Mapping the fractured zones of the carbonate-haloid rocks in Eastern Siberia by seismic and electromagnetic survey

I V Buddo 1, I A Shelokhov 1, A S Smirnov 2,3 and N V Musjurkejeeva 1

1 Institute of the Earth’s Crust of the Siberian Branch of the RAS, Russia
2 Gazprom Geologorazvedka, Ltd, Russia
3 Industrial University of Tyumen, Russia

E-mail biv@crust.ru

Abstract. The article deals with the approaches to mapping the fractured zones in the lower Cambrian carbonate-haloid rocks within the Verkhneinsk neotectonic roof raise of the south-east periphery of the Siberian craton. The experimental data shows that broad–azimuth seismic prospecting (3D modification) makes it possible to map the fractured zones by a number of criteria including amplitude anomalies, no-coherence zones, spectral decomposition and scattered waves anomalies. In turn, near-field transient electromagnetic sounding (TEM) using the structural model based on the drilling and seismic prospecting data makes it possible to evaluate the reservoir’s properties (i.e. electrical resistivity) and saturation type. Integration of the geophysical methods of different physical backgrounds increases the validity of the fractured zones allocation for the carbonate-haloid rocks in Eastern Siberia.

1. Introduction

In connection with the growing interest in the research on the carbonate reservoirs in Eastern Siberia, there is an urgent demand for an effective set of geophysical methods providing valid information on the reservoir rock structure. One of such reservoirs is Kovykt gas-condensate field (KGC). Because of the complex structure of the carbonate reservoirs, the standard approaches to the geophysical data interpretation are not always effective. KGC gives a bright example of an integrated approach to the complex geological-and-geophysical information analysis [1, 2, 9, 11, 14]. The paper considers the approaches to the interpretation of the data obtained with broad-azimuth seismic prospecting (3D modification) integrated with near-field transient electromagnetic sounding (3D mode), used at KGC for the project of Gazprom Geologorazvedka, Ltd.

The KGC geological section is characterized by geologically-complicated drilling conditions. All the stratigraphic levels of the sedimentary cover section contain reservoir horizons hindering the drilling process [9].

Comparison between the intervals of the high-flow-rate carbonate beds opened up with deep well-drilling, and seismic sections in the target areas shows that the brine-filled zones are associated with the highly-fractured carbonate rock zones of the saliferous rock mass [2, 11].

The physical-geological model of the brine-filled horizon based on the connection of the anomaly section zones with the haloid-carbonate rock zones is considered to be most acceptable. In turn, the lower Cambrian carbonate reservoir horizons are promising sources of natural gas [5, 10], which
enhances the importance of studying the fractured zones that, along with the cavernosity, control the reservoir capacitive storage volume.

2. Materials and methods

2.1. Near-field transient electromagnetic sounding

It is known that TEM sounding is characterized by high sensitivity to the well-conducting intervals of the section against the background of the low-conductivity rocks [9]. The KGCF reservoir horizons are such highly conductive intervals because of the high mineralization of the water fluids (up to 400 – 600 g/l) [11]. The physical and petro-physical background predetermines the effectiveness of TEM sounding in mapping the fluid-saturated fractured zones i.e. lower Cambrian carbonate reservoir rocks, at different stages of the geological survey [2].

In turn, the thin-layer inversion of the TEM-sounding curves with the allocation of the Kelor, Bilchir, Birka, Atov, Christophorov-Balykhtyn, Osa and Parvfenovo reservoir horizons makes it possible to evaluate every horizon’s electrical resistivity (ER). When applying the inversion, the horizon’s ER is determined within the structure frame fixed on the basis of the 3D seismic survey and the drilling data. ER of the enclosing deep-lithified lower Cambrian-Vendian rocks (dolomites and salts) is fixed at 500-800 Ohm. The thin-layer resistivity sections as well as the longitudinal impedance and conductivity charts obtained for the reservoir horizons based on the inversion results, characterize the horizons’ capacitive properties and saturation type (Figure 1).

