INTEGRATED SURVEYING OF ELECTROMAGNETIC PARAMETERS OF A MEDIUM ABOVE SEISMIC UPLIFT WITH THE AIM OF DELINEATION OF OIL ACCUMULATION

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ABSTRACT. We discuss the experience of an integrated application of electrical prospecting such as soundings by counter lines, vertical electric currents soundings, and classical transient in time domain electromagnetic soundings for the examination of seismic uplift. The complex allows using a variety of electromagnetic parameters of a medium for detection of oil deposits. An additional advantage of integrated work is optimization of resources through the use of common elements of receiver-generator arrays and equipment in various modes of electrical prospecting.
Keywords: vertical electric currents soundings, circular electric dipole, counter electrical lines, polarization of rocks, migration of hydrocarbons, local prediction.

In conventional methods of electrical prospecting, the parameter of electrical resistivity is studied that, as a rule, is less informative for hydrocarbon targets. Electrical prospecting offers exploration of rock polarizability as an effective additional method. This is regarded as being proved that polarization increases above hydrocarbon accumulations [7, 9]. For studying polarization parameters, the classical horizontal dipole – horizontal line receiver configuration is commonly used in transient measurements (TDEM-IP technique). In the last decade, the similar modification of these methods such as differentially normalized electrical prospecting (DNME) [9] is often used for study the polarization parameter. This method has demonstrated the significant sensitivity to polarization parameters at the expense of using a three-point scheme for measurements (2 counter horizontal line receiver) and applying special transformations of a signal. However, the common horizontal line is applied in this method as a current circuit. Measurements by means of horizontal dipole – horizontal line receiver and horizontal dipole – 2 counter horizontal line receiver configurations provide information on a rather large volume of a medium between generator and receiver lines. Such generator-receiver configuration is justified in the case of regional profiling with sparse observation points, but it is completely unacceptable if the problem is set to delineate an oil deposit as large as several square kilometers. Other methods with new target-oriented parameters are needed for which dense areal measurements are required.

Makeup of integrated system for electrical prospecting

For a long time we successfully propose a method with a dense network of measurements (with stationary current source) by vertical current electric soundings (VECS). Recall that the VECS method is based on using the essentially new electromagnetic field source such as a circular electric dipole (CED). The CED is formed of 8 lines, the currents (strongly the same) in these lines flow from the center of the circle. Fig.1 demonstrates the scheme of the CED array and the scheme of its measurements. The VECS-M method as a modification of the VECS one is most approved. The former with inductive measurement of $\partial B_z / \partial t$ component, has given good results in surveying hydrocarbon accumulations [2, 4, 6, 8]. The nature of signals in VECS-M and electromagnetic parameters governing the method have yet to be discussed, but it has been shown that this is not associated with change in resistivity of a medium or polarization parameters in the area of hydrocarbon accumulations. Presently, the most interesting theory is that the Earth's magnetic field is involved (with the aid of Lorents' effect) into formation of a magnetic VECS signal in the area of altered rocks over an oil accumulation. In any case, there exists the well-established experimental fact about relationship between an areal VECS-M signal with a zone of oil-saturation [2, 6].

