Understanding thin beds within the Bazhenov formation using seismic modeling

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Abstract. The Bazhenov formation (Bazhen) is a nonconventional reservoir with a very high resource potential. According to different estimates, the resources of the Bazhenov formation equal 23-160 billion bbl. Currently, only about 35 million bbl have been produced from Bazhen, which is a rather low production rate in comparison with the resource potential. The reason is the insufficient number of detailed surveys on the formation and the absence of efficient production technologies. The analog of Bazhen is the Bakken formation located in North America. This formation is being actively developed due to the presence of carbonated and sand layers in Middle Bakken. Its development strategy is horizontal well drilling and multi-stage fracturing. The thickness of the carbonated and sand layers in Bazhen are about 0.5-3 m and they cannot be identified by seismic surveys, like in Bakken, as their thickness is smaller than the seismic resolution itself. The distribution of the carbonated layer within the analyzed license areas was estimated by 2D forward seismic modeling. Fractures in well K-1 were determined as planetary fractures. The paleomagnetic investigation determined the nature of these fractures.

1. Introduction

The license blocks of interest are located in Kargasok Region of Tomsk Oblast in West Siberia. There are six exploration wells within the license areas, of which three wells have provided corresponding core data. The analyzed core data and well logs of well K-1 in the Kyleevskaya area suggest the presence of two thin carbonated beds with vertical fractures in the Bazhenov formation. Well testing indicated the presence of oil in this interval. The main challenge is to evaluate the distribution of these thin beds in the Bazhenov formation and to understand the nature of fractures that can be critical for the development of this oil shale.

The carbonated layers cannot be identified by seismic profiles due to the fact that their thickness is smaller than the seismic resolution itself. In this case there are two factors that should be considered. Firstly, the influence of the carbonated bed on the seismic record is interpreted through modeling and could be used as a qualitative indicator of lateral thin bed distribution. This indicator would determine those promising zones of carbonated bed distribution. Secondly, the thickness of these beds should be determined. As the influence of the carbonated bed on the seismic record is defined, the attribute that reflects this influence could be found. This attribute could be used as a quantitative indicator. Further, an attribute map will be plotted to indicate analyzed bed distribution zones, and then a carbonated bed thickness map plotted on the basis of this attribute map.

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2. Bazhenov oil shale

The detailed surveys on the Bazhenov formation began in the 1960s. It was studied by many researchers: F.G. Gurarii, I.V. Goncharov, Yu.N. Karogodin, A.E. Kontorovich, I.I. Nesterov, V.S. Surkov, etc. Bazhen is located in the West Siberian petroleum province within a territory of 1 million km², at the depths from 600 m to 3,500-3,800 m. Bazhen is a source rock in which the processes of oil generation from organic material (kerogen) have not been completed. The formation composition is very different, where the main organic components are liquid hydrocarbons and kerogen and non-organic – clay minerals, silica and carbonates. Today, about 70 fields with oil reserves in the Bazhenov formation have been discovered, however, they are underdeveloped due to the existing inadequate studies and lack of production technologies [1].

There are four types of kerogen divided by the composition proportion of hydrogen, carbon and oxygen. Fields that have type 1 kerogen are represented by oil, type 2 – wet gas with condensate, type 3 and 4 – dry gas. Kerogen of Bazhen refers to type 1.

The Bazhen resource potential is very high, which has been proven by the estimates of different companies. According to their estimates, the Bazhenov formation resources range from 23 to 160 billion bbl, while only about 35 million bbl have been produced from Bazhen [2]. This is very low due to the fact that the development technology of the Bazhen formation is non-efficient.

Now many researchers state that the commercial oil content of Bazhen is connected with the presence of thin compact rocks, and, in this case, the main challenge of geophysicists and geologists is to detect their lateral distribution [1, 2].

More and more attention is focused on such a point as fracturing [3]. Many researchers state that the fractures in Bazhen are not interrelated with tectonic processes [3, 4]. Trofimuk A.A. claims that fracturing (especially, vertical fractures) in Bazhen should be investigated in detail [3].

2.1. Worldwide analogs

There are several analog of Bazhen in the world: Green River, Bakken, Eagle Ford, Wolfcamp, Marcellus, Barnett, etc. The Bakken formation is the target identification as this formation is being developed very actively. The Bakken formation is a part of the Williston Basin in North America. It is located within a territory of 520,000 m². There are three main litho-stratigraphic units: Upper Bakken, Middle Bakken and Lower Bakken, where the highest production rate is within the Middle Bakken.

