COMPARATIVE ANALYSIS OF CONVENTIONAL SEISMIC SURVEY WITH PASSIVE SEISMOELECTRIC EXPLORATION AT GAS CONDENSATE FIELD

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ABSTRACT: The main objective of this work is the comparison of experimental observations by means of the passive seismoelectric method at Bystryanskaya gas condensate field (Krasnoyarsk krai) with the profile acquired by the conventional seismic survey as well as the analysis of the influence of atmospheric electricity on measurements. This article simulates and estimates the influence of atmospheric electricity on the natural Earth's electromagnetic field using calculated data. Measurements by the passive seismoelectric method were carried out in July 2018 using three-electrode facility comprised of a grounded electric dipole with the length of 200 m and a seismic receiver installed at the dipole center. Fields were recorded in the frequency range of 0.1–20 Hz. According to the data of exploratory drilling, the productive formation was at the depth of 2–2.5 km, which corresponded to the signal delay of 1.2–1.6 s. The boundaries of productive formation were detected by the seismoelectric method: 0.15–0.25 of a maximum of cross-correlation function at signal-to-noise ratio equaling to 4.

Keywords: Atmospheric Electricity; Electromagnetic and seismic fields; Seismoelectric Measurements

1. INTRODUCTION

Interaction between seismic and electromagnetic fields at interfaces or in ion conducting media was described in the 1940-s. The first researcher who considered these phenomena in rocks was Ivanov [1]. A theoretical model was developed by Frenkel in 1944 [2] and by Biot in 1956 [3]. They described the occurrence of the electromagnetic field upon elastic mechanic oscillations applied to the crystalline rock. Later Berg et al. [4], Mel'nikov, Bobrovnikov, et al. [5] performed sufficient studies of seismoelectric prospecting for hydrocarbons in Gulf of Mexico and Barents Sea which demonstrated that the seismoelectric method in active variant was capable to detect hydrocarbon anomalies with high probability (up to 70%), which in fact was by two times higher than the existing performances. An active variant of the seismoelectric method is accompanied by high labor consumptions and application of large and powerful sources of electromagnetic and seismic field, thus, at present, such embodiment can be used only for water surveys.

The researchers [6] considered the implementation of seismoelectric effect at a hydrocarbon deposit. Field test of seismoelectric survey was carried out at the site located under a layer of water-saturated clay deposits of Champlain Sea with the thickness of 20 m, known by their applicability for high-level visualization by seismic studies. Seismically induced electrokinetic effects were recorded by means of array comprised of 26 grounded dipole electric field antennas and two different seismic sources, including medium power vibrator (10,000 pounds).

The experimental data were characterized by the fact that the reflected P and S waves observed in seismic records led to the occurrence of electric charges with similar implementations in seismoelectric records. It was demonstrated that electric effects were generated due to the supply of seismic reflections below each dipole at moderate boundary inside the clay by 7 m below the surface. Such phenomena were recently predicted by full-scale seismoelectric simulation and characterized as subtle waves. They were also observed in previous seismoelectric field tests but not measured so accurately and not recognized as an individual seismoelectric mode.

It was theoretically assumed in the work that the observed effect could be considered in terms of physics as a field originated from the separation of moving charges and related with P wave (forward or transformed mode) crossing the subsurface boundary at an angle. On the practical ground, these field results demonstrate that the use of receivers of the electric field in addition to geophones on the surface can provide significantly higher resolutions of seismic reflection in the regions with suitable near-surface layers for the generation of seismoelectric effects.

The researchers in [7–10] presented a

mathematical simulation of seismoelectric effects as a function of various properties of the medium, such as specific resistance, electric conductivity, porosity, water and gas saturation, in addition, the calculations also considered the influence of frequency of the seismic signal on the coefficient of electroseismic connection.

The articles considered seismoelectric effect caused by the impact of a seismic signal on double electric layer. The calculations were compared with laboratory experiments using models simulating processes in actual mediums; during the studies the properties of medium varied, as well as the frequency of the seismic signal being in the range of 10–150 kHz. Comparison of experimental and simulated results demonstrated a high degree of coincidence and confirmed dependence of seismoelectric effect on the properties of medium and frequency of seismic waves which excited interface.

The authors of this study carried out appropriate experiments and demonstrated that it was possible to apply the seismoelectric effect in order to detect hydrocarbon deposits onshore both in passive variant and in semi-active embodiment [11-12], i.e. without an active source of electromagnetic waves, thus reducing significantly weight and dimensions, as well as involved expenses.

This article estimates the influence of nonstationarity of electromagnetic field on measurements, as well as the influence of atmospheric electricity, new measurements are given and compared with already explored profiles by conventional seismic survey at gas condensate deposit.

