Increasing the efficiency of the tem-tdem method while searching for hydrocarbons in conditions of high electric conductivity of sedimentary-terrigenous complexes’ rocks

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Abstract. A possibility to select theoretical signal models for the observed graphs $E_{obs}(t)$ satisfactorily is shown to be steadily absent while prospecting using the TEM-TDEM method among Western Siberia’s high-electroconductive rocks. Examination of this problem showed Western Siberia’s rocks have a high reactive (inductive) resistance $L$ alongside with ohmic resistance $R$. At the same time, thin oil and gas beds’ presence in those rocks causes an additional reactive-capacitive resistance $C_{dep}$ to appear under the influence of the applied electric field. Therefore, the process of field inducing in $RLC$-medium is completely different from the “classic” one which is described with only specific resistance $\rho$. Thereupon, transit process theory, based on process modelling with equivalent loops, was applied. In practice, TEM-TDEM method’s efficiency turned to be very high as the direct search characteristic – anomalous parameter $C_{dep}$ appears. All the parameter c’s anomaly contours predicted as hydrocarbon deposits are confirmed as such with deep drilling with the success coefficient almost equal 100%.

1. Introduction
On the premises of Khanty-Mansi Autonomous Okrug electrical exploration, TEM-TDEM method was used to find carbohydrate deposits mostly to the bed depth of the upper Jurassic Bazhenov Formation (2800-2900 m). The accumulated field data and, particularly, registered signals over different gas-oil deposits (figure 1,a) and outside them were all accompanied with theoretical calculations of those signals according to the known excitation formulas by the “classic” authors of this method (figure 1,b) [1-5], all of whose decisions were oriented only towards gradual electromagnetic field diffusion deep into the earth and the deposit resistor model [6].

As a result, their incomparability in both signal shapes and parameters of real and theoretically chosen profiles was registered persistently. Such an incomparability has gotten obvious to be related to a completely new process of field inducing in the geological environment in the Western part of Western Siberia. The TEM-TDEM method kept being ineffective.

Thereupon, to keep TEM-TDEM method included in searching geological prospecting set finding a completely new model of electromagnetic transients interacting with both homogenic highly conductive medium (800 ÷ 2000 S) and the same medium with gas-and-oil deposits, which are usually very big on a horizontal plane (from 3.5x10 km to 97x50 km) but usually very thin (often from 5 m to 10 ÷ 40 m) [7], was needed to be found.
Based on the abovementioned geological-geoelectric peculiarities and theoretical fundamentals electrotechnology, a way to adapt the TEM-TDEM method to the Western Siberian geoelectric conditions and begin solving the rest of exploratory problems was found [8]. Subsequently, the adaptation is accomplished with solving the theoretical problem which considers both active and reactive environmental electric features. As a result, to develop a new TEM-TDEM technology regarding both fieldwork methods and new data interpretation proved to be possible. Positive interpretation results were normally checked with deep boreholes, which always proved a commercially legitimate amount of oil and gas to be in the section. Materials regarding the new method of TEM-TDEM method data interpretation are considered below.

![Figure 1. Comparison of two signal $E_{obs}(t)$ (1 and 3) graphs, observed over Southern Surgut (a) and Ay-Pim (b) oil deposits, with $E(t)$, calculated with the full TEM formula for the AB-q plant (2 and 4).](image)

For the (a) case productive strata pertain to medium-high oil saturation, while for the (b) case productive strata pertain to medium-low oil saturation; c) Comparison of two signal $E_{obs}(t)$ graphs, observed over Southern Surgut oil deposit (1) with $E(t)$, calculated with the formula (1) – graph 5, and formula (2) – graph 6

2. Mathematical model of a geoelectric section with an electrified oil deposit

Western Siberian sedimentary-terrigenous ore complex is an ionic conductor, mainly low-contrast in resistance, whose total electrical conductivity in the foreland basin reaches 2000 S. This geological environment, with its electrical features, can be compared with a massive metal conductor, which can be described in electrotechnology with the three following parameters: $R$ – ohmic resistance, $\Omega$, $L$ – inductance, H, and $C$ – capacity, F [9]. The latter vanishes when it interacts with the electromagnetic field in quasi-stationary zone while the $L$ section inductance’s significance increases.