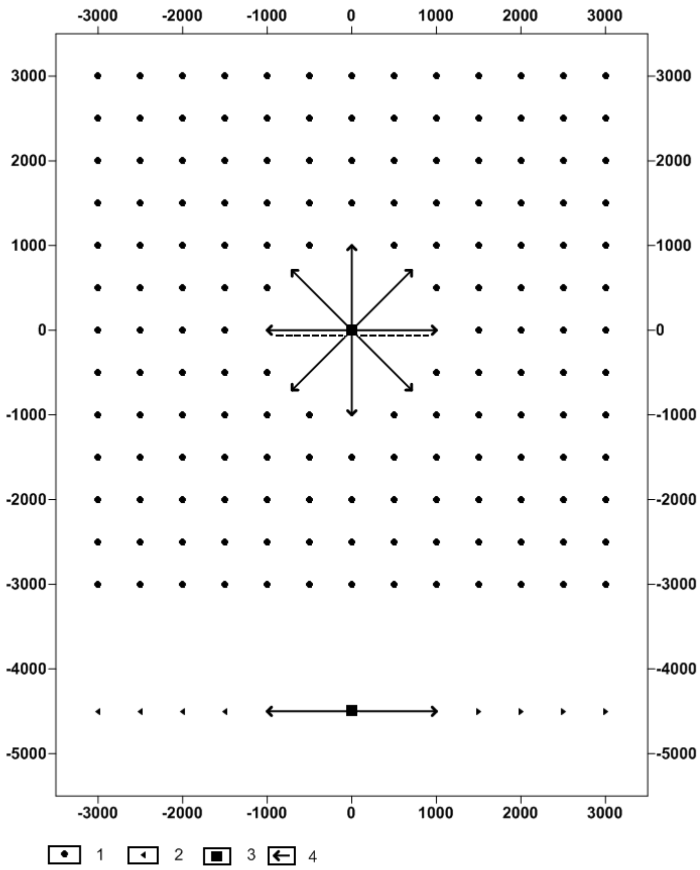

Fig 1. Work scheme - CED (up) и Counter lines (bottom). 1 – VECS stakes. 2- Counter lines stakes. 3-center of CED (Counter lines). 4-current.

We also recall about some features of the fields generated by CED [3,4].

1) The CED field is of the electric type (TM-field) and it is opposed to the current loop field (TE-Field).

2) The magnetic field on the Earth's surface is absent above a horizontally-layered sequence. Hence, the source of a signal recoded by VECS-M is a three-dimensional inclusion of any kind.

3) "Normal" field on the Earth's surface is represented by the radial component of an electric field and it possesses the high sensitivity to high-resistivity layers and to medium polarizability.

Thus, the VECS-M gives us an areal information about distribution of hydrocarbons in Earth. However, this method is expensive enough owing to its expensive equipment and implementation of dense network for measurements. The method should be applied purposefully. It is extremely desirable to anticipate it by means of measurements along profiles intended, nevertheless, for exploration of oil. It seems to be reasonable to use any of TDEM-IP modifications. To the point, their measurements verify also alternative results acquired by VECS-M.

As it was discussed above, horizontal dipole – horizontal line receiver and horizontal dipole – 2 counter horizontal line receiver configurations have disadvantages when works are performed, especially in the case of small oil deposits. Generally speaking, these disadvantages are related to inefficiency of the horizontal line as a source. It is necessary to compensate, at the physical level, the influence of surrounding medium and purely electromagnetic process. The experience of work with CED (where such compensation is nearly absolute) helped us and we knew about the sensitivity of a signal from the radial electric component to parameters of medium polarization. If one attempts to make the field source more mobile, but in doing so to keep the essential portion of CED field properties, then an interesting version will be obtained as it is shown in Fig.2. Here currents flowing in a medium are shown schematically in the case when only the horizontal line is used (on the left), and in the case when two counter lines are

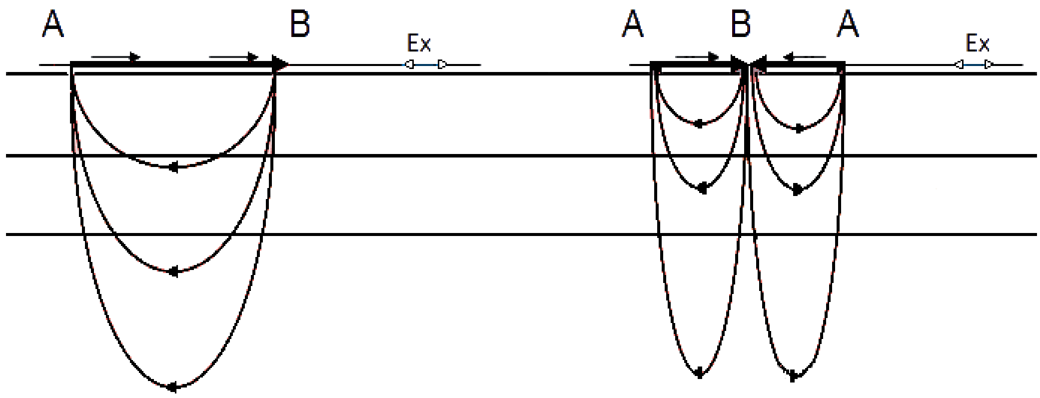

FIg.2. Schematic representation of currents flowing in a medium when working with horizontal line (on the left) and when working with counter line or CED (on the right).

