS/GVP results from a phenomenological point of view, but the objective obscurity of the mathematical regularity of the formation of the IP in time hinders the solution of the question of the prerequisites for interpreting this phenomenon in some form (qualitative or quantitative). The currently accepted and widely used Cole-Cole formula [5] does not give an unambiguous answer to the question of the time law of the induced polarization formation in a specific naturally occurring situation, which does not allow us to actually use it to solve the inverse problem not only by using MTS or GP, but also with traditional methods of measuring the IP with controlled sources.

The induced polarization phenomenon is an interfering factor for using the MTS [4, 6, 8], and hydrocarbon deposits in the form of poorly conducting local inhomogeneities occurring at great

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depth are the most unfavorable objects of exploration. On the contrary, the deposit, surrounded by an aureole of sulfide impregnation, is a favorable object for exploration by the induced polarization method.

In contrast to the MTS, the IP method makes it possible to carry out the prospecting and exploration works at mineral deposits with greater confidence, but mostly at shallow ones (100-300 m) and moreover of ore type [5]. The relatively shallow depth of the IP method is explained by the use of artificial electromagnetic field sources with very limited signal power, which does not allow the use of sufficiently long measuring lines to increase the depth.

Methodology. In the last two decades, new regularities in the structure of the earth crust section in oil-bearing regions have been revealed, which make it possible to determine more confidently the oil-bearing capacity of structures revealed by seismic prospecting. The essence of these studies is that over hydrocarbon deposits, as a rule, sulfide «caps» are formed at a depth much lower than the depth of the reservoir itself [7]. Their appearance is a consequence of the formation of sulfides in the process of iron recovery by a vertical flow of hydrocarbons from deep deposits on geochemical barriers located directly above them. This makes it possible to apply the search results using the IP method as indirect (albeit very reliable) signs of the presence of hydrocarbons in traps of various types. This is confirmed by well logs of IP in oil-promising areas (Fig.1).

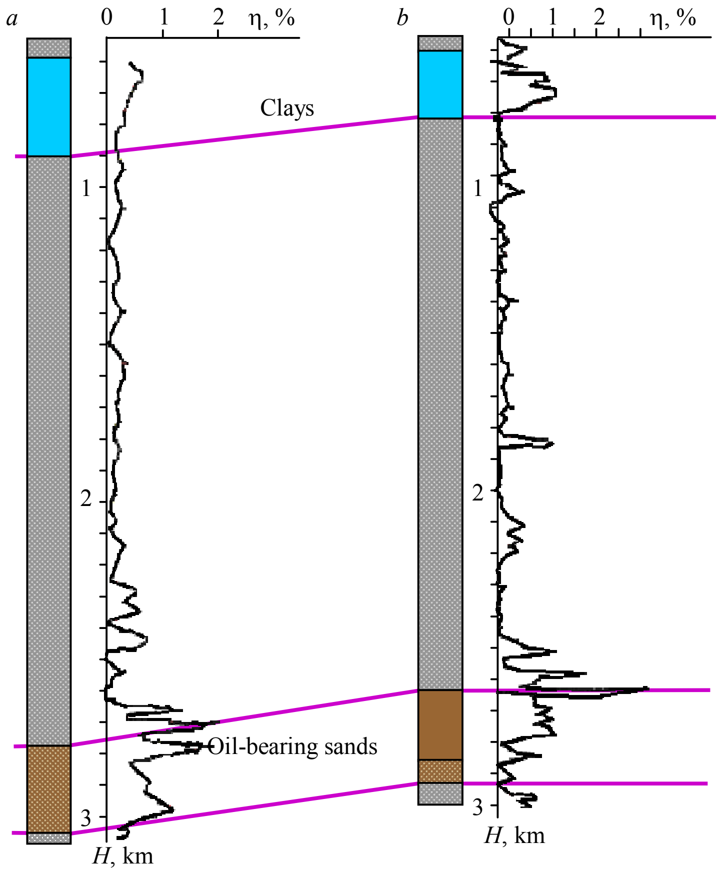

Fig.1. IP well logs at non-productive (*a*) and productive (*b*) wells (according to V.S. Moiseev [7])
The essential details of the cross-section of the wells are marked as following: saturated oil-bearings sands – brown color, unsaturated – brown with dots, clays as a geochemical barrier – blue, insignificant details of columns – gray with dots