Concerning TEM-TDEM method in work [8], the interaction between the electroconductive environment with the electromagnetic field of transition processes was considered. Based on the abovementioned, a problem was formulated for the non-stationary (mainly within the limits of the quasi-stationary model) electromagnetic stage field [10]. That problem is solved for both homogenous sections with no deposit and the same section with a hydrocarbon deposit [10].

Now this task has to be solved for a multilayer environment which can be represented by a conductive environment $V$ geoelectrical model with horizontal layers and specific resistances $\rho_1, \rho_2, \rho_3, \ldots, \rho_N$. For
that, aggregate current lines with integral circuit elements $R_1L_1$, $R_2L_2$, $R_3L_3$,...$R_NL_N$ (figure 2,a) must be selected in each layer. Each current line must be represented by a double-pole electrical equivalent contour involved in the idealized current source circuit from the moment of the line AB shutdown. To register the thermopower signal $E(t)$ which is caused by free (or aperiodic) current oscillations of this or that active contour passive double-pole contours $L_q$ (figure 2,b,c), which correspond to measurement inductive sensors put on the bottom surface, are added to their circuits. Such a quadrupole circuit, with the help of which current inducing process in the sections with either a hydrocarbon deposit or without it can be described, allow us to find the forward problem solution method in both cases for the TEM-TDEM method.

In the end, the following equations to calculate mediums’ theoretical signals were obtained: a) without a deposit (geological environment resistor-inductive model):

$$E(t) = \sum_{i=1}^{N} \frac{a^2n}{10^{-6}\sqrt{\pi D}} \frac{\sqrt{\frac{k_0}{L_0}}(D-2r)A B I_0 k_i}{S_i} e^{-\frac{t}{S_i L_0}}, \text{ (\mu V)}$$

where $a^2n$ is receiving square frame’s effective area, m; $L_0$, $L_q$ are section and receiving frame’s inductances respectively, H; $D$ is effective radius of the interaction of field induction and a cylindrical medium, m; $I_0$ is electric current in the AB line, A; $r$ is installation AB-q straddle; $S_0$ is total section longitudinal conductivity, S; $t$ is electromagnetic field inducing time, s; $k_0$ is a coefficient normalizing the current amount in the layer; for a homogenous half-space $k_0 = 1$.

![Figure 2](image_url)

**Figure 2.** Feeding dipole AB filed current lines being contours with circuit element $R_jL_j$ (a): 1 – upper semi space, 2 - stratified conductive medium, V, 3 – datum; b) conducting medium V’s tetrapolar equivalent contour with no hydrocarbon deposits: 1 – current lines and dipole AB’s closed circuit contour, 2 – measuring ungrounded loop’s equivalent contour q; c) a similar conducting medium V’s tetrapolar equivalent contour containing a hydrocarbon deposit as circuit $R_{dep}, C_{dep}$ elements

b) with a deposit (geological environment resistor-induction-capacity model):

$$E(t) = \sum_{i=1}^{N} \frac{a^2n}{10^{-6}\sqrt{\pi D}} \frac{\sqrt{\frac{k_0}{L_0}}(D-2r)A B I_0 k_i}{S_i} e^{-\frac{t}{S_i L_0}} + \frac{k_{dep}}{p_1-p_2} \left[p_1 \left(p_2 - \frac{R_k}{L_0}\right)e^{p_1t} - p_2 \left(p_1 - \frac{R_k}{L_0}\right)e^{p_2t}\right], \text{ (\mu V)}$$

(2)
where \( k_{\text{dep}} \) is the coefficient which normalizes the current’s part in the contour circuit \( R_{\text{dep}} L_0 \) obeys the equation \( k_1 + k_2 + k_3 + \ldots + k_n + k_{\text{dep}} = 1 \);

\( R_k \) is current line ohmic resistance, determined as \( R_k = \frac{U_0}{I_0} \).