used (on the right). Based on the CED, we use only two lines along a straight line from eight CED lines. In Fig.1, the CED lines aligned with X axis are underlined with dashed line. These lines can be used to form a new source configuration. We term the source consisting of two horizontal lines with equal currents switched on against one another as a counter electric line and the appropriate method applied in this case as sounding by counter lines (SCL). Thus, the counter line is remarkable in that it allows performance of works along profiles on retention of (to some extent) compensating properties of a field arising in a medium excited by the CED. The patent [1] has been granted for the new equipment. As compared with the classical horizontal dipole – horizontal line receiver configuration, the equipment with the counter line is considerably more sensitive to polarization parameters. In comparison with the horizontal dipole – 2 counter horizontal line receiver configuration (as it is in (DNME method), the counter line makes it possible to obtain more localized measurements. In addition, its signals are less subjected to noises. Consequently, SCL is the second component of our system.

For interpretation of SCL data, as well as for data interpretation of DNME and more traditional modification with the horizontal dipole – horizontal line receiver configuration, one-dimensional models of a medium being polarized based on the Cole-Cole formula may be used. For interpretation of SCL data, we widely used programs of the “PODBOR” family for different types of sources and the “VYBOR” program [5].

Besides the one-dimensional modeling, we applied three-dimensional approaches. Procedures for solution of a direct problem based on the Born approximation included in programs of the “PODBOR” family were used as well as programs of outsourced software developers with applying the finite element method.

SCL is intended for measurements along profiles, whereas VECS as an areal method dictates the operation practice. At the first stage, it is efficiently to perform works with the counter line in accordance with operations applied in profiling. At the second stage, in order to delineate a deposit in locality, it is reasonable to mount CED and to carry out a comprehensive operation by the VECS-M method in the places where increase in polarization parameters is observed. Furthermore, the integrated works by the VECS-SCL-TDEM are unified and components of this system are interchangeable. All instrumentations necessary for SCL and TDEM can be parts and components of the VECS equipment.

In addition to operational and economical advantages, there is some more very important feature of the proposed system. When works are carried out by VECS-M and SCL techniques, we obtain deposit outlines using two different electrodynamic characteristics of a medium regarding the presence of hydrocarbons. These characteristics are as follows:

1) Increase in medium polarization according to the Cole-Cole model relying on works by SCL;

2) Epigenetic changes of a medium to which the VECS-M method is sensitive.

When using VECS-M and SCL methods, variations of signals in a medium over a hydrocarbon accumulation cause variations in different electrodynamic parameters of the medium. This has been supported by three-dimensional mathematical modeling. VECS-M signals cannot be explained by anomalous resistivity values or IP parameters. As we said above, here another mechanism provides an explanation. On the other hand, SCL signals fit well in the accepted theory of increase in polarizability of a medium over an oil accumulation [7, 9].

At last, we should say about time-domain electromagnetic sounding (TDEM) as a method by which the distribution of medium resistivity is studied. We also include TDEM methods into our system. In spite of that the distribution of resistivity in a medium is not considered as an independent result useful for determination of the presence of hydrocarbons, we need this information. When interpreting data of operations performed by using SCL and VECS-M techniques, we use the resistivity distribution in a medium. If a customer does not provide such data, we carry out operations by TDEM ourselves, using, for example, the horizontal line - inductive measurement of $\partial B_z / \partial t$ component configuration. What is the way by which we use the information about medium resistivity, we will describe below.

Comparison between modeling results for classical horizontal dipole – horizontal line receiver equipment and equipment with counter line – horizontal line receiver.

We present the results of computer simulation of signals for the horizontal dipole – horizontal line receiver configuration and counter line – horizontal line receiver one. Draw attention to the sensitivity of signals to variation in medium polarizability. The calculations were performed for the five-layer model. Compare signals when the polarizability changed from 0 to 5, 15, and 30 percent. The model parameters are listed in Table 1.

