Prospects for using the reflected electromagnetic wave-CDP method to search for small geological oil-and-gas prospective objects

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Abstract. The publication presents the key results of testing the reflected electromagnetic waves method at one of the fields of the Yamal-Nenets Autonomous District, including a description of the field research methodology, the principal aspects of the use of sounding equipment for subsurface studying based on the GROT-12 series deep ground-penetrating radars, as well as comparative examples of successful experience in the electromagnetic field processing using software designed for seismic data processing. For the first time in the world practice, the depth of the study averaging 500 - 550 meters, was achieved and confirmed by the speed characteristics of the medium.

Presumably, the indisputable fact at present is the wide use of seismic exploration in the search for hydrocarbon deposits (HC), in particular the CDP seismic reflection method, as the main geophysical method. The amplitudes and travel times of the reflected waves recorded by acoustic methods carry information about the properties of the object of interest (reservoir, trap, etc.), i.e. the depth of occurrence, geometry in plan view, and to some extent, the prospects for oil and gas productivity. However, the productivity forecast (i.e. determination of the fluid content ("water", "oil", "gas", "condensate") of a prospective object only according to data of CDP seismic reflection method, before drilling, has an approximate, probabilistic nature. Now, with the use of modern software and algorithmic solutions, CDP seismic reflection method allows to estimate the geometry of the reservoir to a high precision, but the lithology, fluid content and filtration-volumetric parameters in the absence or shortage of drilling data are determined very ambiguously.

To resolve the existing uncertainties, along with the use of acoustic parameters, it is necessary to have additional information about the specific electrical resistance and relative electric permittivity of the layers, with a resolution at that, comparable to the seismic acquired with CDP reflection method.
Electromagnetic prospecting methods, such as transient electromagnetic sounding (TEM sounding) or magnetotelluric sounding, allow one to estimate the electrical resistivity of the section (apparent longitudinal conductivity), but these methods are not wave-based and have a significantly lower resolution compared to CDP seismic reflection method. A modern alternative to standard electrical exploration is the reflected electromagnetic waves (REW) method.

In contrast to the acoustic properties, the electrophysical properties of layers saturated with HC create much more marked contrasts in the parameters (specific electrical resistance, relative electric permittivity), which is also reflected in the characteristics of the wave field of the reflected electromagnetic waves [2].

As an example, Figure 1 shows a processed radargram (section of dielectric permittivity) obtained along the geophysical line from acquisition trials of 2D REW method (Yamalo-Nenets Autonomous District). In-line movement was carried out with a constant separation base, the excitation and registration of electromagnetic (EM) waves were carried out with the use of modern, mass-produced equipment of the GROT-12 series ("TAIMER" LLC). At the top of the radargram, two marks (see Figure 1) indicate the boundaries of the river that was crossed during the work, and at the end of the profile (on the right of the radargram) we can see the power lines crossed. According to the results of the acquisition trials analysis, there was a strong signal attenuation in the area starting from depths of more than 60 meters, as well as the noise effect.

Figure 2 shows the waveform of the signal received at the starting point of the acquisition trials profile, and also a fragment of the radargram with a length of just under 3 km. The waveform is characterized by a pronounced dispersion in the form of a "tail" from a depth of 60 meters at an average speed in the ground of 5 cm/ns. This behavior of the recorded signal indicates an increased conductivity of the medium under study.

Figure 1. Radargram at the average permittivity index 9 (V_{ground} = 5 cm/ns) for the experimental GROT-12 receiver with an antenna 30 m in diameter and a 64 kV transmitter with an antenna 50 mm in diameter.
Thus, the reflected electromagnetic waves method, being an innovative ground-penetrative radar technology based on the most advanced domestic developments in the theory and practice of georadiolocation, is characterized (in contrast to the previously used domestic and foreign ground-penetrative research methods, mostly engineering) by high penetration (hundreds of meters) and resolution. The basis of the georadiolocation method in the study of large and small depths is the shock excitation of the radiating antenna by a gas or solid-state generator of high-voltage nanosecond pulses. Such signals have a number of obvious advantages over broadband signals (with linear frequency modulation) or noise-like signals (with phase modulation). In particular, the aperiodic videopulse is devoid of the main drawback (typical of the above-mentioned signals) associated with the poor resolution of reflected electromagnetic oscillations from nearby subsurface inhomogeneities of the medium. In the spectrum of the sounding aperiodic videopulse there are both significant high-frequency and low-frequency components, which provides both a good spatial resolution and a large sounding depth [1]. Figure 3 shows the different forms of sounding electromagnetic pulses in comparison.

![Figure 2](image1.png)

**Figure 2.** Fragment of the radargram wave image registered along the acquisition trials profile of 2D REW method, and an example of the waveform of the signal.