2.2. Broad-azimuth seismic survey (3D modification)

The high-resolution broad-azimuth seismic survey (3D modification) is effective in the detailed study of the section structure peculiarities, as well as in the fractured zones prediction [13]. In particular, the analysis of the amplitude characteristics as well as the analysis of the seismic-record coherence enables us to add the tectonic peculiarities (including the faults) and the fractured zones' positions to the sedimentary cover structure model. The anomaly reservoirs are usually characterized by the seismic-record high-amplitude zones, while the fractured zones are well-observed in the coherence cubes. Integrated with TEM sounding, the analysis of the seismic-record attributes makes it possible to map the anomaly reservoirs in the lower Cambrian sediments of KGCF [2] (Figure 2).
2.3. **Spectral decomposition of the wavefield**

Spectral decomposition is a widely-known method of defining and studying geological objects in the seismic wavefield by localizing signal components at the assigned frequencies.

Continuous wavelet transform (CWT) has been chosen as a decomposition technique. The appearance of the wavelet notion facilitated the development of the continuous wavelet transform, a new direction in the area of signal analysis. The research applies decomposition in a series of mother-signal-formed wavelets rather than in harmonic functions [15]. The continuous wavelet transform algorithm includes calculation of the discrete coefficient of the correlation between the dominant-frequency wavelet and the seismic trace [4]. The output of the obtained frequency-time spectrum is the traces reflecting the energy distribution by frequency.

The frequencies are selected based on the results of the amplitude-frequency spectrum analysis for the initial time-domain cube. In the research, frequencies of 10, 20 and 40 Hz have been selected, with further calculation of the attribute cubes.

![Figure 3. Map of RGB mixing on the Kelor horizon roof (spectral decomposition of the wave field).](image1)

![Figure 4. Map of the scattered wave energy on the Kelor horizon roof.](image2)

The obtained cubes of the spectral characteristics can be used both for the standard attribute analysis and for RGB-mixing interpretation. The latter procedure is that every input attribute is assigned a color code: red, green or blue. The change of the attribute value is described by the color saturation degree. The output attributes merge into a map with three amplitude values in every point [16] (Figure 3).

2.4. **Scattered waves**

As it is known, the Earth crust is a fractured rock mass with a zonal fractured rock structure [8]. It is the fractured multilayer stratified distribution of the natural reservoirs in the bed sedimentary cover in which every interlayer of the fractured carbonate reservoirs alternates with a fluid-resistive one, that is the most complicated object for the saturation and filtration capacity properties (FCP) prediction because there is a possibility of ambiguous interpretation of the results.

The scattered wave field is formed by a fracture aggregate i.e. an anisotropic void space, and it is of an interference character depending on the discontinuity distribution rather than on the rock acoustic characteristics.

In order to map the fractured zones in the carbonate-haloid mass, seismic data interpretation is used. The first stage of the interpretation excludes the undesired influence of the upper section part (USP) including the permafrost section, the sources of the influence being the karst development zones in the Ordovician section and the local linear and isometric plicated dislocations (salt tectonics). Then, the focusing techniques of seismic-data processing are used to obtain the target object section i.e. the scattered wave energy based on which, the alternating fractured-cavernous complex-structure inter-salt layers are detected, studied and differentially characterized (Figure 4).
3. Physical-geological model of the reservoir horizon of the haloid-carbonate section

Modeling of the fractured medium is often complicated by the lack of the information on the rock fracturing in the target section interval. One can only suggest that the fracturing is caused by the disjunctive processes taking place in the target section.

In general, it is definitely true that fracturing causes a rise in the diffuse oscillation background, and a decrease in the elastic wave velocity. It is also of importance that in case of the one-directional fractures and the fractures’ dominant orientation, there is an increase in the azimuth anisotropy of the velocities that change depending on the angle between the fracture strike and the wave propagation direction.

In natural conditions, fractures occupy a small part of the rock volume and therefore, do not change the substance density. However, when appearing, they significantly change the rock strength and with this, the elasticity modules as well as the longitudinal and transverse velocity values.

At the same time, the fluid elastic properties correspond to oil or gas water properties, while the elastic properties of the fracture-surrounding medium correspond to solid mass data.