Layer number	Resistivity (Ohm*m)	Layer thickness (m)	Polarizability (%)	Relaxation time (s)	Power in Cole-Cole model
1	20	500	0	0	0
2	10	500	0/5/15/30	0.1	0.5
3	100	700	0	0	0
4	3	200	0	0	0
5	10000000		0	0	0

Table 1. The medium used for modeling.

The medium for which modeling was performed is specific for that region of Tatarstan where we carried out operations. The results of these works will be discussed below. Further we will rely on actual parameters of the equipment, which we used in this work as well as on real capabilities of both generator and measuring devices recorded during performance of these works. We will also be guided by the fact that additional problems in the works always arise when interpreting field data, for example, due to three-dimensional targets. Make use of actual parameters of a medium which have been obtained in the course of the works.

For calculations the length of horizontal dipole was taken as 1500m, the length of the counter line was taken as 1500 m (that was defined by the CED diameter equal to 1500m, elements of which we used in the actual work.). The current flowing along lines was 20 A. Measuring and receiving lines were aligned along the straight line, the distance between centers of generator and receiver lines was 1500 m. The length of the receiver line was 100 m. We were able to gain for the equipment, on the area where works were carried out, to measure a signal in horizontal line receiver up to the level of 10 μV ($\partial B_z / \partial t$ signal was measured to the level of 0.5 μV) with confidence. For plotting, we have chosen signals twice as large as this threshold, i.e., signals were more than 20 μV. The universal "VYBOR-TEM" program was used for calculations.

Given in Fig.3 are EMF for horizontal dipole – horizontal line receiver and counter line – horizontal line receiver configurations. The calculations were performed for media with polarization parameters 0.5, 15, and 30 %. Fig.4 demonstrates the ratio of the signal for a medium with induced polarization to the signal for a medium without induced polarization, as well as signals for horizontal dipole – horizontal line receiver and counter line – horizontal line receiver configurations. The results are given for three media in which the polarization takes values 5, 15 and 30 %. Differences in signals are not given in Fig.4, if the signal is less than 20 μV. Therefore, some curves are shorter than others.

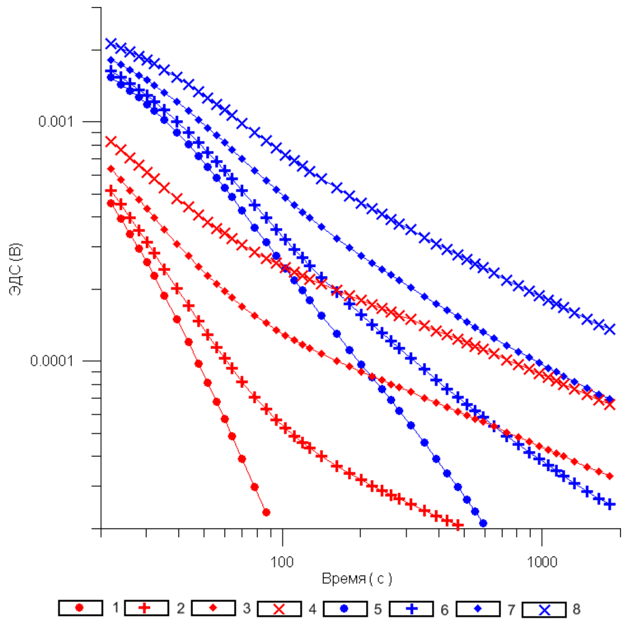

Fig.3. Measured signals for different polarizability.

horizontal dipole: 1-0%, 2-5%, 3-15%, 4-30%,
counter line : 5-0%, 6-5%, 7-15%, 8-30 %.