The processes of iron recovery with the formation of sulfide impregnation occur directly at the contact of the hydrocarbon deposit with the enclosing rocks and even more intensively. A classic physical-geological model of the hydrocarbon deposit is the model of the deposit associated with the anticlinal structures of the platform structure (Fig.2).

The sealing layer is formed in the hydrocarbon contact area with water. In this area, the processes of dissolution of minerals, formation of calcite, quartz, pyrite and other minerals occur. Under the influence of these processes, the porosity decreases and the density of rocks increases. All this leads to the formation of a layer that seals the deposit. The thickness of this layer varies from several to hundreds of meters. At the same time, when the sulfide "cap" is formed at a shallow depth, the anomalies of the IP over the oil fields reach 5-10 % [7], which indicates a high concentration of sulfides in it (and all the more in the sealing layer).

Modeling of the geoelectric situation [9], the results of which are shown in Fig.3, indicate a weak resolving power for separating the oil deposit by apparent resistivity, but very satisfactory in apparent polarizability. These models are as follows: the resistivity of the enclosing medium is $\rho = 10$ Ohm·m, the polarizability is $\eta = 0.1$ % (which corresponds to the conditions of the deposits in Western Siberia). Specific resistivity of the sealing layer $\rho = 5$ Ohm·m, polarizability $\eta = 30$ %,

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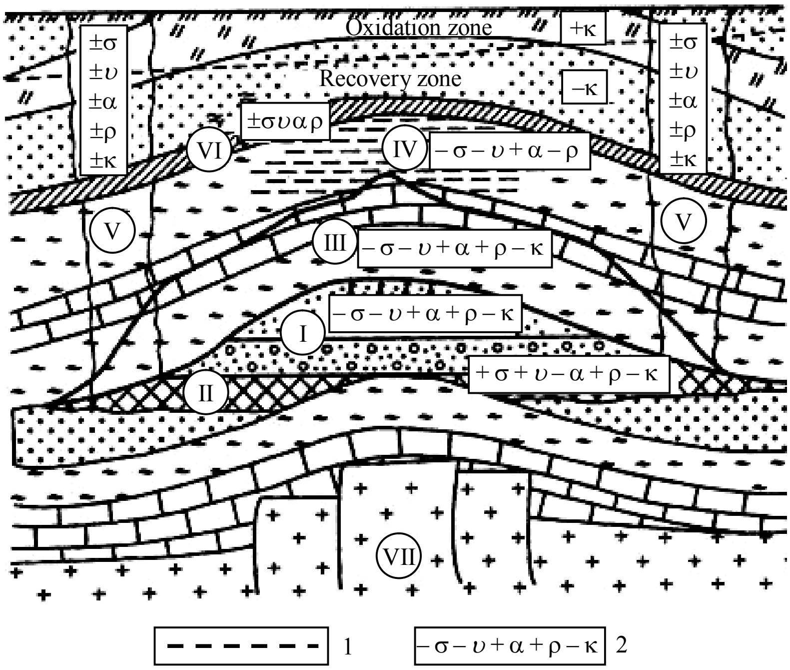

Fig.2. The layout of distribution of physical properties of rocks within the area of oil-bearing structures of platform type (according to V.M. Berezkin [1])