The main feature of the geo-electrical model of the rocks of the carbonate-haloid (and under-salt) rock complex is the structure that can be presented by the combination of two components, the crystalline medium and the fluid system (oil-field water and hydrocarbon fluids saturating the interstice space).

The universal way to evaluate the rock resistance is the use of the so called volumetric porosity parameter in accordance with the known formula (1) by Dakhnov-Archi [9]:

\[
C_t = \frac{1}{\alpha} C_w \varphi^n S_n C
\]

(1)

It is difficult to estimate the real average statistical parameters of the carbonate-haloid complex’ reservoir horizons because the horizons’ real thickness does not correspond to the fluid-loss and inflow intervals determined by the drilling results, as the latter are always higher. To evaluate the horizon porosity, special research on the core material as well as complex interpretation of the well-log data are needed [9].

4. Research results and analysis

Based on the results of the seismic-record attribute calculation and TEM-sounding inverse problem solution, the charts illustrating the fractured zones appearance in the Kelor horizon (correspondingly, the absence/presence of the fluid-loss intervals), have been plotted (Figure 5).

Figure 5. Distribution of the seismic-record attributes and longitudinal conductivity of the Kelor horizon (3D TEM sounding) along the profile lines of the wells 53-74: 1 – scattered component amplitude, m.u.; 2 – amplitude of the frequency component 20 Hz; 3 – longitudinal conductivity, S; 4 – amplitude of RMS attribute (root-mean-square amplitude), m.u.; 5 – coherence, u.f.
For the purpose of the analysis convenience, the attributes are grouped by the wells and are presented in Figure 6, and the calculated coefficients of the parameter correlation are presented in Table 1.

|                          | RMS attribute amplitude, m.u. | Frequency component amplitude 20 Hz | Longitudinal conductivity, $S$ | Dissipated component amplitude, m.u. | Coherenc e, u.f. |
|--------------------------|-------------------------------|-------------------------------------|---------------------------------|--------------------------------------|-----------------|
| RMS attribute amplitude, m.u. | 1                             | 0.47                                | 0.29                            | 0.64                                 | 0.75            |
| Frequency component amplitude 20 Hz | 0.47                          | 1                                   | 0.78                            | 0.76                                 | 0.04            |
| Longitudinal conductivity, $S$ | 0.29                          | 0.78                                | 1                               | 0.88                                 | 0.06            |
| Dissipated component amplitude, m.u. | 0.64                          | 0.76                                | 0.88                            | 1                                    | 0.51            |
| Coherenc e, u.f. | 0.75                          | 0.04                                | 0.06                            | 0.51                                 | 1               |

The obtained results allow us to draw the following conclusions:

1. The RMS amplitude has low coefficients of correlation with the other attributes (except the dependent coherence) and does not directly reflect the fractured zones presence in the wells.

2. The seismic-record coherence attribute has the highest correlation with the RMS amplitude. This is explained by the fact that the coherence directly reflects the amplitude decay between the adjacent traces. In turn, the coherence decay zones indicate the correlation disturbance for the adjacent traces, which allows diagnosing the breaking breaches.

3. The frequency amplitude 20 Hz has quiet high correlation (0.78–0.88) with the longitudinal conductivity and the dissipated component. However, the change of its value does not correspond to the drilling results.

4. The longitudinal conductivity by 3D TEM sounding and the seismic dissipated component have the highest correlation coefficients (0.88) and best reflect the drilling results i.e. the opening-up of the fluid-saturated fractured zones of the Kelor horizon.

5. Conclusion

The research shows that the use of the set of methods (broad-azimuth seismic survey 3D and 3D TEM sounding) makes it possible to map the target objects i.e. fluid-saturated inter-salt anisotropic cavity-
fracture reservoirs with a wide permeability range and the fluids’ expected abnormally high rock pressure in the geological section of the beds’ sedimentary cover as well as in the beds-and-periphery-sags junction zones complicating the drilling process at different stages of the geological prospecting.