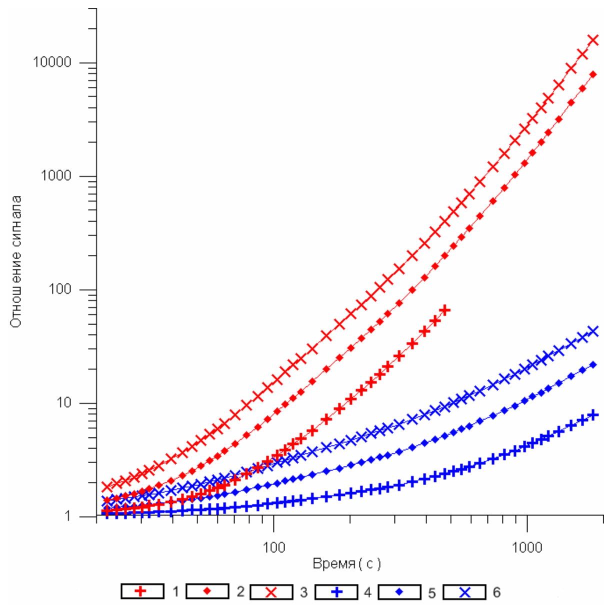

Fig.4. The ratio of signal for a medium with induced polarization to signal for a medium without induced polarization.

horizontal dipole: 1-5%, 2-15%, 3-30%,

counter line : 4-5%, 5-15%, 6-30 %.

From the results of performed modeling it can be inferred that:

1) Absolute value of a signal when working with horizontal dipole – horizontal line receiver configuration is larger than that when working with counter line – horizontal line receiver configuration.

2) Variation in polarization from 0 to 30 % when working with horizontal dipole – horizontal line receiver configuration leads to changes of a signal at late times about tenfold. Variation in polarization from 0 до 30 % when working with counter line – horizontal line receiver configuration leads to change of a signal by about 10000 times (differences become 1000 times stronger).

3) Sometimes, with general considerations, our opponents discuss about CED, and they seem to will discuss about the counter line as though we would build a fire under ourselves and suppress a signal measured by our own equipment. Really, when applying these configurations, we suppress only the inductive (TE) portion of a signal and get nearly clear TM-response [4]. In spite of the fact that a measured signal (in the case of using TM-field) is weaker, its sensitivity to

medium parameters essential for us increases by 100-1000 times. To our mind, this situation is more preferable.

4) We can carry out measurements by means of counter line – horizontal line receiver configuration in regions with the higher level of noises than this is in the case when horizontal dipole – horizontal line receiver configuration is used since the difference in a signal is larger by several times owing to change in polarization of a medium.

5) In working with the counter line, we begin to measure signals caused only by the effect of IP parameters very quickly, i.e., in other words, we efficiently suppress (at the physical level, i.e. in the process of excitation) signals, which are not caused by the effect of IP parameters

6) In working with counter line – horizontal line receiver configuration, we can measure shorter signals. That allows us to speed up the works (to reduce the price of works) or this allows measurements to be more accurate (the number of measured takes is increased).

In fairness' sake we note that we would obtain the same result applying theoretical one-dimensional models for DNME configuration. But such theoretical calculations and field works are very different matters. The counter line possesses the fundamental novelty such as compensation of inductive transient process at the physical level. We consider that suppression of a signal directly, at the physical level, is much more effective in terms of measurement quality than measurement of the signal difference by long measuring lines and subsequent treatment of these signals applying mathematical methods.

Example of integrated surveying of seismic uplift by methods of SCL, VECS-M and TDEM

The works were conducted by "Scientific and Technical Company ZaVeT-GEO" by request of Limited Liability Company "TNG-Kazan'geofizika" in the Tatarstan region. The works were aimed at evaluation of the presence of hydrocarbons in sub-surface positive structure detected by seismic prospecting and delineation of an oil accumulation if hydrocarbons are revealed. The works were carried out not far from a well-known oil deposit and we took advantage of this circumstance for comparison of signals above the oil deposit with those registered in a medium over the seismic uplift being surveyed.

The following techniques were used during these works::

1) Time-domain electromagnetic sounding by means of the horizontal line - inductive measurement of $\partial B_z / \partial t$ component. We considered this stage as preliminary that was necessary for comprehensive processing of results obtained by the methods VECS-M and SCL. The works were conducted along one profile that intersected the uplift being surveyed, as well as the well-known deposit. When working with the help of TDEM method, measurement points $\partial B_z / \partial t$ coincided with measurement points Ex recorded during the subsequent work with counter curves. For determining layer thicknesses, we made use of the data acquired by electrical prospecting. We needed time-domain electromagnetic sounding for: a) development of a layer-by-layer model of a surrounding medium for 3D modeling; b) development of a layer-by-layer model of a surrounding medium for calculation of a residual CED field. We calculated the residual field in order to determine the reliable time range for VECS-M; c) development of horizontally-layered models of a medium prior starting interpretation of SCL data having regard to IP parameters. In interpreting results of SCL works, models of a medium obtained at this stage of works were used as resistivity and thickness of layers.