2. METHODS

The natural Earth's electromagnetic field (NEEMF) is characterized mainly by low frequencies and is concentrated in the range from 10 to 100 Hz. The researchers in [13, 14] reported data on the spectral composition and its daily variations. It should be mentioned that this field is affected by various phenomena: magnetic storms, the oscillation of ions in Earth's radiation belt, braking radiation of charged particles in Earth's magnetic field, meteoric showers, atmospheric electricity, etc. In order to estimate heterogeneity of natural Earth's electromagnetic field which affects hydrocarbon deposits, authors will simulate and estimate the influence of atmospheric electricity on NEEMF and on measurement results by the passive seismoelectric method.

Since both 2D and 3D prospecting procedures are applied in actual field activities, then simultaneous use of several grounded dipoles can

be justified aiming at the decrease in labor consumptions. In our recent works [11] we demonstrated that during studies of hydrocarbon deposits by passive induced polarization using natural Earth's electromagnetic field (NEEMF IP) induced polarization was observed at the edges of a productive anomaly.

This could be attributed to the existence of pyrite above the deposit as well as evidence processes occurring in the deposit. It was demonstrated in [11] that the use of two adjacent dipoles could add the information required for the detection of hydrocarbon deposit without increased labor consumptions. Hence, estimation of the influence of atmospheric electricity on results obtained both by the passive seismoelectric method and by NEEMF IP is necessary for correct interpretation of field experiments.

Let us perform the following simulation in order to estimate the influence of atmospheric electricity. A source of primary NEEMF will be presented by irradiating electric dipole simulating atmospherics with momentum $P = I \cdot dx$, located on the surface of half-space with the dipole coordinates: $z = 0, x = 0, y = y$ (Fig. 1a).

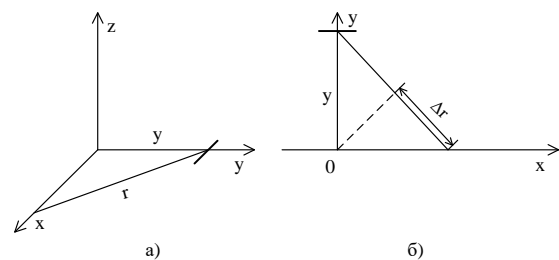a)   б)

Fig. 1. Half-space surface and dipole coordinates.

The medium at $z > 0$ is air, and at $z < 0$ the medium is with conductivity σ and relative dielectric permeability ε. The electric field of grthe ounded electric dipole on the surface of conducting half-space is described as follows:

$$E_x = \frac{P}{2\pi\sigma_1 r^3}\left[\left(\frac{3x^2}{r^2} - 2\right) + \exp(-k_1 r)(2 + k_1 r\right.$$
$$\left. - 3\frac{x^2}{r^2} + \frac{k_1 x^2}{r}\right) - \exp\left(\frac{k_1 r}{\eta}\right)(\eta$$
$$\left. - \frac{3\eta x^2}{r^2} - \frac{k_1 x^2}{r}\right)] \qquad (1)$$

where $k_1 = i\sqrt{\omega^2 \varepsilon \mu_0 + \omega \mu_0 \sigma_1}$ is the wave number of half-space; ω is the frequency of electromagnetic field; μ_0 is the vacuum magnetic permeability; $r = \sqrt{x^2 + y^2}$; η is the anisotropy coefficient.

For isotropic space, the anisotropy coefficient is 1 and the horizontal component of electric constituent will be determined as follows:

$$E_x = \frac{P}{2\pi\sigma_1 r^3}\left[\frac{3x^2}{r^2} - 2 + \exp(-k_1 r)\right.$$
$$\left. \cdot (1 + k_1 r)\right] (2)$$

Let us analyze variation of dipole field phase as a function of spatial shift Δr for various coordinates x, y, and frequencies, Fig. 1b) For each x the following coefficient is obtained:

$$\sigma_x^2 = \frac{1}{n}\sum_{n=1}^{n}\Delta\varphi_n^2 \quad (3)$$

where $\Delta\varphi_n$ is the phase shift for these x, y, and frequencies $f = f_n$; n is the number of analyzed frequencies: $f_1, f_2, \ldots f_n$.