I – oil and gas deposit; II – sealing layer; III – intrusion aureole; IV – rock decompression area in the structure zone; V – subvertical zones of inhomogeneity (states of various stresses); VI – key boundaries between rocks with different physical properties; VII – basement; 1 – boundary between oxidation and recovery zones; 2 – state of physical properties of rocks in relation to rocks of aquifers (σ – density; ρ – specific resistivity; α – absorption index; κ – magnetic susceptibility; υ – speed of ultrasound propagation («+» – excessive, «–» – deficient)

specific resistivity of the sulfide «cap» $\rho = 5$ Ohm·m, polarizability $\eta = 15$ %, depth of the upper edge 380 m, reservoir thickness 70 m. The parameters of the deposit are as following: $\rho = \infty$, $\eta = 0.1$ %, dimensions are 1600 m along the strike, dome height 350 m, depth of the sole 2800 m.

The polarizing field is a horizontal homogeneous electric field, i.e. the deepness is fundamentally infinite. Obviously, the allocation of the reservoir by resistivity is quite problematic, and polarizability, even in the absence of a sulfide «cap», is very promising. The depth of the method with artificial sources of IP is insufficient for direct searching of objects at a depth of 3-4 km. This situation is possible when the sulfide «cap» has not yet formed or there is no geochemical barrier for its formation.

In order to reach greater depths, it is possible to apply the method of the phase technology of the IP of measuring the magnetic field at the GVP, which makes it possible to use a natural field source that is much more powerful than any generator unit. The phase method for measuring the IP is as follows: the phase shift between the first and third harmonics of the meander wave signal is measured, which, as numerous studies have shown, is directly proportional to the apparent polarizability at low field excitation frequencies (up to 10 Hz). In this case, the principal point is the fact that the phase shift of the induced polarization is independent of the frequency and the direct proportionality of the induction phase shift from the frequency [3].

In accordance with the general theory of MTS and GVP, the alternating electromagnetic field that is being studied on the surface is caused by ionospheric currents arising from the action of the solar wind (inductive excitation) or by lightning discharges (galvanic excitation) [3, 6].

The main point here is the greater distance from the source, so that incoming signals can be considered as in-phase at points located from each other at distance of 1-2 km. With inductive excitation, this is obvious, since the height of the ionospheric currents is 300-400 km, and in case of galvanic excitation the thunderstorm front must be sufficiently remote.

The most technologically feasible method in conducting a GVP is to measure the *vertical component* [6] of the magnetic field, which makes it possible to obtain practically meaningful results without dealing with complexity of measuring electrical components.

A random time-varying signal $S(t)$ for a sufficiently large measurement interval for T can be represented by a series of trigonometric functions:

$$S(t) \approx \sum_{k=0}^{\infty} A_k e^{i\left(k\frac{2\pi}{T}t + \varphi_k\right)},$$

where t – time, φ_k – phase of k harmonics.

The response of the media $R(t)$ to this effect consists in changes of the amplitudes of the additive components and shifting of their phase:

$$R(t) \approx \sum_{k=0}^{\infty} a_k e^{i\left(k\frac{2\pi}{T}t+\varphi_k+\varphi_k^{in}+\varphi_k^{ip}\right)},$$

where φ_k^{in} – induction phase shift of k harmonics, which according to the above said is positively related to frequency, that is $\varphi_k^{in} = k\mu$; φ_k^{ip} – IP phase shift, which does not depend on frequency $\varphi_k^{ip} = \nu$; μ – induction parameter.