2) Method of sounding by counter lines. Measurements points Ex from counter lines coincided with measurement points for horizontal line - inductive measurement of $\partial B_z / \partial t$ component configuration. Points at which measurements were conducted were situated at different distances from centers of the counter lines. After measurements, 1D interpretation of medium parameters was executed having regard to polarization parameters by means of the

Cole-Cole formula. The model was constructed from resistivities based on results of the first stage of works by the horizontal line - inductive measurement of $\partial B_z / \partial t$ component configuration.

3) VECS-M method. Measurements were carried out with different observation networks. Maps of signals at various measurement times 10 ms to 100 ms were constructed. During performance of these works, we applied the equipment for sounding consisting of eight current stabilizers GTE-10C, line-operated power supply unit, a control unit, and nine modules of ballast resistors. Measuring assemblages consisted of measuring devices “TSIKL 7” for measurements of the $\partial B_z / \partial t$ component, and measuring devices “TSIKL IP2” for measurement of an electric component of the electromagnetic field. This instrumentation is a component of the “TSIKL” series equipment.

The equipment of the “TSIKL” series is manufactured by the “Scientific and Technical Company ZaVeT-GEO” for more than 15 years. Up to day, the company has produced several hundreds of equipment sets that points to the fact that the equipment set is one of most high-quality sets for performance of works by TDEM. Besides, it is very flexible assemblage of measuring and devices: we worked with all the tree methods using the same set of equipments.

Fig.5 are Results of works by VECS-M for the time 55.7 ms . Green points indicate the profile along which measurements by (TDEM(horizontal line - inductive measurement of $\partial B_z / \partial t$ component) and SCL were conducted. The distance between measurement points was 375 m. The well-known oil accumulation was located to the south of the oil pipe-line shown as the violet line. Four wells in operation and one drilled well were fallen within the area of measurements. The output of wells 1,2 and 3 was more than 20 cubic meters per day and that of borehole 4 was 2 cubic meters per day. The surveyed seismic uplift and the licensed area were located to the north-east from CED. The network of measurements in the licensed area was 150x300 m. The observation set above the oil accumulation was 500x700 m, i.e. rarer than that in the licensed area by ten times. Fig. 5 displays schematically several generators at once. The horizontal line (the part of CED equipment), which we used for the TDEM (in the horizontal line - inductive measurement of $\partial B_z / \partial t$ component form) is shown by light-green color. Two from five counter lines used for SCL are depicted by dark-violet color.

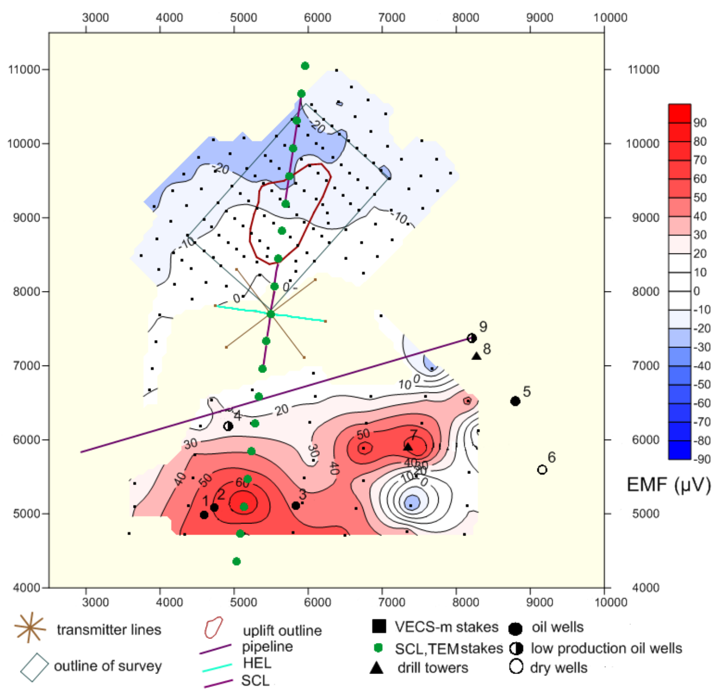

Fig.5. Results of works by VECS-M for the time 55.7 ms. Green points indicate the profile along which measurements by *AB-q* and *ABAMN* were conducted with the step of 375 m.