For the given active contour solving of the system of homogeneous integro-differential equations and their determinant \( \Delta(p) \) results in the following characteristic roots:

\[
p_{1,2} = -\frac{1}{2} \left( \frac{k_1 R_0^1 + k_2 R_0^2}{L_0} + \frac{1}{R_{\text{dep}} C_{\text{dep}}} \right) \pm \\
\quad \pm \sqrt{\left( \frac{1}{2} \left( \frac{k_1 R_0^1 + k_2 R_0^2}{L_0} + \frac{1}{R_{\text{dep}} C_{\text{dep}}} \right) \right)^2 - \frac{k_1 R_0^1 + k_2 R_0^2 + k_{\text{dep}} R_{\text{dep}}}{L_0 R_{\text{dep}} C_{\text{dep}}}} \tag{3}
\]

where \( R_0^1 \) and \( R_0^2 \) are electrical resistances of the conductive medium layers, laying over the deposit \( R_0^1 \) and under the deposit \( R_0^2 \); \( \Omega \);

\( R_{\text{dep}} \) is hydrocarbon deposit electric resistance, \( \Omega \);

\( C_{\text{dep}} \) is hydrocarbon deposit’s capacitance, \( F \).

Resistor and capacitive models of the electromagnetic field interacting with the environment were compared with the theoretical calculation of the signal \( E(t) \) with the curves \( E_{\text{obs}}(t) \) observed over Southern Surgut oil deposit in Middle Prioby (figure 1,c). Evidently, graph 6 considering the parameters \( L_0, R_{\text{dep}} \) and \( C_{\text{dep}} \) calculated for each section matches graph 1, which was observed over the signal \( E_{\text{obs}}(t) \)’s deposit, almost completely. At the same time, signal \( E_{\text{obs}}(t) \)’s graph 2 for the resistor model does not show the real process of field inducing in a highly conductive section of Middle Prioby sedimentary-terrigenous complex with the oil deposits bedded in it (graph 1). The reason is that the formula describing the resistor model uses only the ohmic parameter \( R \) while, in the formula (2), all the real environment and hydrocarbon deposits’ geoelectric features are considered, such as: \( R_0^1, R_0^2, L_0, R_{\text{dep}} \) and \( C_{\text{dep}} \).

That is why all the attempts of using the resistor model for solving problems of finding oil and gas deposits in Western Siberian highly-conductive sedimentary-terrigenous depositions have been ineffective for many years [10,11]. Even if some implausible parameters of the Middle Prioby section model under matching are used, to match the theoretical \( E(t) \) signal with graph 1 (figure 1, c) is impossible from the position of only the resistor model.

In its turn, hydrocarbon deposit capacity model which is for the inducing electromagnetic field in geological environments similar to Western Siberia and is described by the formulas (1) and (2) can be used in solving the inverse problem – deriving section parameters \( (S_i, S_j) \) and hydrocarbon deposit parameters \( (C_{\text{dep}}, R_{\text{dep}}) \) from the observed values \( E_{\text{obs}}(t) \). Mathematical modelling was performed in advance by means of multiple calculations of the inducing field in the conductive section with and without an applied hydrocarbon deposit to solve this problem successfully (figure 3, a). Particularly, when the parameter \( C_{\text{dep}} \) values are low, its contribution to the total signal is quite low, too, while if the values are high, its effect upon the signal is also high especially on its initial and middle parts.