Thus,

$$R(t) \approx \sum_{k=0}^{\infty} a_k e^{i\left(\frac{2\pi}{T}kt+\varphi_k+k\mu+\nu\right)}.$$

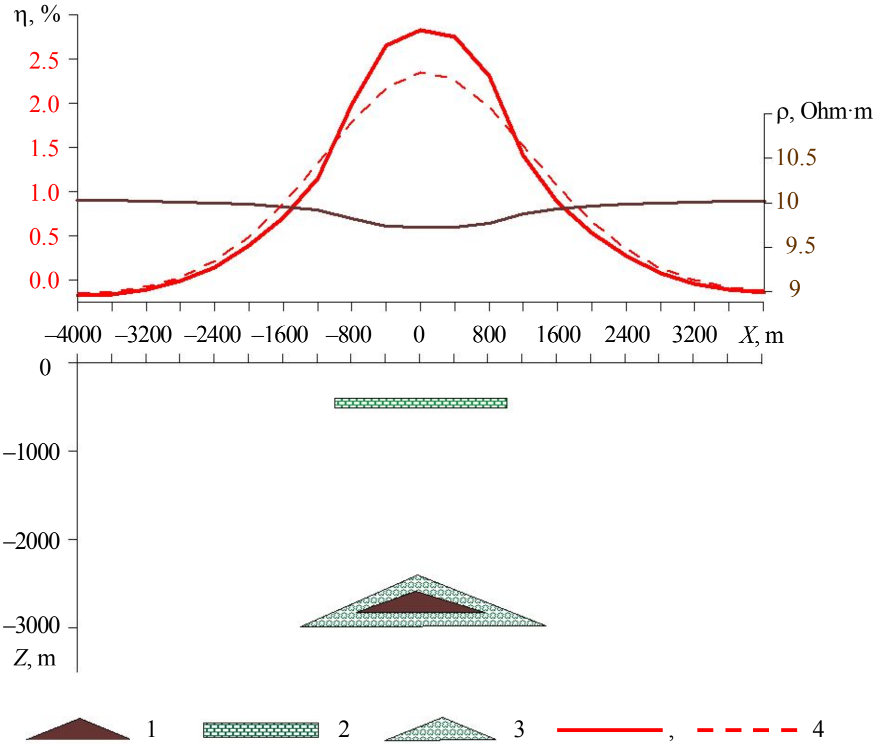

Fig.3. Apparent polarizability and resistivity over the hydrocarbon reservoir

1 – reservoir; 2 – sulfide «cap»; 3 – sealing layer; 4 – red curve – apparent polarizability, solid line – reservoir with a «cap», dotted line – without sulfide «cap»

Let us consider the phase shift of the response of the medium $R(t)$ in two points (1 and 2) – $R_1(t)$, $R_2(t)$, which are located not very far from each other (about 300-500 m), for some harmonic n. In *synchronous measurements* [6, 10], due to in-phase, φ_n-phase of n harmonics is the same. Then the phase difference between points 1 and 2 is

$$\Delta\varphi_n^{12} = n(\mu_2 - \mu_1) + (\nu_2 - \nu_1).$$

We obtained a linear frequency function (harmonic number) with a constant component $\nu_2 - \nu_1$ and a linear coefficient $\mu_2 - \mu_1$. By constructing the curve $\nu_{i+1} - \nu_i$ (where $i = 0 \ldots N$) along the measurement line and integrating it, we obtain the following

$$\nu_k = \sum_{j=0}^{k} (\nu_{j+1} - \nu_j) + C_\nu,$$

that is the curve of apparent polarizability η_k along the profile within the accuracy to the unknown additive component C_ν, since $\eta_k(\%) \approx -2.5\nu(\text{grad})$ [5]. The background component C_ν does not play a special role and can be chosen arbitrarily as the average value of the studied area. The curve of the induction parameter is calculated in the same way.

Thus, we get an idea of the behavior of η_k along the profile and additional information about the change in the induction parameter. In particular, the weak variability of the induction parameter when measuring the vertical component of the magnetic field is the evidence of the absence of local, well-conducting inhomogeneities in the section, and the presence of zones of increasing polarizability signal about the presence of sulfide impregnation.

In paper [2], we also investigate the possibility of using phase-amplitude characteristics for measuring the IP effect, but without synchronization of measurements, which is much more difficult from the technical point of view, as well as from processing and interpretation processes.