The experience of conducted VECS-M works demonstrates that the zones of oil-saturation are distinguished by the positive signals (red color on the map) [2, 4 and 6]. Wells 1, 2 and 3 with the output of more than 20 cubic meters per day are located in the zone characterized by a reliable positive signal, well 4 with the output of 2 cubic meters per day is located in the zone of a weak positive signal. To disappointment of the customer of works, the licensed area (uplift being studied) turned to be in the zone of a negative response that indicated the absence of hydrocarbons here. Since the observation network above the well-known oil accumulation was too rare for the VECS-M method, then the map to the south from the pipe-line turned to be not sufficiently exhaustive (Fig.5).

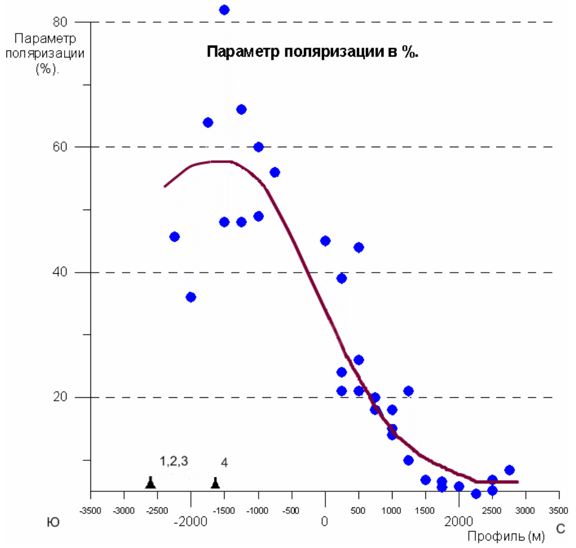

Fig.6. Polarization parameter obtained from results of 1D inversion of SCL data.

Ii Fig.6, the polarization parameter obtained from the results of 1D inversion of SCL data is plotted along the profile. Both resistivity and layer thicknesses have been obtained from the data acquired by the horizontal line - inductive measurement of $\partial B_z / \partial t$ component configuration. We attributed the total IP effect to the second layer, the sequence being matched in accordance with this condition. The coordinates pointed on the plot are shifted from the measurement point to the center of the counter line – horizontal line receiver configurations by 1/3 of the distance between them. As it may be seen from the plot, the polarization parameter increases by seven-ten times in the south direction along the profile. At the bottom of Fig.6, the arrangement of wells 1,2 3 and 4 is shown. Fig.6 also shows that the SCL data agree with both the VECS-M data and prior ones. In the north where the target being studied is located, the polarization parameter is small that evidences the absence of hydrocarbons. On the contrary, in the south where the well-known deposit is located, the polarization parameter is large that evidences the presence of hydrocarbons. It is impossible to explain the measured SCL signals by a change in medium resistivity. The interpretation of data acquired by the horizontal line - inductive measurement of $\partial B_z / \partial t$ component configuration demonstrates the change in the longitudinal conductance along the profile by 10 % at most. In this case, when working with SCL equipment, a signal is changed by ten times, that, certainly, cannot be explained by such insignificant change in the conductivity.