At the same time, inductivity \( L_0 \) has another feature: when its value increases, inducing process duration also increases simultaneously (figure 3, b).
3. Examples of exploration capabilities of TEM-TDEM-SV technology on the territories of Khanty-Mansiysk Autonomous Okrug and Yamalo-Nenets Autonomous Okrug

Results of the TEM-TDEM-SV technology must be systematically compared to the seismic tomography results, which is based on revealing traps with a huge amount of hydrocarbons, on the stage of prospect and exploration works to estimate the future dislocation for using the TEM-TDEM-SV technology. For example, one of the prospecting areas in Khanty-Mansiysk Autonomous Okrug is examined.

3.1. Sakhalin and Seliyarovsk prospecting areas

A map with the seismic and electrical prospecting combined data is given in figure 4. In particular, in the East of Seliyarovsk area, a supposedly oil-bearing structural trap was located by 2D seismic tomography. At the same time, simultaneously in both od the areas the TEM-TDEM-SV electrical prospecting discovered two-parameter $C_{dep}$ abnormal zones, within borders of which oil deposits of recoverable reserves were supposed to be [10, 11].

Within the electrical prospecting anomaly $C_{dep}$ borders two recommended test holes P-1 and P-2 were decided to be drilled (figure 4). As a result, oil fountains appeared from both of the holes with flow rates of 62.9 and 76 m$^3$/day$^{-1}$ respectively. Further drilling anomaly $C_{dep}$ proved the forecast completely – four of the open productive strata of Neocomian age (early Cretaceous) are really hydrocarbon deposits of a non-structural type. The deposit was named Priobsky and the oil deposit integral contour which was occasionally renewed by the geologists started to be more and more like the electrical prospecting contour which was initially installed on both the areas of the parameter $C_{dep}$'s electrical prospecting contour. At the same time, drilling results showed the revealed seismic trap was not proved to have any physical connection to oil-bearing strata deposits bedded there. That can also be found from the incomparability of the area sizes of the productive strata already opened with the holes and the seismic trap.

3.2. Middle-Pim prospecting area.

Middle-Pim area was estimated as having low prospects according to the geologists’ data (figure 5). According to the 2D seismic tomography data, an extension of a long structure is definitely observed in the southeast direction on the Middle-Pim area. That structure is Ay-Pim swell, which consists of two positive structures: Chigorinskaya and Bittemskaya. Considering the latter can be related to some structural deposits, seismic tomography specialists suggested the geologists drilling two testing holes there (figure 5a).
Figure 4. Comparing the geophysical research results by seismic and electric tomography TEM-TDEM method with the drilling data

As for the second anomaly $C_{dep}$ it was also justified by testing holes 3232, 3237 and 3238, drilled in the Northern part of it from the side of the discovered earlier Tretyakovsky deposit.

In general, given data analysis shows $C_{dep}$ anomalies which are discovered by TEM-TDEM-SV register hydrocarbon gathering regardless of them belonging to the positive structures’ domes or wings or to the basins between the folds.

Figure 5. Exploration results on the Middle Pim area by means of seismic tomography and TEM-TDEM method
3.3. Arctic Region of Western Siberia
In 2013 works with the use of the TEM-TDEM-SV technology were performed at one of multilayer oil and gas deposits of Yamalo-Nenets Autonomous Okrug for the purpose of testing the technology in the conditions of Polar Region. One of the informative parameter $C_{dep}$ graphs is given in figure 6,a for profile 4 as an example. The graph is superimposed on the projection plan on the bottom contour surface of oil and gas layers (figure 6, a).

As can be seen from figure 6, a, parameter $C_{dep}$ intensity gradually increases from the moment when deeply immersed productive strata (2790-2810 m and 2885-2895 m) are intersected by the receivers from the Eastern side of profile 4. Maximum intensity $C_{dep}$ is observed form the moment of measuring signals over the Cenomanian layer PC1 (Pokursky Collector 1), which is 1100-1200 m deep. In the viewpoint piquet 9325 area that stratum’s contour gets broken. Further, along with the profile, it can be seen as protuberances (juts), whose projections on the profiles are registered in the piquet intervals: 9332-9334, 9337-9338 and 9340-9346. Local risings of its values are observed over those intervals on the informative parameter $C_{dep}$ graph simultaneously. PC1 layer has already been ascertained by drilling earlier and its outer contour has been traced by seismic tomography and taken as a correct one, which should be noted.