The calculated data are as follows: the half-space conductivity is $\sigma_1 = 10^{-2}$; the relative dielectric permeability is $\varepsilon = 10$, y = 1,000; 2,000; 3,000; 5,000 m; x is from 0 to 1,000 m; f is from 1 to 20 Hz. The calculations were performed by Eqs. (1–2).
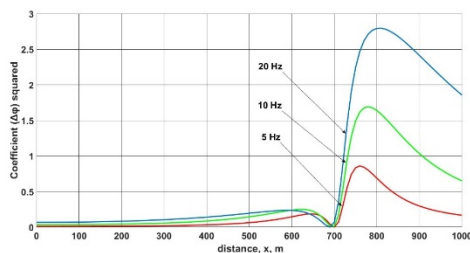

Fig. 2. $(\Delta\varphi)^2$ as a function of x for various frequencies.
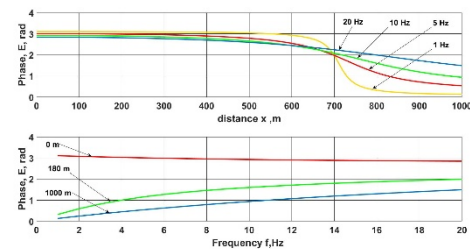

Fig. 3. Phase as a function of x for various frequencies.

According to the plots 2–3, when the coordinate x is displaced to 600 m, the phase shift of field electric component in the receiving dipole varies rather slowly with regard to the metering device. In this case, it is possible to assume that the primary field is conventionally homogeneous. However, the phase shift depends strongly on the distance to the emitter.

Thus, for instance, when a local thunderstorm occurs near the observation point, the field spatial heterogeneity will be more significant. In any case, in order to minimize this effect, it is required to consider for weather conditions during the

interpretation of observation of seismoelectric effects, since upon application of several dipoles or measurements during various weather conditions, the degree of seismoelectric effect can be different due to natural Earth's electromagnetic field.

The data acquired by conventional seismic survey and the observations using seismoelectric effects in passive fields at Bystryanskaya gas condensate area (Krasnoyarsk krai, Minusinsk district) are compared below. In Fig. 4, the dashed lines highlight the deposit according to exploratory drilling (black dots 10-P, 15-P, 5-P), including assumed depth. Yellow dots highlight the profile of observations both by conventional seismic survey and seismoelectric method in 2018.

Fig. 4. Observations using conventional seismic survey and passive seismoelectric method.

The observations were performed by conventional nondestructive seismic survey using single KEM-4 source with the impact force of 100 t, the reflected signals were received by telemetric seismic station, OOO SibGeofizPribor. Fig. 5 illustrates the flowchart of measurements.
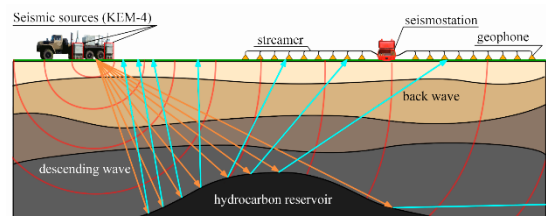

Fig. 5. Flowchart of measurements using a conventional seismic survey.

Recently the seismoelectric effects were observed at this deposit [11], however, during the observations, it was impossible to compare the acquired results with the conventional seismic

survey. In July, 2018 this deposit was used for activities using passive seismoelectric method along with the profile with an already explored geological section which allowed to interpret more accurately the observations. The seismoelectric effect in passive fields along the same profile was observed using a conventional three-electrode facility illustrated in Fig. 6.
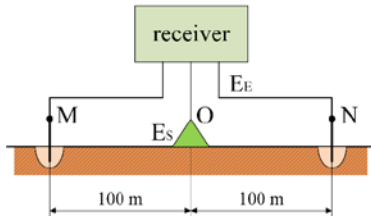

Fig. 6. Flowchart of measurements using the passive seismoelectric method.

The facility is comprised of the grounded electric dipole with the distance between the grounded points of 200 m, and three-component seismic receiver GS installed in the center. The measurement time at a point was 180 s. The distance between the observation points was 100 m. Receiving electrodes were nonpolarized VITR electrodes comprised of ceramic tubes filled with copper sulfate solution and immersed copper electrode. Such design eliminates the parasitic effect of induced polarization at the electrode–nonconducting medium interface.

3. RESULTS AND DISCUSSION

Fig. 7 illustrates the results of observation using passive seismoelectric method and a conventional seismic survey.
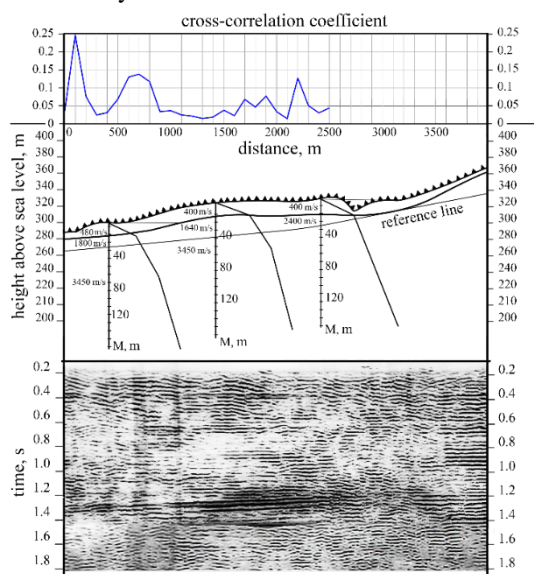

Fig. 7. Observations using passive seismoelectric method and a conventional seismic survey.