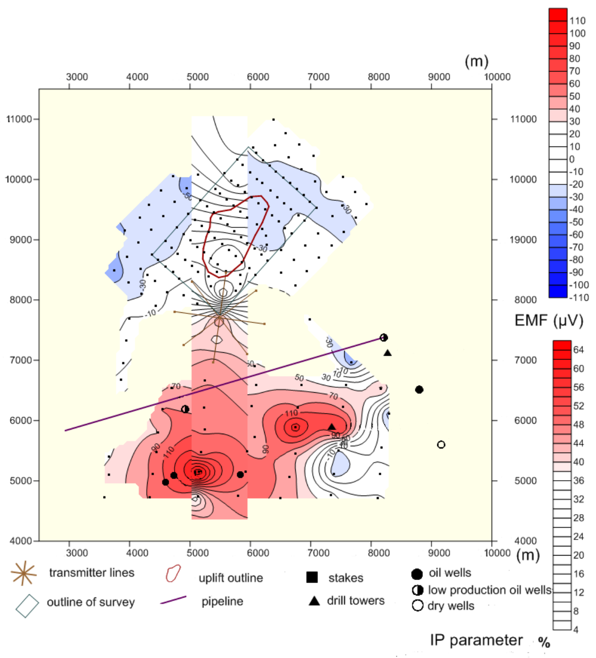

Fig.7. Results of areal works by VECS-M for the time 32.2 ms and the band of isolines for the polarization parameter constructed along the profile of SCL signal measurements.

In Fig.7, the data of areal works by VECS-M for the time 32.2 ms and the band of isolines for the polarization parameter drawn along the profile of SCL measurements are coincident. From the data of SCL measurements, the coordinates of points are shifted from the measurement point to the center of the counter line – horizontal line receiver configuration by 1/3 of the direction between them. This Figure demonstrates that the oil accumulation outlines obtained by two principally different techniques of electrical prospecting such as VECS-M and SCL coincide well.

Discussion of results and Conclusions

Integrated works by different electrical prospecting techniques allows surveying of different electrical parameters of a medium and not just a change in resistivity of a medium.

Works by the VECS-M technique provide outlines of oil accumulations. Such outline is directly conditioned not only by the outline of an oil accumulation itself, but also by the outline of aureole changes in a geological medium above the accumulation. This is very valuable information, but its subsequent interpretation (distribution of geophysical parameters over depth) is hindered owing to the fact that the signal nature is ambiguous. Draw attention to the fact that, as compared to other electrical prospecting techniques, VECS-M *provides information mainly on a medium beneath the measurement point*. It is worthwhile to apply the denser network of measurements in the VECS-M method since a signal provides insignificant information on an averaged medium between the measurement point and CED.

Applying conventional IP parameters increases the interpretation reliability of electrical prospecting data in surveying for hydrocarbons. Because of this, we propose the SCL method in addition to the VECS-M method. For interpretation of SCL data, the Cole-Cole model of frequency dispersion of medium resistivity. We select the SCL technique based on its far greater sensitivity to polarization parameters than it is in conventional IP electrical exploration technique. The SCL techniques provide theoretically justified results understandable to the community of geophysicists. However, signals in SCL, as those in the most electrical prospecting techniques, average the information on a medium between the measurement point and generator and it is not capable to provide such detailed areal information, as it is possible in the VECS-M technique. It is worthwhile to carry out preliminary SCL works along profiles and to set VECS-M method based on the SCL results.

For interpretation process making use of both VECS-M and SCL, the data on the resistivity distribution in a medium are needed. It is necessary to use either data of previously conducted conventional TDEM technique, or to include the TDEM works into the current system of works. We propose different variants of horizontal line - inductive measurement of $\partial B_z / \partial t$ component configuration to be used together with current CED and SCL equipment.

The very important aspect in conducting these works was the fact that similar geophysical results regarding the oil accumulation were obtained based on two *different* electrical prospecting methods such as VECS-M and SCL, as well as on the basis of the distribution of *different* parameters of a medium.

The integrated VECS-SCL-TDEM system is unified because the components forming this system are interchangeable to the extent that the instrumentations for SCL and TDEM can be elements for VECS equipment. Components of receiver-generator circuits are also used in combination.

The new SCL method proposed and tested by us as the IP method exhibits important advantages in comparison with the conventional techniques and even, in our view, in comparison with the DNME technique.

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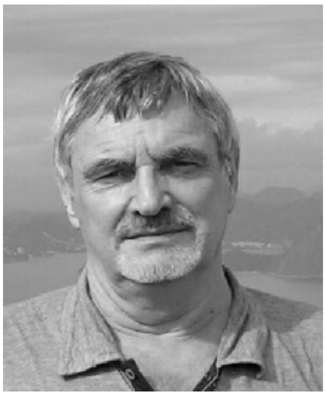

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