Production methods used in Bakken is horizontal well drilling and multi-stage fracturing. The Bakken hydrocarbon production is possible due to the presence of carbonated and sand layers in the Middle Bakken. Originally, these layers had poor reservoir properties, but multi-stage fracturing improved these properties. Long horizontal wells provide a wide drainage area. Kerogen in Bakken refers to type 1 and, partially, to type 2.

Due to the similarities between Bazhen and Bakken formations and the successful development activities in Bakken, many researchers proposed developing Bazhen taking into consideration Bakken development experience, i.e. horizontal well drilling and multi-stage fracturing [1, 2]. However, the main difference is reservoir thicknesses and their distribution. In the Bakken formation, reservoir rocks have thickness of 40 m and even more and are located between thin organic-rich rocks. In Bazhen reservoir rocks are about 0.5-3 m thick and are located within several stratigraphic layers.

If the 40-meter section of the Bakken reservoir could be determined by seismic methods, then, in the case of the thin reservoir layers of Bazhen formation, their thickness is beyond the range of resolution (less than one-fourth of the wavelength) and cannot be determined. Therefore, Bakken development strategy is not applicable in the Bazhen formation. First and foremost, it is essential to provide additional data in order to understand how to detect these thin Bazhen reservoir beds.
3. Seismic working modeling

As stated above if the layer thickness is less than the seismic resolution, information on the existing layer is encoded in the composite reflection amplitude [5]. Field & research service company LM Gochioco Inc. provides information on how thin layer thickness can be estimated by the response effect. The described research involved 2D forward seismic models to determine thin carbonated layers. Based on the data of layer velocities and formation thickness, the linear interpolation of formation properties between reference sections was computerized. Modeled seismic traces were produced as a consequence of convolution between acoustic velocities and synthetic wavelet.

The first step of modeling is to design litho-acoustic models of the wells, including well logging interpretation to determine lithology. The following formation velocity values were used in calculations: coal – 2,500 m/sec, Bazhen bituminous argillite – 3,000-3,300 m/sec, Georgiev formation argillite – 3,300 m/sec, argillite – 4,000 m/sec, carbonated siltstone – 5,000 m/sec, sandstone – 4,400 m/sec, carbonated sandstone – 5,000 m/sec. These values were used to define the rock acoustic properties that directly influence the wave pattern generation and in correlation with the petrophysical core data analysis of rocks with different lithological characteristics from Tomsk Oblast.

This modeling process will be shown on the example of well K-1, which, in its turn, embraces 2 carbonated layers. The litho-acoustic well model of the studied interval is represented in figure 1.

![Litho-acoustic model of well K-1](image)

**Figure 1.** Litho-acoustic model of well K-1

The studied interval is Bazhen formation. The influence of the Bazhen carbonated layer on the generation of reflections in seismic traces will be determined. This influence can be expressed in reflections that correspond to the Bazhenov formation, the Bazhen bottom or in reflections referring to the neighboring layers. Therefore, modeling was not limited to the Bazhen boundaries. The layers that are 50 m higher than Bazhen and 150 m lower were also included in the modeling.

To predict the influence of the carbonated layer on the wave pattern, 2D forward modeling was performed with the involvement of synthetic wells. In these wells, the different carbonated layers thicknesses were assigned: from 0 to 6 m (figure 2). It is a good demonstration of the influence of the carbonated layer on the wave pattern. The presence of this layer is characterized by the two-phase reflection record of that corresponding to reflector IIa – bottom of Bazhen.
The presence of a carbonated layer in the IIa phase change from one-phase wave to two-phase wave was also proved in the modeling of other wells. However, this change can be caused by another factor. It can be the changing position of the carbonated layer, a variation in Bazhen thicknesses or coal pinching out under Bazhen. In this case, all modeled situations should be checked to determine whether they caused the phase transformation or not and then be analyzed.

Apart from one-phase to two-phase change of the IIa wave, another factor can be identified. After the increase in the carbonated bed thickness, the travel time between reflector Ib2 and the negative amplitude above reflector IIa also increases (figure 3).

Consequently, the isochron thickness attribute defined as the time difference between two horizons can be used as a quantitative indicator. This attribute was calculated in the zones of carbonated bed distribution. Then, the attribute map was plotted in order to design a carbonated layer thickness map. In well K-1, the thickness of the two carbonated beds is 2.2 m. The value of the attribute in well K-1 is 26.3. A thickness map was plotted based on this data. The average thickness of the carbonated bed is 2 m.

Figure 2. Determination of carbonated bed influence. A – Geological section. B – Litho-acoustic model. C – 2D seismic model.