The error in measuring the phase should not exceed 0.1° (0.25 % by η_k), which corresponds to the parameters of the measuring equipment of the phase method of the IP and can be achieved by increasing the measurement interval T and the sampling frequency.

Discussion. The formulas obtained on the basis of previous researches allow to substantially increase the depth of the IP method for direct prospecting and exploration of hydrocarbon deposits, which is determined by the thickness of the skin layer in accordance with the formula $d=\sqrt{2\rho/2\pi f\mu_0}$ (where ρ is the resistivity, f is the frequency, and $\mu_0 = 4\pi\cdot 10^{-7}$ is the magnetic permeability of the vacuum [3]).

The expected depth of research when using the frequencies of the order of 0.1 Hz, even in very low-resistivity sections (ρ ≈ 4 Ohm·m), will be at least 3 km, which is sufficient for effective exploration of hydrocarbon reservoirs, including ones located in the offshore zones with depth the sea bed of about 100-200 m.

Conclusions

1. Synchronous phase measurements of IP during the GVP procedure operations transfer the phenomenon of IP from a range of disturbing factors to an independent method of direct exploration of hydrocarbon deposits.

2. The use of extremely low frequency telluric currents (with a period of 10-600 s) as sources of the field provides practically unlimited depth of exploration [6], which is impossible with artificial sources.

3. The high adaptability of the proposed method will significantly improve the productivity of prospecting for oil and gas and the reliability of the results of geophysical prospecting and exploration work.

REFERENCES

1. Berezkin V.M., Kirichek M.A., Kunarev A.A. The application of geophysical exploration methods for direct prospecting for oil and gas fields. Moscow: Nedra, 1978, p. 223 (in Russian).

2. Ermokhin K.M. The method of complex interpretation of data of the IP method and resistances on the example of the Madneul copper-pyrite deposit. Metody razvedochnoi geofiziki: Sb. nauchn. trudov. Leningrad: NPO «Rudgeofizika», 1990, p. 31-37 (in Russian).

3. Zhdanov M.S. Electrical exploration. Moscow: Nedra, 1986, p. 316 (in Russian).

4. Kamenetskii F.M., Trigubovich G.M., Chernyshev A.V. What part of Geo-physics is more important: Geo or Physics. *Geofizika*. 2015. N 2, p. 69-76 (in Russian).

5. Komarov V.A. Electrical exploration by the method of induced polarization. Leningrad: Nedra, 1980, p. 391 (in Russian).

6. Kopytenko Yu.A., Ismagilov V.S., Petrishchev M.S. Investigation of the geoelectric structure of the earth's crust by the method of phase-gradient sounding. *Doklady Akademii nauk*. 2015. Vol. 462, p. 352-355 (in Russian).

7. Moiseev V.S. Methods of induced polarization and ground-bore electrical exploration in prospecting and delineation of hydrocarbon deposits in the West Siberian oil and gas province: The autor ... Doctor of Geological and Mineral Sciences. Novosibirsk: SNIIGGIMS, 2002, p. 40 (in Russian).

8. Moskovskaya L.F. Induced polarization in changes of telluric fields. *Geofizika*. 2006. N 6, p. 29-38 (in Russian).

9. Ingerov A.I., Ingerov I.A., Lozovoi A.L., Mendri Ya.V. Application of amplitude and phase curves of induction sounding with natural sources for cartographic purposes. *Nauchnyi vestnik Natsional'nogo gornogo universiteta*. Dnepropetrovsk, 2012. N 2, p. 5-10 (in Russian).

10. Sokolova E.Yu., Golubtsova N.S., Kovtun A.A., Kulikov V.A., Lozovskii I.N., Pushkarev P.Yu., Rokityanskii I.I., Taran Ya.V., Yakovlev A.G. Results of synchronous magnetotelluric and magnetovariational sounding in the area of Ladoga anomaly of electroconductivity. *Geofizika*. 2016. N 1, p. 48-61 (in Russian).

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