As follows from the data of the conventional active seismic survey, a seismic complex is observed after 1–1.6 s, which according to exploratory drilling contains gas saturated sand at the depth of 1500–2000 m.

At the same time, the experimental seismoelectric observations demonstrate that the maximum of cross-correlation function between seismic and electric fields is observed in the vicinity of P-4 well in the spot with low gas yield, that is, at the boundary where the sand contains minimum content of hydrocarbons which was theoretically predicted in [12]. The edge is marked by 0.25 of a maximum of cross-correlation function, further peaks indicate at heterogeneities in the deposit itself, which is evidenced by the data of the seismic survey.

The cross-correlation functions peculiar for the deposit center and edge are illustrated in Fig. 8 a, b.
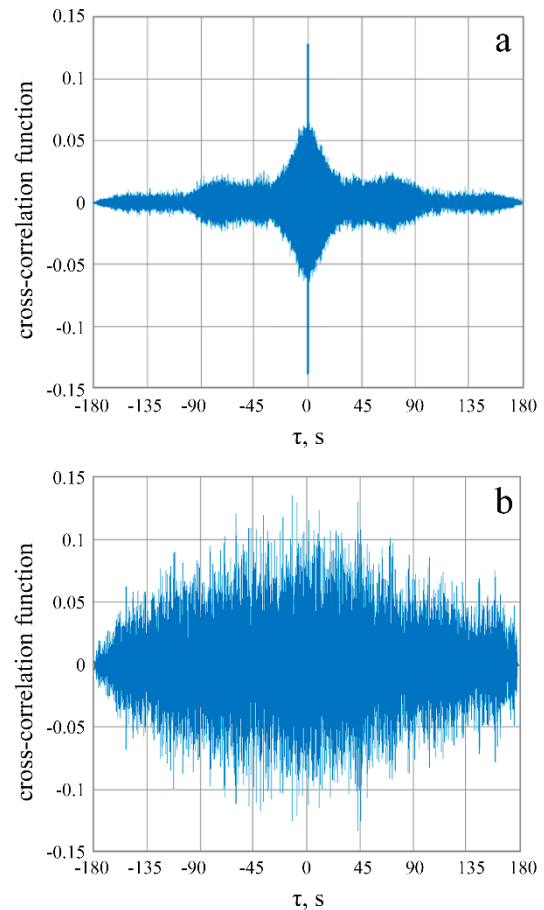

Fig. 8. Cross-correlation: a – deposit edge, b – deposit center.

As can be seen in the plots, the deposit edge is highlighted by peak whereas the cross-correlation function in the deposit center has no peaks, which evidences that there is no correlation between the signals received by electric dipole and seismic sensor, that is, in this case, there are completely

independent signals. The peak at the deposit edge evidences that these processes are mutually dependent and interaction occurs at the interface of hydrocarbon deposit.

4. CONCLUSION

Analysis and quantitative estimation of the atmospheric electricity influence on measurements demonstrated that a source of atmospheric electricity located at the distance in excess of 600 m from measurement profile actually did not effect the seismoelectric method, in that case, it was possible to neglect heterogeneity of NEEMF. If a source of atmospheric electricity was closer than 600 m than it contributed significantly both to the signal amplitude and to its phase composition, which could lead to incorrect interpretation of observed data. Hence, during prospecting in locations with high thunderstorm activity, it would be reasonable to take into account the influence of atmospheric electricity.

This article demonstrates that the passive seismoelectric method facilitates detection of hydrocarbon accumulations at the depths up to 2,000 m, and authors of this study believe that it is an important argument in favor of the passive method, since in this case the respective labor consumptions are minimum in comparison with those required for active seismoelectric method when active sources of electromagnetic and seismic fields are used, the latter method can be applied at this stage only for water surveys. And the passive seismoelectric method can be applied in hard-to-reach places or rugged terrains (wetlands, taiga, mountains, etc.) for primary evaluation of prospectivity of various areas.

According to the authors, the use of this method of searching for hydrocarbons is possible with the initial detection of anomalies and their contouring, followed by detailed supplementary exploration using standard methods, which will reduce the labor costs and the cost of prospecting.

5. ACKNOWLEDGMENTS

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