Figure 3. Quantitative indicator of the carbonated bed.
4. Planetary fracturing

As already mentioned above, fractures in well K-1 are vertical and located only in one layer. Factors suggest that these fractures are planetary. The generation of planetary fracturing is interrelated with tension conversion in the faulting resulting in caused depositions, which, in its turn, is a consequence of Earth rotation activity. Planetary fracturing was studied for Russian and North American plates by Parker (1942), Shtatsky (1945), Permyakov (1946), Novikova (1952), Rac (1970), Dolitsky (1978) and et al.

These fractures have the following features:
- located both in folded and horizontal layers.
- form orthogonal systems.
- not connected with tectonic structures.
- more pronounced in compacted rocks where they are perpendicular to bedding and located only within one bed.
- relationship between fracture spacing and layer thickness.

According to the studies conducted by K.I. Mikulenko, the Jurassic and Neocomian rock fractures in the south-east West-Siberian petroleum play are divided into three orthogonal systems with the following azimuths: 335 and 65, 295 and 25, 270 and 0 degrees [7]. They correspond to the planetary fracturing described by Schultz. The Mikulenko findings are also matched with the directions of global rotational field tensions according to V.D. Dolitsky (figure 4).

To confirm which fractures in the carbonated layer in well K-1 are planetary, a paleomagnetic survey was conducted to identify the direction of the fractures. The direction was compared with the survey results obtained by Mikulenko and Shultz.

The paleomagnetic survey included the following steps:
1. Preparation of samples. Two core samples were from the interval of the carbonated layer. In these samples, an arbitrary coordinate system (in this sample) was introduced into the next magnetic measurements.
2. Magnetic measurements were performed by the MAL-036 astatic magnetometer at a TPU laboratory.
3. The samples were demagnetized to balance the external magnetic field, through Aparin thermal oven. The thermo-demagnetizing step was 25°C, while the final heating temperature was 125°C, the diapason viscous component of natural permanent magnetization is often destroyed at this temperature.
4. The obtained experiment results were used in the calculation of the vector differences to estimate the direction of viscous magnetism caused by the present geomagnetic field and equal to it. This data was used to determine the core dimensional orientation.

The paleomagnetic surveys showed that the fracture azimuths are 344° and 346° (figure 5). These values are similar to the fracture azimuths in the Lower Cretaceous deposits, i.e. 335° (figure 4). As
Bazhenov formation is related to the Late Jurassic and the formation top - to the Early Cretaceous, this could explain the similarities of the fracture azimuths in the investigated carbonated layer and the Lower Cretaceous deposits, according to Mikulenko. It should be noted that measurement errors in paleomagnetic studies may be up to 8°.

The vertical fracture orientation, their relation to specific lithological characteristics and the similarities of the fracture direction to the directions of planetary fractures (according to К.I. Mikulenko and S.S. Schultz) could explain the fact that the fractures in the Bazhen carbonated bed are planetary. Based on the calculated value of an average carbonated layer thickness and relationship of R, the fracture spacing in this bed could be determined. Therefore, according to this dependence, fracture spacing for a 2-meter bed is 2.9 m.

It should be noted that according to the well testing results, well K-1 produces water and oil. The oil chemical properties are identical to Bazhenov oil properties. Such planetary fractures may influence oil production within an interval. The fracture direction ensures the possible identification of productive zones based on seismic surveys or further design of EOR techniques.

5. Conclusion

1. It was proved that the smaller thicknesses the thin beds are, then the seismic resolution can be detected with 2D advanced seismic modeling. The zones of bed distribution can be determined by a qualitative indicator, while the quantitative indicator could estimate the bed thickness;
2. Based on seismic record data the influence of a thin carbonated layer was determined. The zones of its distribution were also defined. The map of promising carbonated bed thicknesses was plotted on the basis of the isochron thickness attribute. The average thickness within the investigated license areas is 2 m. The sign of a carbonate layer can be traced based on a 2D seismic forward model;
3. Fractures in carbonated layers were identified as planetary fractures. The paleomagnetic study showed the direction of these fractures. Based on the stated relationship between fracture spacing and bed thickness, fracture spacing for the layer under consideration was determined. For a 2-meter bed, fracture spacing is 2.9 m. Fracture spacing decreases to bed thickness decrease. For 0.8-meter carbonated bed in well K-1, fracture spacing is 1.3 m;
4. All studies in proposed license areas were considered to be conventional reservoirs. The research results proved the prospects of nonconventional reservoir within the territory of such license areas;
5. This approach based on the visual analysis of the wave pattern could be proposed for thin layer determination.
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