References
[1] Buddo I V and Shelokov I A 2018 The foundations of the AHRP fluid-saturated zones prediction based on the integrated seismic and electromagnetic TEM prospecting Proc. 22nd Int. meeting on the underground waters of Siberia and the Far East of Russia (Novosibirsk) pp 96-101
[2] Buddo I V 2012 Thin-layer models in the study of the sedimentary cover reservoirs by a near-field electromagnetic sounding method: procedure and interpretation results (the Southern Siberian craton case study) Ph.D. thesis in geological-mineralogical sciences (Irkutsk) p 16
[3] Vakhromejev A G, Gorlov I V, Smirnov A S, et al. 2017 Neotectonic stage in Siberian craton periphery intensification as the final phase of the Kovykta oil-and-gas condensate zone formation. Geodynamic evolution of the Central Asian lithosphere shift zone (ocean-to-continent) Proc. Science meeting. (Irkutsk: Institute of the Earth's Crust of the Siberian Branch of the RAS) pp 26–29
[4] Vitjazev V V 2001 Wavelet analysis of time-domain series (Sankt-Petersburg: SPbSU) p 58
[5] Gorlov I V, Smirnov A S, Ignatjev S F, et al. 2016 New gas-promising objects in the Cambrian sediments of KGCF GeoBaikal (Irkutsk) DOI: 10.3997/2214-4609.201601706
[6] Gorlov I V, Misjurkejeva N V, Vakhromejev A G, et al. 2018 Development of a geological model for the inter-salt reservoir horizon on the basis of the geological and geophysical data Proc. 22nd Int. meeting on the underground waters of Siberia and the Far East of Russia (Novosibirsk) pp 161–166
[7] Iljin A I, Vakhromejev A G, Misjurkejeva N V, Buddo I V, et al. 2016 New Approach to the Prediction of Abnormally High Pressure in Cambrian Reservoirs of Kovykta Gas-Condensate Field GeoBaikal (Irkutsk) DOI: 10.3997/2214-4609.201601692
[8] Nikolajevsky V N 2006 Fracturing as the Earth crust genetic attribute Geology and geophysics vol. 47 5 pp 646–656
[9] Pospejev A V, Buddo I V, Agafonov Y A, et al. 2018 Contemporary practice of electromagnetic sounding (Novosibirsk: Geo) p 231 DOI: 10.21782/B978-5-9909584-1-8
[10] Ryzhov A.E., Polyakov E.E., Gorlov I V, et al. 2017 Detecting new promising objects in the salt complex sediments of the Kovykta gas-condensation zone and of the adjacent areas Proc. conf. Gas science bulletin 3 (31) pp 100–111
[11] Smirnov A S, Buddo I V, Shelokhov I A and Kasjanov V V 2018 Geophysical methods in studying the natural inter-salt Cambrian reservoirs and their fluid systems Proc. 22nd Int. meeting on the underground waters of Siberia and the Far East of Russia (Novosibirsk) pp 452–456
[12] Smirnov A S, Gorlov I V, Yaitsky N N, et al. 2016 Integration of geological and geophysical data as a way to develop a valid model of the Kovykta gas-condensate field Oil and gas geology 2 pp 56–66
[13] Aarre V, Astratti D, Dayini T N, Mahmoud S L, Clark A, Stellas M, Stringer J, Toelle B, Vejbaek O, White G 2012 Seismic detection of subtle faults and fractures Oilfield Review 24 2 pp 2–43.
[14] Buddo I V, Pospeev A V, Shelohov I A, Misjurkeeva N V, Agafonov Y A, Smirnov A S 2018 Geoelectric Model of the Section As an Integral Part of the Oil and Gas Fields Geological Model (Case Study From the Kovykta Gas Condensate Field) GeoBaikal (Irkutsk) DOI: 10.3997/2214-4609.201802044
[15] Castagna J 2006 Comparison of spectral decomposition methods First Break 24 p 75–79
[16] Chopra S, Marfurt K J 2007 Seismic Attributes for Prospect Identification and Reservoir Characterization SEG Geophysical Developments Series 11 p. 481