![Figure 6. TEM-TDEM data interpretation results of the profile 4: a) superposed productive strata’s contours with the graphs $C_{dep}$ and $\rho_t$ in the horizontal plane; b) informative parameter $C_{dep}$'s graphs; c) expected section made on the basis of the TEM-TDEM-SV data interpretation.](image-url)
Parameter $C_{dep}$ correlates with deeply lying productive strata and seismic prospecting data on PC1 layer, which shows electrical prospecting in TEM-TDEM-SV modification is not only connected to with forcedly electrified interbedded oil and gas strata but it also has a capability of registering their integral contour on horizontal plane correctly.

A predicted section down to the depth of 3000-3100 m (figure 6,c) was made based on the detailed analysis of the $C_{dep}$ graph (figure 6,b) and effective sounding depth calculation empirical formula, which was found for the Western Siberia’s conductive environment.

At the same time, measurements $\partial B_z/\partial t$ were performed with the same TEM-TDEM plant but according to the “loop in the loop” method (q in Q) through the deposit central part from the East to the West (pr. 3) and along the intersection of the deposit western contours (pr.1 ). Data processing and interpretation were performed standardly with standard programs that allow converting signals into apparent resistivity curve $\rho_\tau$ as well as into apparent conductivity $S_\tau$ from apparent depth $H_\tau$ ($S_\tau(H_\tau)$) curve. Besides, specific resistances $\rho_\tau$ were calculated and their graphs for the intervals of oil-and-gas bearing horizons (Cenomanian, Neocomian and Jurassic (Middle Jurassic)) were plotted with the use of specified data on prospecting holes logging and 3D seismic tomography (figure 6, a).

As can be seen in all the $\rho_\tau$ graphs, neither a multihorizon field (ex. 3) in general nor its outer contours (WOC and GOC) on profile 1 are not found. At the same time, though, surface metal constructions – pipelines and holes with drilling strings are registered with jumping resistances comparing to their usual values from 5 – 10 $\Omega \cdot m$ to 50 $\Omega \cdot m$, especially for later times (graph $\rho_\tau$ for the Jurassic horizon). Unfortunately, the hydrocarbon deposit resistor model should be stated to fail to find the already known deposit despite all of the abovementioned facts.

The abovementioned examples of seismic and electrical prospecting works prove reasonability of using them together to curtail the amount of drilling hollow holes significantly at the stage of search and prospecting.

4. Conclusion
To solve forward and inverse problems of the TEM-TDEM method, a mathematical tool was used with the use of equivalent electrical tetrapolar contours (schemes), as it describes the transition processes in massive conductors, which conduct electric current in rocks well, in the most complete way. As a result, not only these conductors’ active and reactive (inductive) features $R, L$ are considered but the capacitive parameter $C_{dep}$, characteristic of only hydrocarbon deposit, is determined. Abnormal values of that parameter show that hydrocarbon deposit is present in the geological environment.

Hydrocarbon deposits of both structural and non-structural types were ascertained to be equally found on the studied depths (500-400 m) of the Western Siberian sedimentary-terrigenous complex even in Arctic conditions, where continuous permafrost section has grown up to 500 m.

In the upshot, according to the performed research, TEM-TDEM-SV technology has not only high effectiveness but can also be self-sufficient and unattended in search of oil and gas without any advance information of the section based on seismic tomography and geoinformation system data. The latter allows reducing the overhead significantly at the stage of search and prospecting by sensibly reducing the amount of 3D seismic tomography and minimizing hollow holes drilling.

Acknowledgments
Thanks to Abramovich S.A. for checking mathematical calculations and Proskurnina T.V. for efforts to translate the manuscript into English.
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