![Figure 3](image2.png)

**Figure 3.** Examples of different forms of sounding signals used in georadiolocation: (a) oscillating pulse with attenuation, (b) aperiodic pulse. The leading edge of the pulse is highlighted in black, and the trailing edge is highlighted in gray.
At present, due to the improvement of the hardware base, the necessary prerequisites for the implementation of the reflected electromagnetic waves CDP (REW CDP) method into the practice of geological exploration for oil and gas have emerged. There is a prototype of REW CDP method – ultra-wideband subsurface radiometry based on domestic deep radars of the GROT series (without frequency and time gating), and there is a technical possibility of using powerful monopulse sources in the mode of accumulating impacts with a frequency of at least 1000 pulses per second. The schematic diagram of the hardware and methodological complex of the electromagnetic (EM) wave prospecting by REW CDP 2D method is shown in Fig. 4.

In March 2020, at one of the fields in the north of Western Siberia (Nadymskiy sub-district, Yamal-Nenets Autonomous District), for the first time in world practice, acquisition trials testing the REW CDP 2D technology using a 10-bit analog-to-digital converter (ADC), 26 kW monopulse source, and 50-meter source and receiving antennas were successfully conducted. The equipment was moved sequentially using a non-metallic cable, and an all-terrain vehicle was used for profiling. The distance of the receiver and transmitter in the REW CDP sound ranged from 100 to 750 m, in the REW common source point (CSP) sound this distance ranged from 100 to 840 m, the movement of the blocks between the measurement points – 10 m, the distance between the receiving points and, accordingly, the excitation points while profiling according to the single profiling system was on average from 2 to 3 meters.

The technological feature of the beginning of the EM waves registration was its synchronization with the arrival time of the head, refracted wave.

The main task of processing the EM wavefield was to obtain the conditioned resulting materials of the REW method, which later had to be linked with each other and with seismic materials. The purpose of the processing in this case was to select and expediently apply the procedures to the REW method materials that are successfully applied to seismic data. Thus, the possibility of using a standard software package designed for processing seismic survey materials, in particular, the SeisSpace/ProMax processing complex (Halliburton/LandMark, USA), for processing electric magnetograms was tested.
Figure 5. The REW CDP sound. Examples of CDP electric magnetograms at different stages of the processing.

Registration in the field was carried out on an open channel at the maximum input gain, the registration start time corresponded to the arrival time of the head wave. This explains rather unusual (for a field seismologist) appearance of the initial electric magnetograms (EMG) (see Fig. 5a-c). It seems as if static corrections corresponding to the times of the first entries have been introduced to the traces. For EMG tracks, a scaling factor of 1:1000000 was used, i.e. 1 ns is equal to 1 ms, hence 1 MHz = 1 Hz, 1 thousand km/s = 1 m/s. There was no mechanical combination of 50 accumulations to get a CDP trace – the entire array of primary traces was accepted for processing, and a fictitious geometry was assigned with a step of 0.2 m (50 traces for an interval of 10 m). This was done for reasons of ease of visualization and processing efficiency [2].

As we can see, even on the most primary ones, without accumulation and low-frequency filtering of data, the reflected waves are viewed to a depth of about 550 m, and after applying bandpass filtering, spatial filters, and linear kinematics output (inverse LMO), the tracking of the EM reflected waves time-distance graphs become quite confident (see Fig. 5d-f). Figure 6 shows, as an example, the EMG before (Figure 6a) and after (Figure 6c) the input of the kinematic corrections (forward NMO) obtained in the result of the velocity analysis using vertical velocity spectra (Figure 6b).
Figure 6. The result of the calculation, analysis and application of the velocity function $V_{CDP}$ to the EMG CDP sound.

The inversion character of the vertical spectrum of CDP velocity is rather natural due to the influence of permafrost. Permafrost rock mass in its electrophysical properties is close to dielectric, because the speed of EM waves in it approaches the fundamental constant – the light speed.

In the result of the performed acquisition trials, convincing evidence was obtained for the possibility of initiating, recording, and office processing of reflected EM waves using methodological schemes, principles, and processing tools typical for the CDP seismic reflection method in petroleum exploration. An average propagation depth of 550 m was achieved and confirmed, which corresponds to a $t_0$ values of approximately 7,500 ns, while the maximum depth of sounding, corresponding to the final registration time of 10,000 ns, was approximately 700 m.

There is every reason to believe that after solving a number of technical problems to improve the equipment, the world's first hardware and methodological complex of electromagnetic (EM) wave prospecting by REW CDP 2D method with a propagation depth of 2.5-3 km, based on the use of towed streamers and suitable for work in northern latitudes, can be developed.

References

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